Learning from $\tau$ appearance

P Migliozzi$^1$ and F Terranova$^{2,3}$

$^1$ INFN, Sezione di Napoli, Naples, Italy
$^2$ INFN, Laboratori Nazionali di Frascati, Frascati (Rome), Italy
E-mail: francesco.terranova@cern.ch

*New Journal of Physics* 13 (2011) 083016 (24pp)
Received 20 April 2011
Published 12 August 2011
Online at [http://www.njp.org/](http://www.njp.org/)
doi:10.1088/1367-2630/13/8/083016

**Abstract.** The study of $\nu_\mu \rightarrow \nu_\tau$ oscillations and the explicit observation of $\nu_\tau$ through the identification of the final-state $\tau$ lepton (‘direct appearance search’) represent the most straightforward test of the oscillation phenomenon. It is, nonetheless, the most challenging from the experimental point of view. In this paper, we discuss current empirical evidence for the direct appearance of tau neutrinos at the atmospheric scale and the perspectives for the next few years, up to the completion of the CNGS physics programme. We investigate the relevance of this specific oscillation channel for gaining insights into neutrino physics within the standard three-family framework. Finally, we discuss the opportunities offered by precision studies of $\nu_\mu \rightarrow \nu_\tau$ transitions for the occurrence of more exotic scenarios, emerging from additional sterile neutrinos or non-standard interactions.
1. Introduction

The search for neutrino oscillations into flavours different from the initial one (‘appearance’) has a decades-long history. Since 1998, however, the study of the $\nu_\mu \rightarrow \nu_\tau$ transition has played a unique role in the field of neutrino physics for a very special reason.

Neutrino oscillations [1] are a powerful tool for determining the squared mass differences of the rest masses of neutrinos because the oscillation phase is proportional to the ratio $(m_i^2 - m_j^2)L/E \equiv \Delta m^2_{ij}L/E$. Here, $i$ and $j$ denote the mass eigenstates ($i, j = 1, 2, 3$), $L$ the source-to-detector distance (‘baseline’) and $E$ the neutrino energy. Oscillations also depend on the $3 \times 3$ matrix that describes the mismatch of flavour and mass eigenstates. It is the leptonic counterpart of the Cabibbo–Kobayashi–Maskawa matrix and is often referred to as the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix [2, 3]. This matrix can be parameterized by three angles, $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, and one CP-violating phase $\delta$.\footnote{Additional Majorana phases cannot be observed by oscillation experiments [1].}

The experimental results obtained so far point to two distinct mass differences, $\Delta m^2_{\text{sol}} = \Delta m^2_{21} = m_2^2 - m_1^2 = 7.65^{+0.23}_{-0.20} \times 10^{-5}$ eV$^2$ [4] and $|\Delta m^2_{\text{atm}}| = |\Delta m^2_{32}| = |m_2^2 - m_3^2| \simeq |m_2^2 - m_1^2| = 2.32^{+0.15}_{-0.08} \times 10^{-3}$ eV$^2$ [5]. $\Delta m^2_{\text{sol}}$ is called the ‘solar mass scale’ because it drives oscillations of solar neutrinos, but, of course, if the energy of the neutrino and the source-to-detector distance are properly tuned, it can also be measured employing man-made neutrinos, e.g. reactor neutrinos located about 100 km from the detector [6]. Similarly, atmospheric neutrinos mainly oscillate at a frequency that depends on $\Delta m^2_{\text{atm}}$ (‘atmospheric scale’). Accelerator neutrino experiments can see (actually saw in K2K [7] and MINOS [8]) the same effect using neutrinos of energy $\mathcal{O}(1)$ GeV and baselines of a few hundreds of km.

Appearance has always been considered the most direct proof of the phenomenon of neutrino oscillations. Unfortunately, all sources that we have at our disposal to observe oscillations at the solar scale (solar and reactor neutrinos) produce $\nu_e$ (or $\bar{\nu}_e$) with energy well below the kinematic threshold for muon production. As a consequence, it is impossible
to test in a straightforward manner the occurrence of $\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$ transitions through the observation of muons or $\tau$s produced by charged-current (CC) neutrino interactions with matter. At the atmospheric scale (atmospheric and multi-GeV artificial neutrinos from the decay in flight of pions), $\nu_\mu \rightarrow \nu_e$ transitions might be observed in appearance mode. Still, the peculiar structure of the leptonic mixing matrix suppresses this transition at least by one order of magnitude by virtue of the small $\theta_{13}$ angle [9–11]. Therefore, an appearance measurement that is aimed at observing a large (i.e. $\mathcal{O}(1)$) neutrino transition probability must resort to $\nu_\mu \rightarrow \nu_\tau$.

In the current framework of interpretation of neutrino oscillation data—three active neutrinos non-trivially mixed by a $3 \times 3$ unitary matrix [12]—such a probability is quite large for multi-GeV neutrinos at baselines of the order of $10^3$ km. In this case, the oscillation probability is given by

$$P(\nu_\mu \rightarrow \nu_\tau) \simeq \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta_{32},$$

(1)

$\Delta_{32} = \Delta m^2_{32} L/4E$ being the oscillation phase ($L$ is the baseline and $E$ is the neutrino energy in $c = \hbar = 1$ units), whereas $\theta_{13}$ and $\theta_{23}$ are the mixing angles of the third family with the first and second families, respectively. Due to the tri-bimaximal structure [13] of the mixing matrix ($\theta_{13} \simeq 0$ and $\theta_{23} \simeq \pi/4$), this probability is $\mathcal{O}(1)$ at the oscillation peak ($\Delta_{32} = \pi/2$).

Seeking $\nu_\mu \rightarrow \nu_\tau$, i.e. observing the final state $\nu_\tau$ CC interactions, is a major experimental challenge. The source must produce neutrinos well above the kinematic threshold for $\tau$ production (3.5 GeV for scattering in nuclei). Moreover, the far detector has to be capable of selecting an enriched sample of $\tau$ leptons in the bulk of muons and hadrons produced by $\nu_\mu$ CC and NC interactions. It comes as no surprise that the most direct test of the oscillation phenomenon through the observation of $\tau$ appearance still deserves conclusive evidence. In 2010, however, important milestones were achieved, especially by the SuperKamiokande and OPERA experiments. The aim of this paper is to carefully examine current evidence for $\tau$ appearance as a direct probe of neutrino oscillations. In addition, we discuss what can be learned from $\nu_\mu \rightarrow \nu_\tau$ studies in the standard three-family oscillation framework and in more exotic scenarios. We also anticipate the relevance of precision measurements of $\nu_\mu \rightarrow \nu_\tau$ to be carried out by a future generation of short/long baseline experiments.

2. Past searches for $\tau$ appearance

At the beginning of the 1990s, there were theoretical arguments [14, 15] suggesting that, in analogy with quark mixing, neutrino mixing angles should be small and that the heavier neutrino (mostly $\nu_\tau$) may have a mass of 1 eV, or larger, and therefore could be the main constituent of the dark matter in the universe. This hypothesis was based on two key assumptions:

- the interpretation of the solar neutrino deficit in terms of $\nu_e \rightarrow \nu_\mu$ oscillations amplified by matter effects, giving $\Delta m^2 \approx 10^{-5}$ eV$^2$;

- the input from see-saw mass-generation models [16], which predicts that neutrino masses are proportional to the square of the mass of the charged lepton or of the 2/3 charge quark of the same family.

From these two assumptions, one expects a $\nu_\mu \simeq \nu_2$ mass of $\sim 3 \times 10^{-3}$ eV and a $\nu_\tau \simeq \nu_3$ mass of $\sim 1$ eV or higher.

The seeming concordance between cosmological and particle physics hints boosted enormously the search for $\tau$ appearance; in particular, it supported the design and construction
of two high-sensitivity short baseline experiments to discover $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of $\Delta m^2 \sim 10$ eV$^2$. The two CERN experiments performing this search were NOMAD [17] and CHORUS [18], both exploiting the CERN SPS wide-band neutrino beam (WANF [19]) but with two quite different approaches.

2.1. The NOMAD experiment

The NOMAD experiment was designed to search for $\nu_\mu \rightarrow \nu_\tau$ in the WANF. The detector consisted of drift chambers used as a target and tracking medium. They were optimized to fulfil two opposite requirements: a heavy target to collect as many interactions as possible and a light target to allow a precise tracking by reducing multiple scattering. In total, there were 44 chambers with a fiducial mass of 2.7 tons and an active area of $2.6 \times 2.6$ m$^2$. They were followed by a transition radiation detector (TRD) for $e/\pi$ separation. Electron identification was performed with a pre-shower detector and a lead-glass electromagnetic calorimeter followed by an iron-scintillator sampling hadronic calorimeter, an iron absorber and a set of ten muon chambers. The detector was located within a magnetic field of 0.4 T, perpendicular to the beam axis for momentum determination. In fact, the magnetic dipole hosting the NOMAD drift chambers was originally built for the UA1 experiment and it is currently used by the T2K Collaboration for the 280 m near the detector [20].

