Detector summary

Abstract

1 Segmented Magnetic Detectors

In a Neutrino Factory the $\nu_e \rightarrow \nu_\mu$ oscillation channel, the so-called golden channel, provides the cleanest experimental signature, since it only requires the detection of "wrong-sing muons" (ws-muon) – muons with the opposite charge to those circulating in the storage ring – in a detector with charge measurement capabilities. Muon reconstruction is well understood and can be performed with high efficiency keeping a negligible background level. The main backgrounds for the ws-muon search are [1]:

- right-charge muons whose charge has been misidentified, in $\overline{\nu}_\mu$events.
- ws-muons from hadron decays in $\overline{\nu}_\mu$or $\nu_e$neutral current events,
- ws-muons from hadron decays in $\overline{\nu}_\mu$or $\nu_e$charge current events when the main lepton is not identified.

A detector aiming to study the golden channel should be able to identify muons and measure their momenta and charge with high efficiency and purity. Magnetized iron calorimeters have been considered in the past [?, 2, 3]. The ws-muon detection efficiency can be kept above 50% for a background level of the order of 10^{-5}. This kind of detectors is extremely powerful for the measurement of very small θ_{13}, reaching values of $sin^2(2\theta_{13})$ below 10^{-4}. However, they may have troubles in studiying CP violation because the high density of the detector prevents the detection of low energy neutrinos (< 5 GeV), which could provide a very valuable information for the simultaneuous measurement of δ_{CP} and θ_{13}. An alternative to iron calorimeters has been recently considered. A magnetised version of Totally Active Scientillator Detectors (TASD), as NOνA [?], could be very efficient for the ws-muon search, even for neutrino energies of the order of the GeV.

1.1 Magnetised Iron Calorimeters

The wrong-sign muon search at a neutrino factory requires a very massive detector with good muon and muon charge identification capabilities. Magnetic Iron Calorimeters can fulfill these requirements using well known technologies [1]. Two complementary studies have being conducted so far: LMD [1] and Monolith [2]. Recently, a new option, INO [?] similar to Monolith has been proposed to study the golden channel at 7000 Km.

The LMD detector is a sandwich of iron (4 cm) and scintillator bars (1 cm) with a size of $20 \times 20 \times 20\ m^3$ and a mass of 40 $Ktons$. The Monolith detector is made of iron slabs (8 cm) interleaved with glass RPC counters (2.2 cm) forming a structure of $13.1 \times 14.5 \times 30\ m^3$ with a mass of 35 $Ktons$. The LMD study is based in a fast simulation with the smearing parameters of the MINOS proposal [4] while the Monolith study is based in a full simulation.

Both detectors have similar backgrounds: primary muons with the charge misidentified and muons from the hadronic shower (hadron misidentification and hadron decay) in events with no primary lepton detected.

The identification of muons in done by range. Fig. 1 shows the distribution of the length traveled by the longest hadron in the LMD detector. More than 99.9% of the hadrons are below 3 meters, which is the average distance traveled by a muon of 3 GeV/c.

To measure the charge of the muon LMD uses a dipole field of 1 $Tesla$ and Monolith has a toroidal field of 1.3 $Tesla$. Fig. 3 shows the charge misidentification rate for different configurations of the LMD detector. The distance between measurement planes turns out to be the crucial parameter to be optimised. The results obtained by the Monolith group are comparable: a cut of 7.5 GeV/c in the muon momentum gives a charge misidentification rate of 1×10^{-6} for an efficiency of 35%.

Muons from the decay of hadrons constitute the leading background. Fortunately, "real" wrong-sign muons (from oscillated ν_e's) will be in general more energetic and more isolated from

---

[1] They are conceptually similar to existing MINOS detector [4], but with a mass one order of magnitude larger.

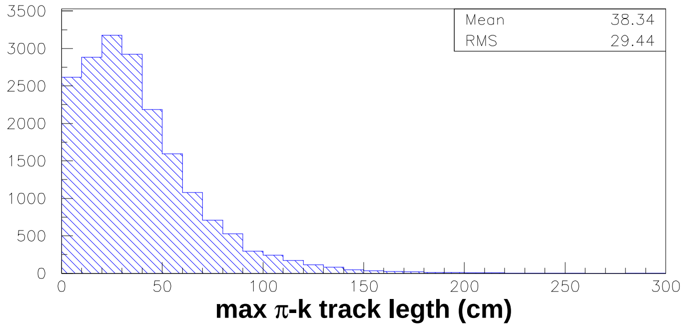

Figure 1: Length of the longest hadron in the LMD detector.

the hadronic jet. Thus, this background can be controlled to a reasonable level by a a combined cut in the momentum of the muon (P_μ) and its angle with respect to the hadronic shower (θ). This is shown in Fig. 4 for the LMD detector. For a baseline of 3500 Km the optimal cuts are $P_\mu > 5\ GeV/c$ and $Q_t > 0.7\ GeV/c$ ($Q_t = P_\mu \cdot sin^2\theta$), which give a total background rate of 8×10^{-6} for an efficiency of 45%.

It has being frequently pointed out that the detection of low energy neutrinos is important for the simultaneous measurement of θ_{13} and δ_{CP}, what prevent us of applying a strong P_μ cut. To reduce this cut keeping constant the signal to noise ratio one needs to improve the P_μ and θ resolutions, which depend strongly on the distance between measurement planes. The θ resolution is dominated by the hadronic angular resolution ($\delta\theta_{had}$), which was studied by the Monolith group in a test beam [5]. For a spacing of 7 cm they found $\delta\theta_{had} = 10.4/\sqrt{E(GeV)} + 10.1/E$ (see Fig. 2), which is significantly better than the resolution assumed by LMD for a spacing of 5 cm, $\delta\theta_{had} = 16.67/\sqrt{E} + 12.15/E$. Although a detailed study of the neutrino detection efficiency as a function of its energy is still missing, this result ensures a good efficiency down to $\sim 5\ GeV$. Another option is the use of iron free regions devoted to the measurement of the muon momentum and charge [**?**].

1.2 Totally Active Scientillator Detectors

The possibility of using totally active calorimeters in a Neutrino Factory was first cosidered at Nufact05 [6]. The detector would be a magnetised version of NOνA: alternative planes of triangular liquid scientillator bars running along x and y coordinates. The readout is done with wave length shifter fibers and APDs. A toroidal field of 1.5 T ensures the measurement of the muon momentum and charge. The low density of the detector together with the fine granularity (∼ 1 cm transverse resolution) should allow an efficient measurement of the muon charge down to less than 1 GeV/c. The mass of the detector would be of the order of 100 Kt.

