THE APPEARANCE OF THE TAU-NEUTRINO

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After three years of running in the INFN Gran Sasso underground laboratory (LNGS), and billions of billions of muon-neutrinos sent from CERN in the CNGS beam, the OPERA detector, located 730 km away from CERN, has catched a first candidate event for the direct transformation (oscillation) of a muon-neutrino into a tau-neutrino. This achievement allows researchers to see good prospects for the final goal of OPERA: the long-awaited discovery of the "appearance" of neutrino oscillations.

1 Recent and less recent history

On August 22nd, 2009 at 19:27 (UTC) the event number 9234119599 was taken by the data acquisition system of the OPERA experiment at the LNGS underground laboratory, during a run in the CNGS neutrino beam, sent from CERN over a baseline of 730 km. Up to that time, a few 10^{19} muon-neutrinos had been sent from CERN from the beginning of the experiment. According to a well-established and complex analysis chain, the signals from the real-time electronic detectors first allowed to predict which one of the 150 000 "bricks" of the lead/emulsion target was hit. The interface emulsion films attached to that brick were then extracted and scanned and three tracks were found to be compatible with the signals of the downstream electronic trackers. This provided the trigger to the exposure of the brick to cosmic rays for the precision alignment of the 57 emulsion films that constitute the brick lead/emulsion sandwich and to the opening of the light-tight brick package.

The emulsion films were developed and shipped to one of the 12 scanning labs of the international collaboration, where, starting from the most downstream film, the track predictions from the interface films were searched for, and one by one extrapolated upstream until a neutrino interaction vertex was finally found. A 40 mrad kink was detected on a track generated from the neutrino interaction in one of the 56 lead plates, after a flight length of ~1.3 mm, while all the other tracks were found to match within a few μm impact parameter. A full volume scan around the vertex region allowed finding a total of 8 tracks and two electromagnetic showers induced by two γ-rays pointing to the decay vertex. The γ energy was measured. The two γ's were found to have an invariant mass compatible to that of the π^0 (120 ± 20 ± 30 MeV).

Following this finding, several additional bricks were removed and scanned, to follow down all the primary tracks in order to determine their nature and measure the momentum by the Multiple Coulomb Scattering method. The films of the brick with the neutrino vertex were shipped to another laboratory to perform an independent measurement of the track parameters, with a different scanning system and method. A careful visual check of the

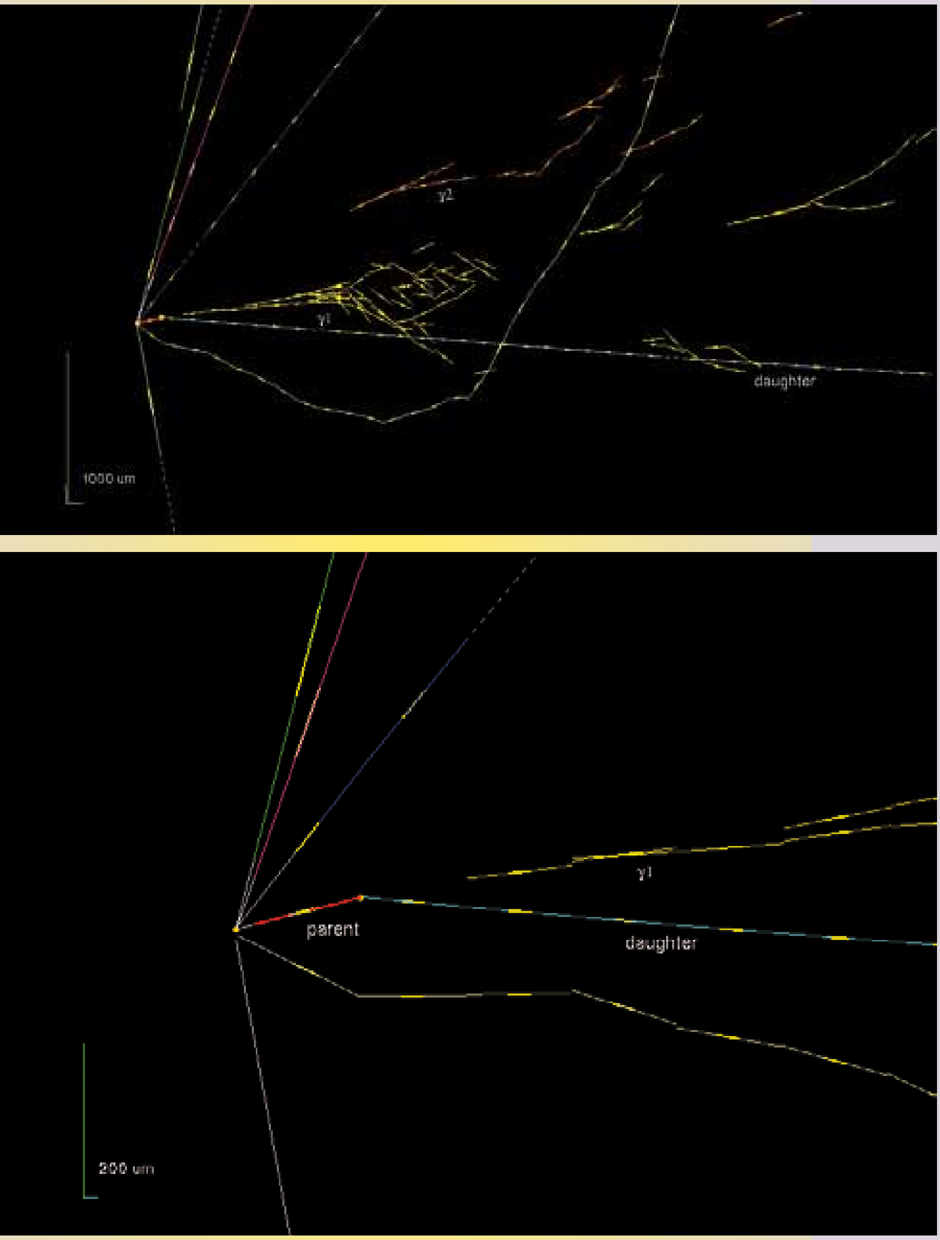

Fig. 1 Top: display of the first OPERA ν_τ candidate event. The "tau" (red short track) decays into a hadron (light blue track) with the characteristic "kink" topology; bottom: a zoom of the vertex region.

