A Neutrino Apparatus with Improved Capabilities for a Short Baseline $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Search

J.J. Gomez-Cadenas^{1,2}, J.A. Hernando^{1,3}, and A. Bueno^{1,4}

Abstract

We propose the conceptual design of a Neutrino Apparatus with Improved Capabilities (NAUSICAA). This detector could be used for a new, short-baseline, high sensitivity $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation search experiment at the CERN-SPS neutrino beam, as well as at the future Fermilab Main Injector neutrino beam.

The heart of the detector is a finely instrumented target, made of a sandwich of a light Z material and high resolution tracking detectors. Downstream of the target there are tracking detectors for momentum measurement, followed by a compensating calorimeter. All these systems are contained within magnet providing a magnetic field of about 1 Tesla. Following the magnet there is a muon detector. Unlike previous experiments, NAUSICAA would be capable of searching for the τ signature using both kinematical and vertex criteria *simultaneously*.

Detailed Monte Carlo calculations show that NAUSICAA could improve the sensitivity of the on-going experiments, CHORUS and NOMAD by an order of magnitude in a four-year neutrino run at CERN. Further improvement on the sensitivity (by a factor of two to five) could be achieved in a four-year run at Fermilab.

1. Department of Physics and Astronomy, University of Massachusetts, Amherst, MA, 01003, USA.
2. CERN-PPE, CH-1211 Geneva 23, Switzerland.
3. Departamento de Fisica Atomica y Nuclear, Universidad de Valencia, Spain.
4. Department of Physics, Harvard University, Cambridge, MA, 02138, USA.

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1 Introduction

At present, several experimental results suggest the possibility of neutrino oscillations. Currently two experiments, CHORUS and NOMAD [1, 2] are searching for the exclusive $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation mode in the CERN-SPS neutrino beam, using complementary techniques. NOMAD identifies τ 's with purely kinematical criteria (i.e. by measuring the event missing transverse momentum vector from which the presence of escaping neutrinos in the event can be deduced) while CHORUS relies on vertex criteria, namely detecting the finite τ path in its emulsion target. The theoretical scenario which encourages this search is one in which the ν_μ and ν_e are light and the ν_τ has a mass in the range of a few eV. This scenario successfully explains the solar neutrino deficit in terms of matter enhanced $\nu_e \leftrightarrow \nu_\mu$ oscillations in the Sun. In addition it provides a candidate (a ν_τ of a few eV) for the hot component of the dark matter of the Universe. However, it fails to explain the atmospheric neutrino deficit. The expected combined level of sensitivity of these experiments to a putative mixing between the ν_μ and the ν_τ can be expressed in the two-family approximation, as $\sin^2 2\theta_{\mu\tau} \leq 2 - 3 \times 10^{-4}$ for large mass differences. The sensitivity to a mixing between the ν_e and the ν_τ is about two orders of magnitude worse.

There are, however, compelling motivations to seek ways of improving the sensitivity of CHORUS and NOMAD. Even if the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation were to occur with a strength at the level of the present limit [3, 4], $\sin^2 2\theta_{\mu\tau} \sim 5 \times 10^{-3}$ each experiment would detect only about 100 ν_τ events by the end of the neutrino run, enough to clearly establish the presence of a τ signal, but too scarce to determine the oscillation parameters. This would require an experiment with an order of magnitude higher sensitivity. If, on the other hand, CHORUS and NOMAD do not find a positive signal, the arguments to improve their sensitivity by at least one order of magnitude are no less compelling. Firstly the mixing angle $\theta_{\mu\tau}$ can be smaller than 10^{-4} (we have no clues about which value to expect). Secondly, even if one considers the most favourable scenario for this short base-line experiments (the one in which there are two light neutrinos and the ν_τ accounts for the hot component of the dark matter), the value of the ν_τ mass can vary by an order of magnitude, typically from 1 to 10eV . Present models favour ν_τ masses as low as 3eV^2 . The sensitivity of CHORUS/NOMAD in this critical region $\Delta m^2 \sim 10\text{eV}^2$ is only $\sin^2 2\theta_{\mu\tau} \sim 5 \times 10^{-2}$.

Improving this sensitivity by an order of magnitude is certainly worthwhile. Thirdly, the sensitivity to $\nu_e \leftrightarrow \nu_\tau$ oscillations achieved by CHORUS/NOMAD is rather poor and it would certainly be interesting to improve it by an additional order of magnitude.

The CERN-SPS is scheduled to deliver neutrinos until the end of 1997. However, the neutrino beam could be available for a longer period of time. Since the projected neutrino beam at Fermilab Main Injector will not begin operations until around 2002, the CERN-SPS neutrino beam would be for at least five years the only place to further investigate the possibility of $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillations. Clearly, to maximize the benefits of such a long run, it would be desirable to design a state-of-the-art apparatus, able to improve on both the CHORUS and NOMAD designs.

In Fermilab, there is an approved experiment (E803, now called COSMOS [5]) to operate in the future neutrino beam. This experiment uses emulsions, and an experimental technique rather similar to CHORUS. Better momentum resolution, combined with a larger data sample permits COSMOS to claim a prospective sensitivity one order of magnitude better than the CERN experiments, after a 4 year run period. Note, however that COSMOS will not start taking data until around the year 2002.

In this paper we propose the conceptual design of a Neutrino Apparatus with Improved Capabilities (NAUSICAA), capable of searching for the τ signature by using *simultaneously* both kinematical and vertex criteria. We present detailed Monte Carlo calculations which show that a new experiment based on NAUSICAA could improve the CHORUS/NOMAD sensitivity by up to an order of magnitude in an extended run period at CERN (i.e. from 1999 to 2003). We have also considered the prospective sensitivity of NAUSICAA in the Fermilab neutrino beam. We estimate that a further improvement of a factor two to five is possible in a four year run at Fermilab.

The proposed detector is based on a finely instrumented target, made of a sandwich of tracking devices (microstrip silicon detectors or capillary detectors) and passive plates of a low Z material. The event vertex can be measured in this target with a precision good enough to detect impact parameters of the order of $90\mu m$, signaling the presence of a τ . The target is followed by a full spectrometer (in the same magnetic volume) able to measure charged tracks and neutrals with excellent resolution.

The detection of the ν_τ from a high resolution measurement of the event vertex, using electronic techniques, has been suggested by several authors [6, 7, 8, 9, 10]. In particular, the idea of a *continuously sensitive* (or active) target (based on capillaries or scintillating fibers) has been discussed in [6, 7]. However attractive, the feasibility of a large device of this type in the near future is unclear, given the very large active surface needed which results in as many as 10^9 channels. Considerable R & D is needed to design (and build at reasonable prices) devices (such as Megapixel CCDs) capable of reading out such a large number of channels.

The bulk of the mass of the NAUSICAA instrumented target comes from the passive material, thus reducing enormously the active surface. Furthermore, the target is light enough (in terms of radiation and nuclear interaction lengths) to enable the use of kinematical techniques to identify the τ . Therefore, one can combine a precise measurement of the vertex and of the kinematics of the event.

This paper is organized as follows. Section 2 reviews the interest of a short base line $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation search. Section 3 briefly describes the on-going experiments CHORUS and NOMAD. Section 4 describes our basic design for the NAUSICAA detector. Section 5 discusses the principles of operation of the experiment with two examples: the search for the $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation looking into the τ decay mode $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ and into the decay mode $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$. In section 6 we discuss the prospective sensitivity of the experiment. Finally in section 7 we present our conclusions.

2 The Physics Interest of the Experiment

2.1 Neutrino Oscillations

If neutrinos are massive, the weak eigenstates need not be the same as the mass eigenstates. By analogy with the quark sector, one can relate the mass eigenstates and the weak eigenstates by means of an unitary matrix U_{ik} ,

$$|\nu_f\rangle = \sum_{k=1}^3 U_{fk} |\nu_k\rangle \quad (1)$$

with $f = e, \mu, \tau$. If a neutrino beam of flavour f and momentum p is produced at a given instant $t = 0$, its time evolution will be given by

$$|\nu_f(t)\rangle = \sum_{k=1}^3 U_{fk}^{-iE_k t} |\nu_k\rangle \quad (2)$$

with $E_k = \sqrt{p^2 + m_k^2}$. If the three mass eigenstates are different, the phase $iE_k t$ will evolve differently for each ν species. This implies that the admixture of mass eigenstates will change with time and therefore with the distance from the production point. Therefore, transitions from the original flavour to a different flavour can be observed.

For two flavour oscillations, $\nu_\mu \leftrightarrow \nu_\tau$, the matrix U_{ik} reduces to a simple rotation. In this case,

$$\begin{aligned} \nu_\mu &= \nu_2 \cos \theta_{\mu\tau} + \nu_3 \sin \theta_{\mu\tau} \\ \nu_\tau &= -\nu_2 \sin \theta_{\mu\tau} + \nu_3 \cos \theta_{\mu\tau} \end{aligned} \quad (3)$$

where $\theta_{\mu\tau}$ is a mixing angle. The probability of finding a ν_τ at a distance L from the origin of a ν_μ beam of average energy E_ν is given by:

$$P(\nu_\mu \rightarrow \nu_\tau) = |\langle \nu_\tau | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta_{\mu\tau} \sin^2 \left(1.27 \Delta m^2 \frac{L}{E_\nu} \right) \quad (4)$$

where $\Delta m^2 = m_{\nu_\tau}^2 - m_{\nu_\mu}^2$ is measured in eV^2 when L is measured in $m(km)$ and E_ν is measured in $MeV(GeV)$.