TO BE COMPLETED.

2 Large Water Cerenkov detectors

Since the pioneering age of Kamiokande and IMB detectors, and after the success of the Super-Kamiokande detector (extension by a factor 20 with respect to the previous detectors), the physicist community involved in this area is continuously growing in the three geographical regions namely Japan, USA and Europe.

To strengthen the know how and R&D exchanges, a series of International Workshops have been set up since 1999, the so-called NNN Workshop standing for "Next Nucleon Decay and

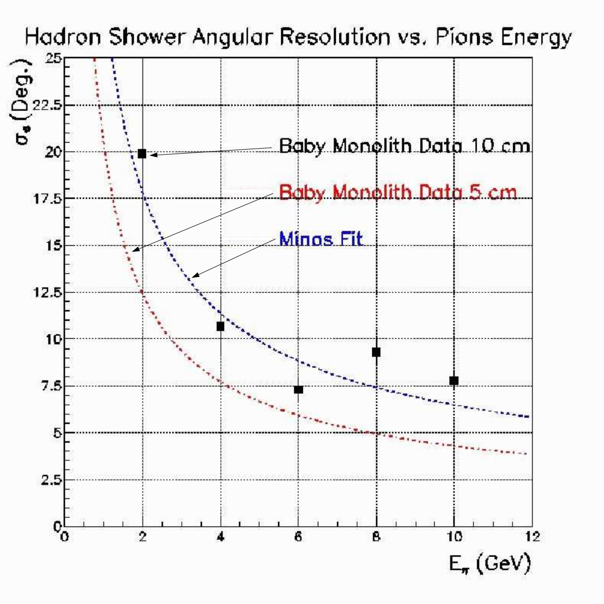

Figure 2: Hadronic angular resolution of the Monolith prototype for two different configurations: 5 *cm* and 10 *cm* of iron (+2 *cm* of RPCs).

Neutrino Detectors". The last meeting was organized at Aussois (France) in 2005, and for the two next years, the workshop will held at Seattle (USA 06) and at Hamamatsu (Japan 07). As, it is clearly stated in the title of this Workshop, detection techniques other than Water Cerenkov are also considered as for instance Liquid Scintillator, Liquid Argon as well as Iron detectors.

Also, if the pioneer Water Cerenkov detectors were built to look for Nucleon Decay, a prediction of Grand Unified Theories, the Neutrino physics has been the bread and butter since the beginning. Just to remind the glorious past: first detection of a Super Novae neutrino burst, Solar and Atmospheric anomalies discovery that was explained as mass & mixing of the neutrinos, the latter being confirmed by the first long base line neutrino beam.

Nucleon decay and neutrino physics are so closely theoretically linked (ie. most if not all of the GUT theories predict nucleon to decay and neutrinos to have non zero masses & mixings) that are for sure area of equally strong interest to motivate the R&D program extension of the next generation Water Cerenkov mass to megaton scale (about a factor 20 more than SuperKamiokande). So, one should keep in mind that the ISS framework tends to reduce the physics potential of such detector: nucleon decay, supernovae neutrinos from burst and from relic explosion, solar & atmospheric neutrinos, long base line low energy neutrinos (beta beam, super beam and combined with atmospheric neutrinos) and other astrophysical aspects.

The scalability and robustness of Water Cerenkov detector are well established and the R&D efforts are concentrated in two engineering aspects: the excavation of large cavities, and the cost reduction of the photodetectors. The addition of Gadolinium salt once it will be safely used in 1kT prototype and after in SuperKamiokande, then it could be a decisive ingredient for the new detectors, especially for neutrinos from Supernovae.

2.1 The present detector design

Up to now the three geographical regions comes with three detector design with a fiducial mass around 500kt. Some characteristics are presented in table 1.

The Japanese design (Fig.5) is based on two twin tunnels with 5 optically independent cylindrical compartments, each 43 m in diameter and 50 m long each covered by about 20,000 photode-

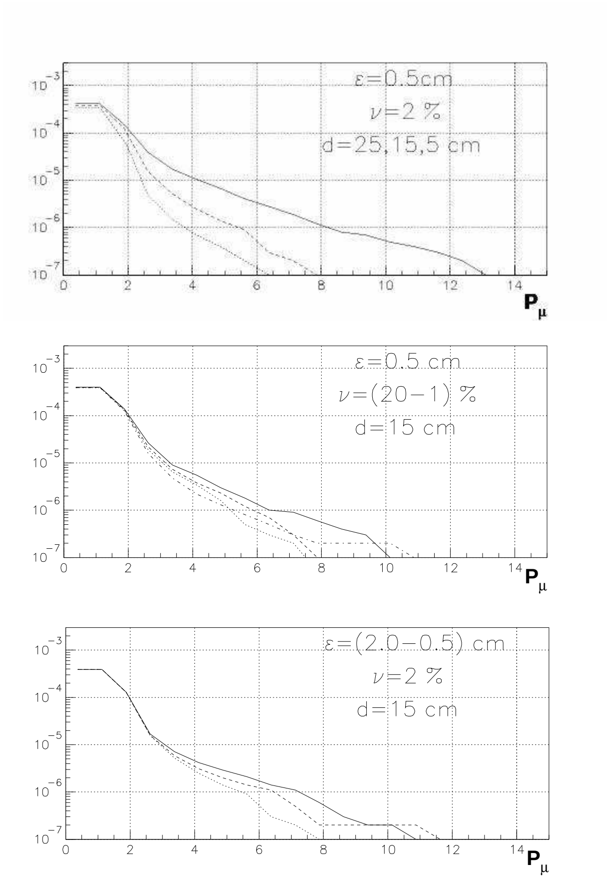

Figure 3: Charge misidentification background as a function of momentum for different configurations of the LMD detector. ε is the transverse resolution, ν is the hit finding inefficiency and d the distance betweeen measurement planes.