kink (decay?) region allowed excluding the presence of micro-tracks that could be potentially attributed to a hadronic interaction generating a kink, topologically similar to what occurs for a decay. The absence of tracks that could be attributed to muons and the fulfillment of all the stringent kinematical cuts required to reject known sources of background, finally allowed the event to be classified as a candidate $\nu_\tau \rightarrow \tau \rightarrow \pi^0$ + charged hadron + ν_τ event. A computer-reconstructed display of the event is shown in fig. 1.

The estimate of the residual background yielded 0.018 ± 0.007 expected events within the statistics of scanned events. This implies that the probability of explaining the observed event (one over about 1000 fully analyzed) in terms of a background fluctuation turns out to be about 1.8%, for a 2.36 σ statistical significance for the observation of a first ν_τ candidate event from ν_μ oscillations in the OPERA experiment. This is just a first candidate, but with a handful more events like this, OPERA will be in the position of claiming the long-awaited discovery of neutrino oscillations in appearance mode.

This apparently short story took actually quite long, several months, during which many checks, measurements, discussions, simulations, etc. took place and converged into a seminar given at LNGS on May 31st, 2010 [1], repeated a few days later at CERN, Fermilab and Nagoya.

We can certainly state that this first ν_τ candidate event, despite its relatively limited statistical significance, is a crucial milestone for the OPERA Collaboration. Neutrino oscillation direct appearance is indeed still one of the missing tiles of the neutrino oscillation scenario, that after many years of controversial and not conclusive results got a convincing confirmation in 1998 with the discovery of oscillations with atmospheric neutrinos, thanks to the beautiful results from the Super-Kamiokande experiment [2].

The oscillation between neutrino weak eigenstates (ν_e, ν_μ and ν_τ) can occur if the neutrino is a massive particle, and therefore mass eigenstates (ν_1, ν_2 and ν_3) exist. The two sets of eigenstates mix through a mixing matrix, and one can then obtain a periodic flavour variation of a given neutrino during its propagation in space and time (oscillation), provided that the corresponding mass eigenvalues are not degenerate.

Neutrino oscillations were originally proposed by Bruno Pontecorvo (fig. 2), initially for the neutrino-antineutrino oscillation mode, around the end of the Fifties of the last century (note that at that time only one neutrino flavour was known) [3]. A few years later, after the discovery of the ν_μ [4], a more general flavour-mixing scheme between ν_e and ν_μ with two states called "true" neutrinos, ν_1 and ν_2, was proposed by Ziro Maki, Masami Nakagawa and Shoici Sakata [5], in the framework of the so-called Nagoya Model [6].

Mixing among massive neutrinos was assumed to occur similarly to quarks, as first described by Nicola Cabibbo, and later on generalized by Makoto Kobayashi and Toshihide Maskawa. This eventually led to the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [7], while for neutrinos, we commonly talk today of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (see section 3 for more theoretical considerations). Neutrino mixing and oscillation are schematically depicted in fig. 3 for the simple case of two arbitrary neutrino flavours.

It is worth noting that soon after the discovery of the second neutrino flavor, partner of the muon, the concept of a third family came about, with its own third neutrino and a (likely heavier) new charged lepton. In 1967, Antonino Zichichi started the search for a possible third lepton family at the ADONE collider in Frascati [8]. However, the tau charged lepton would be found only in 1975 by Martin Perl at the SPEAR collider, which, contrary to ADONE, had enough energy to produce it [9]. As we will see later on, it took almost 25 years more to discover the neutrino partner of the τ, the tau-neutrino.

The possibility of neutrino oscillations was advocated as a possible explanation of the deficit of the detected solar electron-neutrinos soon after its first experimental indications around the end of the Sixties. Already in 1967, Bruno Pontecorvo (again!) put forward this possibility [10], after the first puzzling results from Ray Davis Jr. with the radiochemical Homestake experiment [11], one of the longest lasting in the history of particle physics, who

Fig. 2 Bruno Pontecorvo and the author in a photograph taken in 1984 at JINR, Dubna. Pontecorvo first postulated the hypothesis of neutrino oscillations.