There are several experimental results suggesting the existence of neutrino oscillations. These are the so-called “solar neutrino deficit”, “atmospheric neutrino deficit”, and the cosmological missing matter problem. Below, we briefly describe them.

2.2 The Solar Neutrino Deficit

The Sun produces electron neutrinos from fusion reactions. These neutrinos have been searched for in four large underground experiments, using three different experimental techniques. All the experiments [11] have seen significantly fewer neutrinos than predicted by calculations of the solar neutrino flux [12]. A possible for this deficit would be the oscillation of ν_e to another neutrino species either active or sterile. Different analyses

have been performed to find the allowed mass differences and mixing angles in the two-flavour approximation [13]. The most natural solution seems to be that of non-adiabatic-matter-enhanced oscillations via the MSW mechanism [14] with parameters $\Delta m_{ei}^2 = (0.3-1.2) \times 10^{-5} \text{ eV}^2$ and $\sin^2(2\theta) = (0.4-1.2) \times 10^{-2}$.

In this scheme, if one assumes that the ν_e is oscillating to ν_μ and that $m_{\nu_e} \approx 0$, then, $m_{\nu_\mu} \approx 1.7 - 3.5 \times 10^{-3} \text{ eV}$. One can then invoke the see-saw mechanism [15] to estimate the value of the ν_τ mass. The see-saw formula reads:

$$m_\nu \propto m_f \left(\frac{m_f}{M_X} \right) \quad (5)$$

where m_f corresponds to a charged lepton or quark mass, and M_X is a high energy scale at which some new physics, such as unification, is expected. Taking $m_f = m_{quark}(m_{lepton})$ in eq. 5, leads to $m_{\nu_\tau} \approx 17 - 35(0.6 - 1) \text{ eV}$.

2.3 Atmospheric Neutrinos

Atmospheric neutrinos are produced when cosmic rays (primarily protons) hit the atmosphere and initiate atmospheric cascades. The mesons present in the cascade decay leading to a flux of ν_e and ν_μ which reach the Earth and interact in the different neutrino detectors. Naively, the expected ratio of ν_μ to ν_e is in the proportion 2 : 1, since the main reaction is $\pi \rightarrow \mu \nu_\mu$ followed by $\mu \rightarrow e \nu_\mu \nu_e$. However, the expected ratio of muon-like interactions to electron-like interactions in each experiment depends on the detector thresholds and efficiencies as well as on the expected neutrino fluxes.

Currently four experiments have observed atmospheric neutrino interactions. Two experiments use water-Cherenkov detectors, Kamiokande [16, 17] and IMB [18], and have observed a ratio of ν_μ -induced events to ν_e -induced events smaller than expected. In particular Kamiokande has performed two different analyses for both sub-GeV neutrinos [16] and multi-GeV neutrinos [17], which show the same deficit. On the other hand, the results from the two iron calorimeter experiments, Fréjus [19] and NUSEX [20], appear to be in agreement with the predictions.

The most plausible explanation for this anomaly is to suppose that ν_μ oscillates into another flavour. The oscillation $\nu_\mu \leftrightarrow \nu_e$ is almost completely ruled out by the reactor

experiment data [21]. We are then left with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations or oscillations to a sterile neutrino. The allowed range of masses and mixings in the two-family approximation from a global fit to the previous data can be summarized as [22]:

$$\Delta m_{\mu i}^2 > \sim 2 \times 10^{-3} \quad \sin^2(2\theta) = 0.56-1 . \quad (6)$$

The experiments have also observed an angular dependence on the value of these double ratios. The above limits were obtained without using the angular information. An analysis based on the angular dependence of the ratio leads to an upper limit on the possible value of Δm^2 , as can be seen from the Kamiokande multi-GeV analysis [17] and the IMB data [18].

2.4 Neutrinos as Dark Matter Candidates

There is increasing evidence that more than 90% of the mass in the Universe is dark and non-baryonic. Neutrinos, if massive, constitute part of the dark matter. Stable neutrinos can fill the Universe of hot dark matter if their masses add up to a maximum of about 30 eV. However, scenarios with only hot dark matter run into trouble in the explanation of the formation of structures on small scales of the Universe. On the other hand, models for structure formation favour the presence of cold dark matter. These models, however, fail to reproduce the data on the anisotropy of the microwave background. Currently, the best scenario to explain the data considers a mixture of 70% cold plus 30% hot dark matter [23]. This translates into an upper limit on neutrino masses [24]:

$$\sum_i m_{\nu_i} < \sim 4-7 \text{ eV} . \quad (7)$$

2.5 Combining all Data

Naive two-family counting shows that it is very difficult to fit all experimental information with three neutrino flavors [25, 26]. The solar neutrino deficit could be due to $\nu_e \leftrightarrow \nu_\mu$ oscillations and the atmospheric neutrino deficit to $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the appropriate mass differences, for example with a mass hierarchy $m_{\nu_\tau} \ll m_{\nu_\mu}, m_{\nu_e}$. However,

fitting this together with the present laboratory limits leaves no room for hot dark matter since the maximum allowed mass is of about $m_{\nu_\tau} < 0.7$ eV [27].

Possible theoretical explanations are rather radical. One possibility would be to require that all three neutrinos are almost degenerate [26, 28]. Another, would be to introduce a fourth sterile neutrino [25, 29]. An extensive analysis of present data and the prospects for future $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ experiments in terms of a 4-neutrino scenario is presented in [22].

A less radical solution would be that some of the experimental evidence is not correct or misleading. The uncertainties in the calculation of the solar neutrino flux may still be rather large and new experiments [30, 31] are being planned to further investigate the possible origin of the solar neutrino deficit. As for atmospheric neutrino experiments, one has to add to the uncertainties on the estimation of the atmospheric neutrino flux and on the neutrino-nucleon cross section [32], the uncertainties due to the modest data sample. New experiments are also being planned in this area [31].

A complementary approach is to look for neutrino oscillations in laboratory experiments, where the experimental conditions, in particular the shape, energy, and flux of the neutrino beam are under control. A number of neutrino experiments have recently started taking data. These include the LSND experiment at Los Alamos [33], which looks for $\nu_\mu \leftrightarrow \nu_e$ oscillations, and the CHORUS [1] and NOMAD [2] experiments at CERN, which are primarily sensitive to $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillations.

3 The CHORUS and NOMAD Experiments

The two on-going experiments CHORUS and NOMAD [1, 2], are ν_τ appearance experiments, i.e., they search for the appearance of ν_τ 's in the CERN SPS beam consisting primarily of ν_μ 's, with about 1% ν_e 's. The mean energy of the ν_μ beam is around 25 GeV and the detectors are located approximately 800 m away from the beam source. The ν_τ contamination of the SPS beam is virtually zero. CHORUS and NOMAD have complementary techniques to identify a τ lepton. The NOMAD experiment [2] distinguishes a ν_τ CC interaction from ordinary ν_μ or ν_e interactions by exploiting the fact that the τ lepton produced in a ν_τ CC interaction, decays emitting one or more neutrinos which result in

a measurable amount of missing transverse momentum, in the general direction of the charged lepton. NOMAD is in essence an electronic bubble chamber, with a continuous target alternating panels of a light material and drift chambers, followed by a transition radiation detector and an electromagnetic calorimeter. All the above detectors are located inside a 0.4 T magnetic field. Thus NOMAD measures essentially all the charged tracks and photons in the event, which enables a good reconstruction of the transverse missing momentum magnitude and direction. CHORUS [1] on the other hand, relies on purely vertexing techniques to identify the τ . At the SPS energies, the τ mean decay length is about 1.5mm , giving two distinctive signatures in the CHORUS emulsion. One-prong decays result in a short track with a kink, while three-prong decays appear as a short track splitting into three. After the emulsion target, a magnetic spectrometer enables the use of a loose kinematical cut, necessary to reduce the number of events to be scanned. In the surviving events, tracks reconstructed in the spectrometer are extrapolated to the emulsions in order to determine where to scan.

The initial goal of the SPS is to deliver 4.8×10^{19} protons on target to both experiments. The intense neutrino beam allows very light detectors (NOMAD has a fiducial mass of nearly 2.4 tons, while the emulsion target of CHORUS is 800 kg). Fig. 1 shows the sensitivity expected for the CHORUS/NOMAD experiments in the conventional $\sin^2 2\theta_{\mu\tau}$ vs Δm^2 plane.

4 The NAUSICAA Detector

The basic idea of the NAUSICAA detector is to be able to measure simultaneously the two distinctive signatures of the τ . To be sensitive to the τ finite path, the detector has to measure the event vertex parameters with a resolution of few tenths of microns. The second signature, a sizeable $\mathbf{p}_{\perp}^{\text{miss}}$ in the general direction of the τ candidate in the event, implies excellent tracking and calorimetry *à la NOMAD*.