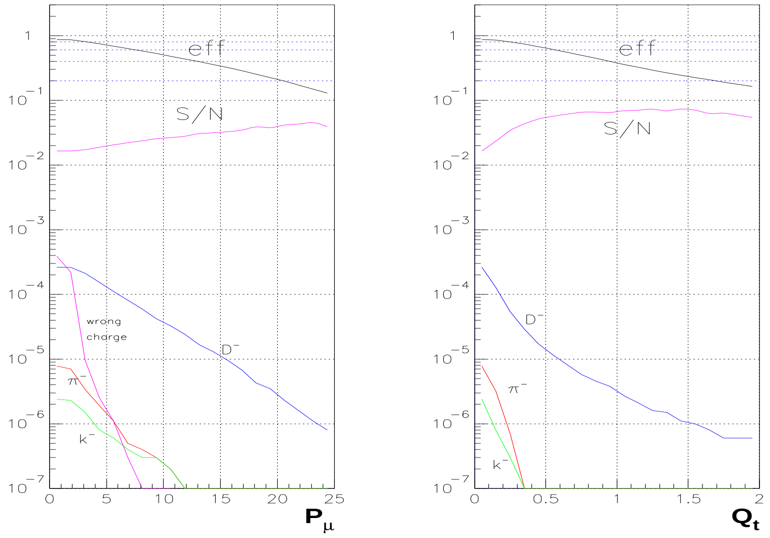

Figure 4: Fractional backgrounds from hadron decays as a function of P_μ (left) and Q_t (right) for $\overline{\nu}_\mu$CC interactions (for 50 GeV/c stored μ^+'s). The charge misidentification rate is also shown on the left. Similar plots for $\overline{\nu}_\mu$+ν_eNC and ν_eCC interactions can be found in [1].

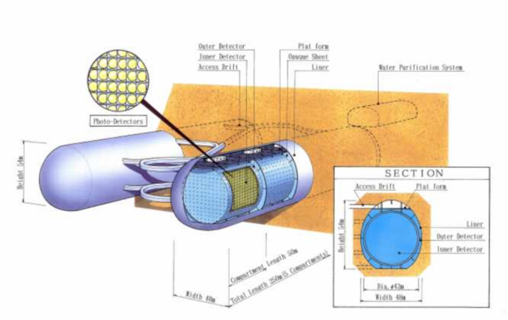

Figure 5: Sketch of the Hyper-K detector (Japan).

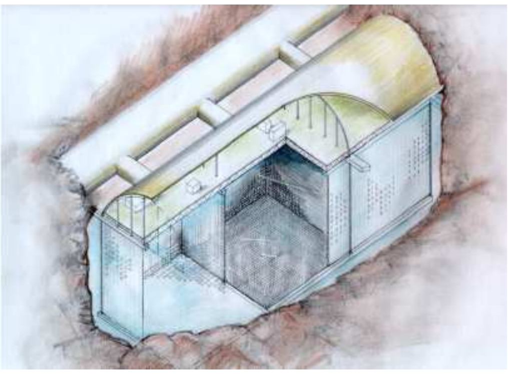

Figure 6: Sketch of the UNO detector (USA).

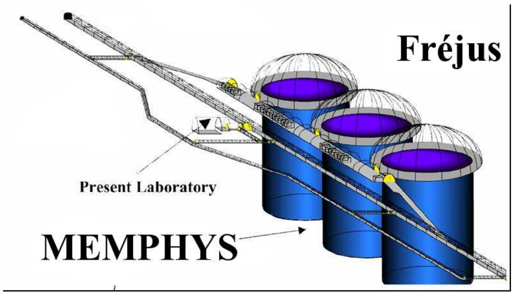

Figure 7: Sketch of the MEMPHYS detector under the Frjus mountain (Europe).

tectors to realize a 40% surface coverage. The US design (Fig.6) is composed by 3 cubic optically independent compartments ($60 \times 60 \times 60$ m^3). The inner detector regions are viewed by about 57,000 20" PMTs, with a photocathode coverage of 40% for the central compartment and 10% for the two side compartments. A outer detector serves as a veto shield of 2.5 m depth and is instrumented with about 15,000 outward-facing 8" PMTs. The European design (Fig.7) is based on up to 5 shafts (3 are enough for 500kt fiducial mass), each 65 m in diameter and 65 m height for the total water container dimensions. The PMT surface defined as 2 m inside the water container is covered by about 81,000 12" PMTs to reach a 30% surface coverage equivalent to a 40% coverage with 20" PMTs (see sec. 2.3). The fiducial volume is defined by an additional conservative guard of 2 m. The outer volume between the PMT surface and the water vessel is instrumented with 8" PMTs.

2.2 Underground large cavities

All the detector projects are located in underground laboratories. The water equivalent depth of the different detectors sites are: $\approx$ 1500 m.w.e for the Tochibora mine in Japan, and around 4200 m.w.e for the Homestake or Henderson mines (the two remaining sites after NSF decision for DUSEL possible site candidates) in the USA, and $\approx$ 4800 m.w.e for the Frjus road tunnel in Europe. A deeper site, so fewer cosmic ray induced background, is especially important in the case of relic supernovae and solar neutrinos, but in case of nucleon decay the detector segmentation may help also.

The main difficulty is the non existence of yet man made large cavities (see Tab. 1) at depth envisaged. But on an other hand, there are no a priori indications that one could not built such large cavities and engineering studies are undertaken in the three geographical regions. In Japan, a preliminary survey of the candidate place for Hyper-K is already done, and the rock properties at the Tochibora mine have been checked. The cavity model has been analyzed in the real environment. The egg transversal shape and the twin tunnels scenario is envisaged as baseline for Hyper-K. In the US, various engineering models have been used by different consultants. It turns out that with the present knowledge UNO cavity seems feasible, although a more refined work with experimental inputs from rock quality measurements and geological faults knowledge in situ is needed to go further in the project design. In Europe, a pre-study have been performed too by the Italian and French companies involved in the building of the existing road tunnel. These companies have taken advantage of the numerous measurements made during the excavation of the present road tunnel and (relatively small) LSM Laboratory to establish a valid estimation of the rock quality as input for simulations. The main outcome of this pre-study is that very large cavities with a "shaft" shape is feasible, while a "tunnel" shape looks disfavored. The next step that can be undertaken in an European Founding framework, is to validate the rock quality at the exact detector location and to finalize the cavities detailed shape and access tunnels in close conjunction with the detector design optimization.

Beyond the cavity shape and excavation scenario optimization, there is the need of an extensive R&D on water container (vessels versus multi-liners). This is an important aspect for radioactivity background suppression and also in detector mechanical design with its associate impacts on detector cost.

