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The OPERA emulsion detector for a long-baseline neutrino-oscillation experiment

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ABSTRACT

We present a new detector concept (OPERA), a massive iron/emulsion target for a long-baseline neutrino-oscillation search. The experiment can perform an appearance search for $\nu_\mu - \nu_\tau$ oscillation in the parameter region indicated by the atmospheric neutrino anomaly. It exploits nuclear emulsion for the unambiguous detection of the decay of the τ produced in ν_τ charged current interactions and features a detector target with relatively small mass (200 ton) and dimensions. The very low background is an essential ingredient to its high discovery potential and promises a unique role in the clarification of the experimental scenario. OPERA can run in the Gran Sasso Laboratory in the proposed neutrino beam from CERN.

1. Introduction

One of the crucial questions in the present scenario of particle physics is whether the neutrino has non-vanishing mass. A massive neutrino would be the direct indication of physics beyond the Standard Model, representing a fundamental milestone in particle physics. Moreover, it would have profound implications for cosmology and astrophysics, giving a clue in the explanation of the dark matter puzzle [1]. The interesting mass range is out of reach of the measurements from decay kinematics. The only way to assess this issue is to search for neutrino oscillation, which may occur for massive neutrinos.

In a first approximation oscillation phenomena occur between two neutrino flavours and are described by two parameters: the mixing angle $sin^2 2\theta$ and the mass squared difference Δm^2. The sensitivity of the experimental searches to these parameters depends on the neutrino energy and on the distance L of the detector from the neutrino source. For experiments at high-energy accelerators one usually defines short ($L \sim 1$ km), medium ($L \sim 10$ km) or long ($L \sim 1000$ km) baseline.

Presently, there are three experimental indications for neutrino oscillation. Matter-enhanced oscillations [2] can explain the solar neutrino deficit with parameters $\Delta m^2 = (0.5\text{–}1.6) \times 10^{-5}$ eV^2 and $sin^2 2\theta = (0.4\text{–}1.2) \times 10^{-2}$ [3]. If one attributes to neutrino oscillation the apparent deficit of atmospheric muon neutrinos, as measured in the Kamiokande experiment, a small Δm^2 ($\sim 10^{-2}$ eV^2) and a large mixing angle ($sin^2 2\theta > 0.5$) emerge [4]; both possibilities of $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_e$ oscillation are contemplated. In addition, the recent claim from the LSND experiment [5] suggests the existence of $\overline{\nu}_\mu - \overline{\nu}_e$ oscillation with $\Delta m^2 \sim 1$ eV^2.

Within the conventional two-flavour oscillation scheme, two independent Δm^2 are available as oscillation parameters. The three Δm^2 indicated above would thus require a fourth (sterile) neutrino [6]. Recently, several phenomenological analyses of the present data have been published [7][8][9][10][11][12][13] where the full mixing matrix of a three-flavour general approach is exploited. Such three-flavour analyses incorporate the experimental observations to a larger extent by attributing at least two of the phenomena to the same mass difference. The contemplated mass/mixing patterns result in interesting predictions for the experiments.

The next generation solar and atmospheric neutrino experiments are expected to substantially contribute, with new data, to the experimental scenario on neutrino mixing. SNO [14] will perform the measurement of the ratio of charged to neutral current events. Both SNO and Super Kamiokande [15] will be able to observe effects that can discriminate between neutrino oscillation schemes, such as time variation of the solar signal and spectrum distortion of the recoil electrons from neutrino interactions. The Borexino experiment [16] can address the energy dependence of the solar ν deficit. The atmospheric ν_μ/ν_e anomaly has been confirmed by preliminary results from Super Kamiokande [17][18].

Specific appearance searches are pursued by accelerator experiments. The evidence for $\overline{\nu}_\mu - \overline{\nu}_e$ oscillation reported by LSND will soon be verified by the upgraded KARMEN experiment [19]. In the $\nu_\mu - \nu_\tau$ channel, the two running experiments at CERN, CHORUS [20] and NOMAD [21], using only a fraction of the available data have recently reported [22][23] no evidence for oscillations at the level of the present best limit [24]. These are short-baseline experiments, therefore sensitive to small mixing angles ($sin^2 2\theta_{\mu\tau} \sim 2 \times 10^{-4}$) and relatively large Δm^2. A positive signal will call for a new dedicated experiment with higher sensitivity, to confirm the discovery and to learn more. In case of a negative search, theoretical speculations incorporating the observation of the solar neutrino deficit and particle physics arguments [25][26][27] suggest to further extend the investigation to smaller mixing angles. A ν_τ mass ranging from 1 to 10 eV is predicted, which would then be a natural candidate for the "hot" component of the dark matter. A new experiment (I213/TOSCA) has been recently proposed at CERN [28] which is able to increase the sensitivity by more than one order of magnitude with respect to the searches presently under way. Finally, similar in design to CHORUS, but expecting a total data sample one order of magnitude larger, COSMOS [29] is approved for a short-baseline search at Fermilab. Within the three-flavour analysis, TOSCA and COSMOS have sufficient sensitivity in mixing to probe a proposed solution of all oscillation evidences and, in this framework, the LSND signal [9].

A complementary approach requires to explore the region of oscillation parameters indicated by the atmospheric neutrino anomaly. This parameter region is not accessible by short-baseline experiments. Long (medium)-baseline experiments are needed to explore the small Δm^2 region favoured by the existing data. Two forthcoming reactor experiments, CHOOZ [30] and Palo Verde [31], will look for $\bar{\nu}_e$ disappearance with a sensitivity in the mass difference of 10^{-3} eV^2. A new generation of accelerator-based experiments is being planned. A neutrino beam will be sent from KEK to the Super Kamiokande detector, about 250 km away [32]. At Fermilab, the experiment MINOS [33] is approved. MINOS will use a beam from Fermilab to the Soudan Mine, at 730 km distance, to test the hypothesis of neutrino oscillation with $\Delta m^2 \sim 10^{-2} - 10^{-3}$ eV^2. Long-baseline experiments [34][35][36] have been proposed using the future beam from CERN to the Gran Sasso Laboratory [37][38], at 731 km from the source. A medium-baseline experiment has also been proposed recently [39], which would use the present SPS beam and a liquid Argon TPC detector of 400 ton located in the Jura mountain, 17 km from CERN, to explore neutrino-oscillation in the region of $\Delta m^2 \sim 1$ eV^2.

The technique of nuclear emulsion, which finds its first large scale application in the active target of the CHORUS experiment, can be further improved for future $\nu_\mu - \nu_\tau$ oscillation experiments [40][41][42][28]. In [43] ideas for emulsion experiments suitable for appearance $\nu_\mu - \nu_\tau$ oscillation searches were presented. In particular, the conceptual design of a massive detector (OPERA[1]) able to explore with high sensitivity the low Δm^2 region ($10^{-2} - 10^{-3}$ eV^2) was outlined. In OPERA, emulsions are used as high precision trackers, unlike CHORUS or TOSCA where they compose the active target. The extremely high space resolution of the emulsion copes well with the peculiar signature of the short-lived τ lepton, produced in ν_τ interactions, and the direct observation of the decay topology allows background reduction to a very low level.

As pointed out in the classic book by Powell, Fowler and Perkins [44], after the impressive work for the development of emulsion plates with high grain density it was generally realized that the method had features of great interest for experiments on the search for unstable particles with mean lifetimes of the order of 10^{-8}–10^{-10} s. Fifty years after the discovery of the pion through the observation of its decay in the emulsion exposed to cosmic rays [45], emulsions appear again important for the observation of particles with lifetimes of 10^{-12}–10^{-13} s and for the study of related processes.

Emulsion experiments benefit nowadays from the impressive progress in the field of computer controlled microscopes, read-out by CCD cameras, with automatic pattern recognition and track reconstruction. After its pioneering work [46], the Nagoya group in the CHORUS Collaboration has produced second generation automatic systems about 10 times faster [47]. A new automatic system has also been designed by the Salerno group [48]. More improvements are expected from the intense R&D programs under way. Fig. 1 depicts, schematically, the operation of an automatic microscope. Fig. 2 shows the CCD image of a neutrino interaction vertex and Fig. 3 displays a neutrino event in the CHORUS emulsion target, as reconstructed by the computer.

As outlined in [49][50], the OPERA concept is appealing for a long-baseline oscillation search. The proposed beam from CERN to the Gran Sasso Laboratory offers such an opportunity. The experiment will be able to explore the parameter region indicated by the atmospheric neutrino deficit, searching for the unambiguous signature of $\nu_\mu - \nu_\tau$ oscillation. OPERA will perform a ν_τ appearance search, through the background-free detection of the decay of the τ lepton produced in the ν_τ interaction with a relatively small-mass target (200 ton). Thanks to the capability of the emulsion in identifying electrons and to the small contamination of ν_e in the beam, OPERA will also accomplish a $\nu_\mu - \nu_e$ oscillation search with good sensitivity. Fig. 4, taken from [13], shows the $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\tau$ flavour conversion-probability implied by [11] and [12] for a baseline of about 730 km. A spectacular signal is predicted by the Cardall and Fuller scheme [12], in particular in the ν_τ appearance channel.

The proposed experiment is complementary to the short-baseline search envisageable with TOSCA which may run in the same beam line. The present experimental situation is such that explorations of the different regions of oscillation parameters domain are needed

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[1] Oscillation Project with Emulsion-tRacking Apparatus.

to effectively contribute to the clarification of the global scenario.

2. The OPERA detector

Fig. 5 shows the experimental set-up introduced in reference [51] to detect γ-pairs from the decay of energetic neutral-pions from cosmic rays. The γ diverge in the air gap and then produce cascades in passing through the sandwich of lead and emulsion. The opening angle of the γ-pair and the development of the cascade offer means to estimate the energy of the neutral pion [44][52][53]. This device, now generally called Emulsion Cloud Chamber (ECC) is very economical in the use of emulsion with respect to pure emulsion targets. The ECC has been used for several (also large scale) applications [54] and recently revised and proposed for long-baseline experiments searching for $\nu_\mu - \nu_\tau$ oscillation [55][43].

In general, the ECC provides a massive target made up of a sandwich of (dense) passive-material plates and thin emulsion sheets (Fig. 6). Employing iron as a target, with the emulsion used only for tracking, the target mass can be increased by two orders of magnitude or more, as compared to other emulsion experiments like CHORUS and TOSCA. However, in the ECC, the direct observation of the τ decay "kink" performed by CHORUS and TOSCA is replaced by an impact parameter measurement.

The OPERA concept is an evolution of the ECC. The idea is to add a "drift space" between consecutive emulsion sheets. As further discussed in the following, this "empty" space between the ES allows the direct detection of the τ decay kink, superior to the impact parameter measurement performed with the conventional ECC. This results in a substantial background reduction.

2.1 The target

The detector described here is a 200 ton iron/emulsion target subdivided in 92 modules (Fig. 7). Each module, whose dimensions orthogonal to the beam direction are about 3×3 m^2, consists of a sequence of 30 sandwiches, each composed of a 1 mm thick iron plate followed by an emulsion sheet (ES), a "drift space" of 2.5 mm, and another ES (Fig. 8). An ES is made up of a pair of emulsion layers 50 μm thick, on either side of a 100 μm plastic base. The drift space can be realistically filled with very low density material. Along the beam axis, the total thickness of one module is about 12 cm. Transverse to the beam direction, each module could be subdivided into elements, *e.g.* with a 30×30 cm^2 area. The insets of Fig. 7 show a target module and its elements. Fig. 9 shows the support structure of the detector elements allowing for their replacement.

When neutrinos hit the iron plates, primary particles are produced, some of which, in turn, may interact or induce showers downstream in the detector. Charged particles give two track segments in each ES. The $\sim 1\ \mu$m granularity of the emulsion layers ensures ample redundancy in the measurement of particle trajectories.

If a τ is produced, most likely it will decay within a few millimeters. Its decay can be detected by measuring the angle formed by the charged decay daughter of the τ with respect to the τ direction, this decay kink angle being due to the invisible neutrino(s) produced in the τ decay (Fig. 8). For decays in the drift space, the directions of the tracks before and after the kink are reconstructed (directly in space) by means of the first pair of ES downstream of the iron plate where the primary vertex occurs.

The 50 μm thickness of the emulsion layers is large enough to achieve high tracking efficiency and angular resolution (~ 5 mrad) and is sufficiently small to allow for industrial production, like commercial photographic or X-ray emulsion. The thickness of the plastic base between the two emulsion layers determines the angular resolution. The use of a thicker base (200 μm) may be envisaged, if this is compatible with the request of minimizing the amount of material in each sandwich. Feasibility and optimization studies will have to be performed by constructing prototype modules and exposing them to charged particle and neutrino beams.

