The CERN-Gran Sasso Neutrino Program

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This paper reviews the current experimental program envisaged with the future CERN neutrino beam called CNGS. Two detectors, OPERA and ICARUS, are under preparation and should investigate the neutrino properties coming from the CNGS to shed light on neutrino oscillation physics.

1. Introduction

Among the various recent experimental results concerning neutrino physics, two of them give very strong hints for the existence of an oscillation mechanism and they are driving the main motivations for the future projects. The first one is the clear ν_μ disappearance observed by Super-Kamiokande, SoudanII and Macro in the atmospheric data which can be very well described by the presence of $\nu_\mu \rightarrow \nu_\tau$ oscillation. The best fit of this hypothesis to the latest Super-Kamiokande data gives the oscillation parameters $\Delta m^2 = 2.5\text{x}10^{-3} eV^2$ with $sin^2 2\theta$=1.0 [1]. The range of allowed values at 90% CL correspond to $1.6\text{x}10^{-3} < \Delta m^2 < 3.9\text{x}10^{-3} eV^2$ and $sin^2 2\theta > 0.92$.

The second result concerns the well established solar neutrino deficit for which a clear flavour change process has been demonstrated with the recently published SNO data [2]. The solar observations are compatible with an oscillation process favouring again a large mixing angle but at a Δm^2 one order of magnitude less than for the atmospheric data.

At this stage it is very important to test in a conclusive manner an oscillation mechanism or not as the origin of those results. The primary goal of the first generation of Long Baseline projects is to confirm and verify the nature of the oscillations observed in the atmospheric data as well as to provide more precise measurements of the corresponding oscillation parameters. Three projects using 'home-made' ν_μ are under progress. The K2K [3] and Numi/Minos [4] projects are looking primarily at ν_μ disappearance using low energy beams, while the main goal of the CNGS project described in this paper is to search for ν_τ appearance in a high energy ν_μ beam at 730 km from the neutrino source.

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2. The CNGS beam line

The CNGS [5] is a ν_μ beam produced with 400 GeV protons extracted from the SPS complex at CERN. During one year in a mode where the use of the SPS is shared with LHC operation, $4.5\text{x}10^{19}$ protons on target (pot) can be delivered, assuming 200 days of operation. The protons hit a target made of graphite rods and the produced secondary particles pass through a magnetic focusing system designed to select high energy (20-50 GeV) π^+ and K^+. This makes the neutrino beam a high energy beam optimised for ν_τ appearance with a mean neutrino energy of about 17 GeV. Fig. 1 shows the expected neutrino energy distribution at Gran Sasso located at 732 km from CERN. In the Gran Sasso underground laboratory, the ν_μ flux should correspond to 3.5 x 10^{11} ν/m^2/year with a contamination of 2.1% $\overline{\nu}_\mu$, 0.8% ν_e and less than 0.05% of $\overline{\nu}_e$. The number of charged current interactions expected from ν_μ is about 2600 /kton/year. If the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis is confirmed the number of τ's produced via charged current interaction at the Gran Sasso is about 15 /kton/year for $\Delta m^2 = 2.5\text{x}10^{-3} eV^2$ at full mixing.

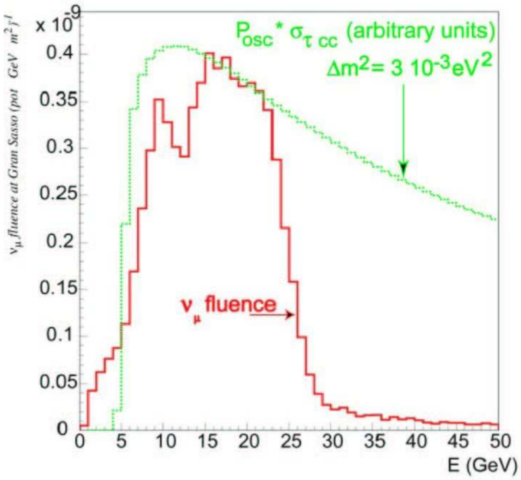

Figure 1. CNGS ν_μ flux as a function of the energy at Gran Sasso. The curve shows the energy dependence of the production rate of τ's produced via charged current interaction for Δm^2 =3x10$^{-3}eV^2$ at full mixing.

