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The emulsion technique for short, medium and long baseline $\nu_\mu - \nu_\tau$ oscillation experiments

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ABSTRACT

Due to the impressive progress in the technique of nuclear emulsion, one can conceive new high sensitivity experiments for neutrino oscillation searches and explore different domains of the oscillation parameters, opting for a short, medium or long baseline configuration. The experience of the CHORUS experiment, in particular, has shown that one can already manage about one ton emulsion target for $\nu_\mu - \nu_\tau$ oscillation searches. Nuclear emulsion can be used as high space-resolution active target, as well as for high-precision tracking. The main features of the experiments are discussed, also in the light of recent phenomenological speculations. For the medium baseline option, we present an experiment which exploits, in a novel application and with new concepts, a technique evolved from the Emulsion Cloud Chamber (ECC).

1. Introduction

One of the most crucial questions in the present scenario of particle physics is whether the neutrino has non-zero mass. A massive neutrino would be the direct indication of physics beyond the Standard Model, and it would have profound implications for cosmology and astroparticle physics, giving a clue in the explanation of the dark matter puzzle. Moreover, a non-zero neutrino mass could be responsible for the apparent deficit of solar neutrinos. The interesting mass range is out of the reach of the direct measurements from decay kinematics. The only way to assess this issue is to search for neutrino oscillation.

Different plausible theoretical frameworks exist. One scheme [1][2] incorporates the observation of the solar neutrino deficit and experimental results on particle physics, to predict very light electron and muon neutrinos, with a tau neutrino mass ranging from 1 to 10 eV, therefore a natural candidate for the "hot" component of the dark matter. The present best limit on the $\nu_\mu - \nu_\tau$ oscillation exclude mixing angle values $sin^2 2\theta_{\mu\tau} > 5 \times 10^{-3}$ for mass differences $\Delta m^2 > 20$ eV^2 [3], while the mixing could be smaller by one order of magnitude or more [1][2].

Other recent phenomenological speculations [4][5] tend to favour a three-neutrino scheme with large or maximal mixing. Under particular assumptions, they accomodate all the existing results and make predictions for new experimental searches.

Presently, the CHORUS [6] and NOMAD [7] experiments at CERN are searching for $\nu_\mu - \nu_\tau$ oscillation, with the aim of improving the present best limit on the mixing angle by about one order of magnitude. The sensitivity on $sin^2 2\theta_{\mu\tau}$ will be extended to the level of $\sim 2 \times 10^{-4}$ for large Δm^2, of interest according to [1] and [2]. A positive signal will call for a new dedicated experiment with higher sensitivity, to confirm the discovery and learn more. In case of a negative search, however, the present uncertainties on the theoretical speculations [2] and on the indirect deductions from other experiments suggest to further extend the investigation to smaller mixing angles, also improving the sensitivity in the interesting region of $\Delta m^2 \sim 1$ eV^2.

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 ($sin^2 2\theta > 0.5$)

emerge [8]. Both possibilities of $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_e$ oscillation are contemplated. Medium or long baseline experiments with τ detection capabilities may test the first of the two solutions.

The emulsion technique, which finds its first large scale application in the active target of the CHORUS experiment, can be further improved for future $\nu_\mu - \nu_\tau$ neutrino oscillation experiments [9][10][11]. In this paper we sketch some options for short, medium and long baseline experiments where emulsion are used as high precision trackers, for very accurate spectrometry or for impact parameter track measurements, in addition to the use as active targets.

The extremely high space resolution of the emulsion copes well with the peculiar signature of the short lived τ lepton, produced in the interactions of the ν_τ with the target. Some of the ideas for short and long baseline experimentation are reviewed. A new concept for medium baseline is presented.

2. The short baseline experiment TENOR

It has been proposed [11] to run in the existing CERN Wide Band Neutrino Beam an experiment (TENOR) based on the use of a heavy (5 ton) emulsion target for the direct detection of the τ lepton decay, clear signature of the $\nu_\mu - \nu_\tau$ oscillation.

Together with the direct detection of the short lived τ in the emulsion target, the main and new feature of TENOR is the high precision spectrometry for charged particles, performed by placing the target modules inside a magnetic field and by using emulsion sheets (ES) for high resolution tracking within a limited space (Fig. 1).

The TENOR experiment has high discovery potential and would be able to study, with improved sensitivity, a positive signal coming from CHORUS and NOMAD. In the case of a negative search, the experiment would yield the limit of $sin^2 2\theta_{\mu\tau} < 9 \times 10^{-6}$ (90% CL) in the mixing angle for large Δm^2, and would be sensitive to Δm^2 down to ~ 0.1 eV^2, which is already one order of magnitude below the range contemplated in [5].

An experiment like TENOR relies on the capability of handling a large amount of nuclear emulsion and, more important, on the possibility of performing high-speed automatic scan of $\sim 5 \times 10^6$ events. This is envisageable thanks to the impressive progress in the field of computer controlled microscopes, read-out by CCD cameras, with automatic pattern recognition and track reconstruction. After the pioneering work in Nagoya [12], the Nagoya and Salerno groups in the CHORUS Collaboration have produced second generation automatic systems about 10 times faster [13][14]. Further improvements are expected from the intense R&D programs under way.

More information about this short baseline experiment may be found in [11].

3. TENOR in medium baseline locations

In the theoretical scenario described in [4] and [5], most of the existing experimental results on oscillation from accelerator, solar and atmospheric neutrinos fit an unique framework, with appealing predictions made for possible future searches. A large mixing angle is predicted, with a Δm^2 of the order of 0.01 eV^2. Also accounting for the still unconfirmed LSND result [15], the three-flavour scheme

$$\Delta m^2_{2,1} \sim 0.01\ eV^2,\ \Delta m^2_{3,1} = \Delta m^2_{3,2} \sim 2\ eV^2$$

with relatively large mixing angles is depicted in [5]. This determines detailed predictions for the path length and neutrino energy dependence of the oscillatory effect, with spectacular enhancement of the signal when the appropriate conditions are met.

It is argued in [16] that the existing CERN-SPS Wide Band Neutrino Beam (WBB) is well suited to prove the above theoretical speculations on ν_μ–ν_τ oscillation, by placing an appropriate detector in the so-called Mount Jura medium baseline location, along the neutrino beam, about 17 km from the source. At such a location, the Δm^2 contemplated in [5] gives a good signal from $\nu_\mu - \nu_\tau$ oscillation, and a negligible probability for $\nu_\mu - \nu_e$ conversion.