The whole target must be kept at constant temperature (10–15 ^oC) in order to protect the emulsion against thermal deformations and "fading" (see Section 3.2).

2.2 Event location and electronic detectors

Obviously, the emulsion sheets have no time resolution. Therefore, electronic detectors are needed to correlate the occurrence of neutrino events to that target element where the interaction occurs and to guide the scanning. For a long-baseline application the detector will naturally be placed underground, shielded against non-penetrating particles and low energy muons from cosmic ray showers. Together with the low neutrino beam flux, determined by the long distance from the source, and with the absence of beam halo muons, this leads to a very low density of background tracks "stored" in the emulsion and removes the need for a precise location of individual tracks in the ES by electronic trackers. Therefore, these detectors may have a moderate space resolution (a few millimeters).

The electronic trackers are placed behind each 12 cm target module. They detect the particles produced by the neutrino interaction and, hence, locate the ES where scanning must start. About 1 cm^2 of this ES is scanned in correspondence with the detected interaction and all the found track segments are measured. These are then extrapolated and searched for in the upstream ESs, until the event vertex is reached. This "scan-back" procedure is performed for secondary tracks, correlating segments in ES which are closely spaced by the thin iron plates and the "empty" drift gaps. The method is intrinsically very efficient to find the position of the event vertex.

The accuracy in the relative alignment of the ES which compose a target element can be of the order of a few hundred microns by means of a suitable mechanical support structure. Due to the very low density of tracks, a further micrometric precision in the alignment may be achieved by using the tracks of any particle crossing the module. In particular, one can consider those tracks belonging to the event itself.

The tracking detectors have the additional task of muon identification with good efficiency and angular acceptance. For this purpose, the tracking sections are arranged in planes with transverse dimensions sufficiently larger than those of the emulsion. Honeycomb chambers [56] may be envisaged, with a design similar to those installed in the CHORUS apparatus [57].

Honeycomb chambers can be made up of several layers of closed hexagonal cells, with a size of approximately 1 cm and a pitch of 1.2 cm. Each cell has a thin (20 μm) sense wire at about 2000 V potential difference *w.r.t.* the cell wall. This wall is composed of preformed conductive plastic. The operation of these chambers is similar to straw tubes. The difference is that the construction of large planes is easier, since wires can be positioned when the cells are still open.

Three orientations may be foreseen, rotated by 60 degrees with respect to each other. Each orientation contains three wire planes. This is sufficient to perform pattern recognition and to obtain three-dimensional information. According to an electronic design available for the read-out of these chambers [57], each wire is connected to its own multi-hit TDC. The precision which can be reached in large systems is 200 μm per plane. The number of wires is 300000 for our application. Fig. 10 shows a typical multi-track event reconstructed by the CHORUS honeycomb chambers [57].

To increase the muon detection efficiency and, consequently, the background rejection, muon detectors could also be added around the target. Honeycomb chambers or limited streamer tubes may be used.

The momentum of the charged τ-decay products can be determined by a multiple scattering measurement in the emulsion. The resolution achievable with this method is weakly dependent upon momentum. It ranges from 10% at 1 GeV/c to 20% at 30 GeV/c, according to preliminary estimates. However, as we will see in Section 3.4, in the proposed experiment there will be practically no need for momentum measurement, due to the very low background level. A magnetized-iron muon spectrometer is placed behind the iron/emulsion target, with the purpose of measuring the charge of forward muons.

The electronic detectors also act as the active component of a (fine-grained) calorimeter, where the 12 cm thick iron/emulsion modules play the role of the absorber material. Each target module is nearly 2 radiation lengths thick. Therefore, a calorimetric measurement of the events can be performed, helping in the kinematical analysis of candidate events. Monte Carlo simulations predict an electromagnetic energy resolution of $35\%/\sqrt{E(GeV)}$.

To complete the energy measurement for events originating downstream in the target, the muon spectrometer is calorimetrized.

The overall dimensions of the experimental apparatus, shown schematically in Fig. 7, are $\sim 3 \times 3 \times 25$ m^3. We stress that the relevant parameter in the target design is the mass. One can envisage to modify the above transverse and longitudinal dimensions in order to optimize the experiment performance and to cope with the actual logistic of the experimental hall.

2.3 Background rejection in OPERA

In the proposed search for $\nu_\mu - \nu_\tau$ oscillation, all the major τ decay channels are studied. For the single prong decays into a charged hadron, which have the largest branching ratio (BR = 50%), an important source of background is potentially given by hadron reinteractions. One of the primary hadrons of the event may, in fact, reinteract in the vertex iron plate giving products invisible in the emulsion, hence faking the decay of the τ.

Given the average number of charged hadrons per event ($\sim$ 4), the iron plate thickness and the number of neutral current (NC) events collected by the experiment, one can predict the number of background events from hadron reinteractions $N_{bg}(reint.) \sim 4 \times (0.050/10.5) \times N_{NC} = 0.02 \times N_{NC}$, where the term in bracket is the ratio between (one half of) the iron plate thickness and the nuclear collision length. It is evident that, even in the case of a relatively low statistics experiment, the reinteraction background can not be disregarded.

The novel feature of the OPERA concept is the 2.5 mm drift space between consecutive iron plates (Fig. 8). By requiring that the decay occurs in this gap, one rejects the reinteraction background. This, at the cost of a somewhat reduced signal efficiency, because of the loss of the τ decaying in the iron plate where the primary vertex occurs ("short decays"). Also the small fraction of "long decays" is rejected, *i.e.* those events where the kink occurs in the following iron plate or further on.

The OPERA concept also allows for a reduced background to the muonic τ decays. The requirement that the decay does not occur in the iron eliminates those charged current (CC) charm events which may fake a large impact parameter of the muon, as shown in Fig. 11. Following arguments similar to those presented in Section 3.4, we can estimate the potential background induced by D^+ mesons to be $N_{bg}(D^+) \sim 4 \times 10^{-4} \times N_{CC}$, where N_{CC} is the total number of charged current events. A factor two higher number of events due to D^0 production and decay is predicted ($N_{bg}(D^0) \sim 10^{-3} \times N_{CC}$).

Both the reinteraction and the charm backgrounds described above are significant in an experiment employing a "standard" ECC detector. In that case, in particular, one may be led not to use the valuable muonic decay channel of the τ [55][43], which has very clear topology but is too much affected by charm background (Fig. 11).

We have seen that removing background events with a kink in the iron, a lower efficiency is obtained for the signal. With respect to this, a denser target material would be advantageous. With higher density (*e.g.* tungsten or lead alloy), thinner foils could be used (500 μm), increasing the τ detection efficiency at constant emulsion mass. Another possibility is to still use 1 mm thick but more massive plates. In the latter case, one would have a more compact detector, reducing the amount of emulsion and the number of electronic detectors. For a denser material alternative to iron, both the above options have to be evaluated in relation to the technical feasibility, to the possible deterioration of the detector performance and to the cost.

3. OPERA at the Gran Sasso Laboratory

Several possibilities can be contemplated for the oscillation scenario, invoked to explain the atmospheric ν_μ deficit. There could be a pure $\nu_\mu - \nu_\tau$ or $\nu_\mu - \nu_e$ conversion or a combination of the two. In both cases, by using a high-energy accelerator neutrino beam, long(medium)-baseline experiments have to be used to explore the interesting oscillation parameter region of low Δm^2 ($\sim 10^{-2}$ eV^2).

A neutrino beam from the CERN SPS to the Gran Sasso (at 731 km distance) is under study [34][37][38][39]. The sensitivity to small mixing angles is, at long-baseline, relatively poor, given the low neutrino flux due to the very long travel-distance and to the divergence of the neutrino beam. Therefore, the target has to be massive.

The OPERA detector appears very attractive for an appearance experiment at the Gran Sasso. In the search for $\nu_\mu - \nu_\tau$ oscillation, the high detection efficiency of OPERA, together with its negligible background and the direct observation of the τ kink, allow to limit the target weight (and dimensions), still retaining good sensitivity in the interesting domain of the oscillation parameters. It uses the 200 ton target previously described, while all the experiments proposed so far for long-baseline oscillation-experiments [32][33][34][35][36] feature very large target-mass (1 kton or more).

In references [55] and [43] the use of a standard, large mass (1 kton) ECC was envisaged to search for $\nu_\mu - \nu_\tau$ oscillation with a long-baseline experiment. The τ detection is accomplished by means of an impact parameter measurement, without topological information about the presumed τ decay vertex. For that detector the relatively high event yield (which allows for a short run) is counterbalanced by a higher background. In addition, a large quantity of emulsion is needed. The OPERA detector seems better suited for an experiment at the Gran Sasso, given its peculiar characteristic of detecting decay kinks in the drift space. Similar experimental considerations apply to the neutrino beam from the Fermilab Main Injector sent to the Soudan mine, where the MINOS experiment is planned

[33]. OPERA could also run in that beam at a long-distance position.

Besides the τ detection capability, which is the distinctive feature of the detector, also prompt electrons (signature of $\nu_\mu - \nu_e$ oscillation) may be identified by exploiting the properties of the emulsion [58][59]. The electron identification is practically feasible due to the small number of events of the experiment, and leads to a search with good sensitivity (see Section 4).

3.1 The neutrino beam

Concerning the features of the neutrino beam from the CERN SPS to the Gran Sasso Laboratory, we refer to published studies [34][37][38][39][60]. Several beam designs exist, differing in the primary proton energy, in the extraction mode, and in the focusing magnets configuration. As a basis for the experiment design, in this paper we will take the scheme described in references [39] and [60], where neutrinos (mainly ν_μ) are produced by a 450 GeV proton beam. The most relevant characteristics of this beam at the Gran Sasso location are given below, evaluated over a surface of 9 m^2.

The present CERN SPS can produce neutrinos by accelerating 2.5×10^{19} pot/year, with a 200 days run, 3×10^{13} pot/ 14.4 s cycle and 70% efficiency [42]. This is a realistic statement, given the current performance of the machine in supplying the CHORUS and NOMAD experiments. For a future beam to the Gran Sasso, the SPS should achieve a comparable performance [61]. Obviously, higher beam intensity, as requested for the TOSCA experiment [28], will allow a faster reach of the sensitivity goal and a higher discovery potential.

The expected neutrino flux and the number of interactions for the different neutrino species of the beam is given in Table 1. The mean energy of the ν_μ is 30 GeV, while the average energy of the ν_e contaminating the beam is 37 GeV. The energy spectra of muon and electron neutrinos are given in Fig. 12. The relative ν_e contamination of the beam is $(0.4 \pm 0.1)\%$.

We observe that for the beam line design of reference [37] a factor two lower neutrino flux is predicted for the Gran Sasso location.

3.2 Neutrino run and interactions

The maximum time of exposure of the emulsion depends on two major parameters: the density of integrated background tracks and the "fading" process, *i.e.* the partial loss of the latent image prior to the development. In the case of a short-baseline location, as in CHORUS and TOSCA, the integration of beam halo muons, of muons associated with

	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
Flux $(\nu/(10^{19} pot \times m^2))$	1.1×10^{10}	1.3×10^{8}	5×10^{7}	0.5×10^{7}
Charged curr. $(evts/(10^{19} pot \times kton))$	1022	16	5	0.7

Table 1: Expected neutrino fluxes and event rates at the Gran Sasso location.

the SPS test beams and of cosmic rays limits the exposure time to about 2–3 years. Also fading, which to some extent may be tuned by modifying the emulsion composition, plays an important role.

Suppose that we were to run OPERA at the Gran Sasso Laboratory. Halo muons are absent and the cosmic background is negligible. In addition, the low event rate has an important experimental implication. The emulsion sheets in the few target elements hit by neutrinos can be developed and replaced during the run, say after each year of data taking (see Section 5). Therefore, fading is also not a limitation. The conclusion is that it is realistic to foresee a long run (4 years, or more) by regularly replacing a small fraction of the target elements. This implies an efficient use of the investment represented by the beam facility and by the experimental apparatus.

Under the previous assumptions on the beam line design and accounting for a total of 10^{20} pot, the expected number of ν_μ interactions in 4 years is 2044 CC, 640 NC and 10 interactions induced by the ν_e contaminating the beam. The amount of ν_e interactions and the uncertainty on its estimate contribute to set the sensitivity limit for a $\nu_\mu - \nu_e$ oscillation search, which will also be discussed here. The number of events produced by $\overline{\nu}_\mu$ is ~ 30. The above estimates are valid in the case of absence of oscillation and for a 200 ton target.

3.3 Detection efficiency for the τ decay

Due to the low statistics, in the proposed experiment no kinematical cuts need to be applied to reduce the number of events to be scanned, so leading to high efficiency for the signal and to an effective use of the detector mass.