2.3 Photodetector R&D

The surface coverage by photodetector is not yet optimized as more feedback are needed from SuperKamiokande I-II and III phases analysis and from MC studies of the foreseen detectors. Nevertheless, one may already state that the very low energy neutrino events (Super Novae neutrinos, ^{8}B Solar Neutrinos) as well as the search of π^0 in Nucleon Decay or the π^0/e separation in ν_e appearance experiment are all demanding on good coverage.

In all the detector design there are at least one order of magnitude more photodetectors than SuperKamiokande I (or III). The R&D is largely shared among the three regions and in very close contact with the two manufacturers, namely Hamamatsu in Japan and Photonis in Europe and USA (since July 05, Photonis had inquired DEP and Burle companies).

The research axis on large HPDs in Japan has been mainly driven by the need to get a lower price for a new photodetector than the presently available Hamamatsu 20" PMTs, especially to get ride of the dynode amplifier system which is introduced manually in such a tube. Their measured characteristics are encouraging: single photo-electron sensitivity, wide dynamic range limited only by the readout, good timing and good uniformity over the large photo-cathod. But these HPD needs to be operated at 20kV High Voltage and a low noise fast electronics. So, the cost per channel is a real challenge.

In Europe, Photonis is very competitive on 12" PMTs and argue that the main parameter to optimize is the $cost/(cm^2 \times QE \times CE)$ electronic included. Some French laboratories are involved with Photonis in a joined R&D concerning the 12" characteristics measurements and improvements and also concerning the integrated electronic Front-end. The main idea is to adopt smart-photodetectors which provide directly digitized data. The front-end requirements are: a High speed discriminator for autotrigger on single photo-electron, a coincidence logic to reduce dark current counting rate (to be defined by MC studies), a digitization of charge over 12 bits with a dynamical range up to 200p.e, a digitization of time of arrival over 12 bits to provide nano-second accuracy, a variable gain to equalize photomultiplier response and operate with a common high voltage (cost reduction). This electronic R&D takes advantage from the past years R&D and concrete realizations for OPERA, LHCb, WSi calorimeter for ILC...

3 The GLACIER project

The liquid Argon Time Projection Chamber (LAr TPC) [7, 8, 9, 10, 11] is a powerful detector for uniform and high accuracy imaging of massive active volumes. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

A very large LAr TPC with a mass ranging from ≈ 10 to 100 kton would deliver extraordinary physics output owing to the excellent event reconstruction capabilities. Coupled to future Super Beams [12], Beta Beams or Neutrino Factories it could greatly improve our understanding of the mixing matrix in the lepton sector with the goal of measuring the CP-phase. At the same time, it would allow to conduct astroparticle experiments of unprecedented sensitivity [13]. Preliminary simulations show that a "shallow depth" operation at about 200 m rock overburden would not significantly affect the physics performance, including the astrophysical observations.

The possibility to complement the features of the LAr TPC with those provided by a magnetic field would open new possibilities [14, 15]: charge discrimination, momentum measurement of particles escaping the detector (*e.g.* high energy muons), and precise kinematics. The magnetic field is required in the context of the Neutrino Factory [14]: (1) a low field, *e.g.* B=0.1 T, for the measurement of the muon charge (CP-violation); (2) a strong field, *e.g.* B=1 T for the measurement of the muon/electron charges (T-violation).

A concept for a liquid Argon TPC, scalable up to 100 kton, has been proposed [16]. It relies on (a) industrial tankers developed by the petrochemical industry (no R&D required, readily available, safe) and their extrapolation to underground or shallow depth LAr storage, (b) novel readout method for very long drift paths with e.g. LEM readout, (c) new solutions for very high drift voltage, (d) a modularity at the level of 100 kton (limited by cavern size) and (e) the possibility to embed the LAr in a magnetic field.

Such a scalable, single LAr tanker design is the most attractive solution from the point of view of physics, detector construction, operation and cryogenics, and finally cost. The first experimental prototype of a magnetized liquid Argon TPC has been operated [17, 18]. These encouraging results allow to envision a large detector with magnetic field [19]. Beyond the basic proof of principle, the main challenge to be addressed is the possibility to magnetize a very large mass of Argon, in a range of 10 kton or more. The most practical design is that of a vertically standing solenoidal

Parameters	**UNO** (USA)	**HyperK** (Japan)	**MEMPHYS** (Europe)
Underground laboratory			
location	Henderson / Homestake	Tochibora	Frjus
depth (m.e.w$\pm$5%)	4500/4800	1500	4800
Long Base Line (km)	$1480 \div 2760$ / $1280 \div 2530$	290	130
	FermiLab$\div$BNL	JAERI	CERN
Detector dimensions			
type	3 cubic compartments	2 twin tunnels 5 compartments	$3 \div 5$ shafts
dimensions	$3 \times (60 \times 60 \times 60)\text{m}^3$	$2 \times 5 \times (\phi = 43\text{m} \times L = 50\text{m})$	$(3 \div 5) \times (\phi = 65\text{m} \times H = 65\text{m})$
fiducial mass (kt)	440	550	$440 \div 730$
Photodetectors[†]			
type	20” PMT	20” H(A)PD	12” PMT
number	38,000 (central) & 2×9500 (sides)	20,000 per compartment	81,000 per shaft
surface coverage	40% (central) & 10% (sides)	40%	30%
Cost & Schedule			
estimated cost	500M$	500 Oku Yen?[*]	161M per shaft (50% cavity) + 100M-infrastructure
tentative schedule	$\sim$ 10 yrs construction	$\sim$ 10 yrs construction	$t_0^{**} + 8$ yrs cavities digging $t_0 + 9$ yrs PMTs production $t_0 + 10$ yrs detectors installation Start of Non Accelerator Prog. as soon as a shaft is commissioned

Table 1: Some basic parameters of the three Water Cerenkov detector baseline designs. [†]: Only inner detector photodetectors are mentioned in this table. *:Target cost, no realistic estimate yet.**: The t_0 date envisaged is 2010.

coil producing vertical field lines, parallel to the drift direction, by immersing a superconducting solenoid directly into the LAr tank.

A rich R&D program is underway with the aim of optimizing the design of future large mass LAr TPC detectors [20] and is briefly summarized below.

The development of suitable charge extraction, amplification and collection devices is a crucial issue and related R&D is in progress. A LEM-readout is being considered and was shown to yield gains up to 800 at high pressure with good prospects for operation in cold. A preliminary resolution of about 28% FWHM has been obtained for a ^{55}Fe source. The experimental results agree with those expected from simulations.

