Search for $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Oscillations with a Detector Based on a Emulsion-Silicon Target

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Abstract

We discuss the performance of a next generation $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation experiment, based on a target consisting of a sandwich of nuclear emulsion layers and silicon detectors. The target would be followed by a full spectrometer for energy-momentum measurement and particle identification.

A τ -enriched sample is selected in terms of vertex and kinematical criteria using the electronic spectrometer, with very high efficiency, while at the same time reducing the load of background events to be scanned by up to two orders of magnitude. Events fulfilling the selection criteria are very efficiently located and scanned in the emulsion, thanks to the very good resolution allowed by the silicon tracker.

In terms of the two-neutrino families mixing angle, this experiment could reach a sensitivity of $\sin^2 2\theta_{\mu\tau} < 1.1 \times 10^{-5}$ in an extended run at CERN and up to $\sin^2 2\theta_{\mu\tau} < 3.2 \times 10^{-6}$ at FNAL.

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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 beam. If neutrinos have mass and oscillations $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ occur with a $\Delta m^2 > 50 eV^2$ and a mixing angle $\sin^2 2\theta_{\mu\tau}$ larger than about 2.8×10^{-4} , those experiments have a large potential to find evidence for it.

There are, however, compelling motivations to seek ways of improving this sensitivity. Even if $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation were to occur with a strength at the level of the present limit [6, 7], $\sin^2 2\theta_{\mu\tau} \sim 5 \times 10^{-3}$, CHORUS and NOMAD would detect only about 70 ν_τ events by the end of the 1997 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 a sensitivity improved by an order of magnitude with respect to the present experiments. Improving the sensitivity by an order of magnitude is also needed if no signal or only a hint for a signal is found. Even if one considers the most favourable scenario which motivates these 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 10 eV. Present models favour ν_τ masses as low as $1 - 3 eV$. The sensitivity of CHORUS/NOMAD in this critical region $\Delta m^2 \sim 10 eV^2$ is only $\sin^2 2\theta_{\mu\tau} \sim 5 \times 10^{-2}$. Improving this sensitivity by an order of magnitude is certainly worthwhile.

The approved neutrino run at CERN ends in 1997 [3]. The planned neutrino beam from the Fermilab Main Injector will not begin operating for several years thereafter [4]. Thus, if neutrino physics were to continue, the CERN SPS WBB would remain a unique place to investigate the possibility of $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillations for many years.

In Fermilab, there is an approved experiment (E803, now called COSMOS [5]) to take data 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 in $\sin^2 2\theta_{\mu\tau}$ one order of magnitude better than the CERN experiments, after a 4 year run period.

In a previous paper we described a possible new neutrino experiment based on a Neutrino Apparatus with Improved Capabilities (NAUSICAA) [8]. The heart of the detector was a finely instrumented target, made of a sandwich of a light Z material and silicon detectors. The identification of τ candidates in NAUSICAA was based on combining vertex selection criteria (i.e, the measurement of the impact parameter for 1-prong τ decays or the measurement of two separated vertices for 3-prong τ decays) with kinematical criteria (the measurement of the event missing transverse momentum magnitude and direction). Detailed Monte Carlo calculations were presented showing that selection efficiencies of the order of 10 % (25 %) were attainable for 1-prong (3-prong) τ decays. The asymptotic sensitivity of NAUSICAA for a 1-ton target in an extended run period at CERN (we assumed a total sample of 2 million ν_μ CC collected, corresponding to an integrated luminosity of 6×10^{19} pots) was $\sin^2 2\theta_{\mu\tau} < 3.8 \times 10^{-5}$ and $\sin^2 2\theta_{\mu\tau} < 1.1 \times 10^{-5}$ in a run at FNAL equivalent to the one proposed by COSMOS (1.3×10^{21} pots).

In this paper we consider the gain in sensitivity that can be achieved by replacing the passive material in the target by layers of nuclear emulsion, of the same type used by CHORUS and COSMOS. Instead of attempting a zero-background τ selection, the NAUSICAA detector with an Emulsion-Silicon TARGET (ESTAR) selects τ candidates if they satisfy *either vertex or kinematical criteria* in the electronic spectrometer. A very efficient τ selection can be achieved by combining these criteria while allowing only a small fraction of the major backgrounds from ν_μ charged and neutral currents to be included in the sample. Furthermore, the precision of the silicon detectors allows to locate the event vertex with excellent precision speeding up scanning time and improving scanning efficiency. Ultimately a τ candidate in this detector will display the striking “kink” (for 1-prong τ decays) or “star” (for 3-prong τ decays) signature characteristic of the $1 - \mu m$ resolution of the nuclear emulsion.