The signal of the occurrence of neutrino oscillation is the charged current interactions of τ neutrinos in the detector target

$$\nu_\tau N \ \rightarrow \ \tau^- X.$$

The detection of the decay of the τ lepton in the final state identifies this reaction. The τ^- can be detected through its decay modes into single hadrons, muons and electrons

$\Delta m^2 = 0.008\ eV^2$	$\Delta m^2 = 0.01\ eV^2$	$\Delta m^2 = 0.1\ eV^2$	$\Delta m^2 \geq 1\ eV^2$
$56 \pm 3\%$	$59 \pm 2\%$	$61 \pm 1\%$	$62 \pm 1\%$

Table 2: Efficiency ϵ_{gap} to detect a τ kink inside the drift space as a function of Δm^2.

$$\tau^- \to h^- \nu_\tau (n\pi^0)$$

$$\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$$

$$\tau^- \to e^- \nu_\tau \overline{\nu}_e$$

and into three charged pions plus neutrals

$$\tau^- \to \pi^+ \pi^- \pi^- \nu_\tau (n\pi^0).$$

In OPERA, the τ decays in the vertex iron plate ("short kinks") are rejected, as well as the small fraction of "long kinks" occurring in the iron plate following the vertex plate. One retains decays in the drift space between ES. In this way, one performs a direct kink detection instead of an impact parameter measurement, with consequent background reduction and improved significance of the signal. As already noted, the price to pay for such an important gain is a reduction in the τ detection efficiency. The oscillation probability depends on $\Delta m^2 \times L/E$. This means that small Δm^2 values correspond to low energy oscillated ν_τ and, hence, to low energy τ leptons. Since the decay length of the τ is related to its energy through the γ factor, the efficiency ϵ_{gap} of the above cut is a function of the Δm^2 value (Table 2). The discarded events with decay in the iron will be available for special analyses.

An additional source of inefficiency is determined by the rejection of small angle kinks (< 15 mrad). This is given by the angular resolution in the measurement of the kink angle by means of two ES, which give four space track-segments. About 95% of the τ decays have a kink angle larger than the 15 mrad. Taking also in account errors on the relative alignment of the ES within a target element, we obtain an overall kink detection efficiency $\epsilon_{kink} = 90\%$.

Due to edge effects, a fiducial volume cut of $\sim 5\%$ has to be applied. This introduces an additional efficiency term $\epsilon_{fid} = 95\%$.

The τ decay into single charged hadron plus neutrals has the highest BR (50%). In the whole kinematical domain accessible by OPERA, the overall detection efficiency of this channel $\epsilon_h = \epsilon_{gap} \times \epsilon_{kink} \times \epsilon_{fid} \times$ BR ranges from 24 to 26.5%, according to the Δm^2 domain.

Similar considerations apply to the muon and electron decay of the τ. The contributions of these two channels to the signal are nearly the same. The BR is 18% for both the decay modes, and an efficiency $\epsilon_\mu \sim \epsilon_e$ ranging from 8.5 to 9.5% is obtained. The global detection efficiency $\epsilon_{tot} = \epsilon_h + \epsilon_e + \epsilon_\mu$ of OPERA is high. It amounts to 45.5% (41%) in the high (low) Δm^2 region.

The three-pion decay mode has a very distinctive topology. The three track segments of the daughter pions match in the drift space with the primary τ track. The BR of this channel is 14% and an efficiency $\epsilon_{3\pi} \sim 5.5\%$ is estimated. However, the expected background for this channel is comparable to the one of the single prong decay modes altogether. For this reason we do not include it for the present sensitivity estimate.

In Fig. 13 and Fig. 14 we show the display of a simulated event with the τ decaying into muon, as reconstructed in the OPERA detector.

3.4 Background

Backgrounds and rejection methods in OPERA are similar to those in CHORUS, which expects less than 2 background events per 500000 CCs for the single pion, three pion and muonic τ decay channels altogether. This number is further reduced to well below one event by the kinematical analysis of the candidate events at the event vertex [20]. Such analysis is only possible by exploiting the features of the emulsion.

The OPERA concept of detecting kinks in the drift space allows to make the reinteraction background irrelevant. The main possible background sources in OPERA are:

1. prompt ν_τ production in the primary proton target and in the beam dump;
2. decay of pions and kaons produced in CC and NC ν_μ interactions;
3. 1-prong decay of charmed particles.

(1) The rate of ν_τ production by the interaction of 450 GeV protons in the Be target and in the downstream iron beam dump has recently been evaluated in [62] and [63] for the present CERN Wide Band Beam. Following the method of calculation of [62], for 10^{20} pot we estimate 3×10^{-3} CC $\overset{(-)}{\nu}_\tau$ events over the OPERA fiducial volume. This number is completely negligible.

(2) The decay in the drift space of pions and kaons produced in NC neutrino interactions can fake the topology of a candidate τ event. Both charge states can contribute to this background. In fact, the single charged-prongs from τ decay are negative, but the charge of the π/K daughter may only be measured for the muonic decay, with the muon detected by the downstream spectrometer. CC interactions are an additional source of this background if the primary muon is undetected.

Both NC and CC contributions have been evaluated by Monte Carlo simulations, where we have taken into account K and π decays into h, e, μ plus neutrals. A 90% kink finding efficiency has been assumed, with 95% efficiency in identifying the primary muon. For forward going muons a charge determination efficiency $\epsilon_{ch} = 70\%$ is obtained by means of the downstream spectrometer. We assume that the charge of electrons and hadrons is not measured.

The expected number of background events from pions and kaons is 0.02, for an integrated number of CC interactions $N_{CC} = 2044$.

(3) Charmed particles are produced in CC and NC neutrino interactions through the reactions

$$\begin{aligned} &\text{a) } \nu_\mu N \to c\,\mu X \\ &\text{b) } \nu_\mu N \to c\bar{c}\,\mu X \\ &\text{c) } \nu_\mu N \to c\bar{c}\,\nu_\mu X. \end{aligned}$$

The above processes may constitute a background to the oscillation signal if one fails to detect the primary muon (a-b) or the charm partner (b-c).

The most relevant background source is given by single charm production (reaction (a)). Charmed mesons have mass and lifetime similar to those of the τ. If the primary muon is missed, a D^+ meson decaying in one charged particle (plus neutrals) can fake a genuine τ event, since the (positive) sign of the D daughter may only be measured for the muonic channel.

The level of the above background is estimated by the following expression

$$N_{bg}(\text{single charm}) = \frac{N_c}{N_{CC}} \times \frac{N(D)}{N_c} \times BR(D) \times (1-\epsilon_{ch}) \times \epsilon_{gap} \times \epsilon_{kink} \times \epsilon_{fid} \times (1-\epsilon_\mu) \times N_{CC}$$

where the factors are, respectively, the probability to produce charm in CC interactions (4%), the D^+ production probability (25%), the BR for the considered decay channel, the charge detection inefficiency (30% for muons and 100% for hadrons and electrons), the probability for the D^+ to decay inside the drift gap (60%), the kink detection efficiency, the fiducial volume efficiency, the probability not to identify the primary muon, and the total number of charged current events ($N_{CC} = 2044$).

For 1-prong hadronic D^+ decay (BR = 24%) we obtain 0.12 background events. Similar calculations lead to 0.02 events for the muonic channel (BR = 10%) and 0.05 events for the electron channel (BR = 9%). In total, one is left with 0.19 background events from single charm production by ν_μ.

The rate of associated charm production in NC interactions has been directly measured by the E531 experiment on the basis of one observed event [64]. They also set a 90% CL on the CC production rate, consistent with the two rates being equal. Indirect measurements exist for the CC process, coming from the experimental data on prompt same sign dimuons. Unfortunately, these measurements strongly depend upon the momentum cut applied to the second muon and on the statistical subtraction of the non-prompt meson decay background. In the following we assume $N(c\bar{c})/N_{CC} = 0.13\%$, as determined in [64].

The contribution of reactions (b) and (c) to the background in OPERA is then

$$N_{bg}^{CC}(c\bar{c}) = \frac{N(c\bar{c})}{N_{CC}} \times \frac{N(D)}{N(c\bar{c})} \times BR(D) \times (1-\epsilon_{ch}) \times \epsilon_{gap} \times (1-\epsilon_{c\bar{c}}) \times \epsilon_{kink} \times \epsilon_{fid} \times (1-\epsilon_{\mu}) \times N_{CC}$$

$$N_{bg}^{NC}(c\bar{c}) = \frac{\sigma_{NC}}{\sigma_{CC}} \times \frac{N(c\bar{c})}{N_{CC}} \times \frac{N(D)}{N(c\bar{c})} \times BR(D) \times (1-\epsilon_{ch}) \times \epsilon_{gap} \times (1-\epsilon_{c\bar{c}}) \times \epsilon_{kink} \times \epsilon_{fid} \times N_{CC}.$$

Taking into account a tracking efficiency of the associated charmed meson (in most cases D^- or D^0) $\epsilon_{c\bar{c}} = 0.55$, and $\sigma_{NC}/\sigma_{CC} = 0.3$, the sum of the two channels amounts to 0.02 events.

In the previous calculations we have neglected the contribution of charm produced by $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$, due to their small relative abundance in the beam (Table 1).

In total, OPERA will be left with 0.23 background events with decay topology, for the three τ decay modes with one charged prong altogether. We stress that for the analysis described above the momentum measurement in the emulsion is not used.

Candidate events will undergo a further kinematical analysis, meant to exclude the charm background at a higher confidence level. With emulsion, the background rejection is particularly efficient as it can be based on the observation of the short track before the decay. A "vertex" kinematical analysis may be exploited, with high rejection power and good signal efficiency.

The direction of all primary and secondary particles at the vertex can be measured. The electrons may be identified by following their tracks in the ES, and by detecting their electromagnetic interactions [58][59]. Photon conversions from neutral pions can be searched for in the ES further downstream of the vertex plate. The calorimetric information of the electronic detectors could also be used. The expected difference in the kinematics of τ decays with respect to charm events is then exploited. Even not accounting for momentum and energy measurement, the determination of the τ production angle will permit to give a further background rejection keeping high efficiency for the τ decays [20][28], so leading to a very low background level, for the proposed experiment.

In conclusion, even in the hypothesis of more pessimistic assumptions about efficiencies and acceptances, OPERA will be a background free experiment in searching for $\nu_\mu - \nu_\tau$ oscillation.

3.5 Sensitivity to $\nu_\mu - \nu_\tau$ oscillation

The overall τ detection efficiency ϵ_{tot} amounts to 45.5% for high Δm^2. The ratio of cross-sections for tau and muon neutrinos is 0.54, averaging over deep inelastic and quasi-elastic events. The total expected number of CC ν_μ events is 2044. With no observed events this leads to the following oscillation probability

$$P \ < 2.3/(N_{CC} \times \epsilon_{tot} \times \sigma_\tau/\sigma_\mu) \sim 4.5 \times 10^{-3} \text{ (90\% CL)}.$$

In the conventional two-flavour mixing scheme, the corresponding limit on the mixing angle, for large Δm^2, is

$$sin^2 2\theta_{\mu\tau} = 2P \ < \ 9 \ \times 10^{-3} \text{ (90\% CL)}.$$

The minimum Δm^2, for full mixing, is given by the following relation

$$\Delta m^2(\text{eV}^2) = \sqrt{P} \times < E_{\nu_\mu}(\text{GeV}) >/(1.27 \times L(\text{km})) \sim 2.5 \times 10^{-3} \text{ eV}^2.$$

The experiment, therefore, will be sensitive to the low Δm^2 region corresponding to the atmospheric neutrino anomaly in the hypothesis of $\nu_\mu - \nu_\tau$ conversion, as reported by the Kamiokande experiment [4] and recently confirmed by Super Kamiokande [17][18].

Assuming that $\nu_\mu - \nu_\tau$ oscillation occurs with parameter values $\Delta m^2 = 8 \times 10^{-3}$ eV^2 and $sin^2 2\theta_{\mu\tau} = 0.9$ (*i.e.* the Kamiokande favoured values in the standard two-flavour scheme), a total of 55 CC ν_τ interactions would be expected in the target. Since the overall efficiency to detect a τ decay in this parameter region is $\sim 41\%$, OPERA would observe about 22 ν_τ interactions. Given the absence of background and the unambiguous experimental signature, this is a large number which qualifies the discovery potential. Preliminary results from Super Kamiokande [18] suggest $\Delta m^2 = 5 \times 10^{-3}$ eV^2.

The above numbers are valid in the usual two-flavour neutrino-mixing scheme. An even more spectacular signal would be detected by OPERA in the hypothesis of the three-flavour mixing scheme described in [12]. In this case, the huge oscillatory effect in the $\nu_\mu - \nu_\tau$

channel, shown in Fig. 4, would produce about 180 τ events detected by OPERA.