The understanding of charge collection under high pressure for events occurring at the bottom of the large cryogenic tanker is also being addressed. For this purpose, a small chamber will be pressurized to 3-4 bar to simulate the hydrostatic pressure at the bottom of a future 100 kton tanker, to check the drift properties of electrons.

Another important subject is the problem of delivering very high voltage to the inner detectors trying to avoid the use of (delicate) HV feedthroughs. A series of device prototypes were realized based on the Greinacher or Cockroft-Walton circuit allowing the feeding into the vessel of a relatively low voltage and operation of the required amplification directly inside the cryogenic liquid. Tests reaching 120 kV in cold have been successfully performed.

The realization of a 5 m long detector column will allow to experimentally prove the feasibility of detectors with long drift path and will represent a very important milestone. The vessel for this detector has been recently designed (Fig. 8) and constructed at INFN Napoli in the framework of a INFN-ETHZ collaboration. The device will be operated with a reduced electric field value in order to simulate very long drift distances of up to 20 m. Charge readout will be studied in detail together with the adoption of possible novel technological solutions. A high voltage system based on the previously described Greinacher approach will be implemented.

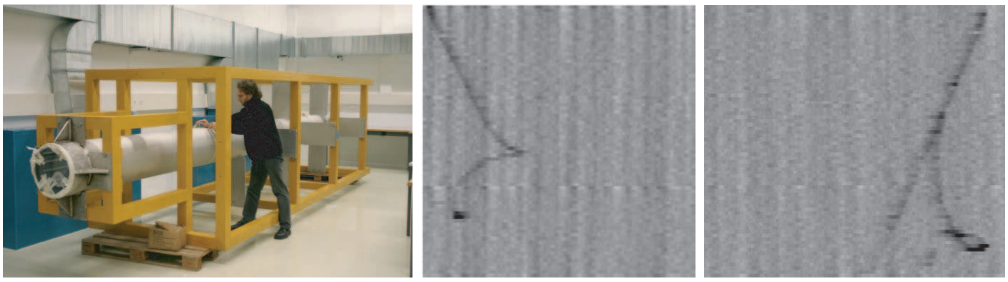

Figure 8: (left) Cryostat for the 5 m long drift test (ARGONTUBE) (right) Cosmic-ray events taken with the LAr TPC detector in magnetic field.

For the immersed magnetic coil solenoid, the use of high-temperature superconductors (HTS) at the liquid Argon temperature would be an attractive solution, but is at the moment hardly technically achievable with the 1st generation of HTS ribbons. We have started an R&D program to investigate the conceptual feasibility of this idea [21] in collaboration with American Superconductor [22].

Technodyne International Limited, UK [23], which has unique expertise in the design of LNG tankers, has produced a feasibility study in order to understand and clarify all the issues related to the operation of a large underground LAr detector. The study led to a first engineering design, addressing the mechanical structure, temperature homogeneity and heat losses, liquid Argon process, safety, and preliminary cost estimate. Concerning the provision of LAr, a dedicated, likely not underground but nearby, air-liquefaction plant was foreseen.

The further development of the industrial design of a large volume tanker able to operate underground should be pursued. The study initiated with Technodyne should be considered as a first "feasibility" step meant to select the main issues that will need to be further understood and to promptly identify possible "show-stoppers". This work should proceed by more elaborate and detailed industrial design of the large underground (deep or shallow depth) tanker also including the details of the detector instrumentation. Finally, the study of logistics, infrastructure and safety issues related to underground sites should also progress, possibly in view of the two typical geographical configurations: a tunnel-access underground laboratory and a vertical mine-type-access underground laboratory.

In parallel, a program to study the technical feasibility of large scale purification system needed for the optimal operation of the TPC is being planned in collaboration with the cryogenic department at Southampton University (UK) and the Institut für Luft und Kältetechnik (ILK, Dresden, Germany).

The strategy to eventually reach the 100 kton scale foresees an R&D program leading to the detailed design study for a tentative 100 kton non-magnetized and 25 kt magnetized detector, including cost estimates. A 1 kton engineering module could be foreseen to investigate the tanker concept, large scale purification, shallow depth operation, etc. A 10 kton detector would have complementary physics reach of the currently operating Superkamiokande detector.

4 On a possible magnetized ECC (MECC) detector operating at a Neutrino Factory

4.1 Introduction

The ideal detector for a Neutrino Factory should be able to exploit all the oscillation channels that are available thanks to the well know neutrino flux composition. Namely, the oscillations $\nu_e \to \nu_\mu$ (the so called golden channel), $\nu_e \to \nu_\tau$ (the so called silver channel), $\bar{\nu}_\mu \to \bar{\nu}_e$, $\bar{\nu}_\mu \to \bar{\nu}_\tau$ when a μ^+ circulate into the decay ring and their CP conjugates in the case of a μ^-. Therefore, the ideal detector should be able to:

- measure the momentum and the charge of the leptons (electrons and muons);
- identify the decay topologies of the τ leptons;
- perform a complete and accurate kinematical reconstruction of neutrino events.

So far, the previous tasks have been tackled by using different techniques. A magnetized iron calorimeter has been (is being) optimized for the study of the golden channel: the muon detection and the charge determination have been studied aiming at a high efficiency and a small pion to muon misidentification probability. A detector *à* la OPERA, based on the ECC technique, has been proposed to search for the silver channel through the direct detection of τ decay topologies. Nevertheless, the task of identifying electrons and of measuring their charge is very tough and so far only a study based on a magnetized liquid argon detector has been presented.

In this paper we discuss the idea of using an ECC detector placed in a magnetic field. This combination provides a detector with very good charge reconstruction and momentum determination capabilities, keeping at the same time the high accuracy and compactness of an ECC. The design of the detector is done with the ambitious aim to fulfill all the requirements that should have the ideal detector for a Neutrino Factory.

The paper is organized as follow: first we briefly recall the basic performances of an ECC, then we discuss the layout of an ECC-based detector to be operated immersed into a magnetic field and operating with a Neutrino Factory. Finally, we summarize the present understanding of the performances of such a detector and discuss the future work.