The estimated rate of ν_μ induced charged current interactions (CC) is about 5×10^5 for 10^{19} protons on target (pot) and 1 kton target mass placed at 17 km from the source. The CERN SPS can deliver in one year 2.5×10^{19} pot, with 200 days run, 3×10^{13} pot/cycle and 70% efficiency [11]. Suitable scaling has to be applied if the experiment is carried-out on a different beam.

With a TENOR-like detector in the medium baseline Jura location, for 5×10^{19} pot (i.e. 2 year's running time), the expected number of CC events would then be about 13000. Assuming at $\Delta m^2_{\mu\tau} \sim 2$ eV^2 an effective $sin^2 2\theta_{\mu\tau}$= 0.06 [5] one would obtain about 75 detected τ events. This number is relatively high, considering that those events can unambiguously be attributed to $\nu_\mu - \nu_\tau$ oscillation, thanks to the direct observation in the emulsion of the τ and of its distinctive decay, and to the fact that the experiment is expected to have a very low background, already for the short baseline location [11]. Another advantage of TENOR is its capability to detect different decay modes of the τ, with comparable efficiencies. A coherent result would give strength to a possible positive signal.

The total number of events to be scanned is relatively low (of the order of 17000). Therefore, the detector configuration can be simplified with respect to the short baseline design described in [11]. In particular, one could avoid using silicon trackers, mainly meant to reduce the scanning time per event, by improving track prediction in the emulsions. The weight of the emulsion target could be brought to 10 tons, so increasing the number of expected events to about 150. Apart from these differences, the detector set-up's could be very similar.

The possibility of sending a neutrino beam from the CERN SPS to the Gran Sasso Laboratory (at about 730 km path distance) is under study [16][17][18]. A massive apparatus placed in the Gran Sasso laboratory can be employed to search for $\nu_\mu - \nu_\tau$ oscillation in the low Δm^2 region (see Section 5). It would be desirable to fully exploit the new neutrino beam by placing another detector in the same beam line at a location closer to the neutrino source. This is advantageous for several reasons. The search for oscillation can be extended to a larger parameter domain, the knowledge of the beam is improved by comparing the two detector responses, and in case of a positive search one could study the specific E and L dependence of the signal.

The foreseen beam to Gran Sasso has a slope with respect to the horizontal plane of about 57 mrad downwards [19]. This requires that a detector placed at ~ 2 km from the source has to be ~ 100 m underground. The actual location must be carefully studied in order to optimize the experiment performance against the excavation cost. However, given the investment needed to build such a new beam line, the cost of the detector cave seems to be affordable. Larger distances from the neutrino source are unrealistic due to the beam slope.

With the beam to Gran Sasso, the expected number of CC events induced by ν_μ is $\sim 100000/\text{ton}/10^{19}$ pot at 2 km distance from the target [16]. Also in this case a TENOR-like detector may be used. With a 2 year's run (5×10^{19} pot) and with a 5 ton emulsion target, about 2.5×10^6 CC can be collected. The estimated background, also for this experiment, is below the one event level. In the case of a negative search, this experiment would yield a (90% CL) limit in the mixing parameter, for large Δm^2

$$sin^2 2\theta_{\mu\tau} < 3 \times 10^{-5}.$$

For full mixing, the minimum detectable Δm^2 is

$$\Delta m^2 \sim 5 \times 10^{-2} \text{ eV}^2.$$

4. An experiment with wide sensitivity domain

4.1 Conceptual design

A medium baseline experiment aimed at high sensitivity, both in mass and in mixing angle, can be designed by exploiting the emulsion technique in a form evolved from the so-called Emulsion Cloud Chamber (ECC) [20]. The ECC technique has been used for several (also large scale) applications [21] and recently revised and proposed for neutrino oscillation experiments [22]. The main features of the experiment (OPERA[1]) are presented in the following.

Basically, the direct observation of the τ decay kink in TENOR is replaced by an impact parameter measurement, allowing to increase the target mass by an order of magnitude. This increase is made possible by employing iron as a target, with the emulsion used only for tracking. There are only emulsion sheets (ES) and no target emulsion. The experiment is designed for $\nu_\mu - \nu_\tau$ oscillation search, but it has also good sensitivity for $\nu_\mu - \nu_e$ oscillation.

The iron/emulsion target is subdivided in 92 modules and has a weight of 100 t (iron). Each module, whose dimensions orthogonal to the beam direction are about 3×3 m^2, consists of a sequence of 30 sandwiches, each made out of a 500 μm thick iron plate followed by an ES, a drift distance of 2 mm, and another ES (Fig. 2). 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 10 cm. Each module could be subdivided into elements, e.g. with a 30×30 cm^2 area, transverse to the beam direction.

The 50 μm thickness of the emulsion layers is large enough to achieve high tracking efficiency and angular resolution, and it is sufficiently small to allow for industrial production. The thickness of the plastic base between the two emulsion layers determines the achievable angular resolution. The use of a thicker base (200 μm) may be envisaged and studied, if this is compatible with the request of minimizing the amount of material in each sandwich.

When neutrinos interact in the iron, primary particles are pro-

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[1] Oscillation Project with Emulsion-tRacking Apparatus.

duced, some of which, in turn, may interact or induce showers in the downstream iron plates, leaving two space-track segments in each ES. If a τ is produced, it can be detected with the impact parameter method, by measuring the angle formed by the charged decay daughter of the τ with respect to the τ direction. This decay "kink" angle is due to the invisible neutrino(s) produced in the τ decay. The directions of the primary (and secondary) charged-particle tracks of the event are reconstructed by means of the first pair of ES downstream of the iron plate where the primary vertex occurs.

The detector is placed in a cave with a depth of a few meters and with a concrete ceiling of approximately 3 meters thickness, to shield it against non-penetrating particles from cosmic ray showers. Together with the low neutrino (and muon) beam flux, this yields a relatively low density of background tracks "stored" in the emulsion, thus removing 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, placed behind each 10 cm target module, detect the shower induced by the neutrino interaction and, hence, locate the ES where scanning must start. About 1 cm^2 of this ES is scanned in corrispondence of the shower axis and all the track segments found are measured. These are then extrapolated and searched for in the upstream ESs, until the event vertex is reached.