4. Search for $\nu_\mu - \nu_e$ oscillation

OPERA will also be sensitive to $\nu_\mu - \nu_e$ oscillation. The primary vertex tracks in muonless events will be measured to look for the occurrence of CC ν_e interactions. The electron identification is performed by following its track in the ES downstream of the vertex plate [58][59]. Given the small iron plate thickness ($\sim$ 0.06 radiation lengths), the probability for the electron to start showering in the first plate is negligible. In Fig. 15 we show the result of a Monte Carlo simulation of the electron identification capability of an ECC by means of multiple energy-loss measurements. The identification efficiency is given as a function of the material thickness traversed (electron track-length). This efficiency is assumed to be 75%, conservatively for our configuration.

In OPERA there are two major sources of background electrons. The first is given by the ν_e ($\bar{\nu}_e$) contaminating the ν_μ beam, with a flux ratio ν_μ/ν_e of about 200. According to Table 1, it yields $\sim$ 10 events per 2044 CC ν_μ interactions. Accounting also for a 95% fiducial volume efficiency, this corresponds to 9 detected events. The other source is represented by the electrons from the Dalitz decay of neutral pions produced in NC ν_μ interactions ($\pi^0 \to e^+e^-\gamma$) and from photon to electron conversion in the iron plate ($\pi^0 \to 2\gamma$ followed by $\gamma N \to e^+e^-N$). Selecting neutrino interactions with one electron (positron) identified, we estimate about 35 background events from neutral pions. In this estimate we have not considered the possible application of kinematical cuts. In particular, simulations show that, by rejecting events with electron energy lower than 5 GeV, one removes 90% of π^0 induced events, with 90% efficiency for the signal.

The statistical errors on the above numbers of background events determine the sensitivity in the measurement of the oscillation parameters, together with the systematic errors due to the uncertainty (5%) on the estimate of the ν_e content of the beam and to the uncertainty (20%) on the number of electrons produced by π^0. These are preliminary guesses, and more studies will be needed.

In conclusion, we obtain 45 expected background events with a total uncertainty of 10 events. The 90% CL single-sided upper limit on this number is about 15 events. In the case of a negative search, accounting for 2044 CC events, an electron identification efficiency of 75% and a fiducial volume efficiency of 95%, OPERA would achieve a 90% CL limit in the mixing parameter $sin^2 2\theta_{\mu e} \sim 2 \times 10^{-2}$, for large Δm^2. For full mixing, the minimum detectable Δm^2 is $\sim 3 \times 10^{-3}$ eV^2. This result is described by the exclusion plot shown in Fig. 16. OPERA can then also test the hypothesis of $\nu_\mu - \nu_e$ oscillation as an explanation of the atmospheric (muon) neutrino deficit and compare this result with the outcome of the

$\nu_\mu - \nu_\tau$ oscillation search.

5. Emulsion and scanning

About 10 ton of emulsion are needed for the OPERA emulsion sheets, with a density of silver bromide (the active component of the emulsion) a factor two lower than in the emulsion target of short-baseline experiments. This is permitted by the much lower background level in the long-baseline location and by the fact that automatic scanning devices do not require particularly high emulsion "grain" densities.

Handling of such a large quantity of nuclear emulsion is a challenge. However, several hybrid experiments were run for more than 20 years both at CERN and Fermilab. This resulted in a progress of the technique. The main problem to be faced is the production of raw material (emulsion gel), with high and uniform sensitivity and with good stability, within a reasonable period (6 to 12 months) and at a convenient cost. Contacts with important companies have been established and several tests will be performed jointly with them. Some points are still open, but the residual problems could be solved in due time. Concerning the emulsion cost, a reduction of at least a factor two with respect to the present one seems achievable.

Another important issue is the preparation of the emulsion before the exposure (pouring and assembling into emulsion sheets). The most serious problem is represented here by the time needed for pouring, *i.e.* for producing the final emulsion from gel. With the presently available facilities, the procedure would take too long and would require too much manpower. We are studying alternative solutions, either based on a new laboratory, with greater resources and mostly automated, or giving the job to the producers of gel, after having carefully agreed upon the specifications and under supervision. Therefore, one may think of emulsion sheets produced by companies or by dedicated machines, similar to those employed for photographic film production, with consequent substantial cost reduction. It is envisageable to run these machines at the experiment site, so reducing the possibility of integrating cosmic background after the pouring procedure.

Both OPERA in a medium baseline location [43] and TOSCA [28] rely on the capability of performing high-speed automatic scanning of the emulsion (sheets or target), given the large number of events to be scanned (up to several million). The situation for the long-baseline experiment here proposed is much more favourable. The total number of events to be scanned, corresponding to a four years' run, is about 2700. However, the scanning procedure is more complicated and time consuming than for TOSCA. In OPERA the electronic detectors locate events rather than individual tracks. For each event, several emulsion sheets must be scanned over a larger area (~ 1 cm^2) and some of the tracks have to be followed upstream to the primary vertex. We can estimate in 30–60 minutes the time needed to completely scan one event. The scanning load is, anyhow, very limited, and would be compatible with the much higher load given by the TOSCA experiment.

Given the small rate of events (of the order of 3 per day) the event analysis can be conducted quasi-on-line. One can periodically remove (and replace) those target elements where the event vertex occurs, and perform the emulsion scanning. This scheme allows a fast analysis, with some complication of the detector set-up. The target is, in fact, a fully modular structure, allowing the automatic access to the target elements (Fig. 7 and Fig. 9). We observe that the number of elements to be dismounted after one year running (~ 650) is small as compared to the total number of target elements (9800).

6. Tests, construction, running and time schedule

We are planning to construct target element prototypes and to test them with charged particle beams and, possibly, with the present CERN Wide Band neutrino Beam which will be operational in 1998. One could then profit from the intense beam and reconstruct a sizeable amount of neutrino events. These would allow to assess the design performance of the OPERA target.

Among the aims of these tests we mention the study of the event vertex finding efficiency, the particle identification in the emulsion, the angular resolution and the kink detection capability (through the study of charm events). The test results will also allow to optimize the mechanical design of the target elements and of the “spacers” to be used to fill the drift space between the ES.

We are presently investigating the possibility to use a lead alloy as passive target material. As already pointed out, this would allow either a reduction of the detector dimensions, and of the amount of emulsion, or an increase of the detector mass, at constant detector dimensions and emulsion mass.

The physics goal of the proposed experiment is complementary to that of the high-sensitivity short-baseline search performed by TOSCA. Also technically, the two experiments could benefit from each other in many respects. The emulsion technology is in common and both expertise and infrastructures could be efficiently shared. The electronic detectors (honeycomb chambers in a tentative approach) could be the same, and also in this case one can think of the same “industrial” production facility. The extra work which a long-baseline experiment would imply for the emulsion and scanning facilities set-up for CHORUS, and which would be used by TOSCA, is very limited due to the much lower number of events.

A possible time schedule for OPERA at the Gran Sasso could be as follows. In 1997 and 1998 Monte Carlo simulations and test beams on prototype modules will allow the feasibility of the experiment to be assessed. With a detailed Proposal and its approval by

1999, the years 1999-2001 would be devoted to the construction of the apparatus and to a first technical run. The commissioning of the experiment will fit with a neutrino run in 2002. Four years' running (2002-2005) will allow to reach the goal sensitivity. The first physics results could come after the first year of data taking, thanks to the "quasi" on-line emulsion analysis and to the negligible physics background.

7. Conclusions

We have presented the conceptual design of a novel detector (OPERA) exploiting the technique of nuclear emulsion, to be used for a new $\nu_\mu - \nu_\tau$ oscillation search. OPERA is an evolution of the so called Emulsion Cloud Chamber (ECC). The detector consists of a massive target made up of a sandwich of (dense) passive-material plates and of thin emulsion sheets for high-resolution tracking. The use of the passive material (iron in the present design) allows to build a 200 ton detector.

In this Letter of Intent we propose to exploit the OPERA detector, already envisaged for a medium baseline application [43], for a background-free appearance experiment searching for $\nu_\mu - \nu_\tau$ oscillation at the Gran Sasso Laboratory in the proposed neutrino beam from the CERN SPS. The high detection efficiency of OPERA, together with its negligible background and the direct observation of the τ decay kink, allows to use a target mass about one order of magnitude lower than for other experiments though yielding good sensitivity in the interesting domain of the oscillation parameters.

In the conventional two-flavour mixing scheme, and for a required number of 10^{20} protons on target, OPERA will be sensitive up to $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2 (90% CL), well below the indication from the atmospheric neutrino anomaly. The limit on $sin^2 2\theta_{\mu\tau}$ for large Δm^2 will be $\sim 9 \times 10^{-3}$ (90% CL). These limits are graphically shown in the exclusion plot of Fig. 17.

The discovery potential of OPERA is high. Thanks to the absence of background, single events are meaningful. If $\nu_\mu - \nu_\tau$ oscillation would occur with parameters $\Delta m^2 = 8 \times 10^{-3}$ eV^2 and $sin^2 2\theta_{\mu\tau} = 0.9$, the experiment would detect the appearance of ~ 20 unambiguous charged current ν_τ interactions. In the phenomenological scenario outlined in [12] with a three-flavour mixing scheme, OPERA would detect a spectacular signal. In this case, the huge oscillatory effect in the $\nu_\mu - \nu_\tau$ channel would produce about 180 τ detected events.

OPERA would also be sensitive to $\nu_\mu - \nu_e$ oscillation, due to its capability of identifying electrons and to the low contamination of ν_e in the ν_μ beam. The expected limits (90% CL), in the absence of a positive signal, will be $\sim 3 \times 10^{-3}$ eV^2 in Δm^2 for full mixing and $\sim 2 \times 10^{-2}$ in $sin^2 2\theta_{\mu e}$ for large Δm^2. Further studies are needed to assess in particular this issue.

The quoted performance will be obtained with a four years' run of the experiment. The limited number of events (about 2700 in total) will permit to remove periodically the small fraction of target elements hit by neutrinos and perform the emulsion scanning "quasi" on-line. Therefore, the first physics results will be obtained soon after the start of the running period, and regularly updated, as in the case of a fully electronic detector.

The OPERA experiment can thus contribute to clarify some crucial aspects of the present scenario on neutrino oscillation, thanks to its sensitivity, discovery potential and time schedule. In particular, it will allow to understand the interpretation of the neutrino atmospheric anomaly in terms of neutrino oscillation with a fast, unambiguous and background-free appearance search.

OPERA is complementary to TOSCA, which in a short-baseline location will explore the small mixing angle domain not accessible by OPERA. The scanning load required by OPERA is much lower than for TOSCA. Both experiments may benefit from "positive interferences" in the use of common resources, expertise and infrastructures.

The importance of the physics case, the unclear experimental situation and the necessity that any result be confirmed in this field indicate that independent and specialized explorations are needed for a conclusive clarification of the scenario. A healthy european research programme is necessary to participate in the world-wide enterprise on neutrino physics together with those projects approved and partly funded in USA and Japan.

The actual realization of OPERA will have to be firmly addressed by means of further detailed studies and simulations. Tests on detector prototypes will help in the assessment and optimization of the experimental performance. The definition of a complete Proposal, incorporating the results of these studies, can be achieved with the joint effort of a scientific Collaboration to be established and made soon operational. We wish to favour the creation of such a Collaboration and we would welcome the interest of experimental groups of the international neutrino community.