We have considered the performance of NAUSICAA-ESTAR both at CERN and at FNAL. We envision a target similar to the one used by CHORUS, with a mass of 1 ton, transverse dimension of $1.5 \times 1.5 m^2$ and 12 cm thick, implying a thickness of 4 radiation lengths. The emulsion target is sliced in layers of 1.2(0.75)cm thick for the CERN (FNAL) set-up (the energy of the interacting τ neutrinos at FNAL is roughly a

factor of two lower than at CERN, thus a thinner slicing to compensate for the increased multiple scattering is necessary), which are alternated with planes of silicon detectors providing $X - Y$ information.

The proposed experiment improves the CHORUS/COSMOS performance by allowing much higher selection efficiencies *for all the major τ decay modes*, and a faster and more efficient scanning, given the high resolution of the silicon trackers. In addition, the spectrometer provides a momentum and energy resolution comparable with the NOMAD experiment. With respect to the NAUSICAA design based on a passive target, higher efficiency is achieved due to the fact that the final τ identification is performed by the emulsion, thus one can relax the τ selection criteria, allowing much higher selection efficiencies.

This paper is organized as follows: Section 2 summarizes the basic design of the proposed detector. Section 3 discusses how the experiment is done. Section 4 discusses the expected selection efficiencies for the different τ -enriched subsamples. In section 5 we discuss the prospective sensitivity of the experiment. Conclusions are presented in section 6.

2 The NAUSICAA-ESTAR Detector

Fig. 1 shows one ν_τ CC event in our simulation of the detector. The bulk of the interactions are produced in the Emulsion-Silicon Target (ESTAR). Downstream of the target, several planes of trackers (i.e, drift chambers) equally spaced over a drift space of $1.5m$ provide lever arm for momentum measurement. The trackers are followed by a calorimeter covering most of the solid angle. The whole detector is located inside a magnet providing a magnetic field of about 1 Tesla. Outside the magnet there is a muon identification system.

For a possible new experiment at CERN, the proposed detector could be built, except for the ESTAR, by re-using parts of the NOMAD spectrometer. For instance, one could use the NOMAD magnet which can provide up to 0.7 Tesla, as well as the electromagnetic calorimeter, the external hadronic calorimeter and muon detector, and about 1/3 of

Figure 1: A simulated ν_μ interaction in the NAUSICAA-ESTAR detector

the drift chambers. For an upgrade of the COSMOS experiment, which has designed a spectrometer with an energy and momentum resolution similar to the one of the NOMAD experiment, it would only be necessary to design (perhaps reuse from the previous CERN experiment?) the ESTAR.

The target consists of 10 (16 for FNAL) emulsion stacks of $1.5 \times 1.5 m^2$ surface area, each 1.2 (0.75 for FNAL) cm thick, providing a mass of 950 kg. Since the beam radius is roughly 1 m at the CHORUS/NOMAD (COSMOS) location, a larger area for the target is not cost-effective. The depth of the stack is a more complex issue. The radiation length of the emulsion is only 2.89 cm , and thus, the total thickness of the emulsion is about $4X_0$, so that many neutrino interactions in the upstream portion of the target produce well-developed electromagnetic showers. For such events, kinematical selection criteria become truly challenging. On the other hand, vertex selection criteria are still possible, since, in order to compute impact parameters only a few silicon hits per track are necessary. To find the main vertex and the slope of the 1-prong τ decay candidate is sufficient to analyze the event in the first few cm to measure 3 or 4 silicon hits for each track. However, it is obvious that the thickness of the target cannot increase indefinitely without compromising the performance of the detector.

The frequency of sampling represents a compromise between price and good impact parameter resolution. To fully exploit the good resolution of silicon detectors, it is best to impose the measurement resolution in the silicon σ_{meas} and the error due to the multiple scattering in the emulsion σ_{ms} to be of the same order. In [8] it was found that the optimal thickness of the absorber layers (made of C) was 2.2 cm . To achieve the same resolution in the impact parameter with emulsion layers one just needs to scale the error due to the multiple scattering, i.e.,

$$d_{em} = d_c((X_0)_{em}/(X_0)_C)^{1/3}, \quad (1)$$

where $d_{em}, (X_0)_{em}, d_C, (X_0)_C$ are the thickness and radiation lengths of the emulsion and carbon layers respectively. Substituting in the above expression we find $d_{em} \sim 1.15 cm$. Thus a thickness of 1.2 cm is satisfactory. For FNAL, since the energy of the interacting τ neutrinos (and thus, the energy of the τ decay products) is roughly half of the energy of the ν_τ 's at CERN, one needs to scale, in order to obtain the same multiple scattering error by $d_{FNAL} \sim (d_{CERN}/4)^{1/3}$, where d_{FNAL}, d_{CERN} are the thickness of the emulsion

layers for the FNAL and CERN set-ups respectively.