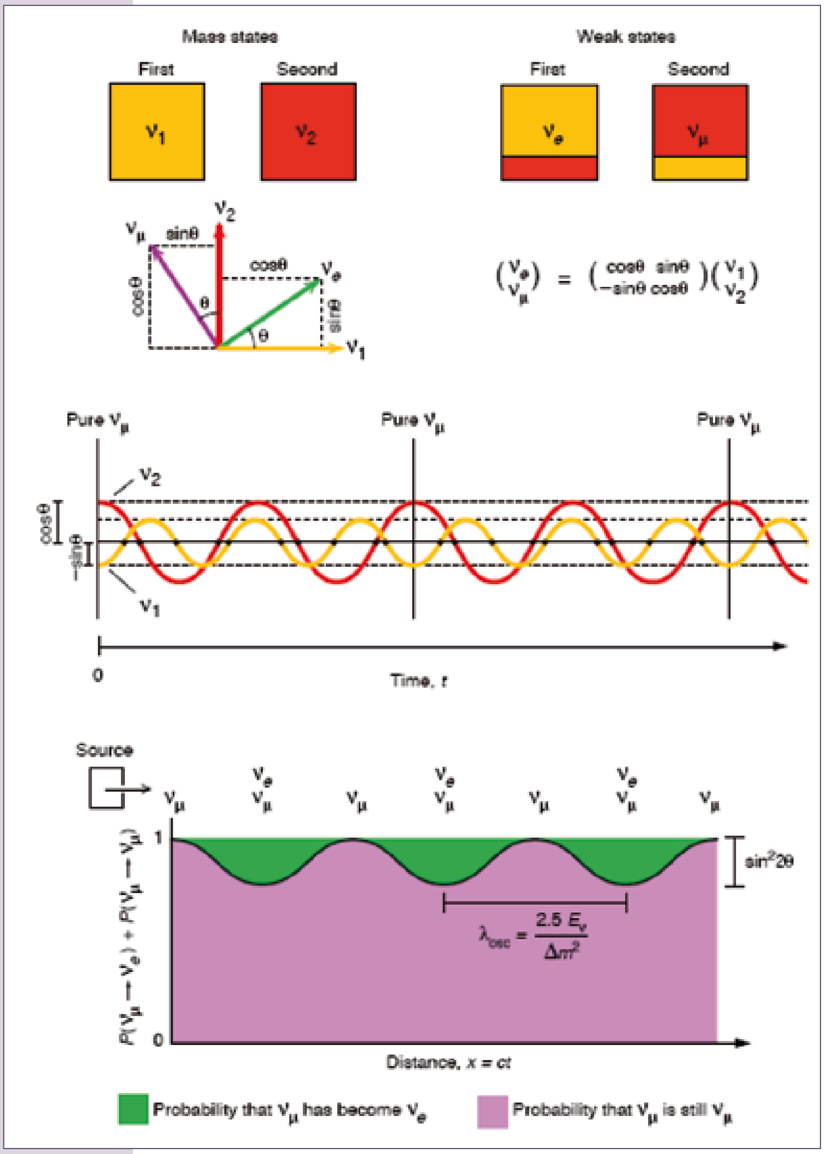

Fig. 3 Schematics of two-flavour mixing and oscillation for an arbitrary ν_μ - ν_e oscillation scenario.

first got hints of the "disappearance" of solar neutrinos.

The solar neutrino puzzle "officially" started in 1964, when two correlated papers were published on solar neutrinos in the same journal issue, a theoretical paper by John Bahcall [12] and an experimental one by Ray Davis Jr. [13]. These papers certified the starting of neutrino astrophysics, and the experimental observation of a deficit in the solar electron-neutrino flux, when compared with the theoretical expectations. Thanks to his work Ray Davis was awarded the 2002 Nobel Prize "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*" together with Masatoshi Koshiba who, with his Kamiokande detector (see below), not only confirmed Davis' observations, but also detected in 1987 neutrinos from the SN1987A supernova explosion [14]. Now we know what the interpretation of the deficit is: during the travel from the inner solar core to the detector on Earth, a fraction of the electron-neutrinos oscillate into muon- or tau-neutrinos, to which the detector is not sensitive.

More sensitive radiochemical experiments, and with a lower energy detection threshold, were conducted later on by the GALLEX [15] and GNO [16] Collaborations (at the LNGS laboratory), and by SAGE [17]. Around the beginning of this century, these radiochemical detectors together with the real-time Kamiokande [18], Super-Kamiokande [19] and SNO [20] experiments, allowed to firmly establish the correctness of the Standard Solar Model of John Bahcall [21], and unambiguously point to the hypothesis of Mikheev-Smirnov-Wolfenstein (MSW) matter oscillations for solar neutrinos [22]. Given the peculiar *L/E* dependence of oscillations (see below) these results were then tested and strongly supported by another key experiment, KamLAND [23], sensitive to the same oscillation parameter region, and carried on by exploiting the detection of anti electron-neutrinos from several Japanese nuclear reactor plants. Figure 4 shows a global fit of the oscillation parameters relative to the "solar neutrino sector" [24].

However, a few years earlier (1998) the first clear evidence, hence discovery, of "atmospheric" neutrino oscillations was reported at the Neutrino98 conference by Takahaki Kajita [25], concluding a phase of work originally and pioneeringly conducted by Masatoshi Koshiba, and then continued under the leadership of Yoji Totsuka, who brought the technique of the large water Cherenkov detectors (Kamiokande and then Super-Kamiokande) to the collection of an incredible number of scientific achievements in neutrino physics and astrophysics.

Atmospheric neutrinos are produced by the interaction of primary cosmic rays with the atmosphere, giving rise to a cascade of particles from which muon- and electron-neutrinos (and antineutrinos) are produced. The Super-Kamiokande experiment has been the first to unambiguously show that, while the number of detected atmospheric ν_e is what one expects, a clear deficit of ν_μ is observed, depending on the neutrino energy *E* and on its path length from the production point to the detector, the baseline *L*.

Figure 5 shows the zenith angle dependence of the flux of atmospheric neutrinos obtained by Super-Kamiokande, well fitted by the neutrino oscillation formula under the hypothesis of ν_μ- ν_τ oscillations [2]. Also for the atmospheric oscillation sector, more experiments contributed to the collection of complementary and clarifying results (Kamiokande [26], Soudan2 [27], MACRO [28], CHOOZ [29] and Palo Verde [30]), while later on projects exploiting neutrino accelerator beams sensitive to the specific parameter region confirmed the atmospheric neutrino results in a spectacular manner (K2K [31] and MINOS [32]), improving the knowledge of the oscillation parameters.

