The OPERA experiment

H. Pessard

LAPP-EXP 2001-04
March 2001

The OPERA Experiment

H. PESSARD
LAPP, IN2P3-CNRS, Chemin de Bellevue, BP 110,
F-74941 Annecy-le-Vieux Cedex, France

Abstract

Following the Super-Kamiokande findings on atmospheric neutrinos, accelerator neutrinos have started to be exploited to confirm the indication for neutrino oscillations and perform more complete measurements of the mass differences and mixing parameters. In Europe, the long baseline beam CERN Neutrino to Gran Sasso CNGS is aimed at direct appearance searches of $\nu_\mu \to \nu_\tau$. The OPERA experiment in Gran Sasso will use photographic emulsions in a large hybrid detector to point at ν_τ interactions coming from the CNGS beam in a "zero background" approach. The principles of the experiment and its projected performances are described.

Invited talk at the Scandinavian Neutrino Workshop (SNOW), February 8-10 2001,
Uppsala, Sweden.

To appear in Physica Scripta T93(2001)59-64.

The OPERA Experiment

H. Pessard *†

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, BP 110, F-74941 Annecy-le-Vieux CEDEX, France

12 March 2001

Abstract

Following the Super-Kamiokande findings on atmospheric neutrinos, accelerator neutrinos have started to be exploited to confirm the indication for neutrino oscillations and perform more complete measurements of the mass differences and mixing parameters. In Europe, the long baseline beam CERN Neutrino to Gran Sasso CNGS is aimed at direct appearance searches of $\nu_\mu \rightarrow \nu_\tau$. The OPERA experiment in Gran Sasso will use photographic emulsions in a large hybrid detector to point at ν_τ interactions coming from the CNGS beam in a "zero background" approach. The principles of the experiment and its projected performances are described.

1 Oscillation searches and the CNGS beam

The OPERA experiment [1] is a search for direct observation of ν_τ appearance from $\nu_\mu \rightarrow \nu_\tau$ oscillations in the CNGS neutrino beam [2] of the CERN SPS.

The strongest evidence for the existence of neutrino oscillations comes from the results of the Super-Kamiokande experiment [3] on atmospheric neutrinos. The anomalous ratio of atmospheric muon neutrinos to electron neutrinos comes clearly from ν_μ disappearance. The complete set of measurements consistently explains this phenomenon by $\nu_\mu \rightarrow \nu_\tau$ oscillations. Oscillations $\nu_\mu \rightarrow \nu_e$ give a much worse fit to the data and are excluded to a large extent by the results of the CHOOZ experiment [4]. The interpretation of the observed ν_μ disappearance by a $\nu_\mu \rightarrow \nu_{sterile}$ transition is also disfavoured with respect to the $\nu_\mu \rightarrow \nu_\tau$ hypothesis by indirect measurements.

Added statistics have coherently strengthened the case. Soudan2 [5] and MACRO [6] experiments have shown results consistent with the Super-Kamiokande observations on the disappearance of muon neutrinos. Nevertheless, the observation of the L/E pattern characteristic of oscillations would require larger atmospheric neutrino detectors with good energy and angular resolutions [7].

The most recent Super-Kamiokande analysis [8] has for best fit $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$ and $sin^2 2\theta = 1$ in a $\nu_\mu \rightarrow \nu_\tau$ oscillation. At the 90% confidence level the oscillation parameters are constrained in the region of $sin^2 2\theta > 0.89$ and $\Delta m^2 = (1.7 - 4) \times 10^{-3}\ eV^2$.

The next steps to confirm ν_μ oscillations and perform more complete measurements of the oscillation parameters use accelerator neutrinos. The first generation of long baseline experiments started in 1999 with the K2K experiment searching for ν_μ disappearance in the long baseline neutrino beam from KEK to Super-Kamiokande 250 km away. Preliminary results recently presented [9] are consistent with the oscillation parameters proposed by Super-Kamiokande.

The MINOS experiment [10], from april 2004 onwards, will use the NUMI beam from Fermilab to the Soudan mine 730 km away to perform a ν_μ disappearance experiment of higher statistics between its near and far detectors. The granularity of MINOS is too coarse to allow the flavour tagging of ν_τ CC interactions but the measurement of the NC/CC ratio will be an indirect probe of ν_τ appearance.

The conclusive test of the $\nu_\mu \rightarrow \nu_\tau$ hypothesis will be the direct observation of ν_τ appearance in an initially pure ν_μ beam, as proposed by the OPERA Gran Sasso experiment.