A target with a mass of around 1 ton, and sampling every 1.2cm would imply 11 (22) layers of double (single) sided silicon detectors to provide $X - Y$ information. With transverse dimensions of $1.5 \times 1.5\text{m}^2$, this results, for the CERN experiment, in a surface of around 25 (50) m^2 of double (single) sided silicon detectors. This large surface, unaffordable only a few years ago is feasible at preset thanks to the mechanical and technical simplicity of the detectors, together with the continuous trend towards lower prices for silicon detectors. To achieve the same level of resolution at FNAL, one needs about 38 (76) m^2 of double (single) sided silicon detectors.

The conceptual design of the silicon system was discussed in [8]. The design of the detectors aims at achieving good spatial resolution ($7 - 10\mu\text{m}$) under the specific conditions of the ESTAR. One of the major challenges of the design is to achieve the above resolution for very long (75cm) detector modules. 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. The main features of the ESTAR are summarized in Table 1. In order to test the design of the silicon system, the NOMAD collaboration is building a prototype of an instrumented target alternating layers of a light passive material (B_4C) and silicon detectors [9], to be installed in the NOMAD detector for the 1997 run.

3 The $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Search with NAUSICAA-ESTAR

Virtually every neutrino interaction in the emulsion target will be recorded on tape. The analysis then proceeds as follows: First, events recorded on tape are reconstructed. Several subsets are then selected for scanning in the emulsion. The number of events to be scanned in the emulsion must represent only a small fraction of the total number of neutrino interactions in the target. At the same time, the efficiency to keep ν_τ events on these subsets must be as high as possible. We consider four subsets, corresponding to the τ signature in the four major modes $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$, $\tau^- \rightarrow h^-(nh^0) + X$ and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$.

ESTAR	CERN	FNAL
Emulsion		
Transverse dimensions (m^2)	1.5	1.5
Thickness of bulk stacks (cm)	1.2	0.75
Number of stacks	10	16
Total mass (kg)	945	945
Number of radiation lengths	4	4
Number of interaction lengths	0.3	0.3
Silicon Surface		
Number of sensitive planes	11	17
Layers/detection plane	2 (1)	2(1)
Detector type	single (double) sided tiles	single (double) sided tiles
Dimensions of tiles	$6.0 \times 6.0 cm^2$	$6.0 \times 6.0 cm^2$
Thickness (μm)	400 (500)	400 (500)
strip pitch (μm)	25 (50)	25 (50)
readout pitch (μm)	50 (100)	50 (100)
Number of detectors ganged per module	12	12
Number of modules per layer	48	48
Read-out	Low noise VLSI	Low noise VLSI
Number of readout channels	$\sim 10^6 (\sim 5 \times 10^5)$	$\sim 1.5 \times 10^6 (\sim 710^5)$
Data Sample		
Number of p.o.t	6×10^{19}	1.3×10^{21}
Number of recorded ν_μ CC	2×10^6	12×10^6

Table 1: Parameters of the ESTAR for CERN and FNAL. The quantities in parenthesis are alternative possibilities in the design

A selected event in one of the subsets is scanned in the emulsion. The excellent resolution of the silicon detectors results in a very precise determination of the event vertex. Fig. 2 shows the resolution on the determination of the longitudinal coordinate z and one of the transverse coordinates y . The average error is $93\mu m$ for z and $13\mu m$ y . This defines a very small region to search on the emulsion for the event vertex. Linking the “leading track” (i.e, the μ, π or e candidate to be a τ decay product) to the emulsion is also straight forward given the point resolution of the silicon detectors.

A τ decay in the emulsion is characterized by a short track of around 1mm which either shows a large kink (typically larger than 10 mrad) or splits into 3 tracks. For events in which a kink or 3 tracks are found, the secondaries are linked through the silicon trackers to the rest of the spectrometer. Finally, in addition to the emulsion signature, one can impose additional kinematical criteria as discussed in section 4.