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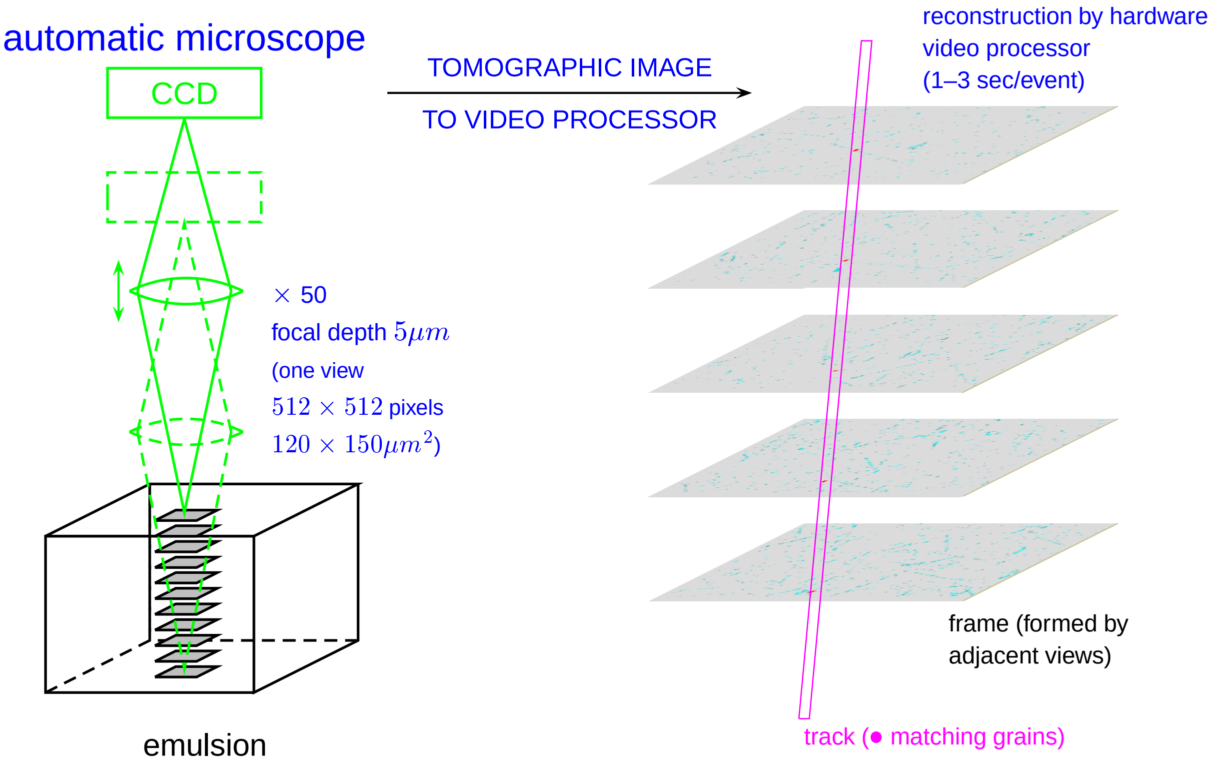

Figure 1: Schematics of the operation of an automatic microscope, as used in CHORUS.

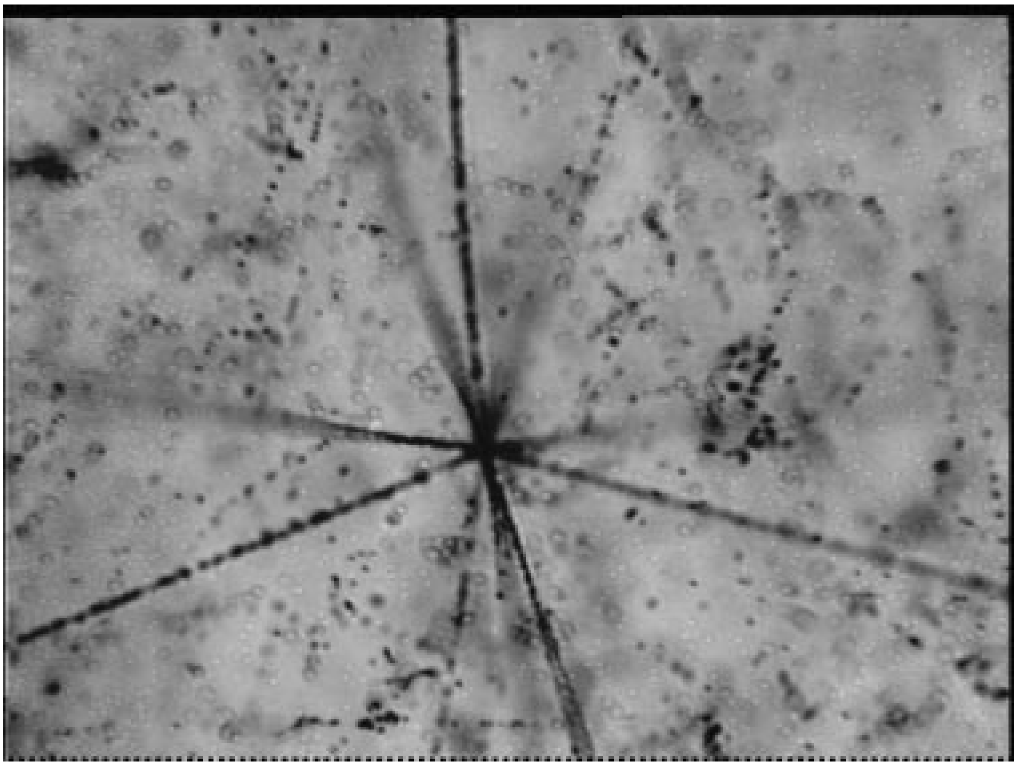

Figure 2: The CCD image of a typical neutrino event in CHORUS. The dimensions of the view are about 120 × 100 μm^2, with a focal depth of a few micron.

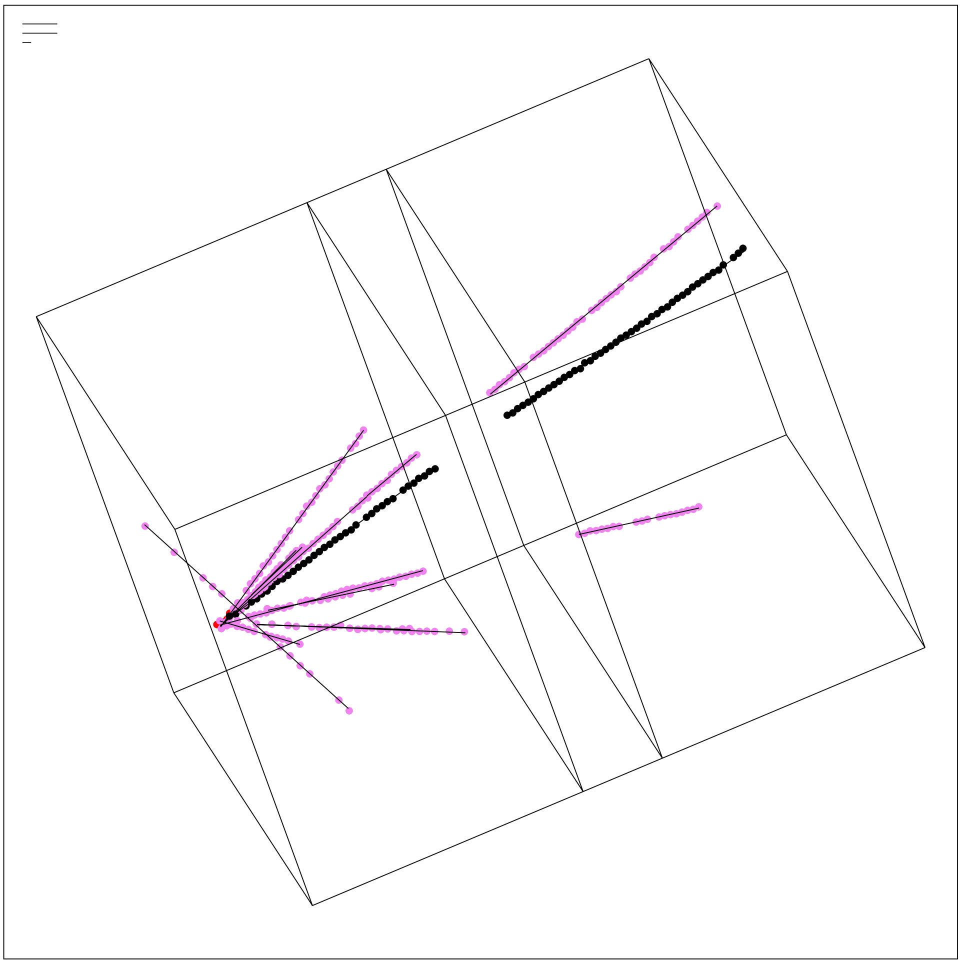

Figure 3: Reconstructed neutrino event as measured in the CHORUS emulsion. Shown are the grains, with reconstructed tracks, in the emulsion layers on both sides of the plastic base. To indicate the scale, the sensitive volumes (emulsion layers) have a thickness of 350 μm each, and the plastic base 100 μm. The black dots identify the so-called "scan-back" track, namely, the one extrapolated from the dowstream electronic trackers. A background track, clearly not related to the event, is also displayed.

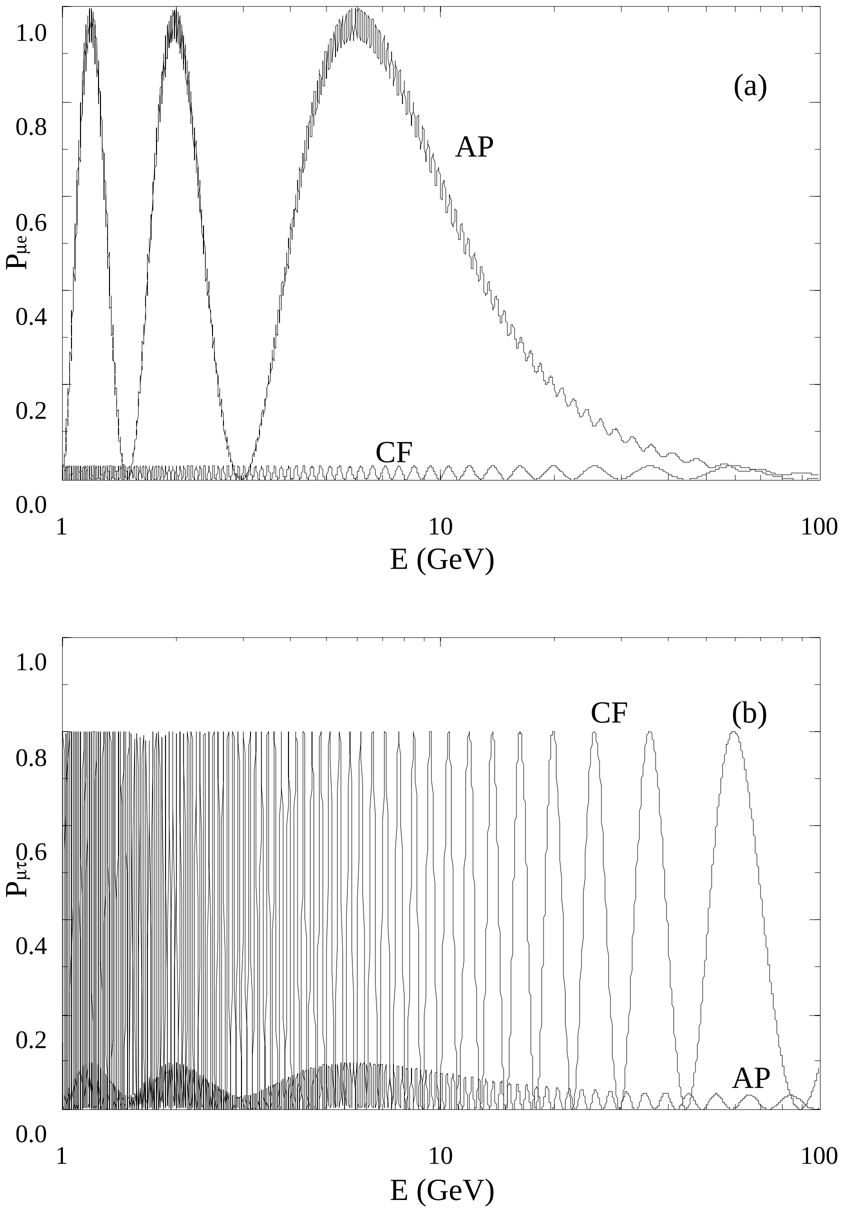

Figure 4: Probabilities for (a) ν_e and (b) ν_τ appearance in the ν_μ beam from CERN to Gran Sasso (or Fermilab to Soudan mine), versus the neutrino energy. "CF" ("AP") stands for the Cardall & Fuller [12] (Acker & Pakvasa [11]) oscillation scheme.

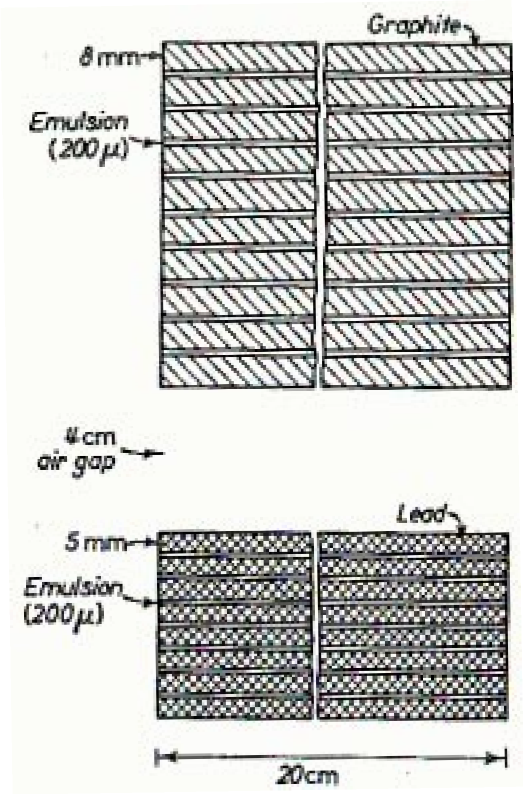

Figure 5: The set-up made of emulsion layers and passive material, as used in [51] (from reference [44]).