Civil engineering work is progressing well and it should be finished by spring 2003. The accelerator team plans to deliver the first neutrino beam by May 2006. The possibility of an increase of the neutrino beam intensity by a factor 1.5 is under study [6].

3. Experimental signature

The ν_τ appearance search is based on the observation of events produced by charged current interaction (CC) with the τ decaying in all possible decay modes. Since the expected event rate is small, it is crucial to separate efficiently the ν_τ CC events from all the other flavour neutrino events and to keep the background at a very low level. For this purpose the detectors will have to identify the events by exploiting the τ specific properties characterised by a non negligible lifetime and the presence of missing transverse momentum due to the final state ν_τ produced in the τ decays.

The two proposed detectors, OPERA [7] and ICARUS [8], are using two different approaches for identifying the events. The choice made by OPERA is to observe the τ decay topology in nuclear emulsions, while ICARUS will separate the ν_τ CC events from the background through kinematical criteria using a large volume TPC filled with liquid argon. The ICARUS and OPERA detectors will be installed in hall B and hall C, respectively, of the Gran Sasso underground laboratory. The 2400 meters of rock above the experimental halls provide a very efficient cosmic ray shielding.
The detectors are described in more details in the following two sections.

4. The OPERA experiment

The principle of the OPERA experiment is to observe the τ trajectories and the decay products in thin layers of emulsion. To provide the large target mass (1.8 ktons) the emulsion films are interleaved with 1 mm thick lead plates. Fig. 2 sketches the basic structure of the detector, called Emulsion Cloud Chamber (ECC). An emulsion film in OPERA consists of two emulsion layers (50 μm thick) put on either side of a plastic base (200 μm thick).

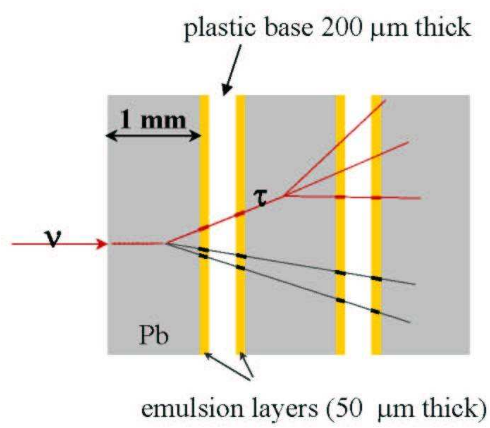

Figure 2. Schematic structure of an ECC cell. The τ decay kink is reconstructed by using four track segments in the emulsion films.

4.1. The detector structure

The basic detector unit, called ECC brick, is obtained by stacking 56 lead plates and emulsion films, plus an extra film before and another one, called Changeable Sheet (CS), behind after 2mm of plastic. The CS can be detached from the rest of the brick for analysis. It will be used to first locate the tracks produced in neutrino interactions which have to be followed in the rest of the brick. The dimensions of a brick are 12.5 x 10.2 x 7.5 cm^3. In terms of radiation length, a brick corresponds to a thickness of 10 X_o.

In order to reach 1.8 kton target mass, 206336 bricks will be installed into walls containing 64 rows of 52 bricks and separated from each other by vertical planes of electronic target trackers.

Fig. 3 shows the general layout of the OPERA detector.

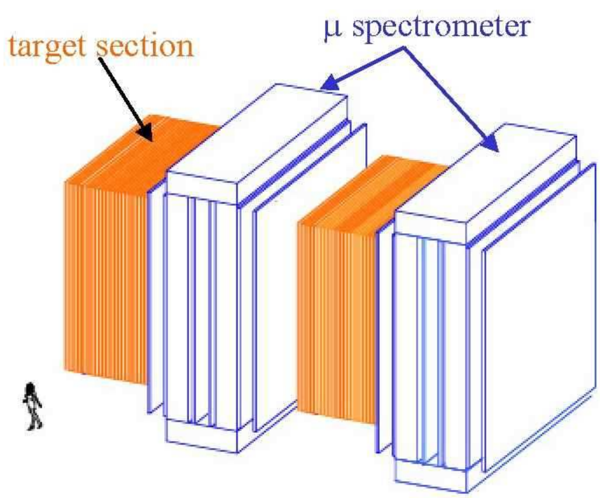

Figure 3. View of the OPERA detector composed of 2 super modules with 2 spectrometers.