The european long baseline beam CNGS (CERN Neutrino to Gran Sasso) is aimed at direct $\nu_\mu \rightarrow \nu_\tau$ appearance searches. Under construction since october 2000, the CNGS beam will start operation in may

*Email address: pessard@lapp.in2p3.fr

†Invited talk at the Scandinavian Neutrino Workshop (SNOW), Uppsala, Sweden, February 8-10, 2001.

2005. Optimised for ν_τ appearance, this beam has a high neutrino mean energy of $\sim 17\ GeV$. The foreseen 400 GeV proton intensity on its target is 4.5×10^{19} pot (protons on target) per year in shared accelerator mode (7.6×10^{19} pot/year in dedicated mode), assuming 200 days of operation per year.

In the Gran Sasso underground site 730 km from CERN, the ν_μ flux will be $7.45 \times 10^{10}\ \nu/m^2$ per 10^{19} pot. The relative yields of ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ will be 100%, 2.0%, 0.8% and 0.05% and the numbers of DIS events produced per year.kton will be respectively 2450, 49, 20 and 1.2.

At Gran Sasso, the number of τ's produced per year.kton will be about 30 for $\nu_\mu \to \nu_\tau$ oscillations at full mixing and $\Delta m^2 = 3.5 \times 10^{-3}\ eV^2$. This number varies approximately like the square of Δm^2. In comparison, the background of ν_τ interactions originating from decays of τ's produced in the CNGS target is completely negligible.

2 The OPERA experimental method

2.1 Detection principles

The ν_τ's are detected through their charged-current interactions. Produced τ^-'s decay after a flight path of one millimeter or less at these energies. Direct observation the τ track can be envisaged with nuclear emulsions which have a granularity of about 1 μm. That is the choice of OPERA as in the CHORUS experiment in which automatic scanning of a large number of events has been applied.

Another approach can consist in using kinematics-based cuts to perform a statistical detection of the τ's without observing the decay topology on an event by event basis. This approach following the NOMAD experience is taken in the ICARUS project [11]. It requires, besides reliable simulations of background tails, the good particle-ID, momentum and angular resolutions that can be achieved in a liquid argon TPC, and can be applied in a long baseline beam provided TPC's of several thousand tons are made operational.

For OPERA also, the large target mass needed should be managed without loosing performance. This has led to adopt a sandwich structure of passive material plates as target, interspaced with emulsion layers used as high precision trackers. This structure, called Emulsion Cloud Chamber (ECC), has proved effective to detect ν_τ interactions in the DONUT experiment [12]. In OPERA, it is made of 1 mm thick lead plates followed by a thin film made up of a pair of emulsion layers 50 μm thick on either side of a 200 μm plastic

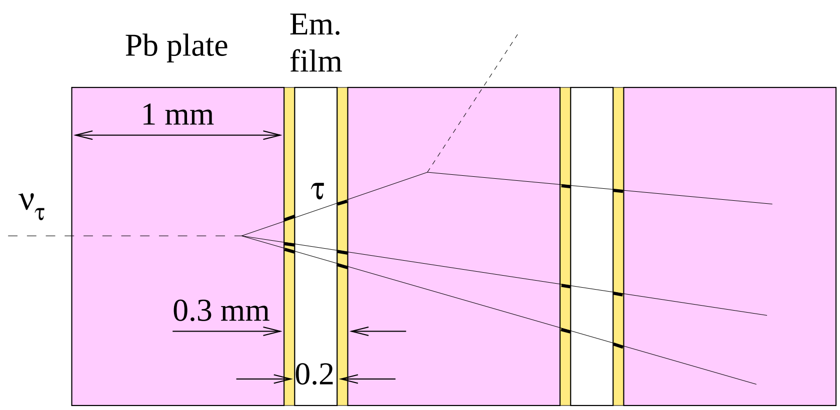

Figure 1: Schematic structure of an ECC cell. The τ decay kink is reconstructed in space by using four track segments in the emulsion films.

base, as seen in Figure 1. A charged particle produces two track segments with 15-20 grain hits in each film.

The τ^- detection using the semileptonic decays $\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$ and $\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau$, and the single hadron decay mode $\tau^- \to h^- + \nu_\tau + n\pi^0$, which amount to about 85% of the τ^- decays, has been studied in a detector with the above described ECC structure. To cover a Δm^2 range down to $\sim 1.5 \times 10^{-3}\ eV^2$, a large detector of target mass about 2 $ktons$ is needed. Even with this size, the basic performance of the ECC can be preserved in the OPERA detector using a highly modular target.