It is within this (not yet over!) fascinating race, already lasted more than two decades, and featuring successes, failures, strong debates, controversial results, errors and intuitions, that the discussion on direct appearance got momentum around the end of the Nineties of the last century, although several colleagues and groups had already previously put forward this opportunity as a required element to support, unambiguously confirm, complement, etc. (everybody is free to use the preferred statement!) the measurement of neutrino oscillations in disappearance mode.

Actually, and this fact sets the scale to the complexity and the inherent difficulties of an appearance oscillation experiment, all the above-mentioned projects had been based on disappearance searches, apart from SNO that performed an "indirect appearance" measurement of neutrino oscillations, culminated with the outstanding results on the study of neutral-current reactions induced by solar neutrinos [33]. The determined muon- and tau-neutrino fluxes were exactly equal to the disappeared electron-neutrino flux. The SNO result, together with those of the previous "solar neutrino" experiments, finally led to a unique determination of the corresponding oscillation parameters. In particular, the actual value of the mixing angle proved the existence of the MSW phenomenon inside the solar matter. In summary, by the beginning of this century, we had measured disappearance of solar electron-neutrinos, disappearance of atmospheric muon-neutrinos, disappearance of reactor anti-electron neutrinos, disappearance of accelerator muon-neutrinos, and "indirect appearance" of muon- and tau-neutrinos (with SNO).

Around 1995, CERN was in the process of designing an accelerator neutrino beam directed towards LNGS, the largest underground laboratory in the world. The latter had been strongly wanted and then realized under the leadership of Antonino Zichichi as president of INFN, who many years before the debate on the CERN long-baseline neutrino beam already put forward (more than 30 years ago!) the conceptual

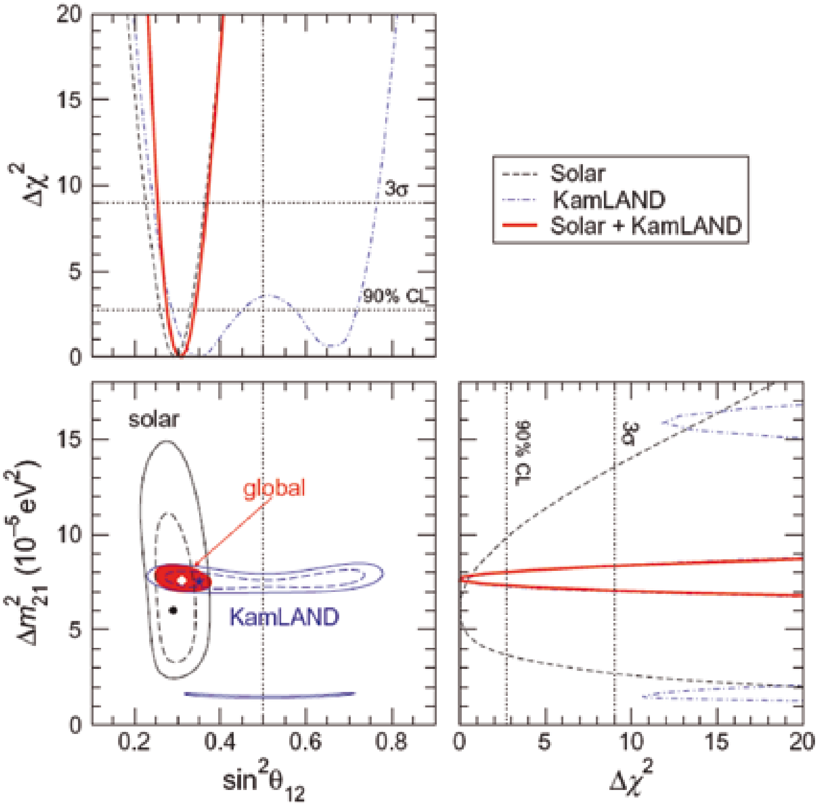

Fig. 4 Oscillation parameter region allowed by solar neutrino experiments, combined with the results from the KamLAND reactor experiment [24].

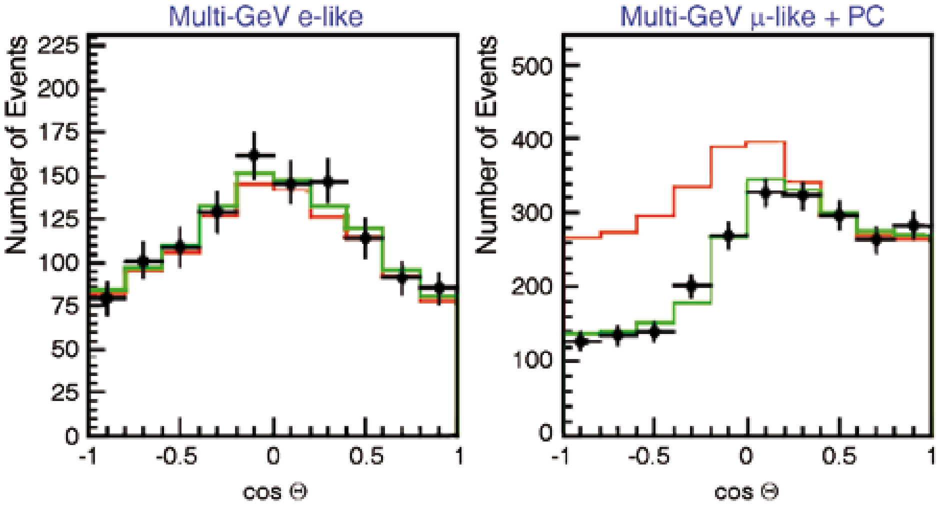

Fig. 5 Zenith angle dependence of atmospheric electron- and muon-neutrinos in the Super-Kamiokande experiment. The observed behavior is well fitted by the muon- into tau-neutrino oscillation hypothesis (green curve) and it is not compatible with the absence of oscillations (red curve). These results represent the discovery of neutrino oscillations in disappearance mode.

design of a "real" underground laboratory, not just a cavern in the middle of nowhere, with its own technical infrastructure, workshops and facilities, along with the visionary idea of the orientation of the large experimental halls towards CERN, ready to welcome a long-baseline neutrino beam.