The tracking detectors have the additional task of muon identification with good efficiency and angular acceptance. For this purpose, they are arranged in planes with transverse dimensions larger than those of the emulsion. Honeycomb chambers or other similar devices can be envisaged. The number of individual detectors can be as high as 200000. To increase the detection efficiency and, consequently, the background rejection, muon detectors could also be added around the target.

The momentum of the τ decay products is determined by a multiple scattering measurement in the emulsion. The resolution achievable with this method is weakly dependent upon the momentum. It ranges from 10% at 1 GeV/c to 20% at 30 GeV/c. 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 part of a (fine-grained) calorimeter, where the 10 cm thick iron/emulsion modules play the role of the absorber material. Each target module is ~ 1 radiation length thick. Therefore, a calorimetric measurement of the events is possible, helping in the kinematical analysis of candidate events. To complete the measurement for events originating downstream in the target, the muon spectrometer is calorimetrized. The overall dimensions of the experimental apparatus are $\sim 4 \times 4 \times 20$ m^3.

We stress that what we present here is a conceptual design of the experiment. The optimization of the target characteristics and dimensions, of the emulsion sheets and of the electronic detector configuration will deserve a careful study and detailed simulations. The technical feasibility of the target elements has to be assessed by constructing and beam testing detector prototypes.

4.2 Data, background and sensitivity to $\nu_\mu - \nu_\tau$ oscillation

The expected number of CC events in OPERA is about 2.5×10^5 for 5×10^{19} pot (2 year's running time), with about 80000 neutral current (NC) interactions.

In OPERA, as in TENOR, no kinematical cuts (or very loose ones) are applied to reduce the number of events to be scanned, leading to a high efficiency for the signal. All the τ decay channels are investigated. For the hadronic decays, which have the largest branching ratio (64%), an important source of background is potentially given by hadron reinteractions. In this case, one of the primary hadrons of the (NC) event may reinteract in the vertex iron plate, giving products invisible in the emulsion, so faking the decay of the τ.

Given the average number of hadrons per event, the iron plate thickness and the number of NC events, one can roughly predict the number of background events from hadron reinteractions

$$N_{bg}(\text{reint.}) = 4 \times (0.025/10.5) \times 80000 \sim 800 \text{ events}$$

where the first term is the average hadron multiplicity, the second is the ratio between (one half of) the iron plate thickness and the nuclear collision length, and the third the total number of NC events. By requiring a sufficiently large impact parameter for the hadronic reinteraction "kink"and just one track produced, one would be left with $\sim$ 10–20 background events for the hadronic decay mode.

A novel feature of the experiment design is that this background is removed by requiring that the τ decay occurs in the 2 mm drift space between consecutive iron plates or in the plastic base of the upstream ES (Fig. 2). Therefore, one rejects those τ decays occurring in the iron plate of the primary vertex ("short decays"), which are the only ones affected by the reinteraction background.

The oscillation depends on $\Delta m^2 \times L/E$. Therefore, small Δm^2 values correspond to low-energy oscillated ν_τ and, hence, to low energy τ leptons. The efficiency of the above cut is a function of the average path length of the τ, which in turn is related to the Δm^2 value. As an example, a Monte Carlo simulation with 550 μm cut (corresponding to one iron plate plus 50 μm emulsion layer) gives the following efficiencies to detect τ decays as a function of Δm^2.

Δm^2 (eV^2)	100	10	1	0.1	0.01
ϵ	0.80	0.75	0.70	0.65	0.65

In the $\Delta m^2 = 0.01$ eV^2 region the efficiency is slightly lower than in the large Δm^2 limit. In the whole kinematical domain accessible by OPERA, the detection efficiency × branching ratio (BR) of the hadronic channels ranges from $\sim$ 40 to 50%, also accounting for a 95% "kink" finding efficiency.

Similar considerations apply to the muon and electron decay of the τ. The BR is 18% and an efficiency × BR ranging from 10 to 14% (according to the Δm^2 domain) is obtained. The requirement that the τ decay does not occur in the iron allows, in particular, to eliminate those CC charm events which may fake a large impact parameter of the muon, as shown in Fig. 3.

We can roughly estimate the potential background induced by D$^+$ mesons, by the following expression

$$N_{bg}(D^+)=0.03\times0.33\times0.2\times0.6\times0.2\times0.98\times0.95\times250000 \sim 50 \text{ events}$$

where the eight multiplicative factors are, respectively, the probability to produce charm in CC interactions, the D$^+$ production probability, the probability that the D$^+$ is produced without additional hadrons, the BR for D$^+$ decay without leptons, the probability for the D$^+$ to decay in the iron, the primary-muon detection efficiency, the impact-parameter detection efficiency and the total number of charged current events. A similar expression allows to predict additional $\sim$ 110 events due to D^0 production and decay.

The drawback of removing background events with a kink in the iron, is a lower efficiency for the signal. In this respect, a denser target material would be advantageous. With doubled density (i.e. tungsten), thinner foils could be used (250 μm), increasing the τ efficiency detection at constant emulsion mass. Another possibility is to still use 500 μm (but denser) plates. In this case, one would have a more compact detector, reducing by one half 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 costwise.

As far as the sources of background are concerned, our estimates are preliminary, although supported by the experience with the CHORUS experiment [6][23], whose background and analysis methods are similar to those in OPERA. In particular, we observe that CHORUS 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 [6].

OPERA will collect about one third of the CC events of CHORUS, but the particle charge is only determined for forward muons. This implies a worse rejection power against background. However, most of the background sources (kaon decay, associated charm production, single charm production by electron and muon antineutrinos) are estimated to give less than one event altogether.

The most relevant background source is given by single charm production by ν_μ, the main component of the beam. If the primary muon is undetected (2% probability), a D^+ meson decaying in one charged particle (plus neutrals) can fake a genuine τ event. The reason is that single prongs from τ decay are negative, while the (positive) charge of the D daughter is only measured for the muonic decay, with the muon detected by the downstream spectrometer.

The high efficiency in detecting the primary muon (98%) is obtained by exploiting, for the small number of candidate events, a detailed analysis of the event primary tracks in the emulsion. The muon identification can be very effective just for those low-momentum particle for which the electronic detectors may fail, as described in [24].