It consists of 2 identical parts called super module (SM). Each SM has a target section and a muon spectrometer. The spectrometer measures the charge and momentum of muons going through by means of a dipolar magnet providing 1.6 Tesla transverse to the neutrino beam axis and equipped with drift tubes and RPC chambers.

The target section is composed of 31 walls of bricks. The bricks will be installed in a support structure and manipulated from the sides of the walls using an automated manipulator.

An electronic target tracker module composed of 2 planes of 6.6 m long scintillator strips in the two transverse directions (X and Y) is installed behind each brick wall. The main goal of the electronic detector is to provide a trigger for the neutrino interactions and a localisation of the brick where the event occured. The strips, 2.6 cm wide and 1 cm thick, have WLS fibers for readout by 64 channel multi-anode photomultiplier tubes. The brick transverse pointing accuracy is about 1.5 cm for CC events and 3.0 cm for NC events. The efficiency to find the right brick is about 70-80%.

The candidate brick is then removed for subsequent analysis. The analysis flow is the following: The brick is removed using the brick manipulator system and the changeable sheet is detached and developped. The film is then scanned to search for the track originating from the neutrino interaction. If none are found then the brick is left untouched and another one is removed. When a neutrino event is observed, the brick is exposed to cosmics to collect alignment tracks before going to the development. After development the emulsions are sent to the automatic scanning microscope in order to start the analysis which consists of finding the neutrino vertex and the decay kink in the vertex region.

4.2. Detector performance

The angular resolution for reconstructing a track in a film from the two emulsion layers is about 2 mrad. This is entirely limited by the scanning accuracy of the microscope stage and the digitisation. However this resolution allows a momentum measurement using the particle multiple scattering occuring within the lead plates. The difference of the track angles before and after lead sheets can be measured accurately all along the track. Test beam results have shown that a resolution better than 20% for momentum below 4 GeV can be achieved using only half a brick (5 X_o) with this angular method.

The brick thickness ($10X_o$) and the high precision in reconstructing track segments makes the brick a good electromagnetic calorimeter. Fig. 4 shows an electron shower reconstructed in a brick exposed to an electron beam at CERN. The shower structure is clearly visible with all the segmets representing electron tracks from the shower seen in the emulsions. The efficiency to identify such showers is about 90%.

The shower energy can be measured by counting the number of track segments reconstructed in a cone of 50 mrad around the incoming electron direction. This technique gives an energy

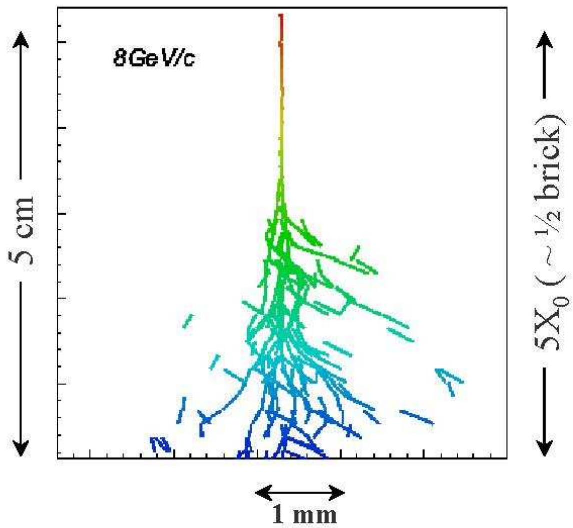

Figure 4. Electromagnetic shower observed in a brick exposed to an electron beam.

resolution of $40\%/\sqrt{E}$.

These results show the high capability of OPERA in $\tau \rightarrow e$ decay studies and in the search for $\nu_\mu \rightarrow \nu_e$ appearance.