2.2 The detector structure

OPERA is an hybrid experiment where electronic detectors associated to the emulsions allow to consider it as an "on-line emulsion experiment". The basic target building block, called ECC "brick", is made of 56 lead plates and emulsion films, plus an extra film before, and another one behind after a 2 mm thick plastic plate (the latter to detect decays of τ's produced in the last lead plate). The dimensions of a brick are $12.5 \times 10. \times 7.5\ cm^3$. In terms of radiation length, a brick has a thickness of 10 X_0.

Bricks are stacked into "walls" made of 64 lines of 51 bricks, perpendicular to the neutrino beam, separated from each other by vertical planes of electronic target trackers. A succession of 24 brick walls and target tracker planes composes a target block. The whole detector is made of three super-modules, each one being a target block followed by a muon spectrometer (Figure 2). Spectrometers, aimed at muon identification

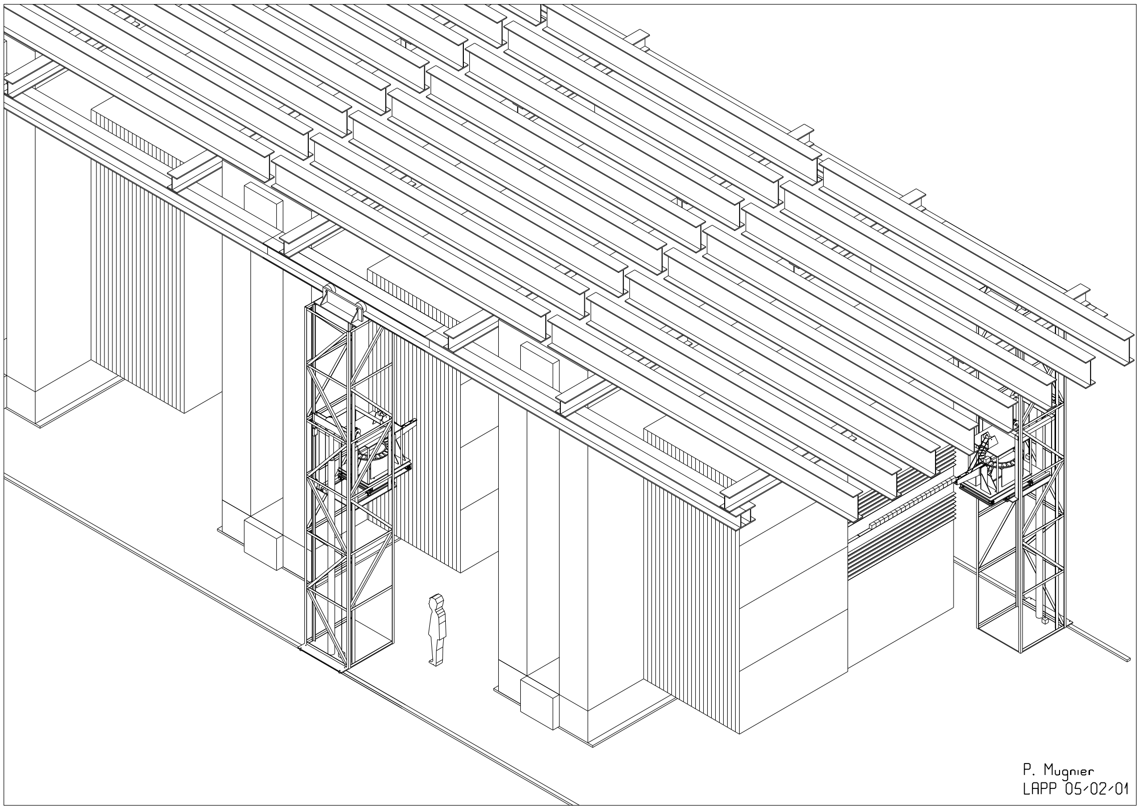

Figure 2: View of the OPERA detector showing the three super-module targets and dipole spectrometers. Brick manipulators removing "fired" bricks are represented.

and measurement of their charge and momentum, use 10 meters high and 8.75 meters wide dipole magnets ($B = 1.55\ T$). Magnet pillars consist of 5 cm iron layers interleaved with RPC's. Vertical planes of drift tubes, used as precision trackers, are located in front, inside and behind the magnets.