We can estimate the above background for the single-hadron decay mode of the τ by the following expression

$$N_{bg}(h^-)=0.03\times0.33\times0.2\times0.8\times0.95\times0.02\times250000 \sim 8 \text{ events}$$

where the factors are, respectively, the probability to produce charm in CC interactions, the D^+ production probability, the BR for 1-prong hadronic D^+ decay (plus neutrals), the probability for the D^+ to decay outside the iron, the kink detection efficiency, the probability not to identify the primary muon, and the total number of charged current events. Similar calculations lead to about 2 background events for the muonic and electron channels together. A 70% efficiency has been assumed to determine the muon charge by means of the downstream spectrometer.

A Monte Carlo simulation has shown that by rejecting low-momentum D-meson daughters (< 1.0–1.5 GeV/c), about 30–35% of the D decays are eliminated for a τ efficiency of $\sim$ 90%. One is left with a total of $\sim$ 6 background events in OPERA.

The above number of candidates is small enough to allow a full kinematical analysis in the emulsion. In particular, the momentum and the direction of all primary and secondary particles at the vertex will be measured. The electrons will be identified by following their tracks in the ES, and by detecting their electromagnetic interactions [25]. Photon conversions from neutral pions will be searched for in the ES further downstream of the vertex plate. The calorimetric information of the electronic detectors will also be used. The expected difference in the kinematics of τ decays with respect to charm events will be exploited to further reduce the background (Fig. 4). A rejection of a factor $\sim$ 10 is achievable, keeping high efficiency for the τ decays [6][11].

In conclusion, OPERA should be left with less than one background event with an overall efficiency × BR ranging from 55 to 70% (according to Δm^2), including the kinematical cut efficiency. The ratio of cross-sections for tau and muon neutrinos is 0.53 for large Δm^2. In the case of no observed candidates, one then obtains the limit of

$$sin^2 2\theta_{\mu\tau} < (2\times 2.3)/(N_{CC} \times \epsilon \times BR \times \sigma_\tau/\sigma_\mu) = 5.5 \times 10^{-5} \quad (90\%\ \mathrm{CL})$$

in the mixing parameter for large Δm^2. The sensitivity is thus improved by a factor of about 4 with respect to CHORUS and NOMAD. The minimum detectable Δm^2 for full mixing is

$$\Delta m^2 \sim 6.5 \times 10^{-3}\ \mathrm{eV}^2.$$

The 100 ton target is, therefore, large enough to also make the experiment sensitive to the low $\Delta m^2_{\mu\tau}$ region, corresponding to the atmospheric neutrino anomaly reported by the Kamiokande experiment.

In addition, one could further improve the sensitivity in the low mass domain by lowering the mean energy of the neutrino beam, since the minimum detectable $\Delta m^2_{\mu\tau}$ decreases linearly with the neutrino energy. The loss due to the smaller cross-section would not affect those neutrinos "oscillating with low $\Delta m^2_{\mu\tau}$". This reduction in energy may be accomplished, for instance, by reducing the distance between the beryllium target hit by the SPS protons and the "magnetic horn", focusing the neutrino parents. An additional possibility is to lower the primary proton energy.

In the case of the previously discussed scenario with large threefold mixing [5] OPERA would yield a huge signal. The number of detected oscillation events is, in this case, as high as 2000.

We observe that, if the experiment is background free, the sensitivity to Δm^2 does not improve by increasing the distance of the detector from the source, as the increased oscillation probability is compensated by the decreased neutrino flux. A shorter distance, conversely, allows to improve the sensitivity in the mixing angle. The specific merit of OPERA, with respect to short and long baseline experiments is, indeed, the high sensitivity both in mixing angle and in $\Delta m^2_{\mu\tau}$, with a detector configuration able to give a clear signature of the neutrino oscillation. Another advantage, in common with TENOR, is given by the possibility of using the existing CERN Wide Band Neutrino Beam, which has still increasing performance.

4.3 Sensitivity to $\nu_\mu - \nu_e$ oscillation

OPERA will also be sensitive to the $\nu_\mu - \nu_e$ oscillation. The E/L ratio is $\sim$ 1.6 GeV/km, similar to the one of the LSND experiment ($\sim$ 1.5 GeV/km). The electron identification can be performed with high efficiency by following its track in the ES downstream of the vertex plate [25]. Apart from the ν_e coming from ν_μ oscillation, 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 150. The other source is represented by the electrons from the decay of neutral pions produced in NC ν_μ interactions. The former background yields $\sim$ 1650 events per 250000 ν_μ CC interactions. For the latter, we estimate about 11000 events. Simulations show that, by rejecting events with electron energy lower than 5 GeV, we are left with $\sim$ 1000 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. In addition, one has to consider a systematic error due to the uncertainty in the estimate of the ν_e content of the beam. The relative error in the ν_e flux is assumed to be 4%. Thus, we obtain 2650 expected events with a total uncertainty of $\sqrt{2650 + 66^2} \sim 80$ events. The corresponding 90% CL sigle-sided upper limit is $\sim$ 100 events.

In the case of a negative search, OPERA would yield a (90% CL) limit in the mixing parameter, for large Δm^2

$$sin^2 2\theta_{\mu e} < 10^{-3}.$$

For full mixing, the minimum detectable Δm^2 is

$$\Delta m^2 \sim 3 \times 10^{-2}\ \mathrm{eV}^2.$$

It is important to observe that the given sensitivity domain fully covers the claimed LSND signal region [15].

4.4 Emulsion and scanning

The number of events to be scanned in OPERA amounts to about 350000, a sample comparable to that of the CHORUS experiment. However, the scanning procedure is more complicated and time consuming than for CHORUS and for TENOR in the short and medium baseline. In fact, in OPERA the electronic detectors locate events rather than individual tracks. For each event, several emulsion sheets must be scanned over a larger area. Moreover, some tracks have to be followed upstream to the primary vertex.

Once the vertex is found, the impact parameter measurement allows the detection of the decay "kink" of one of the tracks, signature of the τ decay. The residual background rejection is accomplished by means of the muon identification and of the kinematical event reconstruction. The latter is based on momentum measurements by multiple scattering in the emulsion and by the muon spectrometer, and on calorimetric measurements for neutrals. As we already pointed out, the very detailed event analysis will be performed for the few candidate events, with the aim of a full kinematical reconstrution.

As in the case of TENOR, OPERA relies on the possibility of performing high-speed automatic scanning of the emulsion sheets. With the present technology, the time needed for a complete event scanning can be estimated in 30 minutes. Assuming 15 microscopes to be available and reasonable scanning downtimes, the complete analysis can be performed within 2 years.