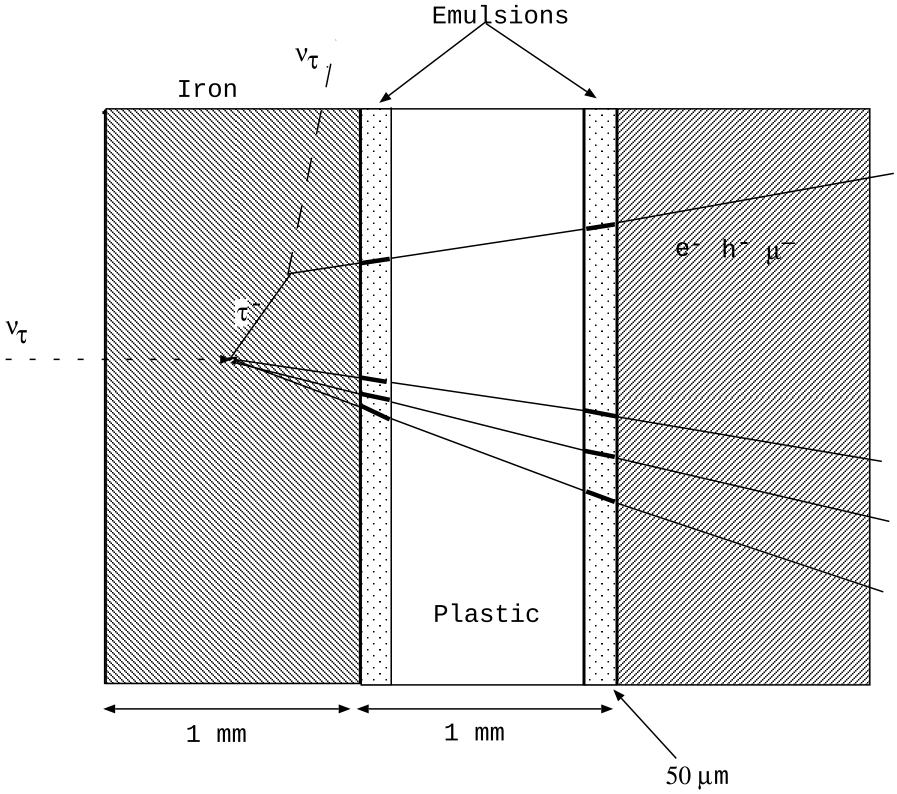

Figure 6: Schematic structure of the ECC target. The use of the impact parameter technique is also shown.

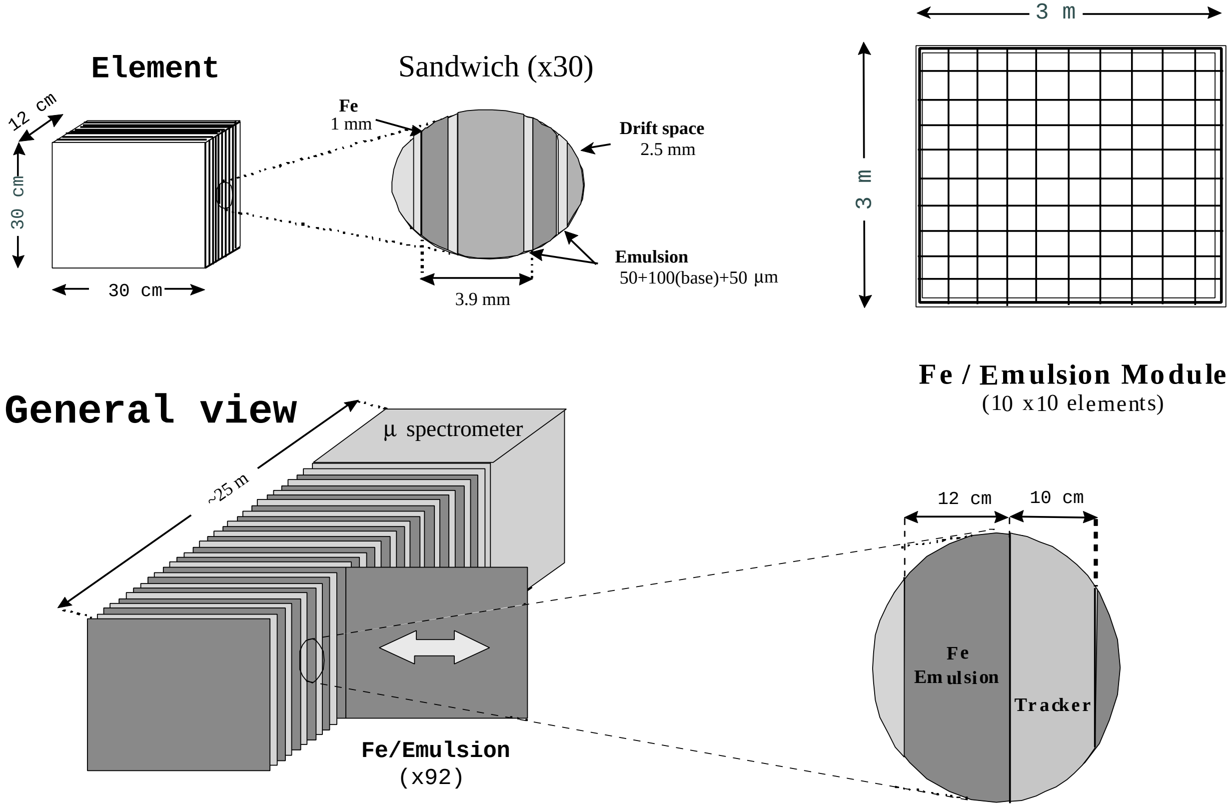

Figure 7: The OPERA detector: elements, modules and general view.

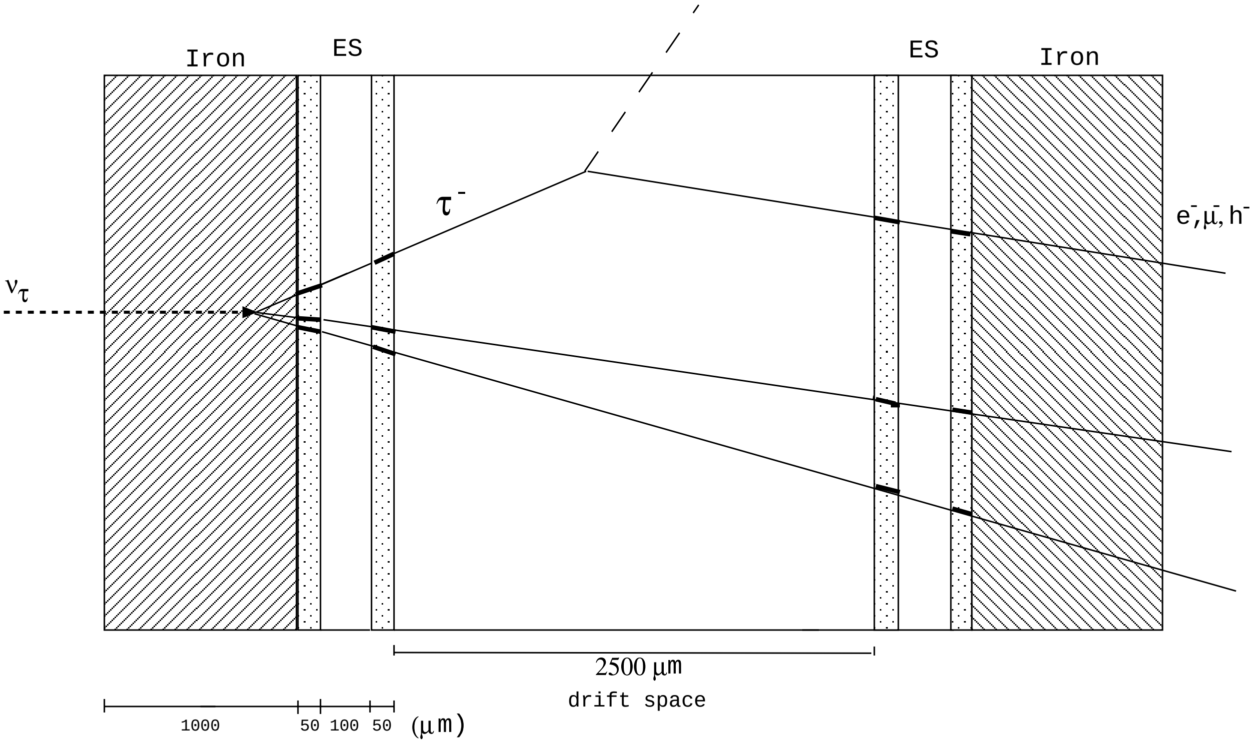

Figure 8: Schematic structure of the OPERA target. The τ decay kink is directly reconstructed in space, by using four track segments in the emulsion sheets.

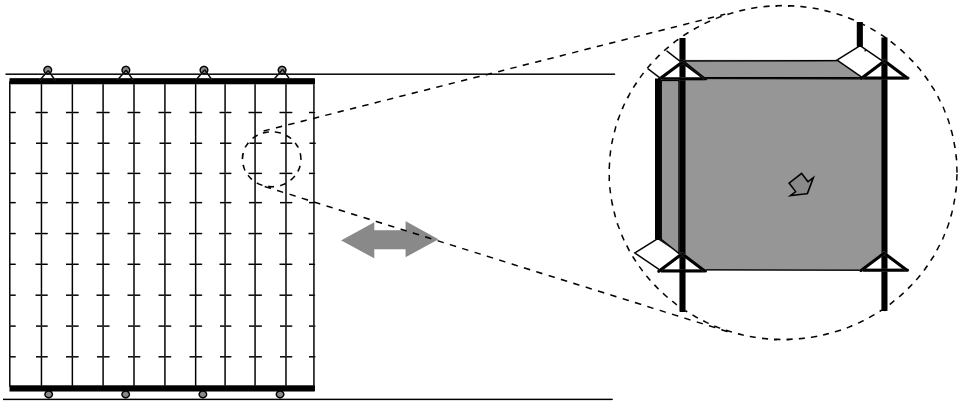

Figure 9: Detail of a module in OPERA: the support structure of the detector elements allows for their replacement.

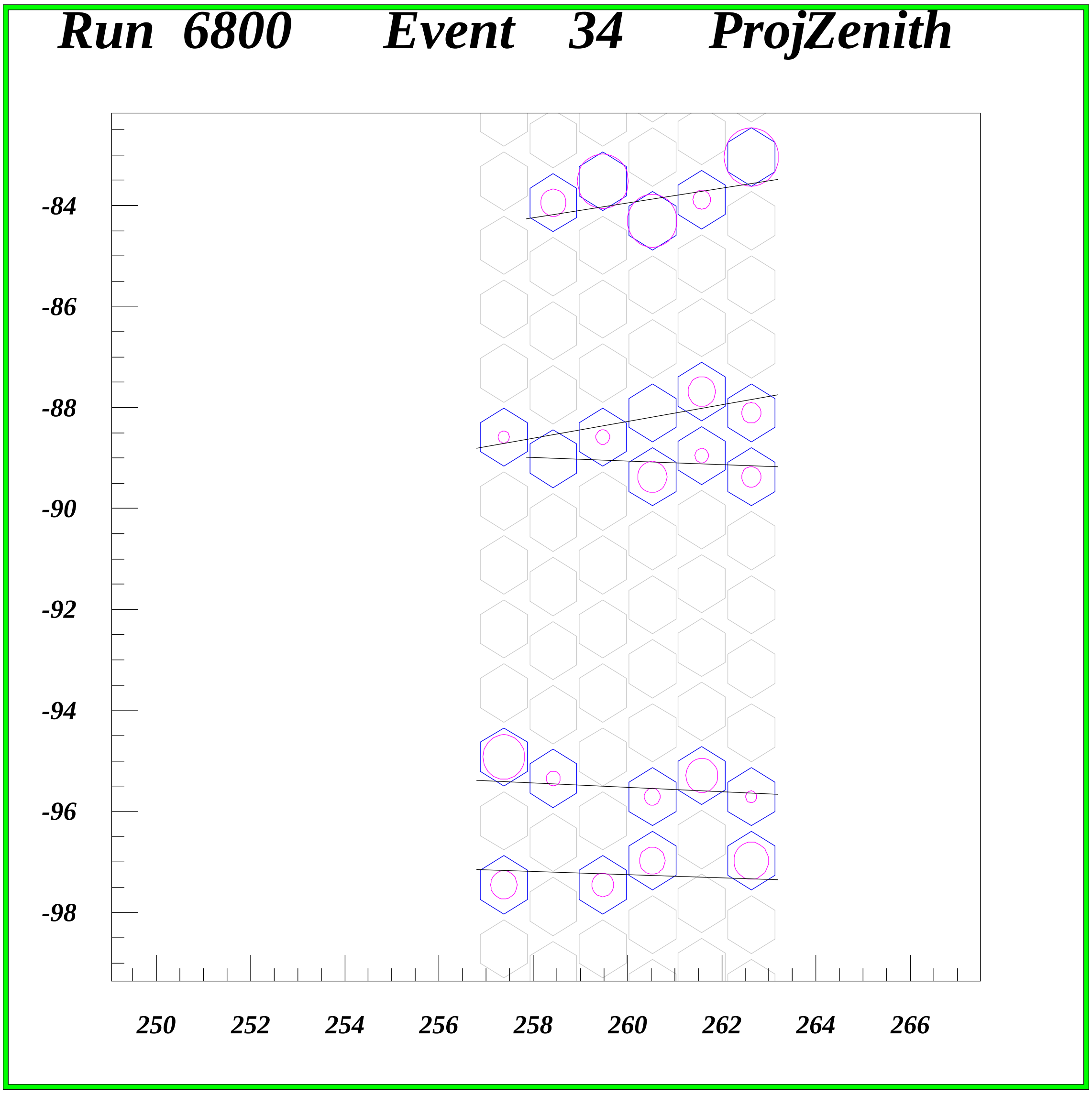

Figure 10: Tracks segments reconstructed in the CHORUS honeycomb chambers. The circles represent the drift time measurement.