Electronic target trackers, whose primary function is to identify the brick where a beam neutrino interacted, are made of two planes of orthogonal scintillator strips 6.7 m long placed behind brick walls. The strips, 2.6 cm wide and 1 cm thick, have a WLS fiber to read out the light, seen at both ends by 64 channels multi-anode PMT's. The passage of a charged particle through a strip will produce 6 or more photo-electrons (p.e.).

2.3 The emulsion bricks

The whole detector contains 235 000 ECC bricks. The high resolution of nuclear emulsions can be exploited on such a large scale only with the development of automatic microscope readout and fast data processing initiated for CHORUS and DONUT. The quantity of emulsion gel in OPERA is equivalent to more than 10 times that of CHORUS (400 liters while DONUT had 50 liters). With the ECC structure, this large increase is made possible by the use of films manufactured industrially.

A joint R&D is conducted by Fuji Co. and Nagoya University to develop mass production of films suitable for OPERA. Using production lines of commercial photographic films, the required 13 millions of emulsion sheets can be produced in about 1.5 years. Lead-emulsions sandwiches will be vacuum packed in laminated paper, folded in origami-style, to protect emulsions against light and humidity and to keep films positionned against lead plates.

The track density in OPERA emulsions will at the contrary be very much lower than in CHORUS and DONUT (about $10^2/cm^2$ compared to 10^4 and $10^5/cm^2$ respectively). This is due to the very low cosmic background rate in the Gran Sasso tunnel, located below 1400 m of rock, and to the low rate of neutrino interactions from the beam. The low track density allows to use electronic trackers of limited space resolution, hence affordable for coverage of 3200 m^2. The price to pay is a larger scan area to find the tracks in the brick emulsions.

To ensure the ECC principle, the brick should be a geometrically rigid body in which emulsion films cannot shift relatively to each other. Brick global positioning is not as critical, even when tracks have to be followed in adjacent bricks, for instance to further measure candidate events. More scanning time can then be dedicated to those events to establish brick-to-brick track connections, in this low track density context.

Studies of the emulsion films under development show that grain densities exceeding 30 grains per 100 μm are commonly achieved. The intrinsic position resolution is related to the 0.2 μm size of crystals before development. This size is well controlled in industrially produced films, as well as the emulsion layer thickness. Actual resolutions have been measured in test beam exposures for base tracks (segments in the two 50 μm layers connected through the 200 μm base) to be $\sigma = 2.1\ mrad$ in angle and 0.21 μm in position.

Industrial films have very small (<0.4 μm) geometric distorsions even within 1 mm of edges (<1 μm), and their fading properties are well under control. As bricks will be extracted and analysed within a few weeks after the event occured, including extra-bricks required in further analysis of candidate events, fading times exceeding a month would contribute to erase older and unwanted tracks.

2.4 Detector operation and data extraction

The operation of the OPERA detector can be summarised as follows: the electronic data acquisition system, triggered in coincidence with the beam by signals in the target trackers corresponding to a neutrino interaction (one or more p.e. in each projection in at least two tracker modules, or five or more p.e. in a single crossed planes module), will record informations from scintillators, RPC's and drift tubes trackers. The on-line reconstruction will immediately apply algorithms to tag a target neutrino interaction and point to the brick where it occured.

About 30 bricks per day will be pointed out in this way for analysis. They will be extracted from the brick support structure by an automated manipulator (see Figure 2). The bricks will be brought in a close-by shallow underground lab to undergo a cosmic ray muon exposure. After addition of two external emulsion films, alignment tracks will be accumulated during about 2 days. Then bricks will be disassembled in a black room and films developped before shipping to the film scanning centers.

Scanning can be considered as the second delayed data acquisition of the experiment. It results in the numerisation of track segments stored in the emulsions under the form of silver bromide micro-crystals alignments. The first scanning operation consists in picking up tracks in the extreme downward film of the interaction brick and in the corresponding alignment film. That is the most time-consuming operation as the surface to scan amounts up to 250 cm^2/brick (i.e. the full film surface, for a NC interaction; the surface is about twice $5 \times 5\ cm^2$ for a ν_μCC event).