In 1997, I had the honor to be a member of the Technical Committee jointly mandated by CERN and INFN, initially led by Kurt Hubner an later on by Konrad Elsener, with the task of designing the new beam facility. The first choice that was taken with the strong support of both institutions was the realization of a beam dedicated to ν_τ appearance from ν_μ oscillations. Luciano Maiani, as CERN Director General, Enzo Iarocci, as INFN President, and Sandro Bettini as LNGS Director, were amongst the main actors of this agreement that materialized in the funding of the largest fraction of the cost of the facility by the Italian agency, with additional extraordinary contributions from Belgium, France, Germany, Spain and Switzerland, and also from the Italian Compagnia di San Paolo, in addition to an in-kind contribution from Russia.

The CNGS beam (CERN Neutrinos to Gran Sasso) was finally approved in 1999 [34]. In a speech at the CERN Staff meeting Luciano Maiani said:"...hope that CERN would continue to play an important role in neutrino physics with the realization of the planned, long-baseline neutrino beam to Gran Sasso. It would be a major disaster if neutrino physics disappeared from Europe".

The main implications of that choice were basically on the energy of the neutrinos (high enough to be above the kinematical threshold for the production of the tau-lepton in the charged-current interactions of the ν_τ possibly coming from the oscillation) and on its intensity. The smallness of the signal, in fact, demands a high-intensity facility for the collection of an adequate statistics in a reasonable time. The layout of the CNGS beam is schematically depicted in fig. 6.

Soon after the final approval of the CNGS project, the procedure for the definition of the scientific program started. Two projects were eventually retained: first OPERA [35] and afterwards ICARUS [36], both proposing a search for ν_μ- ν_τ oscillations in appearance mode based on complementary experimental approaches. On the one hand, the direct observation of the tau-lepton with a nuclear-emulsion–based detector, and, on the other hand, the reconstruction of the event kinematics with a liquid-argon TPC active target. Apparently, the story of the CERN neutrino experiments of the previous generation, CHORUS [37] and NOMAD [38], repeated itself!

OPERA and ICARUS were eventually approved by the CERN Research Board, and by the LNGS Director and INFN Council in the years 2001 and 2003, respectively, and baptized as CNGS1 and CNGS2 CERN projects. For the first time CERN experiments were located outside the boundaries of the site, opening the way to a fully global European laboratory for particle physics, a concept that is becoming more and more attractive and realistic in today's debate.

At this point, we have to make a flash back and jump to early 1996. At that time, the idea of a neutrino beam from CERN to LNGS was just getting momentum and the first Kamiokande result with atmospheric neutrinos was puzzling the neutrino community (as said above we would had to wait for Super-Kamiokande for a definite statement). In parallel, the possibility of ν_μ - ν_τ oscillations at short baseline, namely small mixing angle and large Δm^2 (see section 3), with a sensitivity beyond what could be addressed by CHORUS and NOMAD, also motivated some interest. Although it is not the subject of this paper, I am pleased to mention the idea that the author shared with Paolo Strolin and Giorgio Romano for a very high-sensitivity experiment (TENOR) based on nuclear emulsions for the exploration of the above-mentioned parameter region [39]. This conceptual design was one of the ingredients for the follow-up TOSCA Letter of Intent at CERN [40].

However, the community soon realized that atmospheric neutrinos were telling us something worth to be listened, and most of the attention then moved to long-baseline searches in the complementary parameter region of relatively large mixing angle and small Δm^2. In 1997, with a paper signed by Kimio Niwa, Paolo Strolin and myself [41], the idea of possible medium- and long-baseline experiments aimed at the direct detection of

ν_τ appearance with an ECC (Emulsion Cloud Chamber) based detector was proposed (OPERA, Oscillation Project with an Emulsion tRacking Apparatus). The ECC is a detector that essentially “speaks Japanese” (see, *e.g.,* [42]). This rather old technique features emulsions used as high-resolution tracking detectors with three-dimensional reconstruction capabilities, more than a mere visual and volume-sensitive detector. This is obtained by sandwiching emulsion films (or plates) with passive material layers, usually made of plastic or metal. Today, we would call such a detector a high-frequency sampling calorimeter, by means of which all tracks from charged particles originating from a shower can be reconstructed in space with high accuracy. In the ECC, emulsion films are placed perpendicular to the incoming particles, featuring a spatial resolution down to ~1 μm. ECC detectors were successfully employed for the study of the cosmic-ray spectrum and of very-high-energy interaction processes [42]. Among the various important achievements with this detector, a notable example is given by Kiyoshi Niu’s discovery of the so-called X-particle in 1971 [43] (fig. 7). Today we know that this event had to be attributed to a charmed-meson production and decay. This happened three years earlier than the discovery of hidden charm with the J/Ψ particle by the groups of Burton Richter and Samuel Ting.