4.3. Physics performance: $\nu_\mu \rightarrow \nu_\tau$ search

The τ decay channels investigated by OPERA are the e, μ and hadron. They are classified in 2 categories: long and short decays. The latter corresponds to the cases where the τ decays in the same lead plate as the neutrino interaction occured. Those events are selected on the basis of the impact parameter of the τ daughter track with respect to the interaction vertex (IP > 5-20 μm). This is applied only for the electron and muon channels. In the long decay category the τ does not decay in the same lead plate and its track can be reconstructed in one film. The τ candidate events are selected on the basis of the existence of a kink angle between the τ and the daughter tracks ($\theta_{kink} > 20$ mrad).

Table 1 summarises the OPERA performance after 5 years of running with the CNGS (2.25×10^{20} pot). The number of expected signal events from $\nu_\mu \rightarrow \nu_\tau$ oscillations is given as a function of the studied channel for three different values of Δm^2 at full mixing. The total efficiency including the branching ratios amounts to 9.1% and the total background is estimated to be less than 0.65 event. The main background sources are charm decays, large angle muon scattering and hadron reinteractions. A 4σ significance is achieved after 5 years for $\Delta m^2 > 2.0 \text{ x } 10^{-3} eV^2$.

Fig. 5 shows the constraint on the value of Δm^2 which can be achieved after 5 years if the observed rate of ν_τ events corresponds to the expectation for full mixing and Δm^2=3.2x$10^{-3}eV^2$. Using the atmospheric result to constrain the mixing angle the precision on Δm^2 at 2.5x10^{-3} eV^2 is about 16%.

Improvement in the background reduction is under progress. A preliminary analysis has shown that low energy muons can be identified in the bricks, using the dE/dX measurement in the emulsions (grain density) as a function of the particle range. Applying this idea reduces the estimated background from 0.65 to 0.42 without changing the signal efficiency.

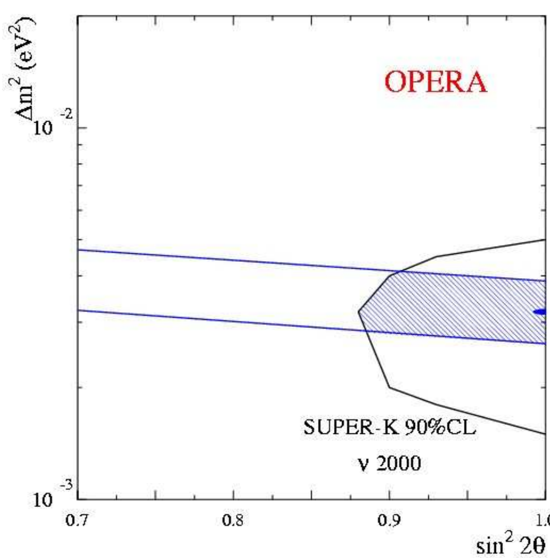

Figure 5. The band represents the 90% CL allowed region for the oscillation parameters determined by OPERA if the observed number of τ events corresponds to the expectation for full mixing and Δm^2=3.2x$10^{-3}eV^2$.

Table 1
Summary of the expected numbers of τ events in 5 years for different Δm^2 with the expected background and detection efficiencies per decay channel for OPERA.

channel	signal for Δm^2 (eV^2)			ϵxBr	Background
	1.6x10^{-3}	2.5x10^{-3}	4.0x10^{-3}		
$\tau \rightarrow$e	1.6	3.9	9.9	3.4%	0.16
$\tau \rightarrow \mu$	1.3	3.2	8.2	2.8%	0.29
$\tau \rightarrow$h	1.4	3.2	8.2	2.9%	0.20
Total	4.3	10.3	26.3	9.1%	0.65

5. The ICARUS experiment

The principle of ICARUS is to reconstruct the event kinematics with enough precision to allow the selection of interesting candidates and the rejection of background events with kinematical criteria based on energy measurements and on very good particle ID. The technology relies on the possibility to do 3 dimensional imaging of events in a large time projection chamber filled with liquid argon, with space resolution similar to that in bubble chambers, but with electronic readout and continuous sensitivity. An important characteristic of this detector concept is the use of very pure liquid argon, with less than 1 ppb of contaminant, allowing the electrons to drift along distances larger than 1.5 m. The scintillation light produced by the ionising particles in liquid argon is used to give a precise reference time of the ionisation track. The readout is achieved with 3 parallel wire planes (2 induction and 1 collection planes) with 3 different orientations, at 0, 60^o and -60^o. The wire pitch is 3 mm. The spatial resolution is 250μm along the drift direction (z) and 1 mm for the x and y directions.