Picked up tracks are scanned back until they stop in one of the films (actually until they are not found in 2 consecutive films). Then in an area of $5 \times 5\ mm^2$ and 4 films around track ends, a scan is conducted to classify the vertex and confirm the presence of a neutrino interaction. If it is the case, the next step is to search for a possible kink decay topology close to the vertex, within an area of $5 \times 5\ mm^2$ and 10 films. Kink like topologies due to particles of low momentum are rejected. At this stage, momentum is roughly measured by multiple scattering in the brick,

2.5 Search for ν_τ candidates

Long decays are defined as those where both parent and daughter tracks are recorded in at least one film. Candidates are selected if both tracks converge within errors and have a kink angle $\geq 9.0\ mrad$, i.e. 3 times the minimum detectable kink angle implied by the angular resolution of 2.1 $mrad$ in one film. Short decays are those where the decay occured in the same lead plate as the primary interaction. Selected candidates should have two tracks with an impact parameter (I.P.) larger than 1.8 μm, i.e. 3 times the I.P. resolution in the worst case where the vertex is most upstream in the lead plate.

Vertex location and decay candidate selection are procedures, well established in the CHORUS and DONUT experiments, which imply heavy scanning work. This intensive scanning must be performed quasi on-line in a few large scanning centers (that will be in Japan and in Europe). The total emulsion area to scan is about $5 \times 10^6\ cm^2$. This is almost 100 times the area scanned in CHORUS. To deal with such a large scanning load, scanning speeds should increase by a factor 20 relative to the present system, called UTS.

In the past recent years, scanning power of automated microscopes has been boosted by the unceasing multiplication of PC computers speed and storage capacities. The next generation system under development, the Super-UTS, is designed to be at least 20 times faster than the UTS using a fast CCD camera (3000 frames/s) coupled with continuous X-Y movements of the stage. First Super-UTS prototypes will operate in autumn 2001.

Candidate ν_τ events are a small fraction of the located neutrino interactions. They will go through a full analysis using recorded electronic detector data and further measurements in emulsions. First, the daughter track momentum is precisely re-measured by tracing it along 10 X_0 to define cuts on the decay transverse momentum. Re-measurements are also performed in case of a small kink angle or small impact.

Major background components are, for all decay modes, charm decays with an undetected, generally soft, primary muon, and for the $\tau \rightarrow h$ decay channel reinteractions in the lead plate. Muon identification is performed with the target and spectrometer trackers, but low momentum tracks with $p \leq 500\ MeV/c$ can also be followed down to the brick where they stop. In this brick, $\pi - \mu$ separation can be achieved looking at the ionisation of the last part of the track. Similarly, electron identification of a primary track can suppress charm background asssociated with ν_eCC interactions.

Background from reinteractions in the Pb plates comes mainly from NC events. These background events are identified by a large missing P_T at the primary vertex. To measure P_T, all track segments are read out in a cone $tg\theta \leq 1$ on a 5 X_0 (or 28 films) length to identify all charged tracks associated with the event including γ conversions into electron pairs.

Some of the above operations can require track following or exploration of the downstream cone of a vertex in the next bricks, which have then to be quickly extracted for analysis.

3 OPERA expected performance

3.1 Efficiencies for τ signal events

In this short paper, one cannot describe in detail the algorithms used to isolate ν_τ interaction events. We summarise the efficiencies to signal events of the various selections. Extensive Monte-Carlo simulations have been used, which take into account the experience gathered in CHORUS and DONUT, as well as in test measurements.

The method of finding the interaction brick with the electronic trackers is presently based on scintillator strip centroïds to find the right brick in a wall. If present, the muon track is used in addition, leading to a transversal position resolution of 1.5 cm in CC events compared to 3.0 cm in NC events. A neural network algorithm is used to find the right brick wall, as the abundance of backward tracks makes difficult to use simple criteria.

The global brick finding efficiencies ε_{brick}, given in Table 1 for deep inelastic (DIS) and quasi-elastic and resonance events (QE), assume that only one brick will be removed per event. In the vertex search, the

	ε_{brick}		ε_{geom}	ε_{vertex}		ε_{kink}		ε_{kine}	
	DIS	QE	All	DIS	QE	DIS	QE	DIS	QE
$\tau \rightarrow e$ Long	79.4	81.4	94.0	86.6	60.0	88.2	90.5	83.	84.
Short	"	"	"	"	"	30.0	–	22.	–
$\tau \rightarrow \mu$ Long	73.5	72.1	94.0	95.8	87.0	89.8	91.7	78.	76.
$\tau \rightarrow h$ Long	76.0	58.7 (π) 78.8 (ρ)	94.0	94.7	82.6	90.2	89.6	20.	28.