Fig. 2 shows one ν_{τ} CC event in our simulation of the detector. The bulk of the interactions are produced in a finely instrumented target (IT), which provides a precise measurement of the event vertex. Downstream of the target, several planes of trackers (drift chambers or scintillating fiber trackers), equally spaced over a drift space of 1.5m

Figure 1: Projected Sensitivity of CHORUS and NOMAD.

provide lever arm for momentum measurement. A compensating calorimeter covers most of the solid angle. All the detector is located inside a magnet providing a magnetic field of about 1 Tesla. Outside the magnet there is a muon identification system.

The main components of the detector are discussed in the next sections.

4.1 The Instrumented Target

The heart of the detector is a finely instrumented target (IT). It consists of a sandwich of an active part (silicon detectors or glass capillaries filled with liquid scintillator) which is readout by electronics means and a passive part (a light Z material) providing most of the target mass. Rather than detecting a “kink” close to the primary interaction –a feat only possible with emulsions–, the τ identification method in the IT exploits the fact that the τ decay products generate tracks with non zero impact parameters with respect to the main vertex, indicating that they originate from the decay of an unseen particle. This impact parameter distribution follows an exponential decay with a mean near 90 microns ($c\tau = 88.6\mu m$). If the τ decays to 3 or more charged tracks a secondary vertex can be

Figure 2: A simulated ν_μ interaction in the NAUSICAA Detector.

reconstructed, and the distance between the two vertices, corresponding to the τ decay length ($\sim 1.5mm$ at SPS energies), can be measured.

Figures 3 and 4 show two simulated ν_τ CC events. In Fig. 3 the τ decays via $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, while in Fig. 4 the τ decays via $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$.

4.1.1 Tracking Detectors

Detecting impact parameters of the order of 90 microns with a reasonable efficiency requires measuring the track-vertex distance with an accuracy of a few tens of microns. This implies a tracking precision of around $10\mu m$. This precision cannot be obtained by increasing indefinitely the number of measurement points, due to the effect of multiple scattering, and thus a measurement resolution of this order is needed on single points coordinates. Point resolutions of $5 - 10\mu m$ are routinely obtained (including alignment errors) by silicon micro-vertex detectors at LEP (see for example [34] and references therein), CDF [35] etc. Furthermore, silicon technology has reached a level of maturity sufficient to allow the design of large scale detectors (for example, the design of the ATLAS and CMS silicon systems [36] foresee about $50m^2$ of silicon detectors), involving not only large surfaces, but also many other challenging problems such as radiation hardness, fast read-out, complex geometries etc.

Very thin glass capillaries filled with scintillating liquid have also been proposed as a finely grained detector [37, 38], able to achieve a point resolution comparable with silicon. The use of capillary bundles provides the additional advantage of a simplified pattern recognition, since segments rather than points can be reconstructed in every tracking layer. However, the application of this technique to a large scale detector, suitable for neutrino physics still requires considerable R & D [38]. Firstly, a large number of capillaries must be drawn, assembled and read-out. Secondly, the read-out electronics (the preferred solution at present is a new type of device called Electron Bombarded CCD or EBCCD) is still under development. It is estimated [38] that about two more years of R & D are still needed for this project. Finally, mechanical issues (such as the level of bending that the capillary ribbon can tolerate) have to be investigated.

Figure 3: (a) A simulated ν_τ event developing in the NAUSICAA IT, and (b) blow-up of the vertex region. The τ decays via $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ giving an impact parameter of the order of $90\mu m$ with respect to the event vertex.

Figure 4: (a) A simulated ν_τ event developing in the NAUSICAA IT, and (b) blow-up of the vertex region. The τ decays via $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ giving two vertexes separated by around 1.5mm .

Material	Beryllium	Boron	Graphite	Boron-Carbide
Z	4	5	6	B_4C
A	0.01	10.8	12.01	
Density (gr/cm^3)	1.85	2.34	1.88	2.51
Radiation length (cm)	35.3	22.7	22.7	21.7
(g/cm^2)	65.2	53.1	42.7	54
Nucl.Int Length (cm)	40.6	34.8	45.9	32.4
(g/cm^2)	75.2	≈ 80	86.3	≈ 81

Table 1: Properties of various low Z materials.

4.1.2 Passive Material

To choose the passive material one has to compromise between getting as much mass as possible (thus a high density material), while at the same time minimizing the effect of multiple scattering as well as photon and electron conversions. Thus a low Z material is preferable. A few materials are possible (see Table 1). Beryllium, which has the longest radiation length is too expensive. The next candidates are Graphite and Boron Carbide (B_4C), both having almost the same radiation length ($X_0 \sim 22cm$). While Graphite is cheap and readily available, Boron Carbide has larger density ($2.5gr/cm^3$ to compare with $1.9gr/cm^3$ for the purest comertial Graphite). In order to maximize the mass per unit radiation length we have chosen (B_4C) as passive material.

4.1.3 Target Granularity

To determine the frequency of sampling one attempts to keep the price reasonable while achieving at the same time good impact parameter resolution. In addition, the effect of nuclear interactions in pattern recognition has to be taken into account. If the plates of passive material become too thick, tracks are likely to interact before they traverse enough sensitive planes to be reconstructed.

The best compromise is to impose that the measurement resolution in the tracking device σ_{meas} and the error due to the multiple scattering in the passive material σ_{ms} are

of the same order. That is

$$\sigma_{ms} \sim q \times \theta_0 \sim \sigma_{meas}, \quad (8)$$

where q is the thickness of the absorber and θ_0 the r.m.s multiple scattering angle

$$\theta_0 \simeq \frac{0.015 GeV}{p} \sqrt{\frac{q}{X_0}}, \quad (9)$$

which deteriorates linearly with $1/p$ (where p is the track momentum), and with the square root of the absorber thickness measured in radiation lengths. The average momentum of hadrons in NAUSICAA (at the SPS) is $3.5 GeV$. Setting $\sigma_{ms} = \sigma_{meas} \sim 10 \mu m$ in Eq. 8, Eq. 9 yields $q \sim 1.1 cm$. Since, the distribution of the neutrino interactions is flat across the plate thickness, then $q \sim thickness/2$. Thus we find a thickness for the absorber plate of $2.2 cm$.

To illustrate our choice of the absorber thickness, consider a $\nu_\tau + N \rightarrow \tau + X$ interaction followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$. The average energy of the muon produced in the τ decay is $E_\mu \sim 15 GeV$. Fig. 5 shows the error on the extrapolation of one of the muon transverse coordinates (say σ_y) as a function of the extrapolated distance d , between the neutrino interaction point and the first measurement plane (a measurement resolution of $7 \mu m$ is used in the simulation). For $d \approx 0$, $\sigma_{ms} \sim 0$ and $\sigma_y \sim \sigma_{meas} \sim 7 \mu m$, while for $d \approx 2.2$, $\sigma_{ms} \sim 2.2 \times \frac{0.015}{E_\mu} \sqrt{\frac{2.2}{18.8}} \sim 7.5 \mu m$ and $\sigma_y \sim \sigma_{meas} \oplus \sigma_{ms} \sim 10 \mu m$.

4.1.4 IT Parameters

To decide upon the total mass of the IT one has to consider three parameters: detector thickness, beam profile and cost. The thickness of the detector cannot increase indefinitely if a good measurement of the kinematical quantities *à la Nomad* (rather than a calorimetric device) is attempted. One does not want to go much beyond 0.5 interactions lengths (and about one radiation length) to keep the number of conversions and nuclear interactions manageable. The SPS beam at the experimental location where NAUSICAA would operate has a radius of about $1 m$ with a roughly gaussian profile. A target of transverse dimensions $1.5 \times 1.5 m^2$ intercepts around 41 % of the beam, while a target of $2.0 \times 2.0 m^2$ intercepts 64 %. Going to larger transverse dimensions is clearly not cost effective. Thus, using a light Z material (such as B_4C with $\rho \sim 2.5 g/cm^3$) as passive

Figure 5: The error on the extrapolation of one of the muon transverse coordinates (σ_y) as a function of the extrapolated distance d , between the neutrino interaction point and the first measurement plane, for a $\nu_\tau + N \rightarrow \tau + X$ event followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$.

material, the “natural mass” for the IT is about 1-2 tons. The main parameters of the IT are shown in Table 2.

As pointed out above, both silicon microstrip detectors and capillary detectors are viable high-precision tracking detectors for the IT. While the silicon technology is more mature at present, capillaries offer improved pattern recognition capabilities. This is illustrated in Fig. 6, showing a Monte Carlo simulation of the image of tracks from two capillary layers 1mm thick and from two layers of microstrip silicon detectors. As it can be seen, in the case of capillaries track segments can be easily determined, making pattern recognition much easier.

We have considered two versions of the IT. The SIT version has two layers of single sided silicon detectors pointing into orthogonal directions per detection plane, while the CIT version has two capillary layers (each layer being 2 mm thick) also orthogonal to each other.