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

Due to the limited need for infrastructures and maintenance, the experiment features an apparatus which is particularly well suited for operation in a site like the Mount Jura. If it is run in a different neutrino beam line at a medium baseline location, one should then appropriately scale the performance.

5. A long baseline experiment

The SPS neutrino beam to the Gran Sasso Laboratory will allow to explore the low Δm^2 region, searching for neutrino oscillation with long baseline experiments. However, the sensitivity to small mixing angles is, in this case, relatively limited. Given the very long travel distance and the divergence of the neutrino beam, the target has to be massive: the expected number of CC muon neutrino interactions is about 1000/kton/10^{19} pot, for an average neutrino momentum of $\sim$ 30 GeV/c [16][18]. A similar option exists with the neutrino beam from the Fermilab Main Injector sent to the Soudan mine [26].

Again, a detector of the type of the ECC may be used [22]. We can conceive a 1 kton target made of 140 modules. A module is composed of 256 elements. Each element has the dimensions of $25 \times 25 \times 10$ cm^3 and weights about 30 kg. As in the case of the medium baseline experiment, for event location and muon identification, each module is followed by standard electronic detectors with moderate space resolution.

The fine structure of the modules is similar to the medium baseline option. However, due to the lower number of background events, the OPERA concept of selecting decays outside the iron is not relevant. Therefore, the iron plate thickness may be slightly larger (1 mm). The ES, sandwiched between iron plates, are made of thin emulsion layers ($\sim$ 50 μm thick) on either side of a 900 μm plastic base (Fig. 5). The overall dimensions of the detector target are $4 \times 4 \times 21$ m^3.

The expected number of events in a typical one year exposure (2.5×10^{19} pot) is 2500 muon neutrino CC, 810 NC, and $\sim$ 20 events induced by the electron neutrinos present in the beam [16][18]. In this experiment, τ decays occurring in the iron will be retained. As the charm background for the muonic decay of the τ is too high, the CC muonic events are vetoed. One can compute the main background for the hadronic channel, given by reinteractions. Similarly to the medium baseline case, it is estimated from the 810 expected NC events and the 1 mm iron plate thickness and amounts to 0.1–0.2 events.

The main source of background for the electron decay of the τ is given by the charm events produced by the electron neutrinos. Also this background is at the level of 0.1 events, and therefore unimportant. The overall detection efficiency times BR for the above two channels is about 60%. The σ_τ/σ_μ cross-section ratio is ~ 0.50. If no events are observed, the limits for the oscillation parameters are (90% CL)

$$sin^2 2\theta_{\mu\tau} \; < \; 6 \times 10^{-3} \text{ (large } \Delta m^2\text{)}$$

$$\Delta m^2 < 2 \times 10^{-3} \text{ eV}^2 \text{ (full mixing).}$$

The experiment will be able, even in a short run, to reach very high sensitivity in the exploration of the low Δm^2 region, below the one indicated by the atmospheric neutrino anomaly, at the cost of a relatively poor sensitivity in the mixing angle.

Given the small number of interesting events (of the order of 3 NC per day) the event analysis can be performed quasi-on-line. One can periodically remove those targert 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 must be, in fact, a fully modular structure, allowing the automatic access to the target elements. We observe that the number of elements to be removed after one year running ($\sim$ 3000) is small as compared to the total number of target elements (35840).

The large amount of emulsion needed for this experiment (about 25 tons) requires that the problems of the cost and production rate have to be solved. Industrial production of the ES has to be foreseen on a larger scale as compared to OPERA.

6. Conclusions

We have presented the conceptual design of possible experiments for $\nu_\mu - \nu_\tau$ oscillation searches exploiting the technique of nuclear emulsion, used as large mass active target as well as for high space resolution tracking. One can conceive short, medium and long baseline experiments, able to substantially improve the existing limits in the oscillation parameter plane.

The experiments have great discovery potential, in the light of the arguments which led to CHORUS and NOMAD [1][2], of recent phenomenological scenarios [4][5], and are able to test experimental results interpreted by invoking neutrino oscillation [8][15]. However, the global scenario is undergoing an important evolution. Several experiments are taking data and some others are planned. It is clear that we shall have to take into account the forthcoming results in order to make the correct choice for future experiments.

The sensitivities of the experiments presented in this paper are graphically shown in Fig. 6.

In the short baseline configuration, the TENOR experiment explores the region of very low $sin^2 2\theta_{\mu\tau}$, with a sensitivity more than one order of magnitude higher than CHORUS and NOMAD.

For long baseline $\nu_\mu - \nu_\tau$ oscillation search, for example in the future SPS beam to the Gran Sasso Laboratory, the Emulsion Cloud Chamber (ECC) technique allows to explore a domain with $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2, well below the indication from the atmospheric neutrino anomaly. A near detector like TENOR can be placed in the same beam line at about 2 km distance from the source, $\sim$ 100 m underground, to meet the beam slope. Such an experiment would complement the study performed by a long baseline experiment, allowing for the extension of the sensitivity domain down to small mixing angles.

The medium baseline experiment OPERA is characterized by two new distinctive features: a novel evolution of the ECC technique, employing an iron/emulsion target placed in a medium baseline location. This approach leads to a high sensitivity both in Δm^2 and in $sin^2 2\theta$. This experiment alone can allow to test some of the present experimental indications for neutrino oscillation.

In the case of no observed candidates, with OPERA in the present CERN Wide Band Neutrino Beam, one obtains the limit

$$sin^2 2\theta_{\mu\tau} < 5.5 \times 10^{-5} \qquad (90\%\ \mathrm{CL})$$

in the mixing parameter for large Δm^2, with a minimum detectable Δm^2 for full mixing

$$\Delta m^2 \sim 6.5 \times 10^{-3}\ \mathrm{eV}^2.$$

The experiment will also allow to search for $\nu_\mu - \nu_e$ oscillation. The expected sensitivity fully covers the parameter region corresponding to the LSND signal.

However, we stress that the appealing features of OPERA and, in general, the feasiblity of a large ECC neutrino-experiment have to be confirmed by more detailed studies, simulations and tests of prototype detectors, in order to perform an experiment design.

The feasibility of the discussed experimental programmes relies on the progress in the field of emulsion handling and automatic scanning facilities. The CHORUS experiment has already proven that emulsion detectors can be used with success as modern and performing devices, while further developments are expected in the future.