Table 1: Brick finding, vertex search, kink search, and kinematic selection efficiencies (%) for long and short τ decays.

geometrical efficiency ε_{geom} includes all losses due to emulsion edges and overall fiducial volume effects and is the same for all channels. Vertex finding efficiency in the scanning procedure ε_{vertex} reported in Table 1 is estimated in simulations based on real data or using directly CHORUS and DONUT data.

In the τ decay search, the final selection cut applied on long decay kink candidates is $\theta_{kink} > 20\ mrad$, far above the 3 $mrad$ resolution in kink angle. The corresponding efficiency ε_{kink} is about 90% for all τ decay modes, as seen in Table 1. Short decays are searched only in the $\tau \rightarrow e$ DIS case. A primary track energy $> 1\ GeV$ is required first (66% efficiency), then the impact parameter should be > 5 to 20 μm depending on the primary vertex location along the lead plate (45% efficiency). This cut is also far above the I.P. resolution of 0.6 μm in the worst configuration.

To isolate final τ candidates, simple kinematic selection cuts are used. Mild cuts are sufficient in the leptonic decay channels. A high resolution scanning is applied to the daughter track to determine its identity and energy. Due to brick-to-brick connection, this is possible only for 96% of electrons from τ decays ($> 99.5\%$ for the muons). Then the daughter lepton energy is required to be $> 1\ GeV$ to eliminate low energy electrons (from γ conversions) or muons (having a poor ID) and $< 15\ GeV$ to reduce ν_eCC or ν_μCC interactions. The energy cut efficiency for signal events is $\sim 90\%$. Transverse momentum at the decay vertex p_t is required to be $> 100\ MeV/c$ for electrons and $> 250\ MeV/c$ for muons (respective efficiencies for signal are $> 99\%$ and $\sim 90\%$). Adding in the probability to properly identify the electron or the muon, the global kinematic selection efficiency is 84% and 77% respectively for $\tau \rightarrow e$ and $\tau \rightarrow \mu$ long decays.

For DIS $\tau \rightarrow e$ short decays, a lower cut of 1 GeV/c is applied to the momentum of all tracks used to compute the I.P., to reduce background from low energy tracks. The condition $E_e < 15\ GeV$ is also applied and the minimum P_T compatible with the observed tracks is required to be $> 50\ MeV/c$. The overall efficiency of those kinematic conditions is $\sim 22\%$.

For $\tau \rightarrow h$ decays, to keep background at a very low level, more severe kinematical cuts are applied both at the decay and at the primary vertex. At the decay vertex, cuts similar to the leptonic cases but harder, $E > 2\ GeV$ and $p_t > 600\ MeV/c$, are applied. At the primary vertex, the missing transverse momentum and the angle in the transverse plane between the parent track and the hadronic shower direction are required to be $< 1\ GeV/c$ and $> \pi/2$. These conditions can be applied only to events with more than one fully measured track beside the τ track at the primary vertex. For that reason, the overall efficiency of the selection differ for DIS (20%) and QE (28%) ν_τ interactions.

Overall signal detection efficiencies for each decay channel are shown in Table 2. They are the product of the above efficiencies by the trigger efficiency ($> 99\%$ for all channels), the probability of long or short decay (39 or 60% respectively) and the probability that a hadron track misidentified as an electron or a muon does not lead to reject the candidate signal event (between 90 and 97% depending on the case). The total τ^- detection efficiency amounts to 8.7%.

	Efficiencies (%)			Signal events for Δm^2 (eV^2)		
	DIS	QE	Global	1.5×10^{-3}	3.2×10^{-3}	5.0×10^{-3}
$\tau \rightarrow e$ Long	3.0	2.6	3.7	1.3	5.9	14.2
Short	1.3	–	1.3	0.4	1.8	4.3
$\tau \rightarrow \mu$ Long	2.7	2.8	2.7	1.3	5.7	13.8
$\tau \rightarrow h$ Long	2.2	2.8	2.3	1.1	4.9	11.8
Total	9.3	8.3	8.7	4.1	18.3	44.1

Table 2: Summary of τ detection efficiencies (%) including branching ratios and expected numbers of τ events in 5 years for different Δm^2 values at full mixing.