4.2 Hybrid Emulsion Detector

The Emulsion Cloud Chamber (ECC) concept, a modular structure made of a sandwich of passive material plates interspersed with emulsion layers, combines the high-precision tracking capabilities of nuclear emulsions and the large mass achievable by employing metal plates as a target. By assembling a large quantity of such modules, it is possible to conceive and realize $\mathcal{O}(Kton)$ fine-grained vertex detector optimized for the study of ν_τ appearance. It has been adopted by the OPERA Collaboration for a long-baseline search of $\nu_\mu \to \nu_\tau$ oscillations at the CNGS beam through the direct detection of the τ's produced in ν_τ charged current interactions.

The basic element of the OPERA ECC is a “cell” made of a 1 mm thick lead plate followed by a thin emulsion film which consists of 44 μm-thick emulsion layers on either side of a 200 μm plastic base. The number of grains hits in each emulsion layer (15-20) ensures redundancy in the measurement of particle trajectories and allows the measurement of their energy loss that, in the non-relativistic regime, can help to distinguish between different mass hypotheses.

Thanks to the dense ECC structure and to the high granularity provided by the nuclear emulsions, the detector is also suited for electron and γ detection. The energy resolution for an electromagnetic shower is about 20%. Nuclear emulsions are able to measure the number of grains associated to each track. This allows a two-track separation at ~ 1 μm or even better. Therefore, it is possible to disentangle single-electron tracks from electron pairs coming from γ conversion in lead. This outstanding position resolution can also be used to measure the angle between different track segments with an accuracy of about 1 mrad: this allows the use of Coulomb scattering to evaluate the particle momentum with a resolution of about 20%, and to reconstruct the kinematical event variables.

A lead-emulsion detector has been also proposed to operate at a Neutrino Factory to study the “silver channel” $\nu_e \to \nu_\tau$. It is identical to OPERA but with a total mass of 4 kton. The main limitation factor of this detector is the impossibility to measure the charge of all particles but the muon. This has strong drawbacks on the fraction of the τ branching ratio can be exploited, only 20% (the muonic decay branching ratio) is measurable, on the possibility to measure the electron charge and on the possibility to further reduce the background. A magnetized ECC detector will enable the measurement of all quantities discussed before.

4.3 The Magnetized Emulsion Cloud Chamber (MECC)

The proposed Magnetized Emulsion Cloud Chamber (from now MECC) has the following modular structure (see Figure 9): the upstream part (called *target*) is a sandwich of passive plates and nuclear emulsions used as tracking devices. The passive plate has to fulfill the requirement to provide most of the mass with a relatively long radiation length. The optimization of the passive material is still undergoing. Here we present here the lead as a possible choice. The length of the *target* section has to be a few X_0's: this number should be optimized preventing the majority of the electrons to shower before their charge has been measured by the downstream modules.

Downstream of the *target*, we have placed a *spectrometer*: it consists of a sandwich of nuclear emulsions and very light material that we call ”spacer”. This name indeed indicates that the functionality of this material is to provide a ”long” level arm between two consecutive emulsions (tracking devices) with a stable mechanical structure. A few centimeter thick Rohacell fulfills this requirement. The trajectory measured with the emulsions which precede and follow the ”spacer” provides the measurement of the charge and momentum of the particle.

The first two components could be part of a single brick, since their longitudinal size would be about 10 cm. Downstream of the spectrometer we will place a Target Tracker with the aim of providing the time stamp of the events. We plan to perform the scannig of the events without any electronic detector prediction. Therefore, the time information is mandatory in order to match the emulsion information with the ones from the electronic detector that allow the charged-current to neutral-current separation.

The most downstream element of the detector is the ”analyzer”: its aim is to provide the electron identification, having already measured the charge and momentum of the primary tracks in the ”spectrometer” sector. A good electron identification with, at the same time, a low pion misidentification probability could be attempted either by a conventional electronic detector or by an emulsion calorimeter (emulsion-lead sandwiches). The choice between the two will be done according to the cost/effectiveness optimization.

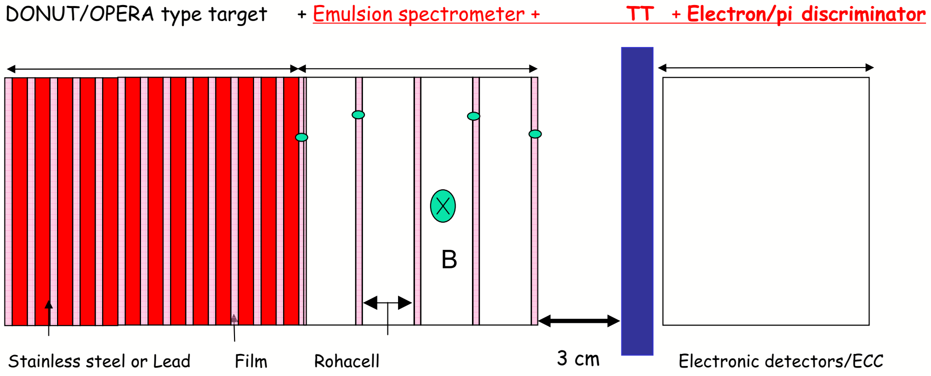

Figure 9: .

The first evaluations of the performances reported below have been carried out using the same nuclear emulsion films as used by the OPERA experiment, 290 μm thick. The thickness of 1 mm and 2 cm has been used for the lead and the Rohacell, respectively. The number of lead plates we have considered is 13 (about 2.5 X_0), while the number of rohacell spacers is 4. Nevertheless, the MECC geometry is being optimized as well as the passive material. Another important parameter is the strength of the magnetic field. In the present calculation we assumed a dipolar field with 1 Tesla strength.

Monte Carlo simulations have been performed in order to compute the momentum resolution and the charge identification efficiency of a MECC. Depending on the magnetic field, on the relative alignment of the emulsion plates in the spectrometer and on the spectrometer geometry the momentum resolution for a 10 GeV muon is better than 25% with a charge misidentification better than 0.2%. As far as the electrons is concerned, the momentum resolution is as good as in the muon case, while the charge misidentification is much worse due to showering. Very preliminary results show that the electron charge misidentification is of the order of 40%. However, further studies are needed before to draw firm quantitative conclusions on the electron charge misidentification.

Another important issue is related to the number of interactions that can be stored in a brick preserving the capability of connecting unambiguously the events occurring in the emulsion target with the hits recorded by the electronic detectors. It has been shown that by using a tracker made by 3 cm strips up to 100 events may be stored into a single brick. This is a very conservative number that insure the capability of the detector to stay on the beam for several years.