Instrumented Target	1ton	2ton
Passive Material (absorber)	B_4C	B_4C
Transverse dimensions (m^2)	1.5	2.0
Thickness of absorber plates (cm)	2.2	2.2
Number of absorber plates	8	9
Absorber mass (kg)	990	1980
Number of interaction lengths	0.54	0.61
Number of radiation lengths	0.81	0.91
Number of ν_μ CC in run (6×10^{19} p.o.t. in target)	2×10^6	3×10^6

Table 2: Parameters of the 1ton (2ton) NAUSICAA IT.

Figure 6: Image of tracks from two capillary layers and from two layers of microstrip silicon detectors. In the case of capillaries track segments can be easily determined.

4.1.1.5 The IT Based on Silicon Detectors

A SIT with a mass of 1 ton would imply a “moderate” ($\sim 40.5m^2$) surface of single sided silicon detectors. The mechanical and technical simplicity of the detectors, together with the possibility of sparsified read-out makes this version of the SIT feasible at a reasonable cost. In the following paragraphs we outline a basic design for a 1 ton SIT.

- *The Silicon Detectors.*

The design of the detectors aims at achieving good spatial resolution ($7 - 10\mu m$) under the specific conditions of the instrumented target. One of the major challenges of the design of the SIT, is to achieve the above resolution for very long ($75cm$) detector modules (see below). This requires a good signal to noise ratio performance (typically $S/N > 10$) for the modules, which in turn imposes, (i) the use of low noise electronics and (ii) a detector design which minimizes both the series and parallel noise to the amplifier.

Table 3 shows the most relevant design parameters of the detectors. The individual sensors are tiles of $6.25 \times 6.25cm^2$ and $300\mu m$ thickness (although a larger thickness of $400 - 500\mu m$ may well be a possibility, since it gives a large signal for a traversing particle while adding negligible radiation lengths). A conservative choice of the strip pitch to achieve a given spatial resolution is to assume hit information only (i.e. only the position of the “hit” strip is known). The spatial resolution then reads,

$$\sigma = p_s / \sqrt{12}; \quad (10)$$

where p_s is the strip pitch. However, the lateral charge diffusion distributes the charge created by the traversing particle on more than one strip. Using non-linear charge interpolation algorithms one obtains optimal resolution. The spatial resolution in this case is roughly [40],

$$\sigma = \beta \frac{N}{S} p_s; \quad (11)$$

where β is a proportionality constant with values (determined empirically) around 4 to 10 and S/N is the ratio of signal deposited by a charged particle traversing the

silicon detector (about 22,000 electron-hole pairs for a $300\mu m$ thick silicon detector) to the noise of the front-end electronics. Choosing a strip pitch near $25\mu m$ one obtains a conservative estimate for the measurement resolution of $\sigma = 25/\sqrt{12} \sim 7\mu m$. In practice, the use of analogue information yields a point resolution of $4 - 5\mu m$, depending on the S/N .

A practical choice of the readout pitch is near $100\mu m$, allowing to save readout channels (and bonding time). One of every four strips is read and the intermediate strips share the charge that they collect with the readout strips via capacitive charge coupling. Choosing a readout pitch of $98\mu m$ gives 640 channels per detector which can be readout with 10 chips, each designed with 64 input channels.

Several biasing schemes are possible. Integrated bias resistors [41, 42] (polysilicon strips connected on one side to the pn-junction and on the other side to a common bias line) and FOXFET $p^+ np^+$ structures [43] are two schemes commonly used. For a neutrino experiment, where long shaping times (a few μs) in the readout electronics are feasible and therefore very low serial noise can be achieved, FOXFET biasing offers an advantage over passive resistors, since the very high dynamic resistance does not introduce potential variations across the strips [40].

At this point it may be useful to recall the important detector parameters which influence the noise performance of the front-end electronics [44]: (i) the load capacitance to the amplifier, which is dominated by the capacitance of the readout strip to the neighbour strips; (ii) the leakage current (shot noise) and (iii) the detector bias resistor. The capacitance (i) is the determining factor for the serial noise and (ii) and (iii) give the main contributions to the parallel noise. To minimize (i), we allow a maximum interstrip capacitance of $1pF/cm$, which results in a maximum total load capacitance (adding the capacitance to the other strips and to the detector back plane) of $1.5pF/cm$. To minimize (ii) we allow low leakage current $< 1nA$ per strip. Finally, to minimize (iii) we require high values ($> 100M\Omega$) for the bias resistors.

- *Readout Electronics.*

Ideally, the readout electronics has to achieve three goals:

	Detectors
Type	single sided
Overall area (cm^2)	6.25×6.25
Thickness (μm)	300-500
Coupling	ac
Strip pitch (μm)	25.0
Readout pitch (μm)	98
Number of strips	2500
Number read out	640
$C_{inter-strip}$	$< 1pF/cm$
$C_{load}(total)$	$< 1.5pF/cm$
$C_{coupling}$	$> 30pF/cm$
$R_{bias}[M\Omega]$	$> 100M\Omega$
Depletion voltage	$< 100V$
$I_{leak}/strip[nA]$ at 100 V	$< 1nA$

Table 3: Design parameters of the silicon detectors for the SIT.

- i) A low noise front-end, to allow ganging together many detectors, while keeping a reasonable S/N .
- ii) A data sparsification back-end, able to supply the digital address of the hit strip (and possibly the two closest neighbours) and the corresponding analog signal. Thus, the read-out logics needs to search only for channels which indicate a hit by a set latch. This method allows daisy chaining of an arbitrary number of chips and provides fast read-out of a system with a large number of channels.
- iii) A continuously sensitive amplifier, given the fixed-target nature of a neutrino experiment.

Fortunately, the intense R & D in the field over the last decade has produced solutions to all of the above requirements. An example of a chip based on a continuously sensitive, low-noise amplifier is the Viking [44, 45]. The noise performance of the amplifier can be summarized by the following equations (for the VA1, one of the latest versions of the Viking):

$$ENC_{preamp} = 165e^- + 6e^- C_{load}[pF] \quad (12)$$

$$ENC_{leak} = 130\sqrt{I_{dl}[nA]}e^- \quad (13)$$

$$ENC_{bias} = \frac{946}{\sqrt{R_p[M\Omega]}}e^- \quad (14)$$

where C_{load} is the total input capacitance to the amplifier, I_{dl} is the leakage current in the strip connected to the amplifier and (R_p) is the parallel resistance of the bias resistor and the feedback resistor of the amplifier. On the other hand, the SVX [46] is a well known example of a chip with built-in zero-suppression capability. Currently, a chip with a low noise front-end *à la Viking* and a data sparsification back-end *à la SVX* is being developed by the CLEO collaboration, for the CLEO-III upgrade [47].

- *Silicon Modules.*

To reduce the number of channels to be read out and to locate most of the supporting mechanical frame outside the active volume (thus avoiding dead regions and extra passive material), one would like to daisy-chain 12 detectors together, forming modules (often called “ladders”) 75cm long. The use of low-noise front-end electronics as described above makes this possible. Given the parameters of Table 3, and the performance of the amplifier described by Eqs. 12-14 we expect a signal to noise ratio, $S/N > 21$ for the SIT detector modules, which is well above of the minimum S/N required to guarantee good performance [48].

Fig. 7 shows a schematic of the configuration of a detector module. Each module, made of 12 individual tiles edge-glued and wire-bonded, is read by 10 VA1 chips (64 input channels each), wire bonded to the detectors and mounted onto ceramic thick film hybrids providing the necessary signal and voltage distribution to the detectors and the electronics. On the edge of the module opposite to the readout chips, a “dummy hybrid” is mounted. The modules are stiffened by means of a very stable low mass carbon fibre profile, glued to the back side of the detectors.

- *Silicon Layers.*

Figure 7: A silicon module for the 1ton SIT.

Layers of silicon detectors are made of 48 modules which overlap slightly, to avoid dead regions, forming a “ladder structure”. The modules are mounted onto an aluminum support frame, the bulk of which is located outside the active tracking volume. Half of the ladders are mounted “upside up” and the other half “upside down”. The ladders are fixed and mechanically aligned to the support frame via two alignment holes, one in the hybrid and the other in the dummy hybrid (Fig. 7). With this arrangement the hybrids and the external support frame are outside the active tracking volume covered by the silicon detectors, and the only support structure inside this volume is a low-mass, carbon fibre composite bar, located in the middle of the layer, to which the “upside up” and “upside down” ladders are fixed and aligned. Each layer is covered in both sides with mechanical protection and shielding made of a thin Rohacell foam sandwiched between two layers of aluminum foil.

In order to provide stereo angle for pattern recognition, three consecutive layers of silicon detectors have the strips pointing at small angles (i.e. $-10^\circ, 0^\circ, +10^\circ$) with respect to the $\hat{y}$ axis (the magnetic field points along the $\hat{x}$ and $\hat{z}$ is longitudinal,

	SIT Parameters
Silicon surface (m^2)	40.5
Layers/detection plane	2 (x-z/y-z views)
Detector type	single sided
Number of detectors ganged per module	12
Number of modules per layer	48
Number of layers	9
Read-out	Low noise/Sparsification
Number of channels	5.0×10^5
Mass added to IT (kg)	14
Number of Int. Length added to IT	$< 1\%$
Number of Rad. Length added to IT	$< 3\%$

Table 4: Characteristics of the active surface of the SIT.

pointing downstream). The characteristics of the active surface of the SIT are described in Table 4.