The NOMAD experiment based its search for $\nu_\tau$ on kinematic criteria. From the kinematic point of view, $\nu_\tau$ CC events in NOMAD are fully characterized by the decay products of the primary $\tau$. The spatial resolution of NOMAD did not allow the observation of a secondary vertex from $\tau$-decay. The presence of visible secondary $\tau$ decay products, $\tau_V$, marks a difference with respect to NC interactions, whereas the emission of one (two) neutrino(s) in hadronic (leptonic) $\tau$-decays provides discrimination against $\nu_\mu$ ($\nu_\tau$) CC interactions (figure 1). Hence, in $\nu_\tau$ CC events the transverse component of the total visible momentum and the variables describing the visible decay products have different absolute values and different correlations with the remaining hadronic system, $H$, than in $\nu_\mu$ ($\nu_\tau$) CC and NC interactions. The optimal separation between signal and background is achieved when all the degrees of freedom of the event kinematics (and their correlations) are exploited.

The maximum $\nu_\tau$ signal allowed by limits from previous experiments [21, 22] was at least a factor of 0.0025 times smaller than the main $\nu_\mu$ CC component and a rejection power against backgrounds of $O(10^5)$ was required from the kinematic analysis. Therefore, the $\nu_\tau$
appearance search in NOMAD was a kinematic-based search for rare events within a large background sample, as in Super-Kamiokande nowadays (see section 3). Similarly, in order to obtain reliable background estimates the Collaboration developed methods to correct Monte Carlo (MC) predictions with experimental data and defined appropriate control samples to check such predictions.

2.2. The CHORUS experiment

The approach followed by the CHORUS experiment was rather different. Instead of relying on a kinematic analysis, a detector based on nuclear emulsions with an ultra-high granularity (1 µm) was employed. A schematic picture of the CHORUS apparatus is shown in figure 2.

The hybrid setup was made of an emulsion target (800 kg), a scintillating fibre tracker system, trigger hodoscopes, a magnetic spectrometer, a lead-scintillator calorimeter and a muon spectrometer.

The nuclear emulsions acted as the target and, simultaneously, as the detector of the interaction vertex and of the τ lepton decay [23]. The emulsions were subdivided into four stacks of 36 plates, oriented perpendicularly to the beam and with a surface of 1.44×1.44 m². Each plate was made of a 90 µm transparent plastic film with 350 µm emulsion sheets on both sides.

The nuclear emulsion target was equipped with a high-resolution tracker made of interface emulsions and scintillating fibre planes. Each stack was followed by three special interface emulsion sheets: two changeable sheets (CS), close to the fibre trackers, and a special sheet (SS), close to the emulsion stack. The sheets had a plastic base of 800 µm coated on both sides by 100 µm emulsion layers. Eight planes of target trackers (TTs) of scintillating fibres (500 µm diameter) [24], interleaved between the emulsion stacks, measured the trajectories of

Figure 2. General layout of the CHORUS detector.
the charged particles with a precision of 150 $\mu$m in position and 2 mrad in angle at the surface of the CS.

Downstream of the target region, a magnetic spectrometer was used to reconstruct the momentum and sign of charged particles. A hexagonal air-core magnet [25] produced a pulsed homogeneous field of 0.12 T. Field lines were parallel to the sides of the hexagon and the magnetized region extended for a depth of 75 cm in the direction of the beam. The tracking before and after the magnet was performed by a high-resolution detector made of scintillating fibres (500 $\mu$m diameter) and complemented with a few planes of electronic detectors (streamer tube chambers in the 1994, 1995 and at the beginning of the 1996 run, and honeycomb chambers [26] afterward). The resulting momentum resolution $\Delta p / p$ was 30% at 5 GeV.

In addition to the detection elements described above and in order to perform a more precise kinematic analysis of the $\nu_\tau$ decay candidates, the air-core hexagonal magnet region was equipped with large area emulsion trackers during the 1996 and 1997 runs.

A 100 ton lead-scintillating fibre calorimeter [27], together with a lead-scintillator calorimeter, followed the magnetic spectrometer and measured the energy and direction of electromagnetic and hadronic showers, together with a lead-scintillator calorimeter.

A muon spectrometer made of magnetized iron discs interleaved with plastic scintillators and tracking devices was located downstream of the calorimeter. A momentum resolution of 19% was achieved by magnetic deflection for muons with momenta greater than 7 GeV. At lower momenta, the measurement of the range yielded a 6% resolution.

CHORUS took advantage of the excellent spatial resolution (below 1 $\mu$m) of nuclear emulsions. Indeed, at the average energy of the WANF neutrino beam the $\tau$ lepton produced in a $\nu_\tau$ CC interaction travels about 1 mm before its decay. Both the parent track ($\tau$ lepton) and the decay product(s) can be seen in the nuclear emulsion and the peculiar decay topology fully reconstructed as shown in figure 3. The main advantage with respect to NOMAD is the capability of identifying $\tau$ candidates on an event-by-event basis, minimally relying on the kinematic analysis.

As discussed in detail in [28], the main source of background in the CHORUS experiment originated from the poor efficiency in measuring the momentum and the charge of the decay products. This was mainly [18] due to the limited geometric efficiency of the spectrometer (85%) and to the actual performance of the trackers, which provided a charge discrimination beyond $3\sigma$ only for momenta lower than 5 GeV. Indeed, the excellent sensitivity of the nuclear emulsions in detecting also nuclear recoils (which is extremely important in rejecting hadron reinteractions mimicking a decay topology) was partially compromised by the low efficiency in performing kinematic analysis of the events. The background level achieved (normalized to CC interactions) was $\approx 10^{-3}$.

2.3. CHORUS and NOMAD results

Eventually, both CHORUS [28] and NOMAD [29] had no evidence for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\tau$ oscillations. The 90% CL upper limit on the appearance probability was

$$P(\nu_\mu \rightarrow \nu_\tau) < 1.6 \times 10^{-4}.$$  

The corresponding limit on the mixing angle is quite stringent; it is $\sin^2 2\theta_{\mu\tau} < 4 \times 10^{-4}$ for large $\Delta m^2$, while the lower $\Delta m^2$ value excluded by the two experiments is $\approx 0.5\text{eV}^2$ for maximal mixing (see figure 4). It is worth noting that at small mixing angles NOMAD has
Figure 3. ντ detection principle exploited by the CHORUS experiment. A τ lepton produced in a ντ CC interaction produces a track of a few hundreds of μm before its decay. The short τ track and the decay product(s) are clearly visible thanks to the excellent spatial resolution of nuclear emulsions.

Figure 4. CHORUS (solid lines) and NOMAD (dashed lines) upper limits on νμ → ντ (left) and νe → ντ (right) oscillations represented by an exclusion plot in the oscillation parameter plane. The latter result is also compared with CHOOZ [9].
a better sensitivity, whereas CHORUS is more sensitive at low $\Delta m^2$. This difference is due to the different experimental techniques employed by the two experiments. NOMAD has been able to collect and analyze a much larger neutrino interaction sample, whereas CHORUS has higher efficiencies at low neutrino energies.

The study of $\nu_e \rightarrow \nu_\tau$ oscillations was possible thanks to the 0.9% $\nu_e$ contamination of the SPS neutrino beam. Assuming that all observable $\nu_\tau$ would originate from this contamination, the above result translates into a limit on the $\nu_e \rightarrow \nu_\tau$ appearance probability. The difference in energy between the $\nu_\mu$ ($\langle E_{\nu_\mu} \rangle \sim 26$ GeV) and $\nu_e$ ($\langle E_{\nu_e} \rangle \sim 42$ GeV) components leads to a different shape of the exclusion plot in the oscillation parameter plane. The corresponding 90% CL upper limit on the appearance probability is

$$P(\nu_e \rightarrow \nu_\tau) < 1 \times 10^{-2}.$$  

The main reason for the large difference in sensitivity between CHORUS and NOMAD (see figure 4) is due to the harder $\nu_e$ spectrum with respect to the $\nu_\mu$ one and to the lower efficiency of CHORUS at high energies.