4.4 Conclusion and outlook

A MECC detector seems to fulfill all the requirements to be a suitable detector for a Neutrino Factory. Indeed, it is able to both detect τ decays and measure the charge of the electron. Furthermore, it would be also possible to study the golden channel by using the electronic detector. Nevertheless, before to quantify the physics reach of such a detector we should quantify the maximum mass affordable in terms of scanning power and costs. Indeed, the detector (MECC part plus electronic detectors plus magnet) should at maximum as expensive as the other proposed ones. Finally, we want to stress that a smaller scale MECC detector would be ideal as near detector as well.

In the next months the topics we want to address in order to have a realistic estimate of the physics reach are:

- study the performance of a MECC that uses stainless steel plates instead of lead. Indeed, given the longer radiation length of the stainless steel it will either improve the electron charge reconstruction in the case the same number of passive plate per target is assumed or keeping the number of X_0 constant and increasing the number of emulsion films it will give a larger mass;
- define the maximum MECC mass that can be affordable in terms of scanning, also on the basis of the experience with OPERA, as well the minimum to have good sensitivity to the silver channel;
- propose a realistic and cost effective design of the detector magnet;
- propose a realistic and cost effective design of the electron/pion analyzer. Given the fact that an electronic electron/pion analyzer would allow a search for the golden channel as well, this is our baseline;
- study the performance of the electron/pion analyzer in searching for the golden channel;
- once the previous points have been carefully studied, a full simulation with neutrino events will be performed in order to evaluate the detector sensitivity for the golden and the silver channels, and for the oscillations that produce an electron in the final state.

5 Near detectors

5.1 Aims

In order to perform measurements of neutrino oscillations at a neutrino factory, it is necessary to establish the ratio of neutrino interactions in a near detector with respect to the far detector. Hence, the careful design of a near detector is crucial to reduce the long baseline neutrino oscillation systematic errors. To achieve this, one needs to measure and control the neutrino flux, the beam angle, divergence, energy and the polarization of the muons in the storage ring. In addition, a near detector needs to perform a high statistics measurement of the charm signal from neutrino interactions, which is one of the main sources of background for the oscillation signal at the far detector.

There is also a rich physics programme that can be carried out at a near detector [24]. Deep inelastic, quasi-elastic and resonance scattering reactions can be studied with unprecedented accuracy. Other measurements include the determination of the weak mixing angle sin2 qW from the ratio of neutral to charged current interactions, measurements of the parton distribution functions (both polarized and unpolarized) in a region of phase space that is complementary to those determined by HERA, a measurement of the strong coupling constant and other effects such as nuclear reinteractions and nuclear shadowing. The large sample of charm events reconstructed for the neutrino oscillation background studies can be used for measurements of the CKM matrix element Vcd, and to search for CP violation in mixing. More accurate measurements of L polarization might shed light on the spin content of nucleons.

This varied physics programme requires a near detector (or detectors) with high granularity in the inner region that subtends to the far detector. The active target mass of the detector does not need to be very large. With a mass of 50 kg, one would obtain 109 charged current neutrino interactions per year in a detector at a distance of 30 m from the muon storage ring, with the straight decay sections being 100 m long.

There are a number of technological choices for a near detector at a neutrino factory, to achieve the general aims stated above. Due to the nature of neutrino beams, one may choose to build a multi-purpose detector that will carry out the physics programme, or instead have a number of different more specialised detectors for individual topics. However, some of the features needed in a near detector include high granularity, to compare the subtended angle between near and far, a magnetic field for charge separation, and muon and electron identification for flavour determination. More specific needs also include excellent spatial resolution to be able to carry out measurements of charm events, the possibility of including different targets for nuclear cross-section determination and maybe the possibility to polarize the target for measurements of polarized parton distribution functions.

5.2 Flux normalization and control

The neutrino beams from the decay of muons at the neutrino factory are calculable:

$$\frac{d^2N\nu_\mu}{dsd\Omega}\alpha\frac{2x^2}{4\pi}\left[((3-2x)+(1-2x)P_\mu cos\theta_{CM}\right] \tag{1}$$

and

$$\frac{d^2N\nu_e}{dsd\Omega}\alpha\frac{12x^2}{4\pi}\left[((1-x)+(1-x)P_\mu cos\theta_{CM}\right] \ , \tag{2}$$

where x is Bjorken x, qCM is the centre of mass angle between the lepton and the neutrino and Pm is the polarization of the muon. This flux depends crucially on the polarization parameter and can modify the spectrum according to this parameter.

One can use the reaction to carry out a beam flux normalisation. This cross-section can be determined in the Standard Model:
$\frac{d\sigma_{CC}(\nu_\mu e^-)}{dy} = \frac{2G_F^2 m_e}{\pi}E_\nu$. The production threshold is 11 GeV, but one can still expect to observe about 6000 events per year, in a detector of mass 50 kg. Alternatively, one can also use the elastic scattering interactions: $\nu_\mu + e^- \rightarrow \nu_\mu e^-$ and $\nu_e + e^- \rightarrow \nu_e e^-$ that also have calculable rates:

$$\frac{d\sigma(\nu_\mu e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\left(-\frac{1}{2}+sin^2\theta_W\right)^2 + sin^4\theta_W(1-y)^2\right] \tag{3}$$

and

$$\frac{d\sigma(\nu_e e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\left(\frac{1}{2}+sin^2\theta_W\right)^2 + sin^4\theta_W(1-y)^2\right] \ . \tag{4}$$

The signature for this event is a low angle forward going lepton with no nuclear recoil. A similar signature was used by the CHARM-II detector to measure sin2 qW from neutrino-electron elastic scattering. The reconstructed spectra can be used to disentagle the effect of the cross-section from the flux, and can be used to fit for the polarization of the muons. These fits can then be used to compare to a muon polarimeter that can be implemented along the straight sections of the storage ring.

5.3 Cross-sections and parton distribution functions

The near detector will carry out a programme of cross-section measurements, necessary for the far detector [25]. Due to the experimental control of the flux, it will be possible to extract the cross-section of the different interactions to be studied, such as deep inelastic, quasi-elastic, D+ and D++ resonance interactions and coherent pion interactions. The aim will be to cover all the available energy range, with particular emphasis at low energies (where quasi-elastic events dominate), since this might be needed to observe the second oscillation maximum at a far detector. At these lower energies, nuclear reinteractions and shadowing as well as the role of Fermi motion play a role, and these effects need to be determined. Very low energy interaction measurements might be achievable using a liquid argon TPC, or other very light tracking detector. We should envisage also the possibility of using different nuclear targets, as well as the direct access to nucleon scattering from hydrogen and deuterium targets.