To summarize, we believe that an instrumented target based on single sided silicon detectors (see Table 4) is well within the existing technology and can be built in a reasonable time (i.e. two years).

4.1.6 The IT Based on Capillary Detectors

A detector with a large surface of capillary detectors may well compete successfully with the SIT if the on-going R & D project on tracking devices based on capillaries produces viable solutions in the next few years. It would probably be the best technique to build an instrumented target of 2 tons after an initial run based on 1 ton SIT. We briefly describe the possible use of capillary detectors as the tracking devices for the IT.

Glass capillaries filled with liquid scintillator combine some of the advantages of glass and plastic fibres, like the good time response of plastic fibres and the reduced optical cross-talk through an extra-mural absorber in the case of glass fibres. Furthermore, glass capillary fibres offer long attenuation lengths ($\geq 2m$ for capillaries of about $20\mu m$ in diameter) and high light yields (about $3.5hits/mm$ for $20\mu m$ diameter fibres at $1m$ distance from the photodetector) [37, 38].

CIT Detector Parameters	CIT 1 ton	CIT 2 ton
Capillaries surface (m^2)	~ 50	~ 100
Layers/detection plane	2 (x/y views)	2 (x/y views)
Layer thickness (mm)	2	2
Capillary diameter (μ)	25	25
Capillary length (m)	1.5	2
Read-out	Megapixel EBCCD	Megapixel EBCCD
Number of channels	8.6×10^7	1.3×10^8

Table 5: Parameters of the silicon detectors for the CIT.

The capillaries are drawn into bundles and then filled with liquid scintillator. The light yield (a few photons per mm) must be amplified by a factor $10^4 - 10^5$ before the image can be stored in a position sensitive receiver such as a Charge Coupled Device (CCD).

For the IT, we have simulated tracking planes consisting of $2mm$ of planes with fibres along the X coordinate followed by $2mm$ of fibres along the Y coordinate. The number of hits per mm (ranging from ~ 2.5 at distances of $2m$ to ~ 7 at distances $\leq 20cm$ from the photodetector) has been simulated according to the results discussed in [38]. The parameters of the CIT are summarized in Table 5.

4.2 Tracking Detectors for Momentum Measurement

After the active target, tracking detectors, equally spaced over a drift distance of $1.5m$ (assuming a magnetic field of around 1 Tesla) would provide the necessary lever arm for good momentum resolution. The transverse size of the trackers must be chosen to guarantee an angular coverage close to 100 % of the solid angle. The mean opening angle of the particles produced in a $\nu_\tau + N \rightarrow \tau + X$ event is about 10^0 . Given the short length of the detector, planes of transverse dimensions $2.5 \times 2.5m^2$ ($3.0 \times 3.0m^2$) are enough to cover around 97 % of the solid angle for the 1ton (2ton) IT.

Fifteen to twenty planes guarantee excellent momentum resolution (of the order of $\Delta p/p \sim 2\%$, see section 5). The trackers can be drift chambers or layers of scintillating fibers. Recent advances in technology, like the maturity of the silicon photon detector

(VLPC) [49] used for read-out and the recent breakthrough in commercially available fibers may make this last option feasible [51].

4.3 Calorimetry

A precise calorimeter covering most of the solid angle is essential to measure the neutral component of the hadronic vector, as well as for particle identification. More than 97 % of the solid angle can be covered by building a calorimeter of transverse dimensions $2.5 \times 2.5 m^2$ ($3.0 \times 3.0 m^2$) situated at about $1.5m$ of the interaction in the 1ton (2ton) IT. The calorimeter must have good energy and position resolution to measure the part of the hadronic shower carried by photons and neutral hadrons and to achieve good electron identification. A good position resolution is needed to determine the direction of the momentum carried by photons and neutral hadrons and to minimize superimposition of charged tracks and neutrals (pileup). To avoid biases, it is important to give equal response for charged and neutral pions. These requirements of high resolution and equal response for neutral and charged pions can be met by a compensating lead-scintillator calorimeter, with a lead to scintillator volume ratio of 4 to 1.

Our present design is inspired by the CHORUS calorimeter, a segmented device, composed of modules which are oriented laterally to measure the energy flow profile in two orthogonal projections alternating in the horizontal and vertical directions. The average energy of the hadrons is small, around 2 GeV, and thus only about 4 interactions lengths are necessary to contain more than 95 % of the hadronic shower. Thus, the calorimeter can be divided in two segments. A more granular electromagnetic part $22X_0(0.8\lambda_i)$ thick and a hadronic part adding $3\lambda_i$. Both segments are made of lead and $1mm$ scintillating fibers and have transverse dimensions of $2.5 \times 2.5 m^2$. The modules are made of lead and $1mm$ scintillating fibers.

Combining the pulse height information of all modules and layers, the position of electromagnetic showers can be determined with a resolution of a few mm , while the expected energy resolution will be $\sim 10\%/\sqrt{E}$. For the hadronic part, a spatial resolution of $1 - 2cm$ and an energy resolution of $\sim 30\%/\sqrt{E}$ can be achieved.

Because of the large fraction of high-Z absorber material (80 % in volume), this

calorimeter is very compact, with an effective radiation length of $7.5mm$ and an effective interaction length of $21cm$.

4.4 The Magnet

In order to reconstruct the full kinematics of the event, a magnetic spectrometer is required. NAUSICAA is a rather compact detector, and can therefore be fitted in a magnet of moderate dimensions. One could probably re-use one an existing analyzing magnet (e.g. the NOMAD magnet).

4.5 Muon system

An external muon detector is located downstream of the calorimeter, outside the magnetic volume. As with the magnet, there are several large muon chambers which could be salvaged from previous experiments.

4.6 Cost of the Detector and Time Scale

We briefly discuss here an estimate of the cost and the time scale to build the detector. NAUSICAA is in many aspects a natural evolution of NOMAD. An interesting possibility to reduce costs would be to re-use parts of NOMAD, and possibly parts of CHORUS too. The main investment would then be in the instrumented target. While it is difficult at present to estimate the cost of the CIT, reasonable estimates can be made for the SIT. A large production of single sided detectors with the specifications described above would range between \$100,000 and \$150,000 per square meter at today's prices. On the other hand, the possibility of a substantial reduction in the price of silicon detectors exists, if East-European countries succeed in their on-going effort of developing silicon technology. Thus, a reasonable estimate for the price of the silicon detectors for the 1ton SIT would be about 5 million dollars. The VLSI electronics price would range between half and one million dollars. The cost of the complete detector, would depend, of course, on how much of previous detectors would be re-used, but it seems well within the reach of a moderate high energy physics collaboration.

Ideally, one would like to have NAUSICAA operative in 1998, after the initial CHORUS/NOMAD run is finished. In practice, however, it seems difficult to build a large silicon detector such as the SIT (which as discussed seems to be at present the most straight-forward solution) in less than two years. An interesting possibility would be to build a reduced version of the SIT, which could be located in the NOMAD detector, in the 1997 run. A detector involving $1m^2$ of silicon and a mass of $50kg$ would be of great interest to test realistic solutions which could be readily extended to the construction of a large SIT. Note that many of the time consuming steps, such as the design of the masks for the silicon detectors, the design of the mechanics, the initial tests of the detectors, etc, are essentially independent of the size of the project. Furthermore, even a small SIT of $50kg$ would enable to collect a sizeable data sample (30,000 ν_μ CC in one year run) thus permitting allow a deeper understanding of the combination of kinematical and vertexing techniques.

With the experience gained in a small-scale device, the construction of a 1ton SIT should be feasible in two years, and therefore the full NAUSICAA detector could operate in 1999. However, the modular character of the IT and the easy access to the detector typical of a neutrino experiment would make possible to operate in 1998 with a smaller (perhaps half the mass) SIT. This run would prove very useful in understanding the performance of the detector.

5 The $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Search with NAUSICAA

NAUSICAA can detect the ν_τ induced charged current interaction

$$\nu_\tau + N \rightarrow \tau^- + X \quad (15)$$

by using the distinctive information of the event vertex and kinematics. *All* the τ decay modes can be used for the search. The performance of the detector is illustrated by considering the study of the $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ in two cases. In what follows we will discuss in detail the sensitivity that can be reached by studying the decay channels $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$. The first search is a very challenging one, since it has to deal with the very large background due to the ν_μ induced CC. We will illustrate how

the measurement of the impact parameter, combined with the event kinematics allows a relatively high selection efficiency for ν_τ CC while completely eliminating the large background. On the other hand, in the channel $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ the precise measurement of two vertexes (the main interaction and the τ decay vertexes) enables a very clean, background-free signal. We describe the analysis corresponding to the CERN-SPS neutrino beam. The analysis for the Fermilab neutrino beam would proceed along very similar lines.

5.1 Simulation of the CERN-SPS Neutrino Beam

For these studies we have assumed that NAUSICAA will be at the same location as the present NOMAD detector. We use the detailed simulation of the SPS wide band neutrino beam developed by the NOMAD collaboration [52]. The beam originates when the primary SPS 450 GeV protons impinge on a Be target. The secondary π^+ and K^+ mesons are horn-focussed into a decay tunnel. The distance between the proton target and the end of the decay tunnel is 414m. An iron and earth shield follows to absorb the muons. The NOMAD detector is situated 406m downstream of the end of the decay tunnel, giving a total distance of 820m distance from the primary source. Fig. 8 shows the relative composition of the incident neutrino spectra.