In addition, the energy deposited by an ionising particle along its path (dE/dx) is measured accurately from the charge collected on each wire of the collection plane with a time sampling of 400 nsec. Since the particle momentum can be measured from the range of stopping particles or from multiple scattering measurement, it provides a very clean method for particle identification of soft particles.

5.1. Detector structure

The ICARUS detector has a modular concept which should allow to build a multi kton device by replicating the basic component. The smallest detector unit contains 300 tons of liquid argon and corresponds to half a T600 module. Figure 6 shows the internal view of the first T600 half module. The cryostat has dimensions of 4x4x20 m^3. A high voltage system produces a uniform electric field, perpendicular to the wire planes allowing the drift of the ionisation electrons towards the wires over a maximum path of 1.5 m.

Figure 6. Internal view of the T600 first half module.

This first module has been fully instrumented and succesfully tested during a technical run last-

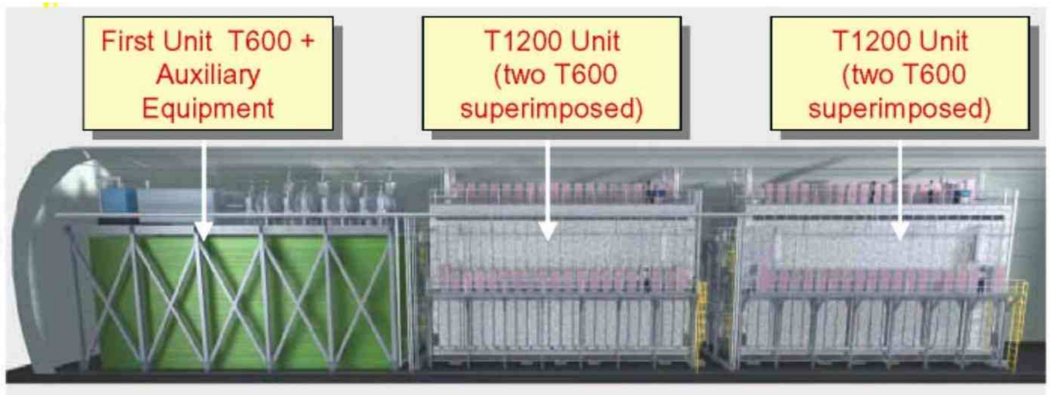

Figure 7. General view of the ICARUS T3000 detector composed of 5 T600 modules.

ing 5 months during 2001 in Pavia (Italy). The results were found to be in agreement with the expectations and have validated the LAr TPC technology at these large scales.

The aim of the ICARUS collaboration is to build a 3000 ton detector (T3000) which should be installed in the Gran Sasso Hall B. To fully exploit the know-how acquired with the first half T600 construction and running, the T3000 design is based on cloning the T600 module to reach a sensitive mass of 2.35 ktons of liquid argon. Fig. 7 shows the general layout of the T3000 detector in the Gran Sasso laboratory.

The first part to be installed is the existing T600 module composed of the tested half module prototype and a second half module under construction. The complete module should be installed early 2003 with the aim of starting the collection of atmospheric and solar neutrino events in 2003. Then the mass should be increased gradually with time with the installation of two T1200 units (1 T1200 module is made of 2 T600 modules superimposed in the same insulation enveloppe) before summer 2006.

The ICARUS physics program is quite broad. It should cover, in addition to the CNGS program, the study of solar, atmospheric and supernovae neutrino as well as proton decay search.

5.2. Detector performance

The large homogeneous tracking medium allows to fully identify and sample electromagnetic and hadronic showers. The total shower energy is obtained from integrating the charge collected on the wires. As a result ICARUS has excellent calorimeter capabilities with very good energy resolution, featuring excellent electron identification and e/π^o separation in addition to its high capability of dE/dx measurements.