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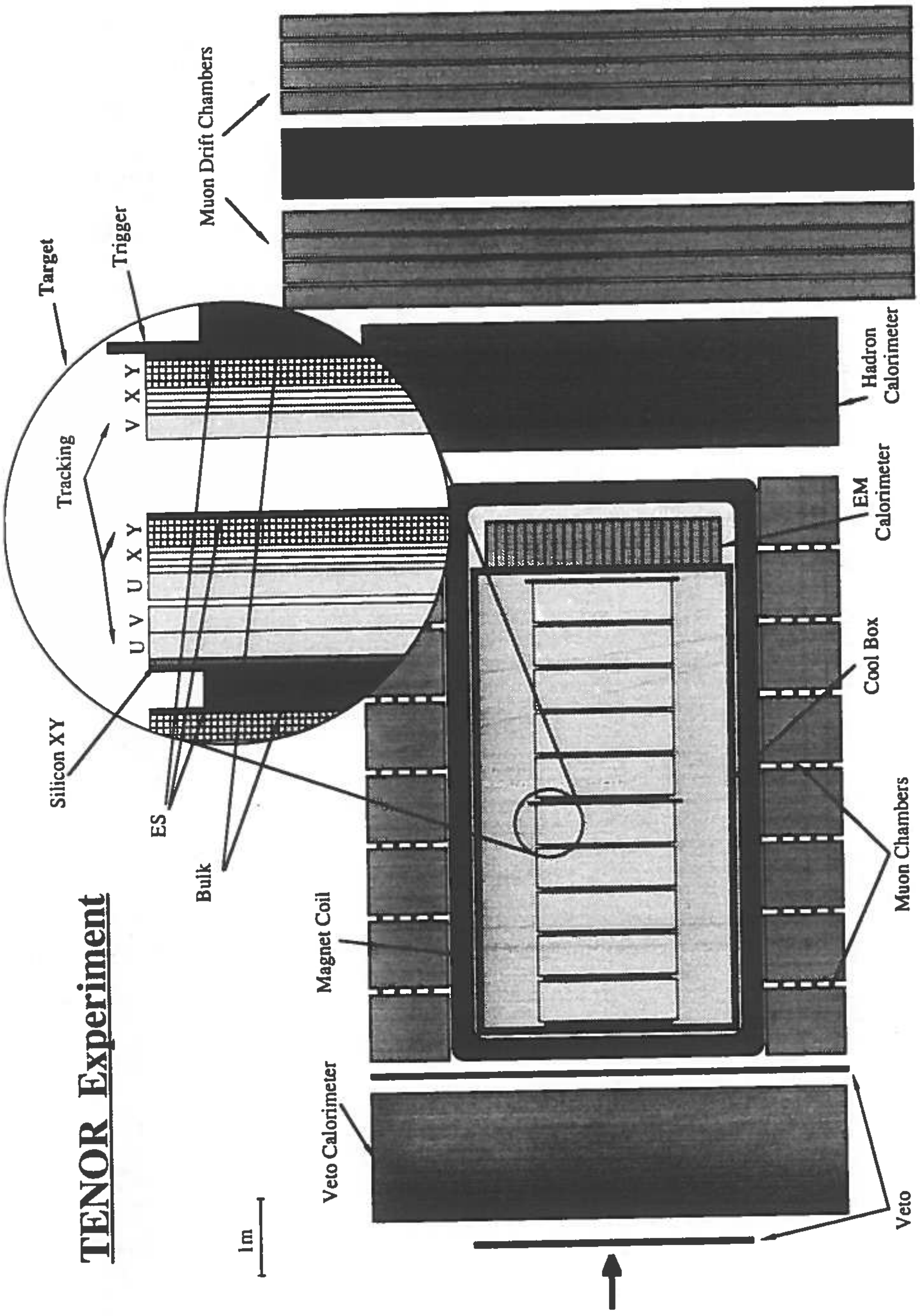

Figure 1: Side view of the TENOR detector layout.