5.2 Simulation of the Detector

To perform these studies we have written a Geant-based Monte Carlo program [53, 54] simulating the response of the NAUSICAA detector. Large numbers of background and signal events were generated using the LEPTO6.1 generator [55] tuned to generate neutrino interactions in the energy and Q^2 region typical of the CERN-SPS neutrino beam. This studies are based in a Monte Carlo sample of 10^6 ν_μ CC, 10^6 ν_μ NC, 10^4 ν_τ CC followed by $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ and 10^4 ν_τ CC followed by $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$.

The resulting charged and neutral particles were propagated through the detector. Our simulation includes all the relevant physical processes in this propagation, such as multiple scattering, energy losses, bremsstrahlung, photon conversions, nuclear interactions etc. To simulate the detector response, charged tracks were followed in the target,

Figure 8: The relative composition of the incident neutrino spectra. The ratio of $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e$ is about 1:0.07:0.012:0.0026.

hits on the tracking detectors were generated and their coordinates stored. The resolution assumed for the silicon detectors was $7\mu m$ per point. For the tracking devices, an effective point resolution of $150\mu m$ was assumed. Neutral particles were also followed until they converted, escaped the detector or hit the calorimeters, in which case an electromagnetic or hadronic shower was generated according to the projected parameters of the calorimeter. In order to obtain an accurate description of the physical processes that can affect the tracking and vertexing resolution, we *reconstructed* the tracks from the generated hits, rather than simply smearing the track parameters. We thus took into account potential sources of background such as photon conversions where the electrons were badly reconstructed, nuclear interactions generating a false impact parameter or a white star etc. On the other hand, in order to speed up the generation of events and keep the reconstruction code within reasonable limits, we assumed good pattern recognition if the track was sufficiently long. Hit confusion in the IT was crudely simulated by eliminating from the track hit list those hits closer than $100\mu m$ to another track hit. Also, tracks which traversed less than 3 silicon planes (either due to a nuclear interaction or because the track ranged out)

were not reconstructed in the SIT, while we assumed that a single segment was enough to reconstruct a track in the CIT, thus, tracks were reconstructed in the latter case if they traversed a volume (one layer in x and one layer in y) of capillaries.

Electromagnetic and hadronic showers were not fully developed in the detector, since this can be extremely time-consuming. Instead, electrons and photons were stopped in the electromagnetic calorimeter and their energies and positions smeared according to the expected energy and position resolution (see section 4).

5.3 Event Reconstruction

1. *Track Fitting.*

In situations where the effect of multiple scattering becomes important, a standard fitting technique is the use of the Kalman filter [56, 57]. The basic mechanism to fit a track is to “follow” the track parameters from one detector plane to the next, updating them at each plane. If $\mathbf{p}_i$ is the vector of the track parameters in the measurement plane i (the five parameters of a helix), the estimation of the track parameters vector in the plane $i + 1$ proceeds by propagating the vector of the parameters and its covariance matrix to the plane $i + 1$ according to the track model without multiple scattering, by computing the error due to the multiple scattering in the transport from plane i to plane $i + 1$ and finally by obtaining a new estimate in this plane as the weighted average of the propagated quantities, the multiple scattering error and the actual measurement in plane $i + 1$. This method of “progressive fit”, while strictly equivalent to a least squares fit from a mathematical point of view, has the enormous advantage of avoiding the inversion of large covariance matrices.

Track projections were reconstructed from the stored hits in the x - z and y - z planes (z is the direction parallel to the ν beam axis), following the procedures described above. A projection was kept for further use only if a sufficiently large number of points could be retained, and if the χ^2 of the fit was low enough.

To illustrate the fit results, Fig. 9 shows the relative resolution σ_p/p while Figs. 10 a and 10 b show the χ^2 and χ^2 probability distributions obtained from the Kalman filter fit to muons produced in ν_μ CC interactions.

Figure 9: $\left(\frac{\sigma_p}{p}\right)$ obtained from a Kalman filter fit to tracks identified as muons on $\nu_\mu + N \rightarrow \mu + X$ events.

2. Vertex Fitting.

Having obtained the track projections, a fit was performed to find the primary vertex. The fit used again the Kalman filter technique. Two projections $y_v - z_v$ and $x_v - z_v$ were determined, and the impact parameters of the μ candidate with respect to each projection d_x, d_y were computed. Figs. 10 c and 10 d show the χ^2 and χ^2 probability distributions obtained from the vertex fit.

A vertex fit was also performed to identify secondary tracks due to nuclear interactions, and/or gamma conversion as well as neutral hadron decays. The first step of the analysis, after track fitting was to find the primary vertex, and the tracks associated to it. Secondary vertexes were then sought and classified as due to nuclear interactions, gamma conversion, V^0 etc.

Figure 10: (a) $\chi^2/d.o.f$ and (b) χ^2 probability obtained from a Kalman filter fit to tracks identified as muons on $\nu_\mu + N \rightarrow \mu + X$ events. (c) $\chi^2/d.o.f$ and (d) χ^2 probability obtained from a Kalman filter fit to the event vertex.

5.4 Analysis of the channel $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

The goal of the analysis is to distinguish the muon produced in the reaction $\nu_\tau + N \rightarrow \tau + X$ followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, from the huge background of ν_μ CC, $\nu_\mu + N \rightarrow \mu + X$. Other sources of background (i.e. the background due to ν_μ NC) are far less severe.

There are two uncorrelated signatures of a ν_τ CC event followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$.

1. Magnitude and direction of the $\mathbf{p}_\perp^{\text{miss}}$ vector.

The undetected neutrinos in the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ result in an unbalance of the event total energy and momentum. The constraint of missing energy cannot be applied since the energy of the interacting neutrino is not known. On the other hand, the momenta of the produced particles must be balanced in the transverse plane. Escaping neutrinos result in a transverse momentum of about 1GeV for CC ν_τ events, while in a perfect detector the CC ν_μ events should have $\mathbf{p}_\perp^{\text{miss}} \sim \mathbf{0}$. Apparent $\mathbf{p}_\perp^{\text{miss}}$ in CC ν_μ events arise from badly measured or undetected particles. Fig. 11 shows the $\mathbf{p}_\perp^{\text{miss}}$ distribution for CC induced by ν_μ and ν_τ (followed by $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) events in the NAUSICAA detector. Resolution effects together with track losses (due to early nuclear interactions) account for the width of the $\mathbf{p}_\perp^{\text{miss}}$ distribution for ν_μ CC events. In the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, the μ and the neutrinos are emitted boosted along the τ line of flight which, in the plane perpendicular to the beam direction, is opposite to the hadrons resulting from the fragmentation of the struck nucleon. Therefore, in the transverse plane, the resultant hadronic momentum vector, $\mathbf{p}_\perp^{\text{had}}$, forms a large angle ($\sim 180^\circ$) with the τ momentum vector and thus with the vectors of the muon ($\mathbf{p}_\perp^\mu$) and the neutrinos ($\mathbf{p}_\perp^{\text{miss}}$) emitted in the decay. On the other hand, in ν_μ CC background events, fake $\mathbf{p}_\perp^{\text{miss}}$ is created if some particles in the hadronic vector are badly measured or undetected. Therefore, for background events, $\mathbf{p}_\perp^{\text{miss}}$ tends to be at smaller angles (for undetected particles such as a K_L^0) or at random angles (for mismeasurements) to $\mathbf{p}_\perp^{\text{had}}$.

Fig. 12 illustrates the above concepts for the muonic decay mode of the τ . $\phi_{\mu-h}$ is the angle between the μ and the hadronic vector, while ϕ_{m-h} is the angle between

Figure 11: $\mathbf{p}_\perp^{\text{miss}}$ distribution for (a) ν_μ and (b) ν_τ CC events.

Figure 12: Definition of the angles $\phi_{\mu-h}$ and ϕ_{m-h} for ν_τ CC and for ν_μ CC events.

$\mathbf{p}_\perp^{\text{miss}}$ and $\mathbf{p}_\perp^{\text{had}}$. Fig. 13 shows the distribution of these angles, for ν_τ and ν_μ induced CC currents, while Fig. 14 shows the correlation between them. Note the presence of a region for $\nu_\tau + N \rightarrow \tau + X$ events—the triangle between the two dashed lines—where a moderate fraction of the signal is concentrated while there is only a very small fraction of background events.

2. Impact Parameter.

The events produced in the IT can be characterized, in addition, by vertex criteria. To characterize ν_τ CC events we compute the impact parameter —i.e. the signed distance between the μ track and the reconstructed vertex— in two (quasi independent) projections, $d_{x,y}$. For background events, the impact parameter distribution is centred at zero, and its width reflects the effect of the finite resolution in the measurements and the multiple scattering. The central part of this distribution is roughly gaussian, with a r.m.s. of $15\mu m$ but the effect of multiple scattering in both track and vertex fitting results in longer tails (Fig. 15 a). For ν_τ CC events the impact parameter distribution contains also the effect of the τ lifetime, and it can therefore be described by an exponential with a slope of $90\mu m$ convoluted with a

Figure 13: The angles $\phi_{\mu-h}$ and ϕ_{m-h} for (a),(b) $\nu_{\mu} + N \rightarrow \mu + X$ and (c),(d) $\nu_{\tau} + N \rightarrow \tau + X$ events.