3. Evidence from inclusive measurements

Atmospheric neutrinos provided the first convincing evidence for flavour transitions in 1998 [30, 31]. In fact, $\nu_\mu$ and $\nu_e$ produced by the interaction of primary cosmic rays with the nuclei in the Earth’s atmosphere are a powerful discovery tool: their energy spans several orders of magnitude, the flux dropping as $E^{-2.7}$, and oscillations can be probed from medium baselines—$O(10)$ km for neutrinos produced just above the detector—up to a length comparable with the Earth’s diameter for neutrinos produced on the other side of the Earth. The characteristic oscillation frequency due to the squared mass difference of the second and third mass eigenstates ($\Delta m^2_{32}$) lies within the atmospheric energy-baseline range and it is prominent in the multi-GeV region. It manifests as a deficit of $\nu_e$ for zenith angles larger than $\pi/2$ (up-going events). This depletion is absent in atmospheric $\nu_e$ and, when combined with reactor data, excludes the occurrence of a large $\nu_\mu \rightarrow \nu_\tau$ conversion, which in turn demonstrates that $\theta_{13} \ll \theta_{23}$. In 2003, this result has been confirmed with artificial sources by the K2K experiment [7] and, more recently, by MINOS [8]. The measurement of MINOS, in particular, provides the most precise measurement to date of $\Delta m^2_{32}$ ($\Delta m^2_{32} = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV$^2$ [5]). Similarly, atmospheric and accelerator data [32] exclude sizable oscillation probabilities into new types of neutrinos that are singlet under the electroweak gauge group (‘sterile neutrinos’) and point toward a disappearance pattern that follows the sinusoidal law characteristic of oscillations [33]. We therefore expect the large disappearance of $\nu_\mu$ in the multi-GeV range to be due to a high $\nu_\mu \rightarrow \nu_\tau$ transition rate. Such a conversion could be revealed in a direct manner by the observation of atmospheric-induced $\tau$ leptons from $\nu_\tau$ CC events occurring in the detector.

Initial state atmospheric neutrinos are almost devoid of $\nu_\tau$. Tau neutrinos can be produced by the leptonic decay of $D_1$ in $p + N$ interactions and the level of contamination does not exceed $10^{-6}$ [34]. In addition, the rate of $\nu_\tau$ CC interaction is heavily suppressed by the large kinematic threshold and the $E^{-2.7}$ damping factor in the $\nu_\mu$ spectrum. Assuming the current best fit value of $\Delta m^2_{32}$ and maximal atmospheric mixing ($\theta_{23} = \pi/4$ and $\theta_{13} = 0$), about 1 $\nu_\tau$ CC event per year is expected in a detector with a 1 kiloton mass [35]. On top of this, identification of the $\tau$ lepton on an event-by-event basis is impossible with coarse-grained detectors such as the ones employed for the study of atmospheric neutrinos. The $\tau$ lepton decays promptly
Table 1. Main decay channels for the $\tau$ lepton observed in direct appearance searches [12]. $h^\pm$ stands for $\pi^\pm$ or $K^\pm$.

| Decay channel height | Branching ratio (%) |
|----------------------|---------------------|
| $\mu^- \bar{\nu}_\mu \nu_\tau$ | 17.36 ± 0.05 |
| $e^- \bar{\nu}_e \nu_\tau$ | 17.85 ± 0.05 |
| $\pi^- \nu_\tau$ | 10.91 ± 0.07 |
| $h^- \pi^0 \nu_\tau$ | 25.94 ± 0.09 |
| $h^- \geq 2\pi^0 \nu_\tau$ | 10.85 ± 0.12 |
| $h^- h^+ h^- \geq 0$ neutrals $\nu_\tau$ | 14.56 ± 0.08 |

(lifetime: 291 ± 1 fs) in a variety of final states that are briefly summarized in table 1. As a consequence, unlike in $\nu_e$ and $\nu_\mu$ CC interactions, the final state lepton in $\nu_\tau$ CC (the $\tau$) is unobservable in the detector and can only be identified by the topology or kinematics of its decay products. Still, a vast majority of the decays are characterized by a one-prong topology, i.e. one long-living charged particle ($e$, $\mu$ or $\pi^-$) accompanied by the large missing energy that is carried by final state neutrinos. This feature is exploited by both inclusive and exclusive measurements (see section 4). Unfortunately, a one-prong + missing energy topology can be easily mimicked by neutral-current (NC) interactions, which represent the dominant background of any inclusive analysis, while the signal-to-noise ratio is ultimately limited by the granularity of the detector.

At the atmospheric scale, evidence for $\tau$ appearance has been gained by the Super-Kamiokande experiment using water Cerenkov techniques. The huge fiducial mass of the detector (22.5 kilotons) combined with a decade-long exposure compensates for the poor signal-to-noise ratio. Larger purities could be obtained by a fine-grained detector similar to NOMAD (see section 2) or by homogeneous liquid-Ar TPCs [36]. Still, the size of these detectors cannot compete with Super-Kamiokande: the weight of the largest liquid-Ar detector at present under operation is just 600 tons [37]. Multi-kiloton liquid-Ar detectors are, however, considered a viable option to overcome the limitations of water Cherenkov detectors in future atmospheric and long-baseline accelerator experiments. In particular, the opportunities offered by this technology at the 10 kiloton scale for the inclusive measurement of $\tau$ appearance with atmospheric neutrinos was recently discussed in [38].

The Super-Kamiokande Collaboration published its first analysis of $\tau$ appearance in 2006 [35] after an exposure of 1489.2 days (‘Super-K I data taking’). The detector consists of two concentric, optically separated regions filled with radiopure water and read out by large photomultipliers (PMT): the inner region is employed for vertex location and it is equipped with about 11000 20-inch PMTs (‘inner detector’); the outer—read out by sparser 8-inch PMTs—is used to veto cosmic-ray background, shield neutrons and $\gamma$s from the surrounding rock (‘outer detector’) and identify partially contained events. The overall detector mass is 50 kilotons but the fiducial volume includes only reconstructed vertices with a minimum distance from the walls of the inner detector of 2 m. It corresponds to an effective mass of 22.5 kilotons. Super-Kamiokande identifies charged particles by the corresponding Cherenkov rings in water. In particular, the $\nu_\tau$ analysis aims at selecting an enriched sample of hadronically decayed $\tau$ leptons. Semileptonic $\tau$ decays as $\tau \to \mu \nu_\mu \nu_\tau$ or $\tau \to e \nu_e \nu_\tau$ are not employed due to the overwhelming background of $\nu_\mu$ and $\nu_e$ CC interactions. Minimum ionizing particles (mainly muons and charged pions) produce sharp ring edges with variable openings, while
(ultrarelativistic) electrons and converted photons generate diffused ring patterns with a fixed opening angle of $42^\circ$. $\tau$ CC interactions occur at $E > 3.5$ GeV and are therefore mostly dominated by deep-inelastic scattering. Except for the $\tau \rightarrow \mu \nu_\mu \nu_\tau$ decay channel, most $\nu_\tau$ events show a multi-ring topology without a leading $\mu$-like (sharp) ring (‘$e$-like sample’). Super-Kamiokande has thus performed its inclusive analysis in a subsample of events having the vertex located inside the fiducial volume, a visible energy greater than 1.33 GeV and the most energetic ring clearly identified as $e$-like. This subsample has a signal ($\nu_\tau$ CC events)-to-noise ratio of 3% for maximal mixing and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$. Further enrichment can be obtained considering kinematic variables that enhance the difference between $\tau$-like decay topologies and NC or $\nu_e$ CC events. In particular, five variables have been considered in [35]: the visible energy, the maximum distance between the primary interaction and electron vertices from pion and then muon decay, the number of rings, the sphericity in the laboratory frame and the clustered sphericity in the centre-of-mass frame. Shape information from these variables is combined in a likelihood or, equivalently, in a neutral-network output and ‘$\tau$-like’ events are defined as candidates with a likelihood (neural-network output) greater than 0 (0.5). The $\tau$-like final subsample has a signal-to-noise ratio of about 5%. Although this analysis is, in principle, strongly dependent on detector simulation, the sample of down-going events provides a unique tool for MC validation. Down-going events are generated by neutrinos that were produced just above the detector, at an average height of 15 km from sea level if they originate from the decay in flight of $\pi$ and 13 km if they arise from muon decays. At these baselines the $\nu_\mu \rightarrow \nu_\tau$ probability is negligibly small; therefore they represent a pure sample of unoscillated neutrinos. Evidence for $\tau$ appearance can be drawn by the binned fit of the zenith angle ($\theta$) distribution of $\tau$-like events. The fit is done assuming an arbitrary overall normalization ($\alpha, \beta$) for both signal ($N^f_i$) and background ($N^{bkg}_i$), i.e. minimizing

$$\chi^2 = \sum_{i=1}^{n} \frac{(N^{obs}_i - \alpha N^f_i - \beta N^{bkg}_i)^2}{\sigma^2_i},$$

with $\sigma_i$ being the statistical error for the $i$th bin. A large Min($\chi^2$) for the null hypothesis ($N^f_i = 0$ for any $i$) is an indication of the regions rich in oscillated $\nu_\tau$. In fact (see figure 3 of [35]), the zenith distribution shows a rather clear excess of $\tau$-like events in the up-going region, i.e. in the region where oscillations are expected to be large. Thanks to good knowledge of the leading oscillation parameters $\Delta m^2_{32}$ and $\theta_{23}$ and to the up/down comparison of the rates, the contributions to the systematic error that, in principle, should dominate the measurement (the $\sin^2 2\theta_{23}$ factor and the flux overall normalization) mostly cancel out. In fact, systematics are dominated by unknown size of the $\theta_{13}$ angle and by the uncertainties on the $\nu_\tau$ cross-section.