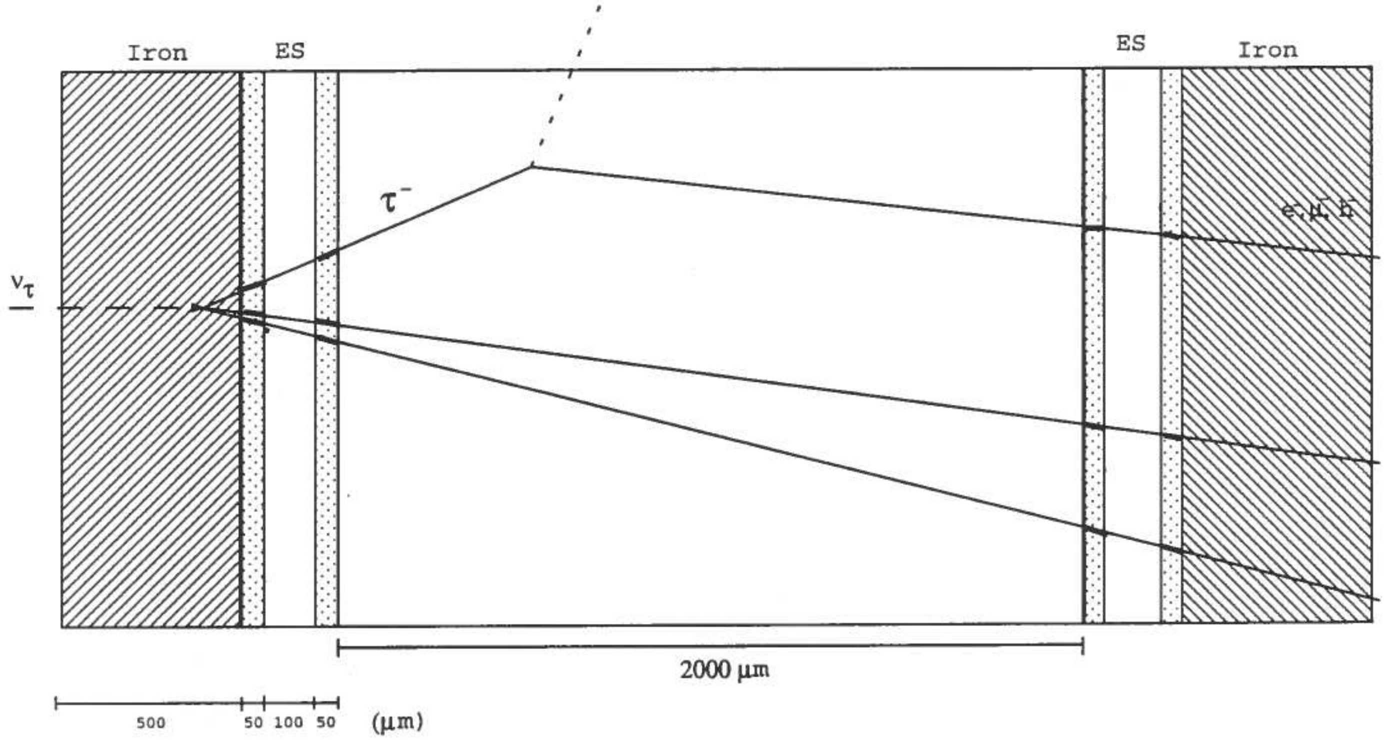

Figure 2: Schematic structure of the OPERA target.

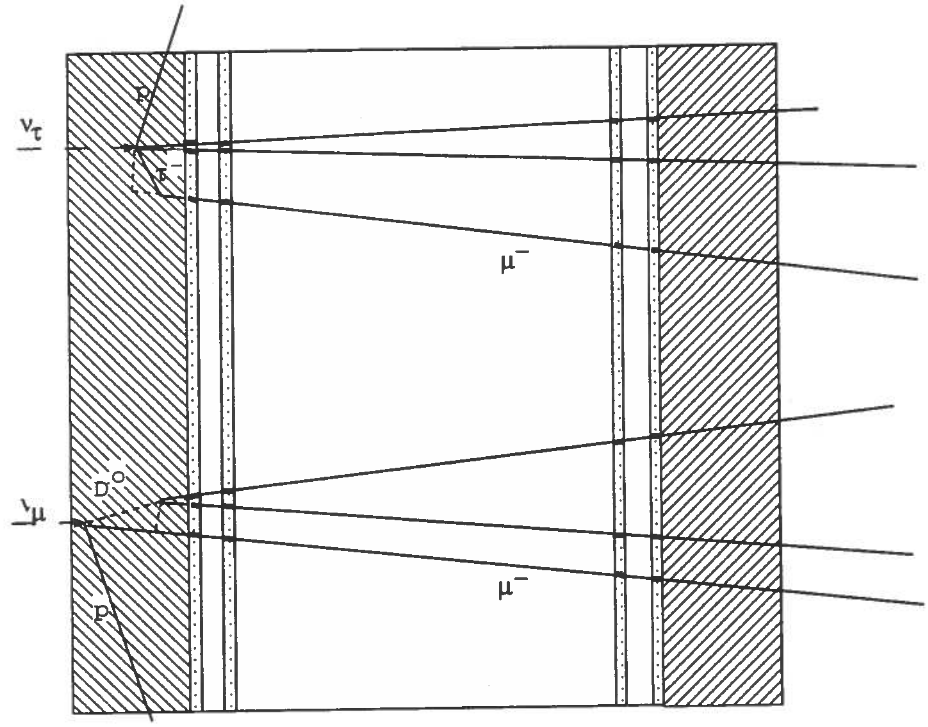

Figure 3: Signal and charm background for the muon channel if short decays are not rejected.

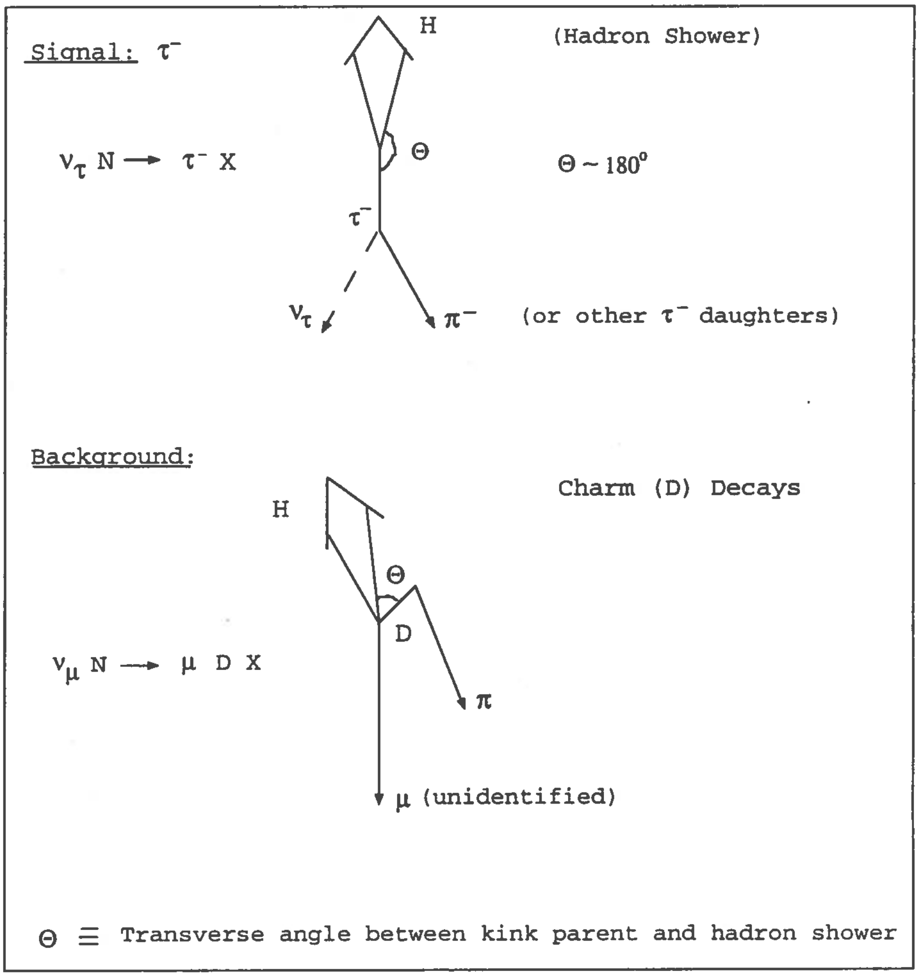

Figure 4: The basic principle of the event vertex kinematics, for charm background rejection.