Figure 14: The correlated distribution of the angles $\phi_{\mu-h}$ and ϕ_{m-h} for (a) $\nu_{\mu} + N \rightarrow \mu + X$ and (b) $\nu_{\tau} + N \rightarrow \tau + X$ CC events.

resolution function which is essentially the same as that for the background (Fig. 15 b).

The error on the impact parameter depends of two terms: the error on the μ track parameters, and the error on the vertex determination. These quantities are obtained from the fit procedure and thus the error on the impact parameter $\sigma(d_{x,y})$ can be determined. Thus, one can construct the significance of the impact parameter, $d_S = d_{x,y}/\sigma(d_{x,y})$. This quantity is a “pull variable” with mean zero and width (approximately) unity for background events (Fig. 15 c) while ν_τ events have a wider distribution as a consequence of the τ lifetime (Fig. 15 d).

Thus, to be identified as $\nu_\tau + N \rightarrow \tau + X$, an event has to satisfy the following criteria:

1. *Good muon candidate.* At least one good track (good χ^2 probability obtained from the fit) of relatively high momentum ($p_\mu > 3\text{GeV}$) identified as a muon. The momentum cut is necessary to reduce backgrounds arising from hadron decays (in ν_μ neutral currents) and to guarantee a good measurement of the impact parameter, since the error due to the muon multiple scattering becomes very large at low momentum.
2. *Good hadronic vertex.* At least two good tracks reconstructed in addition to the μ candidate to form the hadronic vertex.
3. *Vertex Cut.* The event vertex is determined using the primary reconstructed hadrons and the significance of the impact parameter d_S is computed. Cutting at $d_S > 4$ reduces the ν_μ CC background by more than 3 orders of magnitude, while leaving 20 % (30 %) of the signal for the SIT (CIT).
4. *Kinematical Cut.* If the muon candidate in the event has a large value of impact parameter significance $d_S > 4$, only very soft kinematical cuts are needed. Figs. 16 b and 16 d show the $\phi_{\mu-h}, \phi_{m-h}$ plane for ν_μ and ν_τ CC events when $d_S > 4$. Notice the large region which is background-free in the signal plot. On the contrary, when the muon of the event has $d_S < 4$, harder kinematical cuts are needed to accept the event. This is illustrated in Figs. 16 a and 16 c which show the $\phi_{\mu-h}, \phi_{m-h}$ plane for ν_μ and ν_τ CC and events when $d_S < 4$.

Figure 15: Impact parameter d_y and impact parameter significance d_S for (a) and (b) $\nu_\mu + N \rightarrow \mu + X$ (c) and (d) $\nu_\tau + N \rightarrow \tau + X$ events.

Figure 16: Scatter plot of $\phi_{\mu-h}$ versus ϕ_{m-h} , (a) ν_μ CC events with $d_S < 4$; (b) ν_μ CC events with $d_S > 4$; (c) ν_τ CC events with $d_S < 4$; (d) ν_τ CC events with $d_S > 4$.

Cuts	ν_μ CC (SIT & CIT)	ν_τ CC (SIT)	ν_τ CC (CIT)
Fraction of events in Class I	2×10^{-3}	0.18	0.26
Kinematical Cuts ($\phi_{\mu-h}$ vs ϕ_{m-h})	$< 10^{-6}$	0.07	0.10

Table 6: Selection efficiency and background reduction for Class I events in the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ analysis in NAUSICAA.

Cuts	ν_μ CC (SIT & CIT)	ν_τ CC (SIT & CIT)
Fraction of events in Class II	0.31	0.33
Kinematical Cuts ($\phi_{\mu-h}$ vs ϕ_{m-h})	3×10^{-4}	0.08
($ \mathbf{p}_\perp^{\text{miss}} > 1.5 \text{ GeV}$)	$< 10^{-6}$	0.03

Table 7: Selection efficiency and background reduction for Class II events in the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ analysis in NAUSICAA.

For the analysis, two classes of events are considered in terms of the vertex information. Class I contains events with a high impact parameter significance ($d_S > 4$). Only very soft kinematical cuts are needed to completely eliminate the remaining background in this class (see Figs. 16 b and 16 d).

Class II contains events with low impact parameter significance ($d_S < 4$). In this case one needs much harder kinematical cuts, (Figs. 16 a, 16 c). Since the measurement of the $\mathbf{p}_\perp^{\text{miss}}$ vector has to be excellent in this case, events where a nuclear interaction is detected are rejected. This is a very conservative cut, intended to guarantee maximal background rejection. If no nuclear interaction happens in the event, the measurement of the $\mathbf{p}_\perp^{\text{miss}}$ vector is very good, given the compactness of the detector and the good momentum and energy resolution. Tables 6 and 7 summarize the effect of these cuts on ν_τ and ν_μ CC events for the SIT and CIT. Notice that the limit in the background, $< 10^{-6}$, corresponds to *no background event* surviving the cuts in our Monte Carlo sample (10^6 events). Table 8 summarizes the selection efficiency for the SIT and CIT versions of NAUSICAA.

	ν_τ CC (SIT)	ν_τ CC (CIT)
Efficiency (%)	10	13

Table 8: Selection efficiency for ν_τ CC events followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ in NAUSICAA.

Figure 17: Variables signaling the presence of a τ decaying via $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n \pi^0$.

5.5 Analysis of the channel $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n \pi^0$

The goal of the analysis is to distinguish a $\nu_\tau + N \rightarrow \tau + X$ event, where the τ subsequently decays via $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n \pi^0$ from the background (the main one in this case are ν_μ NC). The distinctive signature of the τ is the decay to 3 charged hadrons which allows the reconstruction of the τ decay point. Since the main interaction vertex is also measured, one knows not only the flight distance but also the τ flight direction, which goes along the line connecting the two vertices. Thus, one has three variables in hand to discriminate the signal and the background (see Fig. 17):

1. The angle ϕ_τ between the τ and the hadronic jet in the transverse plane. Note that for one prong decays one approximates this angle by the angle between the lepton

and the hadronic jet. Fig. 18 shows the distribution of ϕ_τ for ν_μ NC and ν_τ CC (followed by the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) events.

2. *The angle β_τ between the resultant of the τ decay products and the τ flight line defined by the two vertices.* Fig. 19 shows the distribution of β_τ for background and signal events.
3. *The distance l_τ between the two vertices.* Fig. 20 shows the distribution of l_τ for background and signal events. The l_τ distribution for the signal is an exponential with a long decay constant (about 1.5mm) convoluted with a narrow gaussian function of typically $100\mu m$ due to the resolution of the measurement. Notice that this resolution function can be measured directly from data by simply fitting the negative values of the distribution, since the flight distance is always positive. Thus, the exact shape of the background can be measured from the data themselves.

In order to accept an event as a ν_τ CC ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) candidate, the event is required to have at least 5 charged hadrons. The most energetic combination of 3 charged hadrons, with overall negative charge and an invariant mass smaller than the τ mass, $M_{had}^{3\pi} < 1.6 GeV$ is considered to be a $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ candidate event *if a good vertex can be formed with those 3 hadrons*, i.e. if the probability that these 3 tracks belong to the same vertex is not too small, $Prob(\chi^2) > 0.005$. The primary vertex is reconstructed with the rest of the charged tracks on the event. Having computed the positions of the primary vertex and the τ vertex, one can immediately obtain the τ flight distance, as well as the angles ϕ_τ and β_τ . We define the significance $l_S = l_\tau / \sigma_{l_\tau}$. A cut at 5 standard deviations on this significance (see Fig. 21) keeps a large fraction of the signal while suppressing the background by more than 3 orders of magnitude. Cuts on ϕ_τ and β_τ as well as in the kinematics variables (as in the case of one prong) completely eliminate the background in our event sample when still leaving a large fraction of the signal, as detailed in Table 9.

Figure 18: The distribution of the angle ϕ_τ for (a) ν_μ NC and (b) ν_τ CC ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) events.

Figure 19: The distribution of the angle β_τ for (a) ν_μ NC and (b) ν_τ CC ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) events.

Figure 20: The distribution of the distance l_τ for (a) ν_μ NC and (b) ν_τ CC ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) events.

Figure 21: $l_S = l_\tau / \sigma_{l_\tau}$ for (a) ν_μ NC and (b) ν_τ CC ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n \pi^0$).

Cuts	ν_μ CC (SIT & CIT)	ν_τ CC (SIT)	ν_τ CC (CIT)
Preselection			
hadron and τ vertex OK	0.1	0.45	0.55
Cut in flight distance			
$l_S > 5$	10^{-4}	0.30	0.36
Cuts in ϕ_τ, β_τ			
$\phi_\tau > 0.65, \beta_\tau < 0.1$	$< 10^{-6}$	0.23	0.26

Table 9: Selection efficiency and background reduction for the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n \pi^0$ analysis in NAUSICAA.