A non-zero value of the $\theta_{13}$ mixing angle between the first and third families causes a $\nu_\mu \rightarrow \nu_e$ conversion that enriches the $e$-like sample. The enhancement cannot be corrected by the up/down comparison because it is driven by the same phase $\Delta_{23}$ as for the leading $\nu_\mu \rightarrow \nu_\tau$ oscillations and therefore builds up only for large baselines (up-going). Note also that the systematic shift due to $\theta_{13}$ is asymmetric since, for any value of the angle, it always causes an apparent increase in the statistics of up-going events. Super-Kamiokande estimated this effect to be smaller than 21%. The estimate relies on the present best limit on $\theta_{13}$ from the CHOOZ experiment ($\sin^2 2\theta_{13} < 0.027$ at 90% CL [9, 39]). Since the measurements of $\theta_{13}$ by reactor or long-baseline experiments are uncorrelated with the atmospheric measurement, a significant improvement of this systematics is expected in the next few years, taking advantage of the results from Double-CHOOZ [40], RENO [41], T2K [42], Daya Bay [43] and NOvA.
(see also http://www-nova.fnal.gov [44]). The effect being proportional to \( \sin^2 2\theta_{13} \), we expect such systematics to drop at the level of a few per cent in less than 5 years. In contrast, no major improvements can be anticipated from the other dominant contribution, i.e. knowledge of the \( \nu_\tau \) cross-section. Although this number is immaterial when testing against the no-appearance (null) hypothesis (i.e. the hypothesis corresponding to no evidence for \( \tau \) in the enriched sample), it is of relevance in order to compare the data with the expected rate within the standard three-family oscillation framework. Super-Kamiokande is particularly sensitive to the uncertainty in the cross-section because the oscillated \( \tau \)-events are mostly at low energy, i.e. in the proximity of the sharp rise in the cross-section just beyond the kinematic threshold. This effect is due to the \( E^{-2.7} \) cutoff of the unoscillated \( \nu_\mu \) spectrum. The Super-Kamiokande collaboration estimated the size of contribution comparing different theoretical models [45] and they have shown that it does not exceed 25%.

The 2006 (SuperK-I) analysis provided evidence for \( \tau \) appearance at the 2.4\( \sigma \) level, the best fit of the signal in the \( \tau \)-like sample being \( 138 \pm 48 \) (stat)\(^{-15}_{+32}\) (sys). A priori, the expected sensitivity was about 2\( \sigma \) and a larger rejection power against the null hypothesis has been reached thanks to the larger number of observed events.

In 2001, during the refill after a shutdown aimed at replacing dead PMT, an accident occurred in the Super-Kamiokande detector, which caused the loss of about 60% of the photodetectors. The remaining 20-inch PMT were redeployed in the inner detector (ID), while the PMT of the outer veto were fully rebuilt. In this configuration, which is clearly not optimal for inclusive \( \tau \) search due to the reduced ID coverage (47% of the original one), Super-Kamiokande took data until 2005 (‘SuperK-II’). Still, the atmospheric results obtained during SuperK-II are in good agreement with previous results in both the disappearance [46] and the appearance [47] analyses. The repair of Super-Kamiokande was completed in July 2006 and, since then, full coverage at the inner detector has been restored (‘SuperK-III data taking’). The data taking of this third phase was completed in 2008 and the preliminary SuperK-I, II, III combined data were presented in December 2010 [48]. SuperK-III adds 518 days of statistics at nominal coverage; moreover, the inclusive \( \tau \) appearance analysis has been improved. It now employs a two-dimensional (2D) unbinned likelihood fit that uses the complete distribution of the neural network output instead of a sharp cut (\( >0.5 \)) to distinguish between background-like and \( \tau \)-like topologies. It also makes use of a modified set of inclusive variables with higher sensitivity. The overall expected sensitivity of the new analysis computed from simulation and assuming nominal cross-sections is significantly better than that of 2006 (2.6\( \sigma \) versus 2\( \sigma \)). On top of this, a larger enhancement has been observed in the up-going sample with respect to the down-going reference data. Such enhancement excludes the null hypothesis (no \( \tau \) oscillation) at the 3.8\( \sigma \) level. If these preliminary results are confirmed, we can safely expect that inclusive measurements will dominate the experimental evidence for \( \nu_\mu \rightarrow \nu_\tau \) transitions in the next few years, before the final results of CNGS.

4. Evidence from exclusive measurements

Inclusive analyses try to distil a \( \tau \)-enriched sample in the bulk of \( \nu_\mu \) and \( \nu_e \) interactions and take advantage of the large statistics and of the peculiar kinematics of \( \tau \) decays. Exclusive measurements are even more ambitious since they aim at observing the appearance of \( \tau \) leptons on an event-by-event basis. It necessarily requires a detector with very high spatial resolution, such as to observe the decay in flight of the \( \tau \) and, at the same time, a high-intensity source with an energy well exceeding the kinematic threshold for \( \tau \) production. The only facility that

New Journal of Physics 13 (2011) 083016 (http://www.njp.org/)
is able to fulfil these requirements simultaneously is the CNGS facility in Europe. The CNGS beam [49] is a pure $\nu_\mu$ beam with a mean energy of 17 GeV produced at CERN and pointing to the Gran Sasso Laboratories of INFN in Italy (LNGS), 730 km distant from the source. The intrinsic $\nu_\tau$ contamination, originating mainly from the decay of $D_s$, is negligible ($<10^{-6}$). The beam is also contaminated at 0.8% by $\nu_e$, resulting from the decay in flight of muons along the decay tunnel and from $K_{e3}$ decays. Since the $\tau$ lepton is identified from its decay topology, the background from prompt $\nu_\tau$ is irrelevant.

The observation of $\tau$ leptons at the far detector will thus prove unambiguously that the $\nu_\mu \rightarrow \nu_\tau$ oscillation is the dominant transition channel at the atmospheric scale. This is the main goal of the OPERA experiment [50–52], which was built from 2004 to 2008 [53] in Hall C of LNGS as a far detector for CNGS.

In OPERA, the $\nu_\tau$ appearance signal is detected by the measurement of the decay daughter particles of the $\tau$ lepton produced in CC $\nu_\tau$ interactions. Since the short-lived $\tau$ particle has an average decay length of about 1 mm at the CNGS beam energy, a micrometric detection resolution is needed. In OPERA, neutrinos interact in a large mass target made of lead plates interspaced with nuclear emulsion films acting as high-accuracy tracking devices. This kind of detector is historically called an emulsion cloud chamber (ECC) and has been successfully applied by the DONUT experiment to perform the first direct observation of $\nu_\tau$ CC interactions in a $\nu_\tau$ enriched beam at Fermilab [54].

OPERA is a hybrid detector [55] (see figure 5) made of a veto plane followed by two identical super-modules (SMs). Each SM consists of a target section of about 625 tons made of 75 000 emulsions per lead ECC module, or ‘bricks’, of a scintillator TT detector to trigger and localize neutrino interactions within the target, and of a muon spectrometer. A target brick consists of 56 lead plates of 1 mm thickness interleaved with 57 emulsion films and with a mass of 8.3 kg. Their thickness along the beam direction corresponds to about ten radiation lengths. In order to reduce the emulsion scanning load, CS films have been used. They consist of tightly packed doublets of emulsion films glued to the downstream face of each brick.

Charged particles from a neutrino interaction in a brick cross the CS and produce signals in the TT that allow the corresponding brick to be identified and extracted by an automated system. The hit pattern in the TT provides information on the bricks where the neutrino interaction has occurred. The brick with the largest probability to contain the vertex is, hence, extracted and its CS is detached, developed and scanned. If tracks are found in the CS matching the expectation from TT, the brick is developed and the tracks are traced back up to the interaction vertex. Otherwise the procedure is repeated for the second most probable brick.

Large ancillary facilities are used to bring bricks from the target up to the automatic scanning microscopes at LNGS and various laboratories in Europe and Japan [56, 57]. Extensive information on the OPERA detector and its support facilities is given in [55, 58].

A reconstructed CC event is shown in the bottom panels of figure 6. In this case the dimensions of the event views are of the order of a few millimetres, to be compared with the $\sim10$ m scale of the whole event reconstructed with the electronic detectors (top panels of figure 6).