5.4 Charm measurements

The wrong-sign muon signature of the neutrino oscillation “golden channel” can be identified, for example, in a large magnetised calorimeter, by distinguishing between muons, hadrons and electrons, and measuring the charge of the lepton. The main backgrounds for this signal are due to wrong charge identification and to the production of wrong sign muons from the decay of a charm particle (for example, from a D-), produced either in neutral current interactions or in charged current interactions where the primary muon has not been identified. The charm background is the most dangerous, due to a long tail in the distribution. A cut using the variable can reduce the background to the 10-6 level, but it relies on an accurate knowledge of the Qt distribution of charm particles.

A near detector should be able to operate at a high rate and have very good spatial resolution, to be able to distinguish primary and secondary vertices needed to identify charm events. It should also have a small radiation length so that it may distinguish electrons from muons in a magnetic field. This can be achieved by a vertex detector of low Z (either a solid state detector, such as silicon, or a fibre tracker) followed by tracking in a magnetic field and calorimetry, with electron and muon identification capabilities.

A prototype silicon detector, consisting of four passive layers of boron carbide (45 kg) and five layers of silicon microstrip detectors (NOMAD-STAR) was implemented within the NOMAD neutrino oscillation experiment. Impact parameter and vertex resolutions were measured to be 33 mm and 19 mm respectively for this detector. A sample of 45 charm candidates (background of 22 events) was identified. An efficiency of 3.5

Another possibility for a near detector dedicated to the study of charm is an emulsion cloud chamber followed by a tracking detector such as a scintillating fibre tracker (similar to OPERA or CHORUS). Emulsion technology has already demonstrated that it is a superb medium for the study of charm, due to its unrivalled spatial resolution. The main issue, however, is whether it can cope with the high rate needed.

In addition to the important measurement of the oscillation background, this sample of charm events can be used to determine the strange quark content of the sea, the CKM parameter Vcd to unprecedented accuracy and search for CP violation in mixing. The sign of the lepton produced at the primary vertex can be used to tag the initial charm particle, with the decay products determining whether there was any change in the flavour of the charm meson.

5.5 Outlook

The near detector at a neutrino factory is an essential ingredient in the overall neutrino factory complex, necessary to reduce the systematic errors for the neutrino oscillation signal. There are many choices for a detector technology that could be implemented. Liquid argon TPCs in a magnetic field would be able to carry out most of the near detector programme. Also, more conventional scintillator technology (similar to Minerva), a scintillating fibre tracker or a gas TPC (like in the T2K near detector) would also be able to perform cross-section and flux control measurements. However, it seems likely that only silicon or emulsion detectors can achieve the necessary spatial resolution to perform the charm measurements needed to determine the background for the oscillation search. These options shall be further studied within the context of the International Scoping Study.

References

[1] A. Cervera, F. Dydak and J.J. Gomez Cadenas. *Nucl. Inst. Meth.* A **451**, 123 (2000).
A. Cervera *et al. Nucl. Phys.* B **579**, 17 (2000).

A. Cervera. Nucl.Phys.Proc.Suppl.149 (2005),201-202,

[2] M. Selvi, Ph. D. thesis, Bologna University, 2002. http://www.bo.infn.it/selvi/tesi.ps.gz

[3]

[4] E. Ables et al. (MINOS Collaboration), Fermilab Proposal P-875 (1995).

[5] G. Bari *et al.*, *Nucl. Inst. Meth.* A **508**, 170 (2003).

[6] http://www.lnf.infn.it/conference/nufact05/talks2/WG1/Nelson_Magnetic_Tracking_WG1.pdf

[7] C. Rubbia, CERN-EP/77-08 (1977).

[8] S. Amerio *et al.*, Nucl. Instrum. Meth. A 527 (2004) 329 and references therein.

[9] P. Benetti *et al.*, Nucl. Instrum. Meth. A 332 (1993) 395.

[10] P. Cennini *et al.*, Nucl. Instrum. Meth. A 345 (1994) 230.

[11] F. Arneodo *et al.*, arXiv:hep-ex/9812006.

[12] A. Ferrari, A. Rubbia, C. Rubbia and P. Sala, "Proton driver optimization for new generation neutrino Super Beams to search for sub-leading $\nu_\mu \to \nu_e$ oscillations (θ_{13} angle)", New J. Phys. 4 (2002) 88.

[13] A. Rubbia, arXiv:hep-ph/0407297.

[14] A. Rubbia, arXiv:hep-ph/0106088.

[15] A. Bueno, M. Campanelli, S. Navas-Concha and A. Rubbia, Nucl. Phys. B **631**, 239 (2002) [arXiv:hep-ph/0112297].

[16] A. Rubbia, arXiv:hep-ph/0402110.

[17] A. Badertscher, M. Laffranchi, A. Meregaglia and A. Rubbia, New J. Phys. **7**, 63 (2005) [arXiv:physics/0412080].

[18] A. Badertscher, M. Laffranchi, A. Meregaglia, A. Muller and A. Rubbia, Nucl. Instrum. Meth. A **555**, 294 (2005) [arXiv:physics/0505151].

[19] A. Ereditato and A. Rubbia, arXiv:hep-ph/0510131.

[20] A. Ereditato and A. Rubbia, arXiv:hep-ph/0509022.

[21] T. Strauss, "First test of a liquid Argon TPC in magnetic field producted by a HTS coil", ETHZ diploma work. Available at *http://neutrino.ethz.ch.*

[22] American Superconductor, *http://www.amsuper.com.*

[23] Technodyne International Limited, Unit 16 Shakespeare Business Center, Hathaway Close, Eastleigh, Hampshire, SO50 4SR, see *http://www.technodyne.co.uk*

[24] A. Blondel (ed.) et al., ECFA/CERN Studies of a European Neutrino Factory Complex, CERN-2004-002- ECFA-04-230, CERN, Geneva, (2004), 365 p.

[25] See International Workshop on Neutrino-Nucleus Interactions. NUINT-04: http://nuint04.lngs.infn.it/ and NUINT-05: http://fphy.hep.okayama-u.ac.jp/NuInt05/