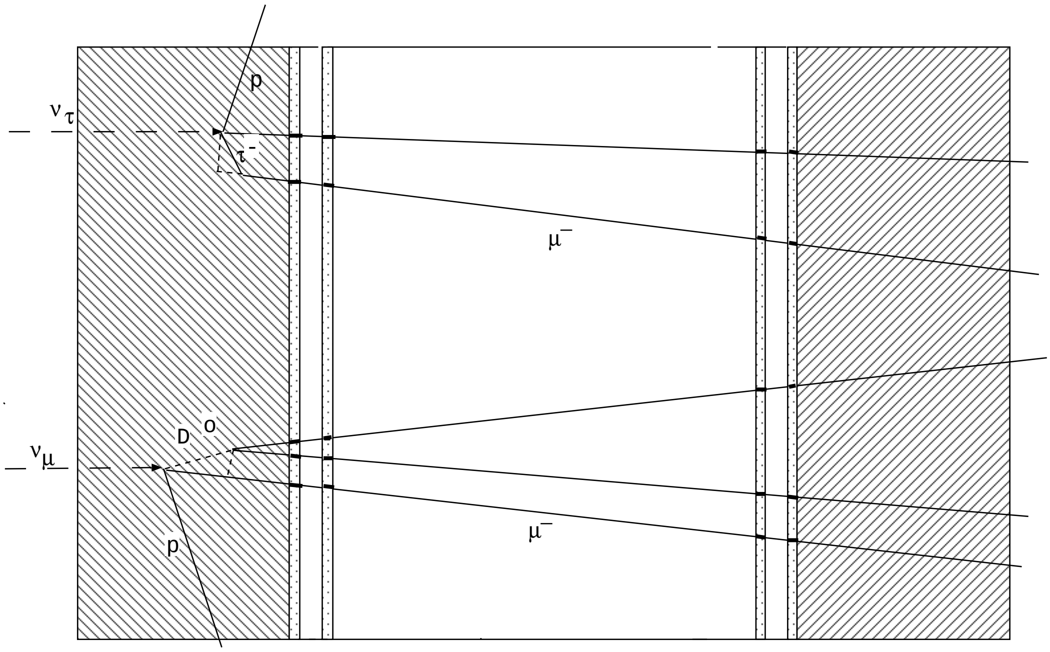

Figure 11: Signal and charm background for short decays (rejected in OPERA) in the muon channel.

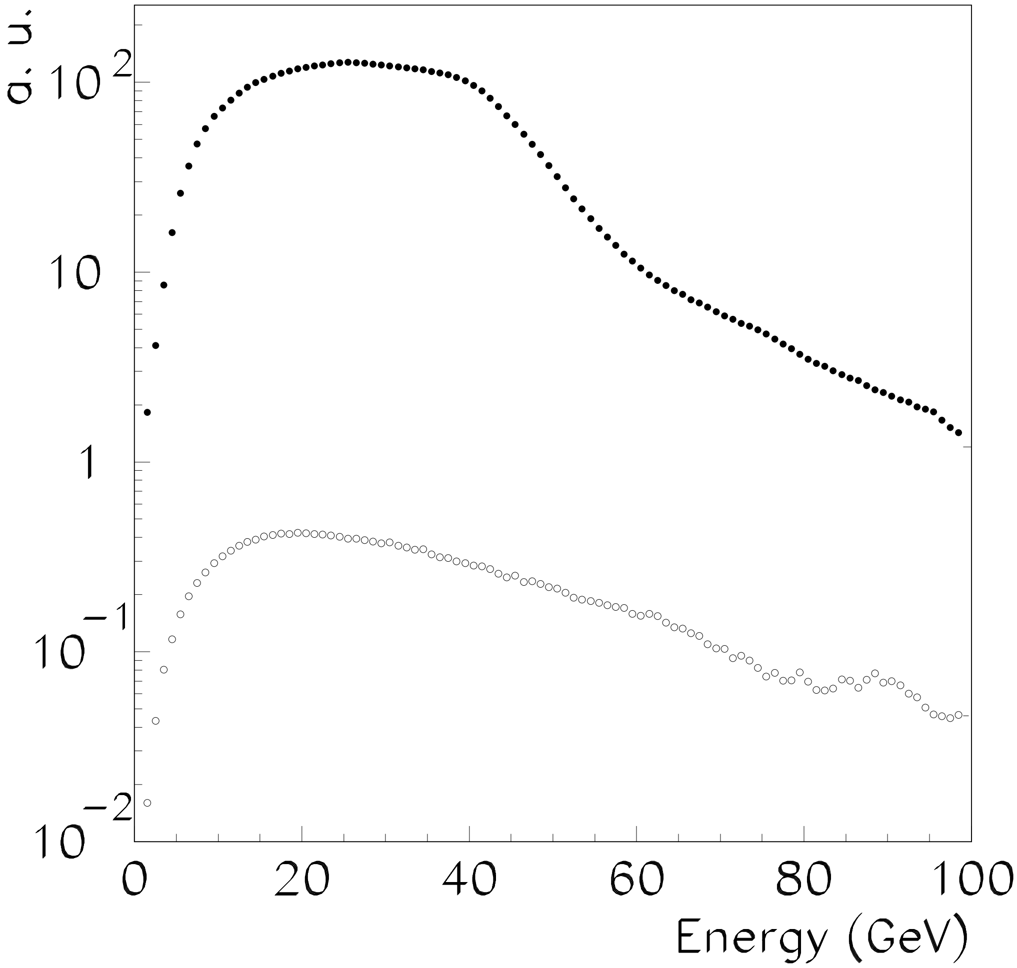

Figure 12: Expected ν_μ (black circles) and ν_e (open circles) energy spectra at the Gran Sasso location.

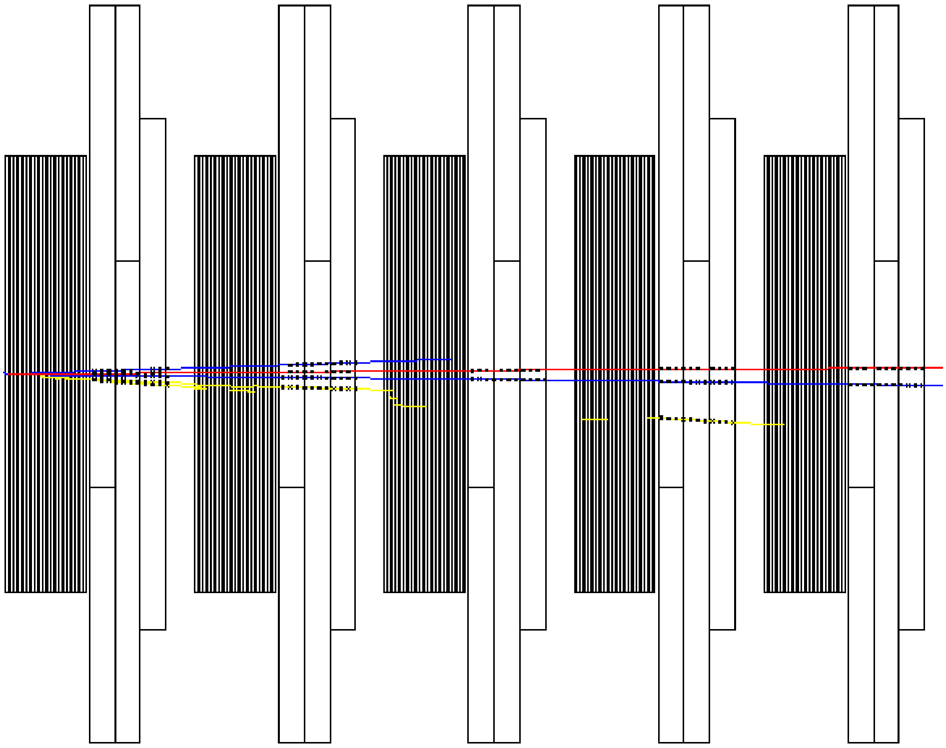

Figure 13: Event display of a muonic τ decay in OPERA (Monte Carlo simulation).

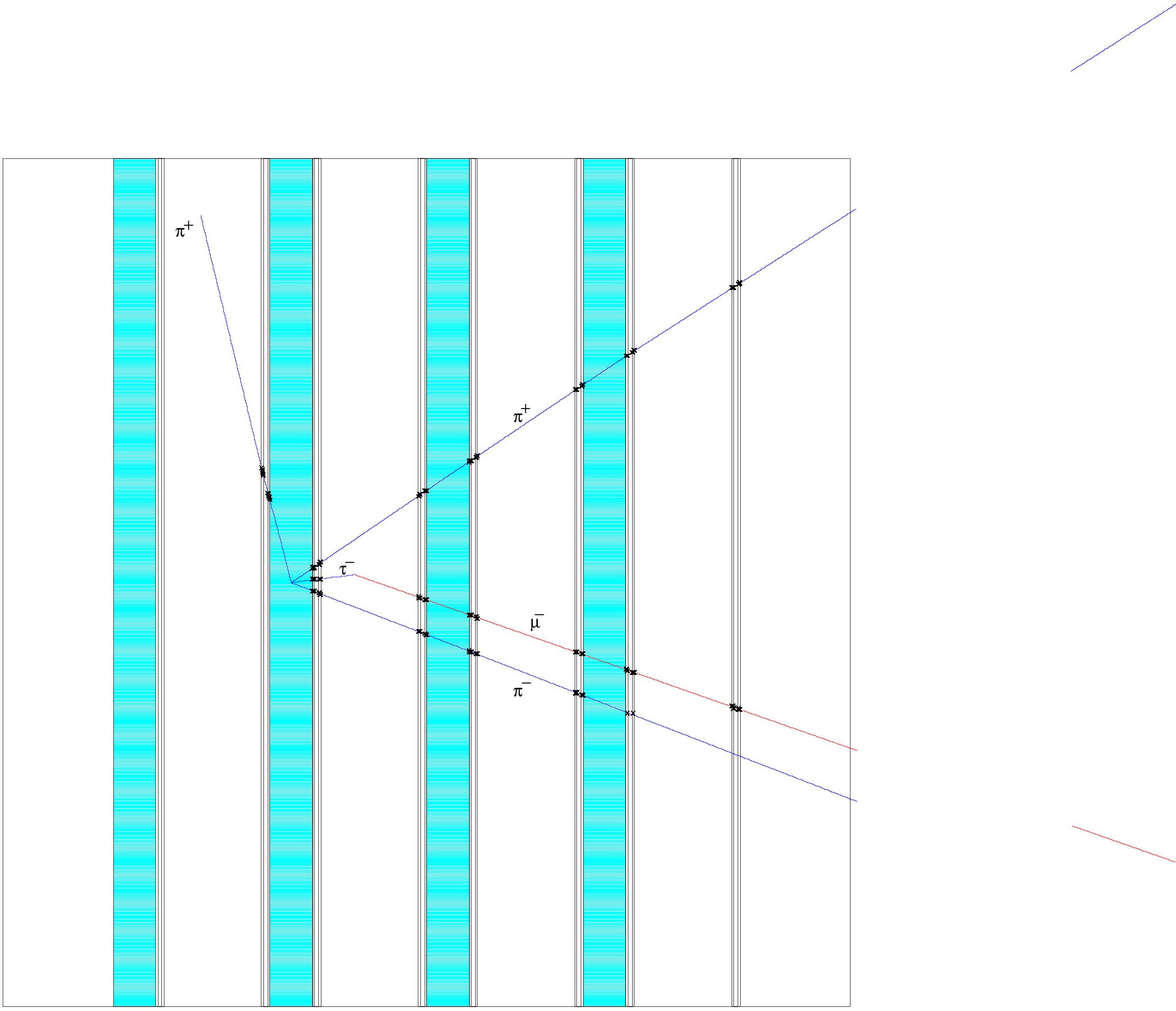

Figure 14: Detail of the vertex region of the event shown in the previous Figure.