As mentioned before, the CNGS beam is optimized for the observation of $\nu_\tau$ CC interactions. The average neutrino energy is $\sim17$ GeV. The $\bar{\nu}_\mu$ CC contamination is 2.1%; the $\nu_e$ and $\bar{\nu}_e$ contaminations are less than 1% and, as noted above, the number of prompt $\nu_\tau$ is negligible. With a total CNGS beam intensity of $22.5 \times 10^{19}$ protons on target (p.o.t.), about 24 300 neutrino events would be collected.
The $\tau$ decay channels investigated by OPERA cover all the decay modes. Indeed, the $e$, $\mu$, single-prong (lines 3–5 of table 1) and multi-prong (line 6 of table 1) decays are measured. They are classified into two categories: ‘long’ and ‘short’ decays. Short decays correspond to the cases when the $\tau$ decays in the same lead plate as that in which the neutrino interaction occurred. The $\tau$ candidates are selected on the basis of the impact parameter of the $\tau$ daughter track with respect to the interaction vertex ($\text{IP} > 5$–$20 \mu m$). In the long decay category the $\tau$ does not decay in the same lead plate and its track can be reconstructed in one film. The $\tau$ candidate events are selected on the basis of either the existence of a kink angle between the $\tau$ and the daughter tracks ($\theta_{\text{kink}} > 20 \text{ mrad}$) or the presence of a secondary multi-prong vertex along the $\tau$ track.

In order to improve the signal-to-background ratio, a kinematic analysis is applied to $\tau$ candidates selected on the basis of the topological criteria discussed above. Since for short decay candidates the main background comes from charm production, a lower cut at 2 GeV on the invariant mass of the hadronic system is imposed. This cut reduces the background by more than a factor 1000, while retaining about 15% of the signal. For long decay candidates it is worthwhile to consider leptonic, single-prong and multi-prong decays separately. For leptonic decays soft cuts on the daughter momentum, a lower one to minimize the effect of the particle misidentification ($p > 1 \text{ GeV}$) and an upper one ($p < 15 \text{ GeV}$) to suppress the beam-related background.
Figure 6. Top panels: online display of an event seen by the OPERA electronic detectors (side and top views): a $\nu_\mu$ interacts in one of the first bricks of the first SM, yielding hadrons and a muon that is detected in both SMs and whose momentum is measured by the magnets of the two SMs. Bottom panels: the vertex of the same event observed in the emulsion films (side, top and front views). Note the two $\gamma \rightarrow e^+e^-$ vertices: the opening angle between them is about 300 mrad. By measuring the energy of the $\gamma$s, one obtains a reconstructed invariant mass of $110 \pm 30$ MeV, consistent with the $\pi^0$ mass.

background ($\nu_e$ from the beam and the high-energy $\nu_\mu$ tail of CNGS), and a soft cut on the measured transverse momentum ($p_T$) at the decay vertex are enough to reduce background to a reasonable level. The applied cut at the decay vertex is $p_T > 100$ MeV and $p_T > 250$ MeV for the electronic and muonic decay channels, respectively.

For the single-prong decay the kinematic analysis is slightly more complicated. The main background for this channel originates from the reinteraction of primary hadrons without any visible recoil at the reinteraction vertex. In order to keep the background for this channel as low as possible, kinematic cuts are applied both at the decay and at the primary vertex. The kinematic analysis is qualitatively similar to that of the electronic and muonic channels. However, the cut applied to the $p_T$ is harder ($p_T > 300$ MeV if a $\gamma$ is attached to the decay vertex and $p_T > 600$ MeV otherwise) and the daughter particle is required to have a momentum larger than 2 GeV. The kinematic analysis at the primary vertex uses the variables $p_T^{\text{mass}}$, defined as the missing transverse momentum at the primary vertex, and $\phi$, which is the angle in the transverse plane between the parent track and the shower direction. Due to the unobserved
outgoing neutrino, $p_T^{\text{miss}}$ is expected to be large in NC interactions. Conversely, it is expected to be small in CC interactions. For $\tau$ candidates the measured $p_T^{\text{miss}}$ is required to be lower than 1 GeV. The $\phi$ angle is expected to peak at $\pi$, because the $\tau$ and the hadronic shower are back-to-back in the transverse plane. In contrast, the hadron mimicking a $\tau \to h$ decay is produced inside the hadronic shower in NC interactions. Therefore, $\phi$ peaks near 0, and for $\tau$ candidates the $\phi$ angle is required to be larger than $\pi/2$.

For the multi-prong decay channel the main background is given by multi-prong decay of charmed particles. The hadronic reinteraction background is not a major issue. Indeed, the probability for a hadron to undergo an interaction with multi-prong is much smaller (1–2 orders of magnitude) than for single-prong interactions. The signal-to-background ratio is enhanced by performing a kinematic analysis mainly based on the following variables: $p_T^{\text{miss}}$, defined as the missing transverse momentum at the primary vertex, the invariant mass of the hadronic system and the total energy of the event.

In [59], the OPERA Collaboration reported the observation of a first candidate $\nu_\tau$ CC interaction in the detector. The primary neutrino interaction consists of seven tracks of which one exhibits a visible kink. Two electromagnetic showers due to $\gamma$-rays have been located; they are clearly associated with the event and were produced at the decay vertex. Figure 7 shows a display of the event, which was identified in a sample corresponding to $1.89 \times 10^{19}$ p.o.t.
in the CNGS $\nu_\mu$ beam. The total transverse momentum $p_T$ of the daughter particles with respect to the parent track is $(0.47^{+0.24}_{-0.12})$ GeV, above the lower selection cutoff at 0.3 GeV. The missing transverse momentum $p_T^{\text{miss}}$ at the primary vertex is $(0.57^{+0.32}_{-0.17})$ GeV. This is lower than the upper selection cutoff at 1 GeV. The angle $\Phi$ between the parent track and the rest of the hadronic shower in the transverse plane is equal to $(3.01 \pm 0.03)$ rad, largely above the lower selection cutoff fixed at $\pi/2$. The invariant mass of $\gamma$-rays is $(120 \pm 20(\text{stat.}) \pm 35(\text{syst.}))$ MeV $^2$, supporting the hypothesis that they originate from a $\pi^0$ decay. Similarly, the invariant mass of the charged decay product assumed to be a $\pi^-$ and of the two $\gamma$-rays is $(640^{+125}_{-80}(\text{stat.})^{+100}_{-90}(\text{syst.}))$ MeV, which is compatible with the $\rho(770)$ mass. The branching ratio of the decay mode $\tau \to \rho^- \nu_\tau$ is about 25%. The observation of one possible $\tau$ candidate in the decay channel $h^- (\pi^0) \nu_\tau$ has a significance of 2.36$\sigma$ of not being a background fluctuation from a background of 0.018 $\pm$ 0.007. If one considers all decay modes included in the search, corresponding to $0.54 \pm 0.13$ expected $\tau$s, the significance of the observation becomes 2.01$\sigma$ from the total predicted background of 0.045 $\pm$ 0.023.

5. Future experiments

5.1. $\tau$ appearance in the standard oscillation scenario

The role of $\tau$ appearance as a direct proof of oscillations is unique. In the standard three-family framework, precision measurements of the leading oscillation parameters $\theta_{12}, \theta_{33}, \Delta m^2_{31}$ and $\Delta m^2_{23}$ can be made more easily by studying the disappearance of solar+reactor $\nu_e$ and atmospheric+accelerator $\nu_\mu$. Similarly, the unknown angle $\theta_{13}$ and the CP violating phase $\delta$ will likely be addressed by studying subdominant $\nu_\mu \to \nu_\tau$ (or $\nu_\tau \to \nu_\mu$) oscillations at the atmospheric scale. That is why there are no facilities that have been pursued since 1998 and that are specifically tuned for precision measurements of $\nu_\mu \to \nu_\tau$ transitions. In fact, among the many setups proposed to study CP violation in the leptonic sector, just a few setups [60, 61] work beyond the kinematic threshold for $\tau$ production. The most prominent are the neutrino factories [60], where neutrinos are produced by the decay-in-flight of muons or antimuons. (Anti)muons produce final-state neutrinos from the decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$. The neutrino factories allow for the study of the transition $\nu_e \to \nu_\mu$ if one identifies the signal of ‘wrong sign’ muons coming from $\nu_\mu$ CC events in the bulk of ‘right-sign’ muons originating from $\bar{\nu}_\mu$ CC interactions. As a consequence, the most natural far detector for the neutrino factory is a high-density magnetized calorimeter [62] with outstanding charge reconstruction capabilities. The need of charge identification efficiencies well above 99.9% requires a strong muon energy cut to filter punch-through pions or pions that have decayed in flight. In the classic high-energy neutrino factory configuration [63, 64], 50 GeV muons are accelerated and stacked in a decay ring, producing $\nu_e$ of $\sim$30 GeV energy. In order to achieve charge misidentification of $O(10^{-4})$, a tight muon energy cut is applied so that the detector efficiency drops to zero at energies below 10 GeV. For typical baselines of 2000 km, it means that the peak of the oscillation (neutrinos where $\Delta m^2_{32}L/4E \approx \pi/2$) remains completely unobserved in the neutrino factories, as well as in CNGS. Such a tight cut is the origin of one of the main drawbacks of the neutrino factories: unlike more traditional setups that study $\nu_e\nu_\mu$ transitions at the oscillation peak (‘Superbeams’), a strong parameter degeneracy appears once we go from the measurement of the $\nu_\mu \to \nu_e$ and $\bar{\nu}_e \to \nu_\mu$ probabilities to the determination of the $\delta$ and $\theta_{13}$ angles (‘intrinsic degeneracy’ [65]). The degeneracy is particularly severe for $\sin^2 2\theta_{13} \simeq 10^{-3}$, i.e. in a region where the performance
of the neutrino factory should be unbeatable with respect to Superbeams [63] or Betabeams [66].

\[ \tau \] appearance can help us to overcome this drawback, at the price of a dedicated detector located at a shorter baseline and specifically aimed at observing \( \nu_e \rightarrow \nu_\tau \) transitions.