3.2 Background

A thorough background evaluation has been performed using a full simulation which includes the beam properties, the physics processes and the detector structure. Prompt ν_τ production at the primary proton target or dump has a completely negligible contribution to the background. The most important background source in all channels is the production and one-prong decay of charmed particles, while prompt electrons and π^0's for $\tau \rightarrow e$, large angle muon scattering for $\tau \rightarrow \mu$, and hadronic reinteractions for $\tau \rightarrow h$ are decay specific backgrounds. All have been studied in detail using direct comparison with CHORUS and DONUT data or simulations driven when possible by real data, together with conservative assumptions when needed. The total number of background events expected in 5 years of data taking, as shown in Table 3, is 0.57. The

	Charm	ν_eCC and π^0	μ scatt.	Hadron reint.	Total
$\tau \to e$ Long	0.15	0.01	–	–	0.16
Short	0.03	$\ll$0.01	–	–	0.03
$\tau \to \mu$ Long	0.03	–	0.10	–	0.13
$\tau \to h$ Long	0.15	–	–	0.10	0.25
Total	0.36	0.01	0.10	0.10	0.57

Table 3: Expected background events in 5 years.

uncertainty on this number is about 0.2 events.

3.3 Sensitivity to $\nu_\mu \to \nu_\tau$ oscillations

In the following, the removal of a single brick per event and its replacement by a brick taken on the periphery of the detector is assumed. With 5 years of data taking, this corresponds to an average target mass of 1800 *tons*. The estimated sensitivity to $\nu_\mu \to \nu_\tau$ oscillations takes into account the energy dependence

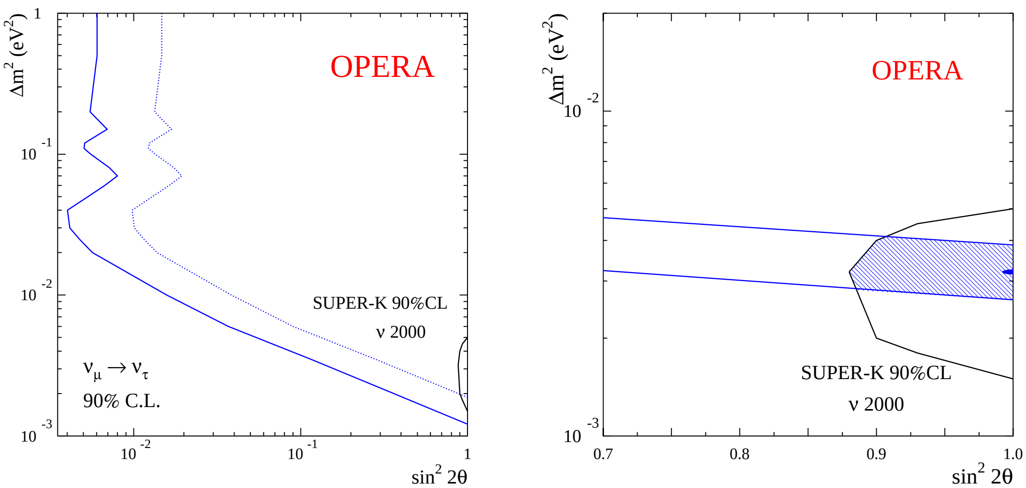

Figure 3: Left: sensitivity of OPERA to $\nu_\mu \to \nu_\tau$ oscillations at 90% CL for 2 and 5 years exposure (dotted and continuous lines). The region allowed by the SuperKamiokande analysis is also shown. Right: The band shows the 90% CL allowed region of the oscillation parameters determined by OPERA if the observed number of τ events corresponds to the expectation for full mixing and $\Delta m^2 = 3.2 \times 10^{-3}\ eV^2$.

of neutrino spectra and of detection efficiencies. Expected number of τ events in 5 years of shared SPS operation (assuming a total of 2.25×10^{20} *pot*) are shown in Table 2. For a 4σ discovery claim of $\nu_\mu \to \nu_\tau$ oscillation, about 5 events are required, given the Poisson probability distribution of the number of expected background events. If $\Delta m^2 = 1.7 \times 10^{-3}\ eV^2$, the average number of signal events expected is above 5. It has been calculated with an approximated distribution of probability for the Super-Kamiokande allowed region, that OPERA has 92% chance of observing more than 5 events after 5 years of running.

The sensitivity calculation has been carried out with an overall uncertainty of 15% assumed on the number of expected signal events. The background uncertainty was taken to be 15% for charm and 50% for other sources. The average upper limit at the 90% CL which would be obtained from negative searches has been derived from the simulation of a large number of experiments. As seen in Figure 3-Left, the sensitivity covers already after two years of running most of the region presently allowed by Super-Kamiokande.