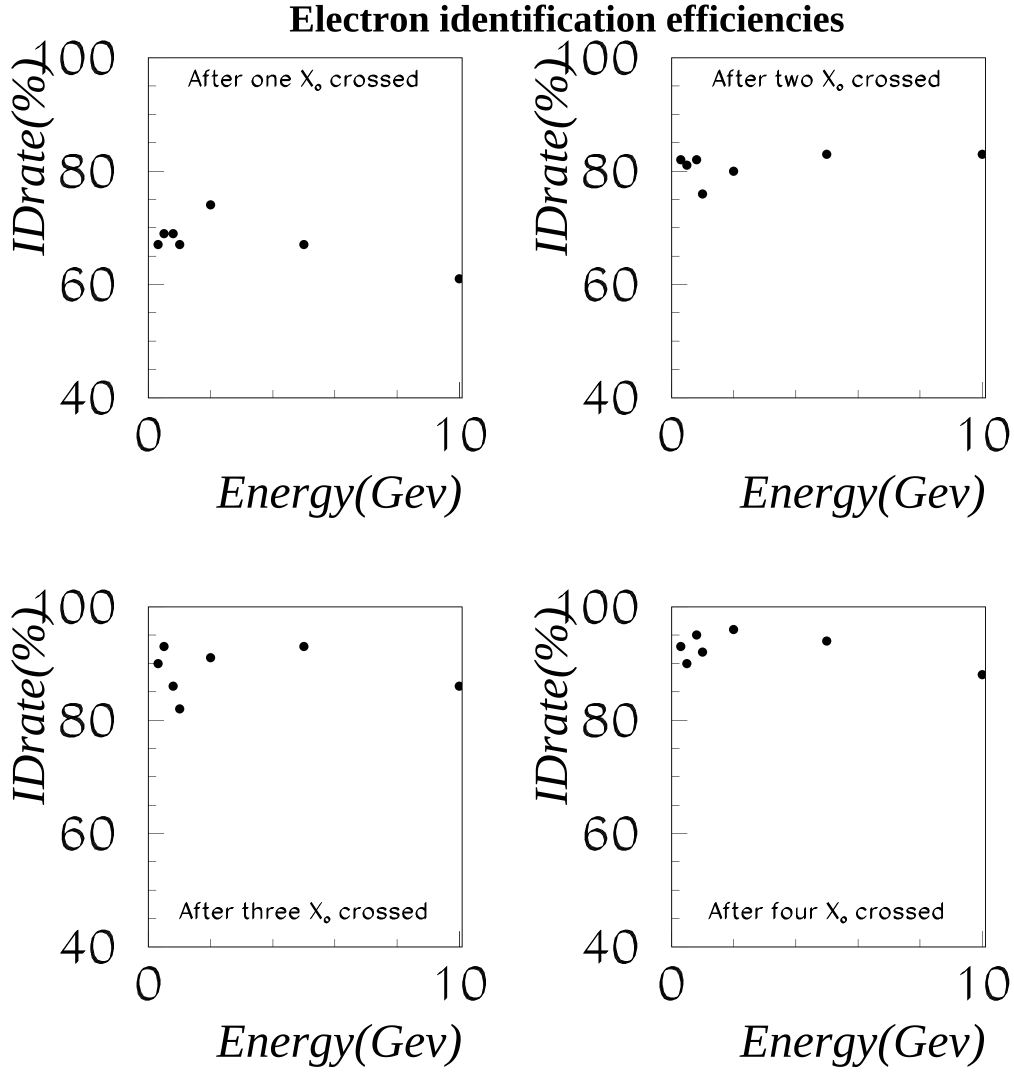

Figure 15: The electron identification efficiency is reported as a function of the electron energy for different track lengths (Monte Carlo simulation).

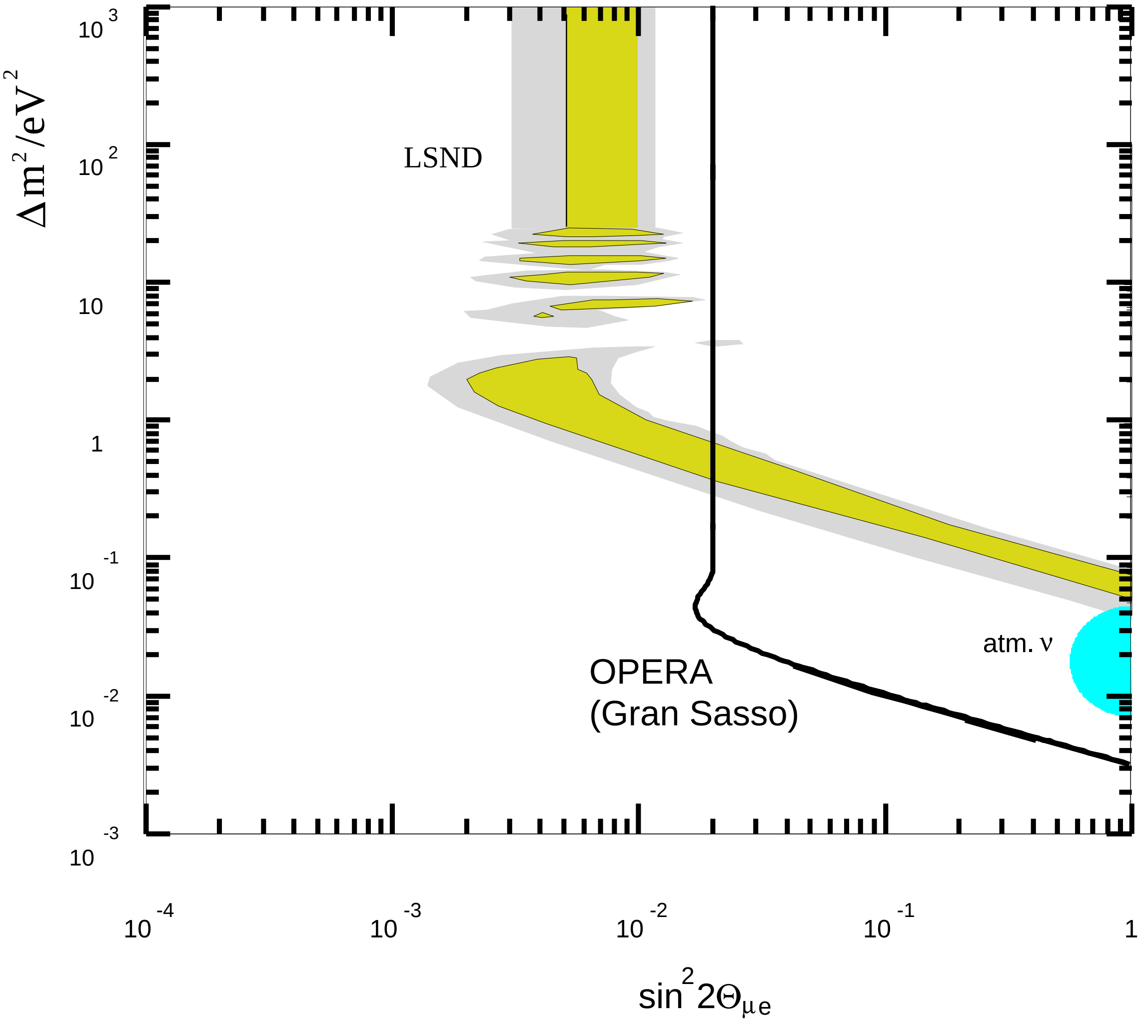

Figure 16: Sensitivity of OPERA in the search for $\nu_\mu - \nu_e$ oscillation. The 90% CL contour limit is shown together with the LSND signal and with the region indicated by the atmospheric neutrino anomaly.

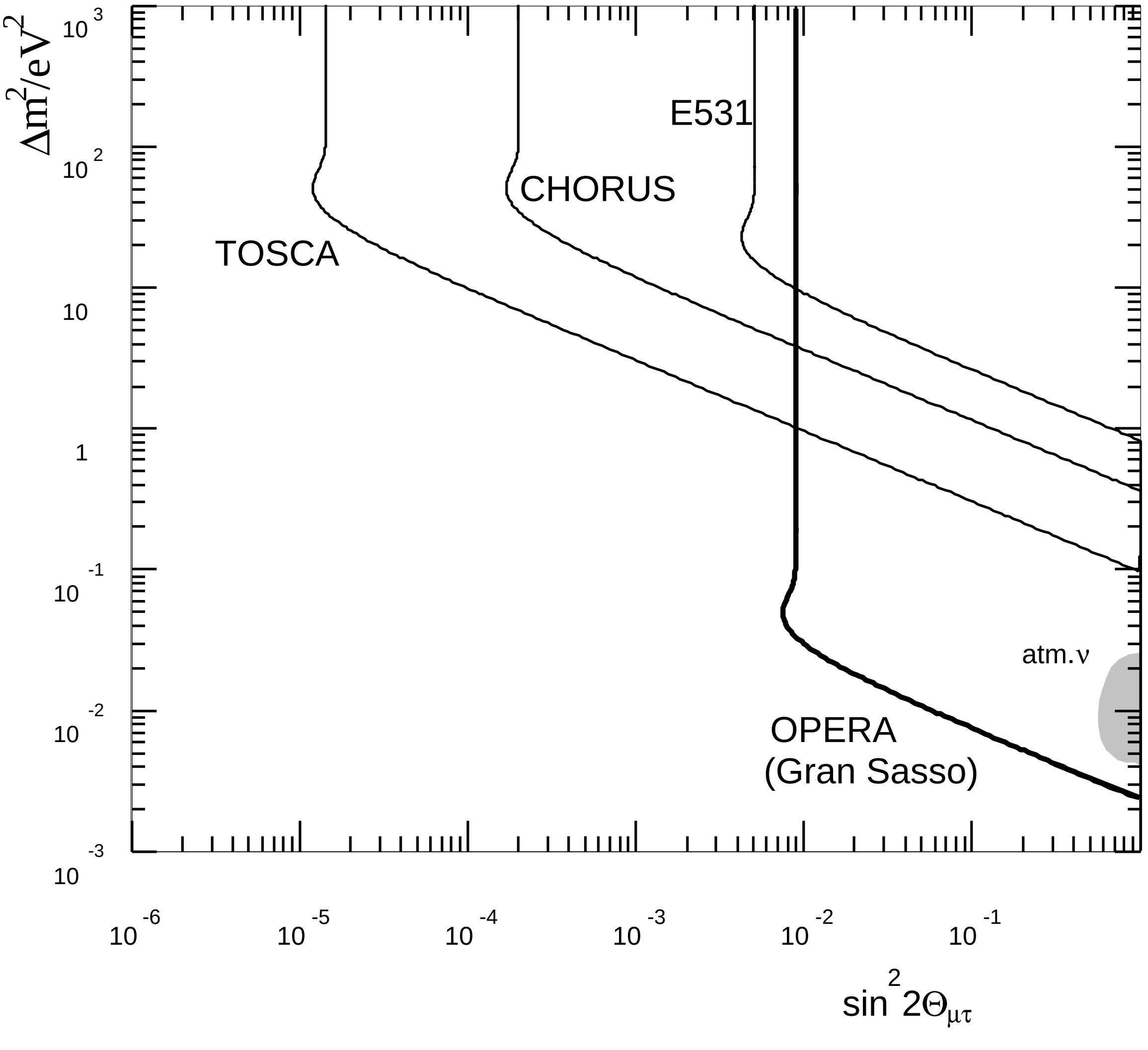

Figure 17: Sensitivity of OPERA in the search for $\nu_\mu - \nu_\tau$ oscillation, as compared to other experiments. 90% CL contour limits are shown, together with the region indicated by the atmospheric neutrino anomaly.