In fact, an emulsion-based detector similar to OPERA can make this measurement identifying ‘wrong sign’ muons in the magnetic spectrometer and tracing back the particle up to lead-emulsion or iron-emulsion bricks to observe the appearance of a decay kink \[ \text{[67]}. \]

The pattern of \( \nu_e \rightarrow \nu_\tau \) (\( P_{e\tau} \)) closely resembles the one of \( \nu_e \rightarrow \nu_\mu \) (\( P_{e\mu} \)). If we expand the \( \nu_\mu \) appearance probability to second order in \( \sin 2\theta_{13} \) and the hierarchy parameter \( \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \simeq 0.03 \) [68], we obtain

\[
P_{e\mu} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 [(1 - \hat{A}) \Delta_{31}]}{(1 - \hat{A})^2} \]

\[
\pm \alpha \sin 2\theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin(\Delta_{31}) \frac{\sin(\hat{A} \Delta_{31}) \sin[(1 - \hat{A}) \Delta_{31}]}{\hat{A}} \frac{\sin[(1 - \hat{A}) \Delta_{31}]}{(1 - \hat{A})}
\]

\[
+ \alpha \sin 2\theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta_{31}) \frac{\sin(\hat{A} \Delta_{31}) \sin[(1 - \hat{A}) \Delta_{31}]}{\hat{A}} \frac{\sin[(1 - \hat{A}) \Delta_{31}]}{(1 - \hat{A})}
\]

\[
+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A} \Delta_{31})}{\hat{A}^2}.
\]

Here, \( \Delta_{31} \equiv \Delta m^2_{31} L/(4E) \) and \( \hat{A} = \pm 2 \sqrt{2} E G_F n_e/\Delta m^2_{31} \), \( G_F \) and \( n_e \) being the Fermi constant and the electron density in the earth crust, respectively. The signs in the second term and \( \hat{A} \) are positive for neutrinos and negative for anti-neutrinos. On the other hand, in \( P_{e\tau} \) the signs of the second and third terms are flipped and the replacement \( \sin^2 \theta_{23} \leftrightarrow \cos^2 \theta_{23} \) takes place in the first and fourth terms. In particular, for maximal atmospheric mixing, only the signs of the second and third terms change. As a consequence, measurement of the ‘golden channel’ \( \nu_e \rightarrow \nu_\mu \), of its CP conjugate \( \bar{\nu}_e \rightarrow \bar{\nu}_\mu \) and of the additional transition \( \nu_e \rightarrow \nu_\tau \) (‘silver channel’) can solve the intrinsic degeneracy for values of \( \theta_{13} \) larger than 1° and \( \simeq 5 \) kilotons of detector mass [69].

More recently, it was pointed out that a significant improvement in the neutrino factory performance could be achieved by relaxing the energy cut to smaller values and putting up with a worse charge identification efficiency below 10 GeV [70, 71]. In this region, however, \( \tau \) appearance still plays an important role [72]. For coarse-grained detectors such as magnetized iron calorimeters, the golden channel is highly contaminated by unidentified silver channel events [73], i.e. \( \nu_e \rightarrow \nu_\tau \) transitions where the \( \tau \) decays in \( \mu \bar{\nu}_\mu \nu_e \). The detector reconstructs the events as standard ‘wrong sign’ muons although the actual neutrino energy shows poor correlation with the measured muon momentum, due to the large missing energy in \( \tau \rightarrow \mu \bar{\nu}_\mu \nu_e \). Hence, the silver channel populates the golden signal region as a broad-band background and introduces a large systematic error in the extraction of \( \theta_{13} \) and the CP violating phase [73]. Still, once the silver channel ‘background’ is accounted for in the fits of the golden event spectra, the correct values of the parameters can be recovered [71] and, in addition, the problem of the degeneracies is further relieved due to the lowering of the muon energy cut. Clearly, consistency among these spectra, which entangles subdominant \( \nu_e \rightarrow \nu_\tau \) and \( \nu_e \rightarrow \nu_\mu \) oscillations, would be an impressive test for the standard three-family interpretation of leptonic mixing, even without an explicit observation of a \( \nu_e \rightarrow \nu_\tau \) sample.
5.2. $\tau$ appearance and non-standard interactions

Mass-generation mechanisms for neutrinos naturally produce perturbations in the standard model couplings of these particles, referred to as non-standard interactions (NSI). Broadly speaking, NSI can manifest themselves in two different ways. If they perturb CCs they can affect neutrino production and detection; conversely, if they modify NCs, they affect neutrino propagation.

If we consider NSI in the production and detection mechanisms, then the NSI themselves can be parameterized as a small mixture of the wrong flavour $\nu_\beta$ to a neutrino produced or detected in association with a charged lepton $\alpha$, i.e.

$$\nu'_\alpha = \nu_\alpha + \sum_{\beta = e, \mu, \tau} \varepsilon_{\alpha\beta} \nu_\beta,$$

where the parameters $\varepsilon$ give the strength of the NSI relative to the standard weak interactions. Here, a short distance between the source and the detector is mandatory in order to minimize the oscillation probability and therefore enhance the NSI contribution. On the other hand, long-baseline neutrino experiments mainly constrain NSI affecting NC since these NSI perturb neutrino oscillation in matter at macroscopic distances. In this case, NSI appear in the Hamiltonian describing neutrino propagation in matter:

$$\mathcal{H} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \frac{1}{2E} \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \mathcal{H}_{\text{NSI}},$$

where $U$ is the leptonic mixing matrix and $V = \sqrt{2} G_F n_e$ is the contribution arising from ordinary matter effects (the Mikheyev–Smirnov–Wolfenstein effect \[74\]), $G_F$ being the Fermi constant and $n_e$ the density of electrons in the medium.

NSI can be simply induced by non-unitarity of the leptonic mixing matrix, e.g. in seesaw models—or caused by one-loop exchange of new particles—e.g. by spinless bosons in supersymmetric models \[75\]. If the scale of new physics is high, these effects are small but models where NSI are significantly enhanced are possible and have been investigated in the literature. In the 1990s, the study of these models was boosted by a possible non-oscillation explanation of the solar neutrino puzzle \[76\]. In recent years, both the hint of a non-zero value of $\theta_{13}$ from solar data and the Miniboone anomalies \[77, 78\] have revived interest in NSI, which can now act as a sub-dominant contribution to neutrino oscillations \[79–81\]; as a consequence, a precision measurement campaign is considered mandatory. Since precision oscillation physics is a young field of research, limits on NSI affecting the propagation of neutrinos are rather loose. On the other hand, more stringent bounds can be drawn from processes that involve the production and detection of neutrinos in short baseline experiments or radiative contributions to rare decays \[82\].

Even accounting for short-baseline experiments, current model-independent bounds on $\varepsilon$ are quite loose—$\mathcal{O}(0.1–1)$. Here, a new generation of high-precision experiments at short baselines would represent the ideal tool for probing much smaller values of $\varepsilon$.

Clear evidence for NSI working at production and detection would be the measurement of non-unitarity \[83\] of the leptonic mixing matrix. A possible approach to investigate the non-unitarity is to measure all oscillation probabilities $P(\nu_\mu \rightarrow \nu_\mu)$, $P(\nu_\mu \rightarrow \nu_e)$, $P(\nu_\mu \rightarrow \nu_\tau)$ (or...
\( P(v_e \rightarrow v_\mu), P(v_e \rightarrow v_\nu), P(v_e \rightarrow v_\tau) \) and check that they sum up to one. In this case, the best approach would be to build a dedicated near detector for measuring all oscillation channels.