Kimio Niwa, successor of Kiyoshi Niu at Nagoya, further developed the ECC technique introducing automatic emulsion scanning by computer-driven microscopes. His experience with this detector and with modern emulsion technology has been essential for the development of the ideas that led to the conceptual design of the OPERA experiment [44], for its construction and for its current successful exploitation. Following this line, Kimio Niwa and collaborators obtained another outstanding result with an ECC detector, namely the discovery of the tau-neutrino, promptly produced in proton collisions at Fermilab with the DONUT experiment [45]. For this discovery he was awarded the Nishina Prize. The display of a ν_τ event detected in DONUT is shown in fig. 8.

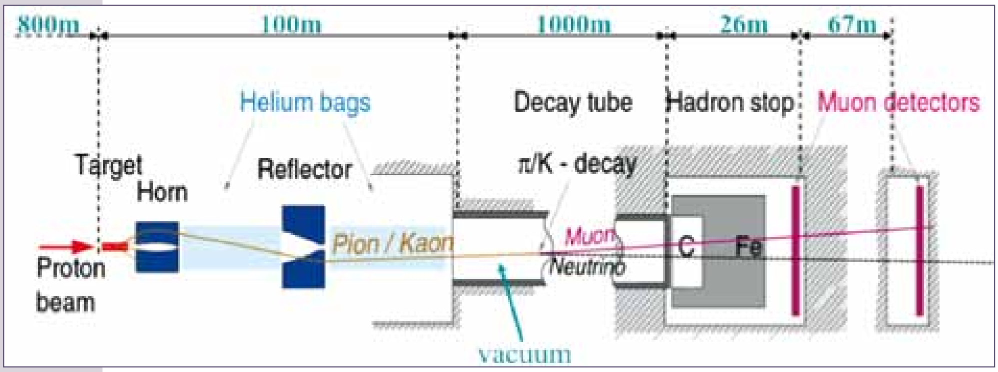

Fig. 6 Schematic layout of the CNGS beam.

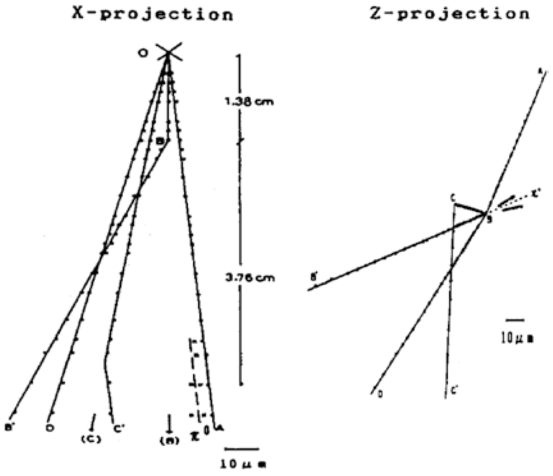

Fig. 7 Original display of the first X-events (today attributed to the decay of charmed mesons produced in cosmic rays) measured by Kiyoshi Niu in 1971 with an ECC detector as the one used by OPERA, three years before the discovery of the J/Ψ [43].

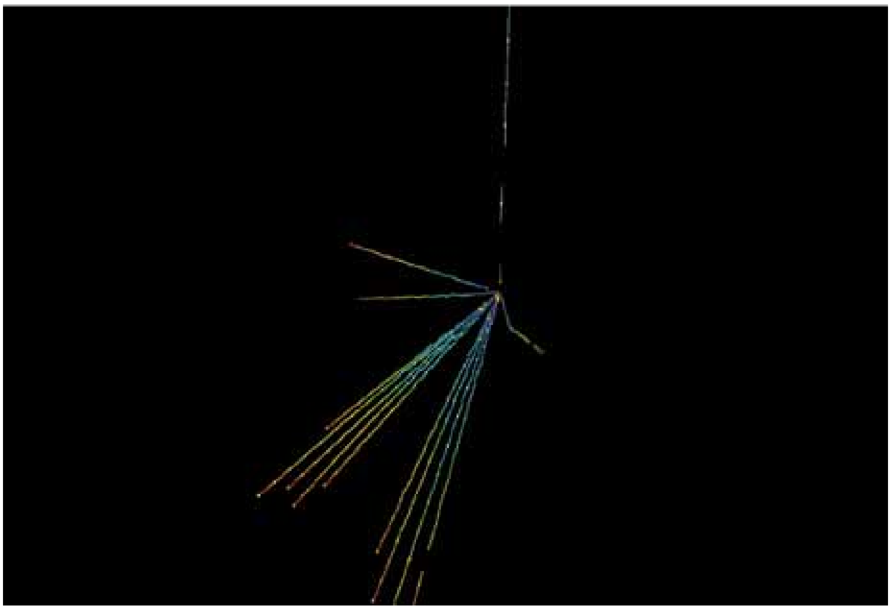

Fig. 8 Event display of one of the prompt tau-neutrinos detected by the Fermilab DONUT experiment. The tau is identified from its “kink” decay, visible on the right of the picture. A few detected events like this constituted the discovery of the third neutrino flavour by Kimio Niwa and collaborators in 2000. Also in this case, an ECC detector was employed as active neutrino target [45].

The idea of OPERA had soon a positive resonance and a small group including colleagues from Nagoya, Napoli, Salerno, Toho and Utsunomiya jointly submitted a Letter of Intent for the OPERA experiment to CERN and LNGS [46]. The Collaboration soon increased with the joining of more groups, in parallel to the conduction of preliminary studies and of the experiment technical design. In 1999 I was honored to present the OPERA concept at the CERN SPS Scientific Committee. Since then, more than 10 years passed. The Collaboration now counts about 170 colleagues from 33 institutions[1].