3.1 Simulation of the Detector and Event Reconstruction

These studies have been realized with the same Monte Carlo program used for the calculations presented in [8]. The NOMAD simulation of the SPS WBB beam is used [10] for the simulation of the CERN experiment, and a numerical parametrization of the FNAL beam, obtained from the COSMOS proposal [5] is used for the FNAL experiment. Neutrino interactions are generated using the LEPTO6.1 generator [12] tuned up to generate neutrino interactions in the energy and Q^2 region typical of the CERN-SPS neutrino beam. The resulting charged and neutral particles are propagated through the detector. In order to obtain an accurate description of the physical processes that can affect the tracking and vertexing resolution, pattern recognition is simulated and tracks are reconstructed and fitted, using a Kalman filter technique [13, 14], which is also used to perform a vertex fit to determine the interaction vertex. On the other hand, in order to speed up the generation of events and keep the reconstruction code within reasonable limits, electromagnetic and hadronic showers are not fully developed in the calorimeters. Instead, electrons and photons are stopped in the electromagnetic calorimeter and their energies and positions smeared according to the expected energy and position resolution. More details can be found in [8].

Figure 2: Vertex resolution obtained with the silicon trackers: (a) resolution on the longitudinal coordinate z , (b) resolution in one of the transverse coordinates y .

To illustrate the fit results, Fig. 3:a, shows the relative resolution σ_p/p and 3:b, shows the χ^2 probability obtained from the fit to the leading μ^- produced in ν_μ CC events.

3.2 Kinematical and Vertex signatures of the τ

There are two uncorrelated signatures of a ν_τ CC event followed by the decay $\tau \rightarrow l^-(h^-) + X$.

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

The undetected neutrinos in τ decays result in a sizeable transverse missing momentum $\mathbf{p}_\perp^{\text{miss}}$ (Fig. 4:a), which goes in the general direction of the τ decay products and thus, tends to form a large angle with the hadronic jet vector $\mathbf{p}_\perp^{\text{had}}$ (Fig. 4:b). The apparent $\mathbf{p}_\perp^{\text{miss}}$ (Fig. 4:c) in $\nu_\mu(\nu_e)$ CC events due to badly measured or undetected particles, on the other hand, has a rather flat distribution with respect to $\mathbf{p}_\perp^{\text{had}}$ as is illustrated in Fig. 4:d

Backgrounds arising from $\nu_\mu(\nu_e)$ NC have large missing transverse momentum, of 1.5GeV on average. In this case, however, the angle in the transverse plane between the “leading hadron(s)” and the hadronic jet, $\phi_{\pi-h}$ is larger on average for ν_τ events. This is illustrated in Fig. 5.

2. *Impact Parameter and Flight Distance.*

The excellent resolution of the silicon trackers allows an additional signature of ν_τ events produced on the ESTAR namely an impact parameter of the order of $90\mu\text{m}$ for 1-prong τ decays and two vertices separated by a flight distance of 1-3mm for 3-prong decays, as illustrated in Fig. 6a:b, where the impact parameter (flight distance) of the leading hadron (3 hadron system) for ν_τ events followed by the decay $\tau^- \rightarrow h^-(nh^0) + X$ ($\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau + n\pi^0$) is shown.

4 Selection of τ Candidates

Before classifying the event in a subsample, general quality conditions are required. The event is required to have at least two well-fitted tracks and a well fitted primary vertex.

Figure 3: (a) $\left(\frac{\sigma_p}{p}\right)$ and (b) χ^2 probability obtained from a Kalman filter fit to the leading μ^- produced in ν_μ CC events.

Figure 4: Characterization of ν_τ CC events followed by the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ and ν_μ CC events in terms of the magnitude of the missing transverse momentum and the angle ϕ_{m-h} between $\mathbf{p}_\perp^{\text{miss}}$ and $\mathbf{p}_\perp^{\text{had}}$: (a) $\mathbf{p}_\perp^{\text{miss}}$ and (b) ϕ_{m-h} for ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) events; (c) $\mathbf{p}_\perp^{\text{miss}}$ and (d) ϕ_{m-h} for ν_μ CC events.