Indeed, neutrino oscillations constitute an irreducible background for such possible rare processes. Nevertheless, the short-baseline choice has the drawback that the NSI signal is given by the product of the production and detection mechanisms. In order to disentangle the two mechanisms it is important to exploit different neutrino sources and as many final states as possible. In this respect, it is useful to exploit high-energy neutrino beams where the \( \tau \) production yield increases with the neutrino energy and, therefore, final states with \( \tau \) leptons can be studied. This consideration motivated proposals [84] for a new generation of short-baseline experiments in \( \tau \) appearance mode. They are aimed at precisions better than \( 10^{-6} \) to investigate theory-driven enhancements of NSI: at these baselines, the dominant contributions come from the production/detection of neutrinos, while propagation effects are negligible.

If the propagation mechanism is affected by NSI, then long-baseline experiments are required. In general, these experiments compete with the information that can be drawn from current atmospheric data [79, 85], but the purity of the source can be fruitfully employed to tighten some bounds. In particular, \( \tau \) appearance in OPERA can be used to improve our knowledge of \( \epsilon_{\mu\tau} \) [86], whereas the CNGS statistics is too poor to impact bounds on \( \epsilon_{\tau\tau} \) or \( \epsilon_{\tau\nu} \) [87]. Large statistics \( \tau \) appearance experiments where matter effects are dominant and therefore NSI due to propagation are sizable are possible only in the framework of the neutrino factories (see section 5.1). A systematic assessment of the performance of these facilities with respect to NSI has been carried out in [88]. Here, the use of the \( \tau \) appearance channel, the ‘silver channel’ of section 5.1, is relevant only for high-energy neutrino factories with muon energies larger than \( \sim 25 \text{ GeV} \) and its sensitivity is mainly limited to \( \epsilon_{\tau\nu} \).

5.3. \( \tau \) appearance and sterile neutrinos

The possible confirmation of the LSND anomaly [89] by the MiniBoone antineutrino data [78] makes the study of hypothetical neutrinos that are singlet under the electroweak gauge groups, sterile neutrinos, a very lively field of research. It is therefore interesting to assess the contribution of the \( \tau \) appearance channel to the clarification of this issue, at least in the simplest scenarios where just one sterile neutrino is added to the three active families, the \((3+1)\) scheme. Unfortunately, this oversimplified scheme is not able to account for all experimental data and the current global fit is very poor. More sophisticated models (see e.g. [90]) show better agreement with the data, but the \((3+1)\) scheme illustrates the experimental challenges very well. Moreover, many of the considerations in section 5.2 hold for sterile neutrino searches, too. The impact of \( \nu_\mu \rightarrow \nu_\tau \) appearance searches in the framework of the \(3+1\) scheme has been studied for both conventional [91] and neutrino factory beams [92, 93]. In the first case, if the OPERA detector is exposed to the nominal CNGS beam intensity, a null result can slightly improve the present bound on \( \theta_{13} \) but not those on the active–sterile mixing angles, \( \theta_{14}, \theta_{24} \) and \( \theta_{34} \). If the beam intensity is increased by a factor of 2 or beyond, not only the sensitivity to \( \theta_{13} \) increases accordingly, but also significant sensitivity to \( \theta_{24} \) and \( \theta_{34} \) can be achieved. The \( \theta_{24} \) and \( \theta_{34} \) sensitivities strongly depend on the value of the CP-violating phase \( \delta_3 \), highest sensitivities being available for \( \delta_3 \approx \pi/2 \). In order to attain significant improvement of \( \theta_{13} \), the

\[ \text{For a definition of the } \epsilon \text{ couplings relevant for neutrino propagation, see e.g. [79].} \]

\[ \text{This angle is different from the } \theta_{13} \text{ angle defined in section 1. It represents the mixing angle between the first and third families in a three active neutrino+one sterile neutrino mixing scheme.} \]
angle should better be constrained by high-intensity $\nu_e$ disappearance experiments. Once more (see section 5.2), OPERA is limited by the small detector mass. It is, however, very interesting to note that the sensitivity of OPERA to $\theta_{13}$ and to the other angles of the $3+1$ model mainly comes from the study of $\nu_\mu \rightarrow \nu_\tau$ transitions, whereas the corresponding sensitivity due to $\nu_\mu \rightarrow \nu_e$, the CP conjugate of the LSND measurement, is marginal. This is due to the rather large baseline compared with LSND/Miniboone and to the additional constraints coming from the Super-Kamiokande atmospheric data.

Clearly, the results that can be obtained at a neutrino factory are much better than those obtained by exploiting the CNGS beam, even assuming a major upgrade of the facility [91]. As for the case of the silver channel (section 5.1), the setup must be equipped with a massive OPERA-like detector; the ideal baseline is, nevertheless, $\sim 3000$ km, i.e. the detector can be positioned in the same underground site as for the magnetized calorimeter. In this case, the detector seeks ‘right sign’ muons in coincidence with a decay kink, i.e. it measures the leading $\nu_\mu \rightarrow \nu_\tau$ transition, which is sometimes called the ‘discovery channel’, in contrast with the $\nu_e \rightarrow \nu_\tau$ silver channel of section 5.1. Further improvements can be achieved by exploiting magnetized ECCs [94, 95] made of iron bricks and photographic films. The magnetization of the iron allows for sign measurement of the final state particles even in the occurrence of muon-less $\tau$ decays. A viable alternative to the study of $\tau$ appearance seems, however, to be the exploitation of near detectors located close to the muon decay ring [93], especially if $\Delta m_{41} \gg \Delta m_{31}$.

6. Conclusions

The search for an explicit observation of flavour changing neutrino oscillations by identifying a different lepton than that of the initial flavour has a decades-long history. In 1998 it became clear that the bulk of oscillations at atmospheric scale is probably constituted by $\nu_\mu \rightarrow \nu_\tau$ transitions: this consideration has boosted enormously the search for $\tau$ appearance in long-baseline experiments with both natural and artificial sources. Between 2006 and 2010, Super-Kamiokande and OPERA gained evidence for such a transition using quite different techniques, and significant improvements are expected in the next few years. Although no dedicated facilities for precision measurements of $\tau$ appearance have been designed so far, it is clear that the study of $\nu_\mu \rightarrow \nu_\tau$ will play a relevant role in any experiment operating beyond the kinematic threshold for $\tau$ production and especially in the far detectors of the neutrino factories. Novel short-baseline experiments along the lines of CHORUS and NOMAD can be of interest beyond the standard three-family oscillation scenario, mainly for precision searches of non-standard interactions.

Acknowledgments

We are grateful to Andrea Donini, Antonio Ereditato and Chris Walter for many useful discussions and a careful reading of the manuscript.

References

[1] Giunti C and Kim C W 2007 Fundamentals of Neutrino Physics and Astrophysics (Oxford: Oxford University Press)
[2] Pontecorvo B 1957 Sov. Phys.—JETP 6 429
  Pontecorvo B 1957 Zh. Eksp. Teor. Fiz. 33 549

New Journal of Physics 13 (2011) 083016 (http://www.njp.org/)
Pontecorvo B 1968 Sov. Phys.—JETP 6 984
Pontecorvo B 1967 Zh. Eksp. Teor. Fiz. 53 1717

[3] Katayama Y, Matunoto K, Tanaka S and Yamada E 1962 Prog. Theor. Phys. 28 675
Maki Z, Nakagawa M and Sakata S 1962 Prog. Theor. Phys. 28 870
Pontecorvo B 1968 Sov. Phys.—JETP 26 984
Pontecorvo B 1967 Zh. Eksp. Teor. Fiz. 53 1717

Grigor V N and Pontecorvo B 1969 Phys. Lett. B 28 493

[4] Schwetz T, Tortola M A and Valle J W F 2008 New J. Phys. 10 113011

[5] Adamson P et al (MINOS Collaboration) 2011 Measurement of the neutrino mass splitting and flavor mixing by MINOS arXiv:1103.0340 [hep-ex]

[6] Abe S et al (KamLAND Collaboration) 2008 Phys. Rev. Lett. 100 221803

[7] Ahn M H et al (K2K Collaboration) 2003 Phys. Rev. Lett. 90 041801
Ahn M H et al (K2K Collaboration) 2006 Phys. Rev. D 74 072003

[8] Michael D G et al (MINOS Collaboration) 2006 Phys. Rev. Lett. 97 191801
Adamson P et al (MINOS Collaboration) 2008 Phys. Rev. D 77 072002
Adamson P et al (MINOS Collaboration) 2008 Phys. Rev. Lett. 101 131802

[9] Apollonio M et al (CHOOZ Collaboration) 2003 Eur. Phys. J. C 27 331

[10] Boehm F et al (Palo Verde Collaboration) 2001 Phys. Rev. D 64 112001

[11] Mezzetto M and Schwetz T 2010 J. Phys. G: Nucl. Part. Phys. 37 103001

[12] Nakamura K and Petcov S T (Particle Data Group) 2010 J. Phys. G: Nucl. Part. Phys. 37 075021