Since there is no magnetic field, momentum for energetic muon is measured using multiple coulomb scattering in liquid argon. The resulting momentum resolution is about 20% for 10 GeV muons.

5.3. Physics performance: $\nu_\mu \to \nu_\tau$ search

ICARUS has considered two τ decay channels for the $\nu_\mu \to \nu_\tau$ search. Their "golden" channel corresponds to $\tau \to e\nu_e\nu_\tau$. The main background should come from the ν_e present in the beam which interact via charged current. It is suppressed kinematically exploiting the fact that signal events have missing momentum due to the final state neutrinos which is not the case for the background events. An analysis based on a 3 dimensional likelihood built for the signal and background events with 3 distributions derived from the visible energy and transverse missing momentum distributions has been used. Fig. 8 shows the ratio of the corresponding signal and background likelihoods for background (shaded area) and τ events normalised to 5 years of CNGS in shared mode. The two components are clearly distinct and a cut on this variable allows the selection of a rather clean signal sample.

The other channel which has been exploited is

Table 2
Summary of the expected numbers of τ events in 5 years for different Δm^2 with the expected background and detection efficiencies per decay channel for ICARUS.

channel	signal for Δm^2 (eV^2)			ϵxBr	Background
	$1.6\text{x}10^{-3}$	$2.5\text{x}10^{-3}$	$4.0\text{x}10^{-3}$		
$\tau \rightarrow$e	3.7	9.0	23	4.4%	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	3.9	0.8%	<0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	3.9	0.7%	<0.1
Total	4.9	11.9	30.5	5.9%	0.7

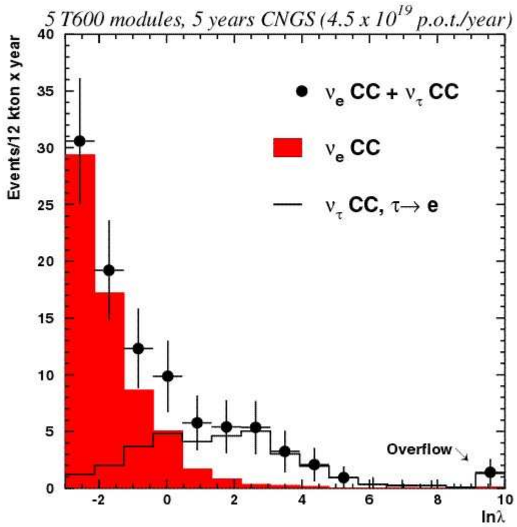

Figure 8. Distribution of the multi-dimensional likelihood for ν_e CC and $\tau \rightarrow e$ events.

the $\tau \rightarrow \rho$ where $\rho^- \rightarrow \pi^-\pi^o$. The main background comes from ν_μ NC events and in this case, both signal and background events have missing energy. The selection is then based on some isolation criteria instead of energy balance since the candidate hadron is more isolated with respect to the total momentum for the signal. Table 2 summarises the overall ICARUS performance after 5 years of running with the CNGS ($2.25\text{x}10^{20}$ pot) for $\nu_\mu \rightarrow \nu_\tau$ search. The number of expected signal events from $\nu_\mu \rightarrow \nu_\tau$ oscillations is given as a function of the studied channel for three different values of Δm^2 at full mixing. The total efficiency including the branching ratios amounts to 5.9% and the total background is estimated to be less than 0.7. These results show that ICARUS can reach a sensitivity comparable to OPERA for this study.

6. Search for $\nu_\mu \rightarrow \nu_e$ appearance

In addition to the dominant $\nu_\mu \rightarrow \nu_\tau$ oscillation, it is possible that a sub-leading transition involving ν_e occurs as well. In the 3 flavour neutrino oscillation framework, assuming $\Delta m^2_{12} << \Delta m^2_{23} = \Delta m^2_{13} = \Delta m^2$, oscillation probabilities can be expressed like:

$$P(\nu_\mu \rightarrow \nu_\tau) = cos^4\theta_{13} sin^2 2\theta_{23} sin^2(1.27\Delta m^2 L/E)$$
$$P(\nu_\mu \rightarrow \nu_e) = sin^2\theta_{23} sin^2 2\theta_{13} sin^2(1.27\Delta m^2 L/E)$$