Figure 5: Characterization of ν_τ CC events followed by the decay $\tau^- \rightarrow h^-(nh^0) + X$ and ν_μ NC events in terms of the magnitude of the missing transverse momentum and the angle $\phi_{\pi-h}$ between the leading hadron and $\mathbf{p}_\perp^{\text{had}}$: (a) $\mathbf{p}_\perp^{\text{miss}}$ and (b) $\phi_{\pi-h}$ for ν_τ ($\tau^- \rightarrow h^-(nh^0) + X$) events; (c) $\mathbf{p}_\perp^{\text{miss}}$ and (d) $\phi_{\pi-h}$ for ν_μ NC events.

Figure 6: Characterization of ν_τ CC events followed by the decay $\tau^- \rightarrow h^-(nh^0) + X$ ($\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau + n\pi^0$) and ν_μ NC events in terms of the impact parameter d_y (flight distance l_τ): (a) d_y and (b) l_τ for ν_τ events followed by the decay $\tau^- \rightarrow h^-(nh^0) + X$ ($\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau + n\pi^0$).

Tracks belonging to the primary vertex are classified as either τ decay candidates or hadrons belonging to the hadronic jet. Four types of τ decay candidates are allowed (i) $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ when the τ candidate is identified as a negative muon, (ii) $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ when the τ candidate is identified as an electron, (iii) $\tau^- \rightarrow h^-(nh^0) + X$ when the leading track is consistent with being a negative hadron and (iv) $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ when the τ candidate consists of 3 hadrons with overall negative charge and invariant mass smaller than the τ mass.

Muons are identified by combining the information of the electromagnetic and hadronic calorimeters and the muon chambers. The muon identification efficiency of the present NOMAD detector is close to 100 % up to 3 GeV and drops rapidly below this value. This is partly due to the fact that the hadronic calorimeter in NOMAD starts only after the magnet. Better muon identification efficiency at low momentum could be attained in a future experiment at CERN by adding additional hadronic calorimetry inside the magnet. Electrons are identified in NOMAD by the combination of electromagnetic calorimetry and the TRD detector. NAUSICAA-ESTAR has a much thicker target and thus electrons shower in most of the cases. Although this feature makes the kinematical selection of electrons very hard, it allows, nevertheless, the identification of them as "showering tracks", thus a TRD detector will probably not be necessary. Finally, tracks which are consistent with being neither electrons nor muons are classified as hadrons. In every case, to guarantee good particle identification and good vertex measurement, the leading track is required to have a momentum larger than 2GeV .

The most effective criterion to select ν_τ events which decay to one visible prong is to form the radial significance of the impact parameter, $d_s = \sqrt{(d_y/\sigma_y)^2 + (d_x/\sigma_x)^2}$, where d_x, d_y are the impact parameter in the $X-Z$ and $Y-Z$ views, and σ_x, σ_y are the errors on d_x, d_y . One can then cut at any number of standard deviations on this variable, depending on the desired signal to noise ratio. Fig. 7:a,c show d_s for ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) events and ν_μ CC events, while Fig. 7:b,d show the fraction of events retained for ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) and ν_μ CC events as a function of the cut on d_s .

Figure 7: Radial significance of the impact parameter d_s , and efficiency curves (Eff_d) as a function of d_s ; (a) d_s for ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) events, (b) d_s for ν_μ CC events, (c) Eff_d for ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) events and (d) Eff_d for ν_μ CC events.

4.1 $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ Sample

The $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ sample consists of events with a leading track identified as a negative muon which satisfy vertex and/or kinematical selection criteria. Two different selections are considered. A *tight selection*, defined as one which suppresses the ν_μ CC background by roughly two orders of magnitude, and a *loose selection* which suppresses the ν_μ CC by one order of magnitude. The tight selection is based *exclusively* on vertex criteria, i.e, it imposes a cut on the radial impact parameter significance of $d_s > 5$. The loose selection, on the other hand, combines vertex and kinematical criteria, by imposing $d_s > 3$ or $p_\perp^{\text{miss}} > 0.5 \text{ GeV}$ and $\phi_{m-h} > 0.8$.

For an experiment at CERN, the advantage of the tight selection criteria is that it allows a fast “first pass” on the scanning of the events. The selection efficiency is still high, $\epsilon_t \sim 20\%$ and the ν_μ CC events surviving this cut could be scanned in a very short time. An additional advantage of the tight selection is its simplicity, since it is based only on the measurement of the impact parameter. Notice that the resolution on impact parameter can be *measured* in the experiment by comparing the positions of the vertex predicted by the silicon with the actual position of the vertex found on the emulsion for a few thousands of ν_μ CC events. Thus the resolution function, and therefore the efficiency of the selection can be measured rather than estimated by Monte Carlo simulation.