After the early times, when I had the duty of coordinating the "proto-collaboration", the experiment was then successfully led by the spokespersons Paolo Strolin first and Yves Declais later, who took the responsibility of the important phase of construction of the detector and the infrastructure, until the very first data collected in 2006. I wish to recall and acknowledge here the strong commitment of all the funding agencies of the Collaboration for the complete realization of the project.

I mention in particular the continuous support from CERN (through its DGs Luciano Maiani, Roger Aymar and Rolf-Dieter Heuer) and from the INFN/LNGS, with the strong presence of the presidents Enzo Iarocci and Roberto Petronzio, and of the Gran Sasso directors who followed the experiment construction and first operation, Sandro Bettini and Eugenio Coccia, the latter recently replaced by Lucia Votano.

The largest fraction of the cost of the OPERA experiment has been covered by INFN and LNGS, matched by a very substantial contribution from the Nagoya group for the acquisition of the more than 10 million industrial emulsion films from Fuji-Film, and with an overall important support from the European countries of Belgium, France, Germany and Switzerland. In particular, it is worth mentioning the specific efforts of INFN for the spectrometers (magnets and RPCs), the brick mechanical structure, the brick lead, the Brick Assembly Machine, the film development facility, and all the detector logistics at LNGS; the additional contribution from Japan for the interface emulsion films production and for the massive "refreshing" of the emulsion films in Japan, after production; the effort of Belgium on the scintillator Target Tracker (TT); the contribution of France to the TT, the DAQ system, the Brick Manipulation System and the event database hardware; the commitment of the German groups for the production of the brick lead plates and of the high-precision drift tubes; the contribution of Switzerland on TT and lead, as well as the general effort of Croatian, Korean, Russian, Tunisian and Turkish colleagues for the labor intense activities of detector construction, and operation of the facilities. It has also to be mentioned the dedicated effort of many Japanese and European groups for the successful development of the two automatic emulsion scanning-systems, the S-UTS and the ESS (see below). Last but not least, one should not forget the huge amount of work that has been accomplished by many OPERA collaborators to develop the software analysis tools, the simulations and the computer programs needed to transform digits from detectors into physics results!

Thanks to the skill and the dedication of all the groups and individual members of the Collaboration, the apparatus and the complex ancillary facilities were built and set-up in time with the parallel realization and commissioning of the CNGS beam.

I am now in charge of leading the OPERA experiment in the physics exploitation phase proceeding in parallel to the mass data taking in the CNGS beam. Two successful runs took place in 2008 and 2009, with excellent prospects for 2010 through 2012. The first ν_τ candidate event rewards today the whole Collaboration for many years of tireless effort and it is a key milestone in view of the discovery of the appearance of neutrino oscillations.

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[1] Belgium: Brussels; Croatia: Zagreb; France: Annecy, Lyon, Strasbourg; Germany: Hamburg, Münster, Rostock; Israel: Technion; Italy: Bari, Bologna, LNF, L'Aquila, LNGS, Naples, Padova, Rome, Salerno; Japan: Aichi, Toho, Kobe, Nagoya, Utsunomiya; Korea: Jinju; Russia: INR Moscow, LPI Moscow, ITEP Moscow, MSU Moscow, JINR; Switzerland: Bern, ETH Zurich; Tunisia: Tunis; Turkey: Ankara.

2 Experiment, methods and data

Looking at the OPERA experiment more closely, we can realize that it is a typical long-baseline neutrino experiment, characterized by an underground location, a large neutrino-target mass, and an intense ν_μ beam with negligible contamination of other neutrino types, notably of the "appearing" flavour ν_τ [47]. As already said, the experiment exploits the long-baseline CNGS neutrino beam from CERN to LNGS, the largest underground physics laboratory in the world, 730 km away from the source.

The challenge of the experiment is to measure the appearance of ν_τ from ν_μ oscillations. Therefore, the detection of the short-lived tau-lepton ($c\tau \sim 87\ \mu$m) produced in the charged-current interaction of the ν_τ is mandatory. This sets two conflicting requirements: a large target mass to collect enough event statistics, and an extremely high spatial accuracy to detect the tau-lepton.

The tau is identified by the detection of its characteristic decay topologies either in one prong (electron, muon or hadron) or in three prongs; its short track (< 2 mm) is measured with thin nuclear emulsion films industrially produced by Fuji-Film on an unprecedented scale of about ten million films, assembled with the above-mentioned ECC structure. The OPERA detection principle is outlined in fig. 9.

The full OPERA setup (fig. 10) is a hybrid detector made of two identical Super Modules each consisting of a target section made of emulsion/lead ECC modules called "bricks", of a scintillator tracker detector needed to trigger the read-out and localize neutrino interactions within the target, and of a muon spectrometer. The total number of bricks is 150000 for a target mass of 1250 ton. The total volume of the underground detector is roughly $10 \times 10 \times 20\ \mathrm{m}^3$.

Each of the two magnetic spectrometers consists of a large iron magnet instrumented with plastic Resistive Plate Chambers (RPC). Six stations of long drift tubes measure the deflection of charged