6 Sensitivity of the NAUSICAA Experiment

6.1 Sensitivity to the $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Oscillation Mixing Angle

In the limit of zero background, the sensitivity of the experiment to a possible $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation depends only on the total number of CC events recorded by the detector, the selection efficiency for ν_τ events and the ratio between the production cross sections for ν_μ and ν_τ charged currents, σ_τ/σ_μ :

$$P(\nu_\mu \leftrightarrow \nu_\tau) \leq \frac{N_\tau}{N_\mu^{CC} \times (\sum_i \epsilon_i \times BR) \times (\sigma_\tau/\sigma_\mu)}; \quad (16)$$

where N_τ is the number of observed τ 's, N_μ^{CC} the number of ν_μ charged currents, ϵ_i the selection efficiency and BR_i the branching ratio for the i decay modes considered. For large Δm^2 , where the oscillations are averaged out, the sensitivity for the $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ mixing parameter, is simply $\sin^2 2\theta_{\mu\tau} = 2 \times P(\nu_\mu \leftrightarrow \nu_\tau)$. In the limit of maximal mixing ($\sin^2 2\theta_{\mu\tau} \sim 1$), and small Δm^2 , one has:

$$\Delta m^2 \geq \frac{5E_\nu}{2\pi^2 L} \sqrt{P(\nu_\mu \leftrightarrow \nu_\tau)} \quad (17)$$

The dependence of the ratio σ_τ/σ_μ on the energy is shown in Fig. 22.

If no candidates are observed, the 90 % C.L. for N_τ is 2.3 events. If however, the expected background is not zero, the sensitivity decreases almost linearly with the background. Thus the challenge of a short base line, appearance $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation

Figure 22: σ_τ/σ_μ as a function of the energy.

experiment is to obtain a reasonable efficiency, while rejecting completely a huge background. The redundancy offered by the combination of the two independent τ signatures, makes this task easier for NAUSICAA.

6.2 The Overall Efficiency of NAUSICAA

The τ signal can be searched for in NAUSICAA by using essentially all the τ decay modes. It is reasonable to assume that the efficiency for one-prong decay channels will be at least as good as the efficiency for the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ channel, since the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ channel is the one with the largest backgrounds. The combined efficiency for NAUSICAA is then $\epsilon \sim BR(1prong)\epsilon_{1prong} + BR(3prong)\epsilon_{3prong}$ which for the SIT is $\epsilon \sim 0.85 \times 0.1 + 0.15 \times 0.23 = 0.12$ and for the CIT $\epsilon \sim 0.85 \times 0.13 + 0.15 \times 0.26 = 0.15$.

6.3 NAUSICAA at CERN

We assume a total of 6×10^{19} p.o.t. extending over a period of four to five years, yielding 2×10^6 (3×10^6) ν_μ CC interactions in a 1ton (2ton) target, situated at about 800m

NAUSICAA	SIT (1ton)	SIT (2ton)	CIT (1ton)	CIT (2ton)
Total Number of ν_μ CC	2×10^6	3×10^6	2×10^6	3×10^6
Total efficiency (in %)	12	12	15	15
Sensitivity				
$P(\nu_\mu \leftrightarrow \nu_\tau)$	1.9×10^{-5}	1.25×10^{-5}	1.5×10^{-5}	10^{-5}
$\sin^2 2\theta_{\mu\tau}$ (large Δm^2)	3.8×10^{-5}	2.5×10^{-5}	3.0×10^{-5}	2×10^{-5}
$\Delta m^2 (eV^2)$ ($\sin^2 2\theta_{\mu\tau} \sim 1$)	0.2	0.16	0.17	0.14

Table 10: Sensitivity of NAUSICAA at CERN-SPS.

from the neutrino production target. Table 6.3 summarizes the prospective sensitivity of NAUSICAA in an extended run at the CERN-SPS. We have taken $\sigma_\tau/\sigma_\mu = 0.49$ for the value of the energy-averaged ratio.

6.4 NAUSICAA at Fermilab

NAUSICAA could also operate in the future intense ν_μ beam provided by the Fermilab Main Injector. This is projected to be a double-horn, wideband neutrino beam, whose primary component is ν_μ 's, with an average energy of ν_μ interactions of $16 GeV$. The ν_τ interaction cross section is suppressed at low energy by kinematic and helicity effects so that the average energy of a ν_τ is higher, about $26 GeV$.

The expected beam parameters are given in Table 11. Following the COSMOS proposal [5], we assume that there will be at least four runs, yielding 1.3×10^{21} protons on target, and a total number of CC interactions of 1.26×10^7 (2.0×10^7) in a 1ton (2ton) target situated at about 500m from the neutrino production target. Table 12 summarizes the expected sensitivity of NAUSICAA in an extended run at the Fermilab-Main Injector wide band beam. We have taken $\sigma_\tau/\sigma_\mu = 0.29$ for the value of the energy-averaged ratio. We have assumed *ad hoc* the same efficiencies as for the CERN-SPS experiment. This is a somewhat optimistic assumption, given the lower energy of the ν_τ 's at Fermilab, which results in a worst measurement of the impact parameter (or alternatively, in a more granular IT).

To summarize, the sensitivity of Nausicaa can improved with respect to CHORUS/NOMAD by up to an order of magnitude in a four-five year run at CERN, and up to an additional factor of five at Fermilab. Clearly, NAUSICAA can explore to very

Item	Expected Value
Primary proton energy	$120 GeV$
Protons per pulse	6×10^{13}
Cycle time	1.9sec
Total Number of pulses (4yrs)	2.2×10^7
Total protons on target	1.3×10^{19}
Average CC interaction energy	$16 GeV$
CC interactions in target (1ton)	1.25×10^7

Table 11: Expected Parameters of the Main Injector Beam.

NAUSICAA	SIT (1ton)	SIT (2ton)	CIT (1ton)	CIT (2ton)
Total Number of ν_μ CC	1.2×10^7	2×10^7	1.2×10^7	2×10^7
Total efficiency (in %)	12	12	15	15
Sensitivity				
$P_{\mu\tau}$	5.3×10^{-6}	3.2×10^{-6}	4.2×10^{-6}	2.5×10^{-6}
$\sin^2 2\theta_{\mu\tau}$ (large Δm^2)	1.1×10^{-5}	6.4×10^{-6}	8.4×10^{-6}	5×10^{-6}
$\Delta m^2 (eV^2)$ ($\sin^2 2\theta_{\mu\tau} \sim 1$)	0.09	0.07	0.08	0.06

Table 12: Sensitivity of NAUSICAA at Fermilab

small values of the mixing angles and rather small mass differences, thus enabling one to find $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillations even for a very light ν_τ if the scenario where $m_{\nu_e} \sim m_{\nu_\mu} \sim 0$ and $m_{\nu_\tau} \sim 1 - 10 \text{ eV}^2$ is the one chosen by nature. Even in other scenarios the discovery potential of the experiment is very good. This is found for example in [22], where an analysis of *all present data* in terms of four neutrinos (an additional sterile neutrino is added to the well known zoo in the spirit of Pauli) concludes that the chances of NAUSICAA of finding $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ are very high.

The level of background suppression that NAUSICAA needs to deal with in the CERN-SPS experiment is rather “reasonable” (two or 3 million ν_μ CC to compare with one and a half million in the case of NOMAD), thus a “zero background” analysis is feasible. We feel confident that our Monte Carlo studies (based on 10^6 ν_μ events) are enough to guarantee the correctness of the technique. In the case of the Fermilab experiment, the background level is a factor ten higher but, unfortunately, the gain in sensitivity is not proportional to the increase of the total sample due to the smaller ν_τ energy. Attempting to check our efficiencies with a sample of 10 millions exceeds (at least at present) our computational resources. The increase in sensitivity that we find at Fermilab is a factor of five over the CERN experiment, in the most optimistic scenario. However, the lower energy of the neutrinos and the much larger background level will almost certainly result in efficiencies at Fermilab which are at least a factor of two smaller than at CERN, thus making the prospects of improvement at Fermilab somewhat marginal.

7 Conclusions

We have shown that a new neutrino experiment capable of searching for the τ signature by using *simultaneously* both kinematical and vertex criteria, could improve the CHORUS/NOMAD sensitivity by up to an order of magnitude in an extended run at CERN (i.e. from 1999 to 2003). We have also considered the prospective sensitivity of NAUSICAA in the Fermilab neutrino beam. We estimate that a further improvement by a factor of two to five is possible in a four year run at Fermilab. This extraordinary sensitivity results in a very high discovery potential for the experiment.

The sensitivity of NAUSICAA at CERN compares well with that expected for COS-

MOS. The great advantage of CERN is that it can use an existing beam and start taking data as soon as 1999, while COSMOS is only expected to start in 2002, and therefore first results will come only in 2003-2004, a time at which its sensitivity could already have been achieved by NAUSICAA. It is worth reiterating that the experimental conditions at CERN are also more favourable for this type of search, since the higher neutrino energy enables one to face much smaller backgrounds for a given level of sensitivity. One is tempted to conclude that the CERN neutrino beam would be an ideal place for a next generation, short base line $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ experiment such as the one proposed here.

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