On the other hand, in order to increase the sensitivity, a loose selection at CERN, with a very high ν_τ ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) selection efficiency ($\epsilon_l \sim 50\%$), would still imply a manageable load of about 2×10^5 ν_μ CC events to be scanned. At FNAL, the tight selection criteria maybe the only practical one, in order to have a comfortable scanning load. However, the rapid evolution of the scanning techniques combined with the good resolution provided by the silicon may allow the FNAL experiment to deal with a scanning load of the order of 10^6 events [15], thus making it possible the use of loose selection criteria.

The two selections are summarized in table 2. The efficiencies quoted are multiplicative. We assume a scanning efficiency of 90 % which should be possible given the high vertex resolution provided by the silicon detectors. Notice also that events satisfying the tight selection criteria satisfy essentially 100 % of the time the “kink quality criteria” (i.e,

Selection	ν_μ CC	ν_τ CC
Good vertex definition, μ^- reconstructed	0.84	0.76
Tight Selection		
$d_s > 5$	0.015	0.30
Loose Selection		
$d_s > 3$ OR $p_\perp^{\text{miss}} > 0.4$ & $\phi_{\text{m-h}} > 0.8$	0.12	0.66
Scanning Efficiency	0.9	0.9
ϵ_μ (tight criteria)	0.011	0.21
ϵ_μ (loose criteria)	0.091	0.45

Table 2: Selection efficiency and background reduction for $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ events in NAUSICAA-ESTAR.

Selection	ν_e CC	ν_τ CC
Good vertex definition, e^- reconstructed	0.60	0.50
$d_s > 3$	0.09	0.47
Scanning Efficiency	0.9	0.9
ϵ_e (tight criteria)	0.05	0.21

Table 3: Selection efficiency and background reduction for $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ events in NAUSICAA-ESTAR.

the observed kink must have an angle in excess of 10 mrad and a transverse momentum of more than about 0.3 GeV relative to the τ candidate direction, [1, 5]).

4.2 $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ Sample

The $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ sample consists of events with a leading track identified as a negative electron which satisfies exclusively vertex selection criteria. Kinematical criteria are not used in this case, due to the high probability for the electron to shower, thus smearing kinematical variables. The efficiencies for this channel are considerably lower than for the muonic and hadronic channels, since a large fraction of the events in which the electron showers cannot be reconstructed. Table 3 shows the selection of ν_τ ($\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$) events and ν_e CC events.

Selection	ν_μ NC	ν_τ CC
Good vertex definition, h^- reconstructed	0.45	0.81
Tight Selection		
$d_s > 4$	0.03	0.35
Loose Selection		
$d_s > 3$ OR $\mathbf{p}_\perp^{\text{miss}} < 2\text{GeV}$ & $\phi_{\pi-h} > 0.9$	0.11	0.60
Scanning Efficiency	0.9	0.9
ϵ_π (tight criteria)	0.012	0.26
ϵ_π (loose criteria)	0.045	0.44

Table 4: Selection efficiency and background reduction for $\tau^- \rightarrow h^-(nh^0) + X$ events in NAUSICAA-ESTAR.

4.3 $\tau^- \rightarrow h^-(nh^0) + X$ Sample

The $\tau^- \rightarrow h^-(nh^0) + X$ sample consists of events with a leading negative track identified as neither a muon nor an electron. As in the case of the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ selection we consider a tight and a loose selection. The tight selection imposes a cut on the radial impact parameter significance $d_s > 4$. The loose selection imposes $d_s > 3$ or $\mathbf{p}_\perp^{\text{miss}} < 2$ and $\phi_{\pi-h} > 0.9$. The two selection criteria are summarized in table 4.

4.4 $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ Sample

The distinctive signature of the τ in this case is the decay to 3 charged hadrons which allows the reconstruction of the τ decay point using the silicon trackers

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, $M_{had}^{3\pi} < 2.0\text{GeV}$ 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 and the significance $l_s = l_\tau / \sigma_{l_\tau}$.

Selection	ν_μ NC	ν_τ CC
Good vertex definition, $(3h)^- + 2h$ reconstructed	0.25	0.65
Tight Selection		
$l_s > 2$	0.035	0.60
Loose Selection		
$l_s > 2$ OR $\mathbf{p}_\perp^{\text{miss}} < 2\text{GeV}$ & $\phi_{\pi-h} > 0.9$	0.08	0.75
Scanning Efficiency	0.9	0.9
ϵ_π (tight criteria)	0.008	0.35
ϵ_π (loose criteria)	0.018	0.44

Table 5: Selection efficiency and background reduction for $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ events in NAUSICAA-ESTAR.