From the number of detected τ events, a measurement of the oscillation parameters can be obtained. Figure 3-Right shows an example of such a measurement. For full mixing and $\Delta m^2 = 1.5,\ 3.2,\ or\ 5.0 \times 10^{-3}\ eV^2$, the corresponding 1σ errors on Δm^2 are 25., 11.6, or 7.3% if respectively 4, 18, or 44 events are observed as expected.

4 Conclusion

Oscillations $\nu_\mu \to \nu_\tau$ have to be observed to positively identify the source of the atmospheric neutrino deficit. Aimed at a direct appearance search in the european long baseline dedicated beam CNGS, the OPERA experiment has a design based on the Emulsion Cloud Chamber (ECC) principle, proven effective in the ν_τ discovery by DONUT. With a large quantity of ECC modules of the size of a brick made of thin lead plates interspaced with emulsion layers, a ~ 2000 *tons* fine-grained vertex detector can be assembled. The impressive progress of automatic scanning and the capacity of industrial production for emulsion films allow to set up such a massive ultra-high precision tracking device.

The very low background confirms the merits of the emulsions for the direct observation of the τ decay. The option chosen makes it possible to benefit from the detection of various τ decay modes to increase the τ detection efficiency. As seen in the above paragraphs, the OPERA experiment has a range of sensitivity that covers the parameter region indicated for $\nu_\mu \to \nu_\tau$ oscillation by the Super-Kamiokande data. The possible observation of unambiguous τ events in a low background situation gives to OPERA a significant discovery potential.

The number of detected τ events will constrain the oscillation parameters, allowing to provide a independent determination of Δm^2 , complementary of those performed with atmospheric neutrinos and long baseline disappearance programs. Moreover, each brick being a compact fine-grained electromagnetic calorimeter (with the equivalent of 15 successive tracker planes after each 0.2 X_0 sampling), the OPERA structure also favours the search for $\nu_\mu \to \nu_e$ oscillations, which can be used in conjunction with $\nu_\mu \to \nu_\tau$ to perform a three-flavour neutrino oscillation analysis and constrain the MNS mixing matrix parameters.

References

[1] The OPERA Collaboration, M. Guler *et al.*, Experiment Proposal, CERN/SPSC 2000-028 LNGS P25/2000.

[2] G. Acquistapace *et al.*, "The CERN Neutrino beam to Gran Sasso", CERN 98-02 INFN/AE-98/05 and Addendum CERN-SL/99-034 INFN/AE-99/05;
A.E. Ball *et al.*, "CNGS: Update on secondary beam layout", CERN/SL-Note-2000-063 EA

[3] Y. Fukuda *et al.*, Phys. Rev. Lett. **81** (1998) 1562; Y. Fukuda *et al.*, Phys. Rev. Lett. **82** (1999) 5194;
Y. Fukuda *et al.*, Phys. Rev. Lett. **82** (1999) 2644;
H. Sobel (Super-Kamiokande Coll.), Neutrino-2000 Proc., Nucl. Phys. B (Proc. Suppl.) **91** (2001) 127.

[4] M. Apollonio *et al.*, Phys. Lett. **B420** (1998) 397; M. Apollonio *et al.*, Phys. Lett. **B466** (1999) 415.

[5] T. Mann (Soudan-2 Coll.), Neutrino-2000 Proc., Nucl. Phys. B (Proc. Suppl.) **91** (2001) 134.

[6] B. Barish (MACRO Coll.), Neutrino-2000 Proc., Nucl. Phys. B (Proc. Suppl.) **91** (2001) 141.

[7] The MONOLITH Collaboration, N.Y. Agafonova *et al.*, Proposal, CERN/SPSC 2000-031 LNGS P26/2000;
A. Geiser, Neutrino-2000 Proc., Nucl. Phys. B (Proc. Suppl.) **91** (2001) 147.

[8] C. McGrew (SUNY), "New atmospheric neutrino results from Super-Kamiokande", NOON workshop, Tokyo, december 2000,
$http://www-sk.icrr.u-tokyo.ac.jp/noon/index.html$

[9] S. Ahn *et al.*, "Detection of Accelerator-Produced Neutrinos at a Distance of 250 km", hep-ex/0103001.

[10] E. Ables *et al.*, Fermilab Proposal P-875 (1995);
NuMI-L-337 (1998); NuMI-L-375 (1998).

[11] The ICARUS & NOE Collaboration, F. Arneodo *et al.*, INFN/AE-99-17, CERN/SPSC-99-25, SPSC/P314.

[12] M. Nakamura (DONUT Coll.), Proc. of the XXXth Int. Conf. on High Energy Physics, Osaka, 2000.