[13] Harrison P F, Perkins D H and Scott W G 2002 Phys. Lett. B 530 167

[14] Minkowski P 1977 Phys. Lett. B 67 421

Yanagida T 1979 Proc. Workshop on the Unified Theory and the Baryon Number in the Universe ed O Sawada and A Sugamoto (Tsukuba, Japan: KEK) p 95
Gell-Mann M, Ramond P and Slansky R 1979 Supergravity ed P van Nieuwenhuizen and D Z Freedman (Amsterdam: North-Holland) p 315
Glashow S L 1980 Proc. 1979 Cargese Summer Institute on Quarks and Leptons (New York: Plenum) p 687
Mohapatra R N and Senjanovic G 1980 Phys. Rev. Lett. 44 912

[17] Altegoer J et al (NOMAD Collaboration) 1998 Nucl. Instrum. Methods A 404 96

[18] Eskut E et al (CHORUS Collaboration) 1997 Nucl. Instrum. Methods A 401 7

[19] Hejine E 1983 CERN Yellow Report 83-06
Acquistapace G et al 1995 CERN Preprint CERN-EC/F95-14
Casagrande L et al 1996 CERN Yellow Report 96-06

[20] Abgrall N et al 2010 Time projection chambers for the T2K near detectors arXiv:1012.0865 [physics.ins-det]

[21] Ushida N et al (FERMILAB E531 Collaboration) 1986 Phys. Rev. Lett. 57 2897

[22] McFarland K S et al 1995 Phys. Rev. Lett. 75 3993

[23] Aoki S et al 2000 Nucl. Instrum. Methods A 447 361

[24] Annis P et al (CHORUS Collaboration) 1998 Nucl. Instrum. Methods A 412 19

[25] Bergsma F et al 1995 Nucl. Instrum. Methods A 357 243

[26] Uiterwijk J W E et al 1998 Nucl. Instrum. Methods A 409 682

[27] Di Capua E et al 1996 Nucl. Instrum. Methods A 378 221

[28] Eskut E et al (CHORUS Collaboration) 2008 Nucl. Phys. B 793 326

[29] Aster P et al (NOMAD Collaboration) 2001 Nucl. Phys. B 611 3

[30] Fukuda Y et al (Super-Kamiokande Collaboration) 1998 Phys. Rev. Lett. 81 1562

[31] Ashie Y et al (Super-Kamiokande Collaboration) 2004 Phys. Rev. Lett. 93 101801
Ambrosio M et al (MACRO Collaboration) 2001 Phys. Lett. B 517 59
Sanchez M et al (Soudan 2 Collaboration) 2003 Phys. Rev. D 68 113004

New Journal of Physics 13 (2011) 083016 (http://www.njp.org/)
[32] Fukuda S et al (Super-Kamiokande Collaboration) 2000 Phys. Rev. Lett. 85 3999
Adams P et al (MINOS Collaboration) 2008 Phys. Rev. Lett. 101 221804
[33] Ashie Y et al (Super-Kamiokande Collaboration) 2004 Phys. Rev. Lett. 93 101801
[34] Pasquali L and Reno M H 1999 Phys. Rev. D 59 093003
[35] Abe K et al (Super-Kamiokande Collaboration) 2006 Phys. Rev. Lett. 97 171801
[36] Rubbia C 1977 The liquid argon time projection chamber: a new concept for neutrino detector Report CERN-EP/77-08
[37] Amerio S et al (ICARUS Collaboration) 2004 Nucl. Instrum. Methods A 527 329
Menegoli A et al (ICARUS Collaboration) 2010 J. Phys. Conf. Ser. 203 012107
[38] Schwetz T, Tortola M A and Valle J W F 2008 New J. Phys. 10 113011
[39] Itow Y et al (T2K Collaboration) 2001 arXiv: hep-ex/0106019
[40] Guo X et al (Daya-Bay Collaboration) 2007 arXiv: hep-ex/0701029
[41] Acquafredda R et al (OPERA Collaboration) 2006 arXiv: hep-ex/0606025
[42] Agafonova N et al (OPERA Collaboration) 2009 J. Instrum. 4 P07005
[43] Acquafredda R et al (OPERA Collaboration) 2006 New J. Phys. 8 303
Agafoeva N et al (OPERA Collaboration) 2009 J. Instrum. 4 P06020
[44] Kodama K et al (DONUT Collaboration) 2005 Phys. Rev. D 72 052002
[45] Musial K et al (DONUT Collaboration) 2006 Phys. Rev. D 74 032001
[46] Arrenis A et al (PICe Collaboration) 2007 New J. Phys. 9 033005
[47] Musial K et al (DONUT Collaboration) 2006 Phys. Rev. D 74 052002
[48] Acquafredda R et al (OPERA Collaboration) 2006 Phys. Lett. B 650 496
[49] Agafonova N et al (OPERA Collaboration) 2008 J. Instrum. 3 P03018
[50] Armenise N et al 2002 Nucl. Instrum. Methods A 501 247
[51] De Serio M et al 2005 Nucl. Instrum. Methods A 551 261
Arrabito L et al 2006 Nucl. Instrum. Methods A 568 578
[52] Morishima K and Nakano T 2010 J. Instrum. 5 P04011
[53] Anokhina A et al (OPERA Collaboration) 2008 J. Instrum. 3 P07002
[54] Anokhina A et al (OPERA Collaboration) 2008 J. Instrum. 3 P07005
[55] Nakamura T et al (OPERA Collaboration) 2006 Nucl. Instrum. Methods A 577 523
[56] Kato T 2007 PhD Thesis Stony Brook University (available at http://www-sk.icrr.u-tokyo.ac.jp/sk/pub/index.html)
[57] Wendell R 2010 Talk at 11th Int. Workshop on Next Generation Nucleon Decay and Neutrino Detectors (Toyama, 13–16 December, 2010)
[58] Elsener K (ed) 1998 The CERN neutrino beam to Gran Sasso (conceptual technical design) Report CERN-98-02, INFN/AE-98/05
Bailey R et al 1999 The CERN neutrino beam to Gran Sasso (NGS) (addendum to report CERN 98-02, INFN/AE-98/05) Report CERN-SL/99-034(DI), INFN/AE-99/05
[59] Ereditato A, Niwa K and Strolin P 1997 The emulsion technique for short, medium and long baseline $\nu_\mu \to \nu_\tau$ oscillation experiments Report 423, INFN-AE-97-06, DAPNU-97-07
Shibuya H et al (OPERA Collaboration) 1997 Letter of intent: the OPERA emulsion detector for a long-baseline neutrino-oscillation experiment Report CERN-SPSC-97-24, LNGS-LOI-8-97
[60] Guler M et al (OPERA Collaboration) 2000 An appearance experiment to search for $\nu_\mu \to \nu_\tau$ oscillations in the CNGS beam: experimental proposal Report CERN-SPSC-2000-028, LNGS P25/2000
[61] Guler M et al (OPERA Collaboration) 2001 Status Report on the OPERA Experiment CERN/SPSC 2001-025, LNGS-EXPO30/2001 add. 1/01
[62] Acquafredda R et al (OPERA Collaboration) 2006 New J. Phys. 8 303
[63] Kodama K et al (DONUT Collaboration) 2005 J. Instrum. 4 P04018
[64] Armenise N et al 2005 Nucl. Instrum. Methods A 551 261
De Serio M et al 2005 Nucl. Instrum. Methods A 554 247
Arrabito L et al 2006 Nucl. Instrum. Methods A 568 578
[65] Armenise N et al 2005 Nucl. Instrum. Methods A 551 261
De Serio M et al 2005 Nucl. Instrum. Methods A 554 247
Arrabito L et al 2006 Nucl. Instrum. Methods A 568 578
[66] Morishima K and Nakano T 2010 J. Instrum. 5 P04011
[67] Anokhina A et al (OPERA Collaboration) 2008 J. Instrum. 3 P07002
[68] Anokhina A et al (OPERA Collaboration) 2008 J. Instrum. 3 P07005
Adam T et al (OPERA Collaboration) 2007 Nucl. Instrum. Methods A 577 523
Nakamura T et al (OPERA Collaboration) 2006 Nucl. Instrum. Methods A 556 80

New Journal of Physics 13 (2011) 083016 (http://www.njp.org/)
[91] Donini A, Maltoni M, Meloni D, Migliozzi P and Terranova F 2007 J. High Energy Phys. JHEP12(2007)013
[92] Donini A, Fuki K, Lopez-Pavon J, Meloni D and Yasuda O 2009 J. High Energy Phys. JHEP08(2009)041
[93] Meloni D, Tang J and Winter W 2010 Phys. Rev. D 82 093008
[94] Abe T et al (ISS Detector Working Group Collaboration) 2009 J. Instrum. 4 T05001
[95] Fukushima C, Kimura M, Ogawa S, Shibuya H, Takahashi G, Kodama K, Hara T and Mikado S 2008 Nucl. Instrum. Methods A 592 56