Given that the error on the measurement of l_τ is one order of magnitude smaller than l_τ itself, it is enough to cut at two standard deviations to reduce the ν_μ NC by two orders of magnitude. Thus, the tight selection in this case simply imposes $l_s > 2$. The loose selection adds kinematical criteria, $\mathbf{p}_\perp^{\text{miss}} < 2$ and $\phi_{\pi-h} > 0.9$. The two selection criteria are summarized in table 5.

4.5 Scanning Load

Scanning loads are summarized in Table 6. Assuming a total data sample of 2×10^6 ν_μ CC currents the CERN experiment would need to scan a total of 3.5×10^4 for tight selection criteria and 2.2×10^5 events for loose selection criteria. At FNAL one would scan a total of 2.2×10^5 events with tight criteria, and 1.3×10^6 events with loose criteria. The scanning time will also be much reduced with respect to CHORUS given the much improved prediction of the track coordinates. The “tight” sample at CERN could presumably be scanned in less than one month, and the total sample in less than one year.

4.6 Background Suppression

Detailed discussion of the background suppression in an emulsion target such as the one proposed here are given in [1, 5]. One expects a background level compatible with zero. However, some level of uncertainty about the impact of the “white kink” and “white

	CERN	FNAL
Total ν_μ CC	2×10^6	12×10^6
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ CC Tight Criteria	2.2×10^4	1.32×10^5
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ CC Loose Criteria	1.82×10^5	1.1×10^6
Total ν_μ NC	0.67×10^6	4×10^6
$\tau^- \rightarrow h^-(nh^0) + X$ CC Tight Criteria	8.1×10^3	4.8×10^4
$\tau^- \rightarrow h^-(nh^0) + X$ CC Loose Criteria	3.0×10^4	1.8×10^5
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ CC Tight Criteria	5.4×10^3	3.2×10^4
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ CC Loose Criteria	1.3×10^4	7.2×10^4
Total load		
Tight Criteria	3.5×10^4	2.1×10^5
Loose Criteria	2.2×10^5	1.3×10^6

Table 6: Scanning load in NAUSICAA-ESTAR

star” backgrounds (nuclear interactions without visible break-up or inelastic interactions producing a kink or 3 tracks which mimic the τ signature) remains to be better understood (however forthcoming results from CHORUS should contribute to clarify this issue). Here we will just remark that in NAUSICAA-ESTAR additional selection criteria are available by combining vertex and kinematical criteria to further suppress background to the hadronic channels $\tau^- \rightarrow h^-(nh^0) + X$ and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$. As an example we discuss the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ channel (see also [8]) where we believe that a high-efficiency and essentially background free selection of τ candidate events can be performed already with the electronic spectrometer (i.e, before emulsion scanning). For the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$ decay channel one measures two vertexes with the silicon detectors and thus the τ flight direction which goes along the line connecting the two vertexes is known. Thus two more variables are available (in addition to the flight distance) to discriminate between the signal and the background (see Fig. 8):

1. The angle ϕ_τ between the τ and the hadronic jet in the hadronic plane. Fig. 9 shows the distribution of ϕ_τ for ν_μ NC and ν_τ ($\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$) events.
2. The angle β_τ between the resultant of the τ decay products and the τ flight line defined by the two vertexes. Fig. 10 shows the distribution of β_τ for signal and background events.

Figure 8: Variables signaling the presence of a τ decaying via $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0$. ϕ_τ is the angle between the τ and the hadronic jet in the transverse plane. β_τ is the angle between the resultant of the τ decay products and the τ flight line defined by the two vertices. (c) l_τ is the distance between the two vertexes.

Figure 9: 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 10: 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.

Cuts on those variables reduce efficiently possible background due to white star events, while keeping a high percentage of the signal. The same variables can be formed (albeit only after scanning the emulsion to find the τ direction) for 1-prong τ decays.

5 Sensitivity of the NAUSICAA-ESTAR Experiment

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) :

$$P(\nu_\mu \leftrightarrow \nu_\tau) \leq \frac{N_\tau}{N_\mu^{CC} \times (\sum_i \epsilon_i \times BR) \times (\sigma_\tau/\sigma_\mu)}. \quad (2)$$

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^{th} decay modes considered. If no candidates are observed, the 90 % C.L. for N_τ is 2.3 events.