The sub-leading $\nu_\mu \rightarrow \nu_e$ oscillation at the atmospheric scale is driven by the mixing angle θ_{13} which is constrained by CHOOZ experiment to be small ($sin^2\theta_{13}$ <0.14) [9]. Having excellent electron identification capabilities, both ICARUS and OPERA have estimated their sensitivity in searching for $\nu_\mu \rightarrow \nu_e$ appearance with the CNGS beam. The analysis principle is based on a search for an excess of ν_e CC events at low neutrino energies. The main background comes from the electron neutrino contamination present in the beam. The analysis takes into account the electron events coming from $\nu_\mu \rightarrow \nu_\tau$ events where $\tau \rightarrow e\nu_\tau\nu_e$ since both oscillations would occur at the atmospheric Δm^2 scale. These events distort the kinematical distributions where the low energy events contribute. This is illustrated in Fig. 9 showing the ICARUS visible energy distribution for the events contributing in the ν_e CC sample when $\theta_{13} = 7^o$. The contribution from both oscillations have different shapes than the rest of the events.

The sensitivity to θ_{13} is obtained by doing a χ^2 minimisation using the visible energy, the missing transverse energy and the electron transverse momentum distributions in which the oscillation

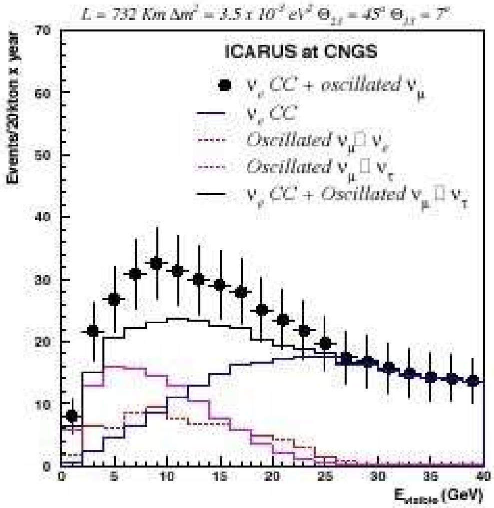

Figure 9. The visible energy distribution for the events contributing in the ν_e CC sample in ICARUS.

parameters are allowed to vary. Table 3 summarises the expected number of selected events for ICARUS assuming 5 years running ($2.25\text{x}10^{20}$ pot) from $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ oscillations in three family mixing and from background ν_e at 3 values of θ_{13}. The limit obtained by ICARUS at 90% CL on θ_{13} is 5.8^o after 5 years.

Table 3
Expected number of signal and background events in 5 years obtained in the search of $\nu_\mu \to \nu_e$ oscillation for ICARUS for 3 values of θ_{13}

θ_{13} (deg)	$sin^2 2\theta_{13}$	ν_eCC	$\nu_\mu \to \nu_\tau$ $\tau \to$e	signal $\nu_\mu \to \nu_e$
9	0.095	50	24	27
7	0.058	50	24	16
5	0.030	50	25	8.4

The recent analysis performed by OPERA and described in details in Ref. [10] gives a limit of 7.1^o at 90% CL. Both experimental results lead to significant improvement over the actual CHOOZ limit and open an important window on the third mixing angle.

7. Conclusion

The CNGS construction is progressing well. The project is on schedule and a startup is expected for june 2006. At the same time OPERA enters the construction phase and should be ready to take data by 2006. ICARUS has successfully demonstrated its principle with the full scale 300 ton prototype technical run and the collaboration aims to build a 3000 ton detector by 2006.
The detector performances are such that an unambiguous $\nu_\mu \to \nu_\tau$ appearance signal should be seen after only a few years of data taking. Combining these observations, the two experiments expect to see 20-25 τ events after 5 years with very little background at $\Delta m^2 = 2.5\text{x}10^{-3}\ eV^2$. They can achieve a measurement of Δm^2 with 10% accuracy. The very good electron identification and measurement of the two detectors give the possibility to explore the $\nu_\mu \to \nu_e$ appearance channel pushing down the θ_{13} limit below 7^o. This may correspond to the best sensitivity that can be reached before the JHF program [11] turns on.

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