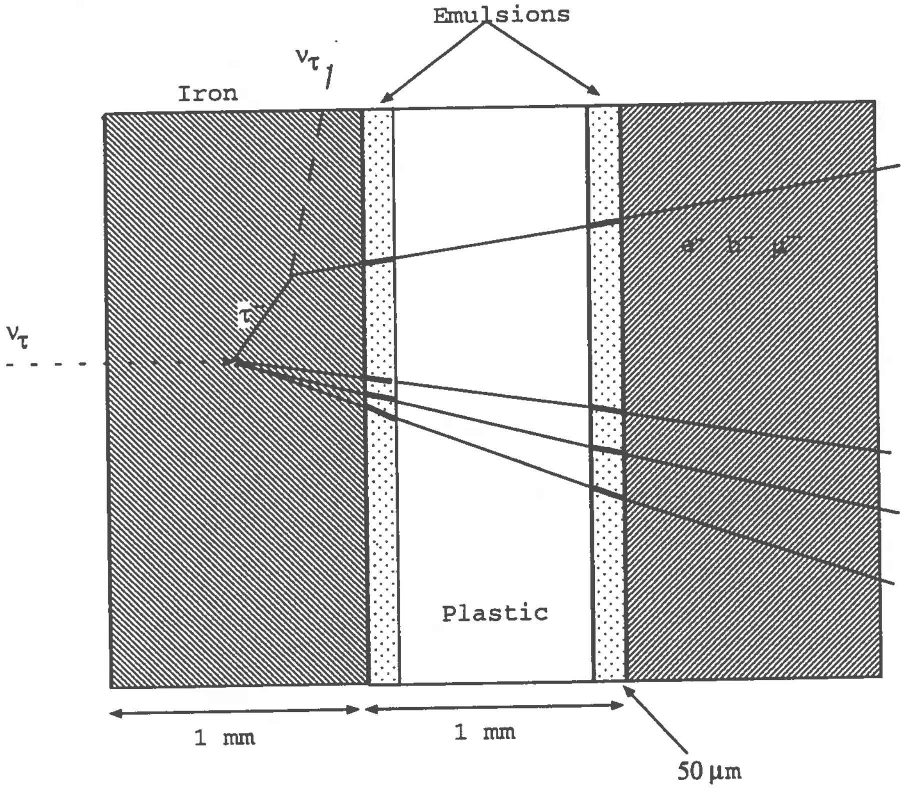

Figure 5: Schematic structure of the ECC target for the long baseline experiment.

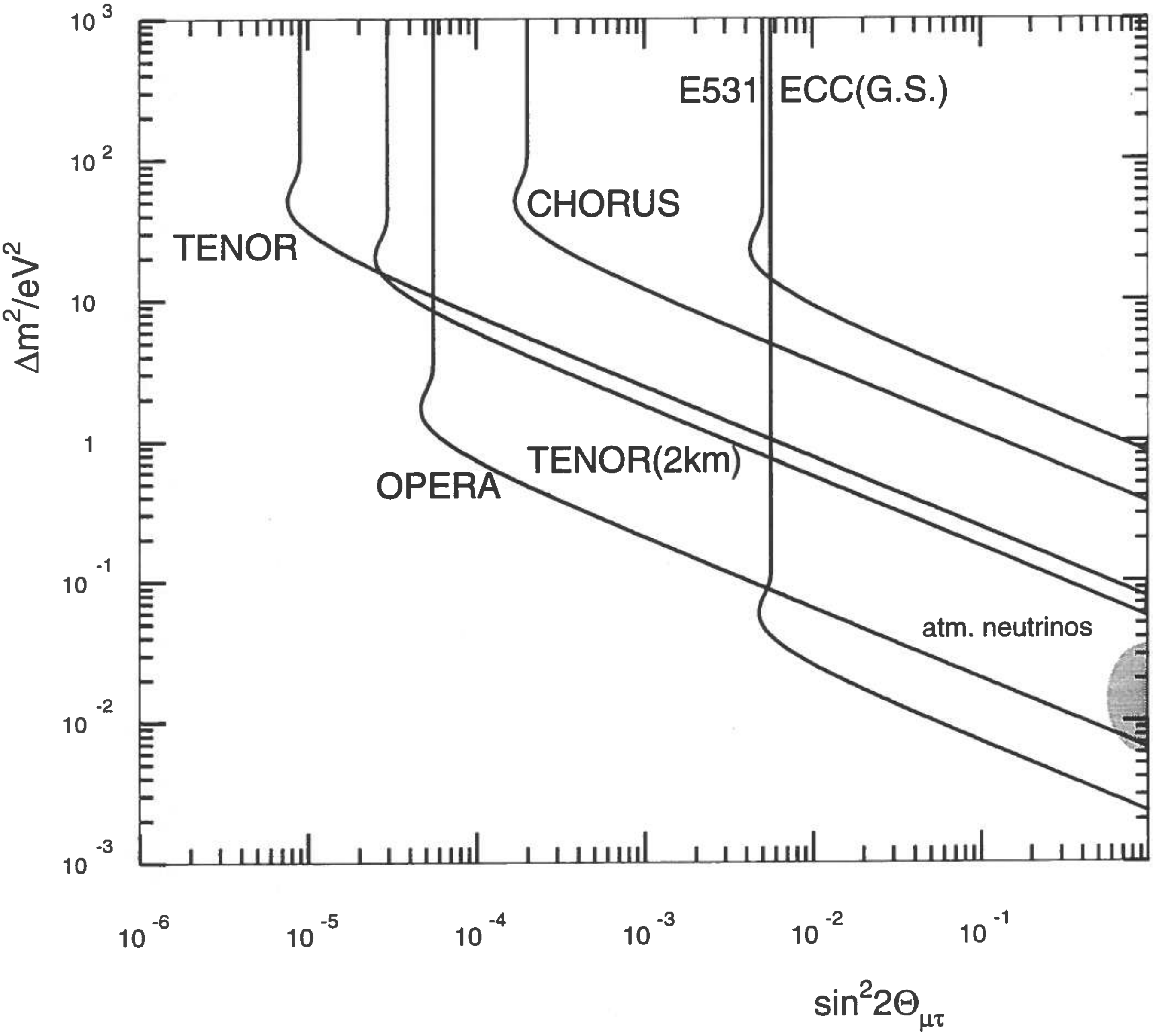

Figure 6: Sensitivities of the searches presented in this paper as compared to other experiments.