Table 7 summarizes the sensitivities that can be reached at CERN and FNAL for the loose selections, assuming null backgrounds. Notice that the tight selection will yield a sensitivity “only” a factor 1.5 worst. This would still result, for an experiment at CERN in a sensitivity one order of magnitude improved with respect to the one expected by CHORUS, with minimum scanning effort.

To summarize, the sensitivity of NAUSICAA can be improved with respect to the CHORUS/NOMAD proposal by more than an order of magnitude (and a factor 3 with respect to the COSMOS proposal) in a five year run at CERN. At FNAL with a tight selection one can reduce the sensitivity to $\sin^2 2\theta_{\mu\tau}$ by an additional factor of 3 in the limit of large mass differences, but the lower energy of FNAL results in an increased sensitivity to the critical region $\Delta m^2 \sim 1 - 10 eV^2$, as illustrated in Fig. 11.

6 Conclusion

We have shown that a new neutrino experiment based on an emulsion-silicon target, capable of searching for the τ signature by using both kinematical and vertex criteria,

Figure 11: Exclusion plot, showing the expected sensitivity of NAUSICAA-ESTAR at CERN and FNAL beams.

	CERN	FNAL
Total ν_μ CC	2×10^6	12×10^6
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \quad \epsilon_\mu \times BR$	0.079	0.079
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau \quad \epsilon_e \times BR$	0.038	0.038
$\tau^- \rightarrow h^- (nh^0) + X \quad \epsilon_\pi \times BR$	0.22	0.22
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau + n\pi^0 \quad \epsilon_{3\pi} \times BR$	0.066	0.066
$\sum_i \epsilon_i \times BR$	0.40	0.40
σ_τ / σ_μ	0.51	0.29
$P(\nu_\mu \leftrightarrow \nu_\tau)$	5.4×10^{-6}	1.6×10^{-6}
$\sin^2 2\theta_{\mu\tau}$ (large Δm^2)	1.1×10^{-5}	3.2×10^{-6}

Table 7: Sensitivity of NAUSICAA-ESTAR at CERN and FNAL

could improve the CHORUS/NOMAD sensitivity by more than one order of magnitude in an extended run period at CERN. The sensitivity of the proposed experiment at CERN is also higher than the one projected by COSMOS. At FNAL, a further improvement of a factor 3 in $\sin^2 2\theta_{\mu\tau}$ for large mass differences is possible, with larger sensitivity to lower mass differences.

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References

- [1] CHORUS Collaboration, N. Armenise et al., CERN-SPSC/90-42 (1990).
- [2] NOMAD Collaboration, P. Astier et al., CERN-SPSLC/91-21 (1991), CERN-SPSLC/91-48 (1991), SPSLC/P261 Add. 1 (1991).
- [3] Minutes of the 119th meeting of the CERN Research Board, November 1994.
- [4] U.S. Department of Energy, DOE/ER-0662, " Subpanel on Accelerator-Based Neutrino Oscillation Experiments", September 1995.
- [5] P-803 Proposal, Fermilab, October 1993.
- [6] F. Dydak *et. al.*, CDHS Collab., Phys. Lett. B134 1984 (281).
- [7] M. Gruwe *et. al.*, CHARM-II Collab., Phys. Lett. B309 (1993) 463.
- [8] J.J. Gomez-Cadenas, J.A. Hernando and A. Bueno. *A Neutrino Apparatus with Improved Capabilities for a short base $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillation search.* CERN-PPE/95-177. Accepted by Nucl. Instruments and Methods.
- [9] A Prototype of an Instrumented Target for the NOMAD Detector, CERN-SPSLC/96-2, SPSLC/P261 Add.3 (8 January 1996).
- [10] NOMAD Collaboration, NUBEAM.
- [11] R. Brun et al., GEANT 3, CERN DD/EE/84-1.
- [12] G. Ingelman LEPTO6.1. TSL/ISV-92-0065 (1992).
- [13] R.E. Kalman, J. Basic Eng. 82(1961)34.
- [14] P. Billoir, These de Doctorat, Universite P. et M. Curie, Paris, 1983, unpublished. R. Fruhwirth, HEPHY-PUB 516/88, Vienna, Dec. 1988. R. Fruhwirth, Nuclear Instruments & Methods A 262(1987)
- [15] A. Ereditato, G. Romano and P. Strolin, *TENOR: a new experiment for the search of $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ oscillations.* CHORUS internal Report 96-03 (16 February 1996).