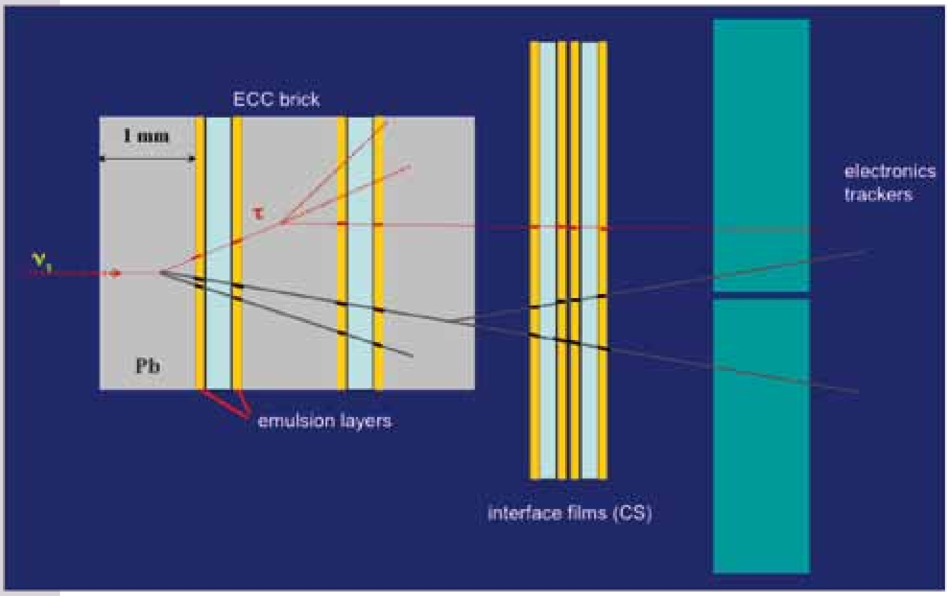

Fig. 9 The neutrino detection principle of OPERA. Electronic trackers predict the brick "hit" by the neutrino with the help of emulsion interface films (Changeable Sheets: CS). The interaction vertex is found by a "scan back" scanning procedure on those tracks identified by the CS.

Fig. 10 The OPERA detector in the LNGS underground Hall C.

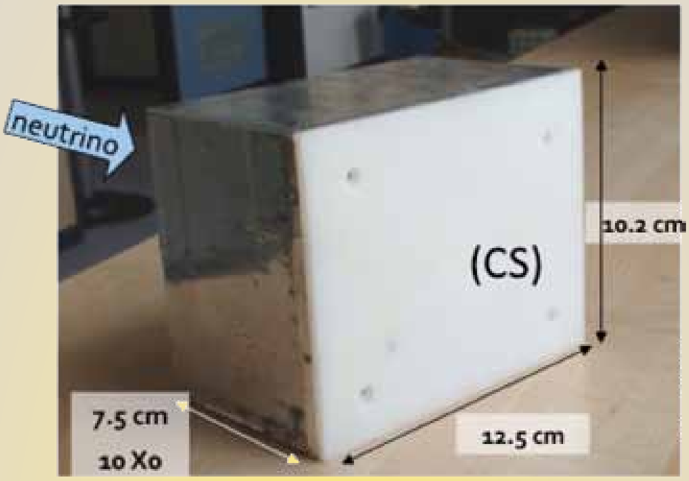

Fig. 11 One of the 150000 ECC target units (bricks) that constitute the OPERA neutrino target. The interface downstream the emulsion film doublet (CS) attached to the brick is also shown.

Fig. 12 Two of the many automatic microscopes used for the analysis of the OPERA emulsion films. Top: the system developed in Europe; bottom: the device used by the Japanese groups.

particles inside the magnetized iron. Left-right ambiguities in the reconstruction of particle trajectories are solved by means of additional chambers with readout strips rotated by ±45° with respect to the horizontal. Finally, two glass RPC planes mounted in front of the most upstream target (VETO) allow rejecting charged particles originating from outside the target fiducial region, coming from neutrino interactions in the surrounding rock material.

One target ECC brick consists of 56 lead plates with 1 mm thickness interleaved with 57 emulsion films. The plate material is a lead alloy with a small calcium content, to improve its mechanical properties. The transverse dimensions of a brick (fig. 11) are 12.8 × 10.2 cm^2 and the thickness along the beam direction is 7.9 cm (about 10 radiation lengths). The bricks are housed in a light, stainless-steel support structure placed between consecutive target tracker walls.

OPERA is the first very-large-scale emulsion experiment. Just to give an idea, the 150000 ECC bricks include about 110000 m^2 emulsion films and 105000 m^2 lead plates.

The detector is equipped with two robots that allow the automatic removal of bricks from the target. Ancillary large facilities are used for the handling, the development and the scanning of the emulsion films. Emulsion scanning is performed with two different types of automatic microscopes (fig. 12) independently developed by the European and the Japanese groups of the Collaboration [48, 49]. Each of the several tens of microscopes is faster by about two orders of magnitude than those used, *e.g.*, in the former CHORUS experiment.

In order to reduce the emulsion scanning load, the use of Changeable Sheets (CS) film interfaces, successfully applied in particular to the CHORUS and DONUT experiments, was extended to OPERA on a much larger scale. Tightly packed doublets of emulsion films are glued to the downstream face of each brick and can be removed without opening the brick itself.

Charged particles from a neutrino interaction in the brick lead plates can cross the CS and then produce a signal in the target tracker scintillators. An automatic classification algorithm provides high efficiency in the selection of neutrino events inside the OPERA target both for charged- and neutral-current events. The correspondingly selected brick is then extracted and the CS developed and analyzed in the two dedicated scanning facilities at LNGS and Nagoya. All tracks measured in the CS are searched for in the most downstream films of the brick and followed back until they are not found in three consecutive films. The stopping point is considered as the signature either for a primary or a secondary vertex. The vertex is then confirmed by scanning a volume with a transverse size of 1 cm^2 in 11 films in total, upstream and downstream of the stopping point. A typical charged-current ν_μ-induced event as reconstructed by the electronic trackers and by the emulsion on two completely different scales, is shown in fig. 13. The complex and time-consuming scanning of the brick emulsions is accomplished in 12 different laboratories of the Collaboration, in Europe and Japan.

As an example of detected classes of interactions, "charm" particles production and decay events have a great importance in OPERA, for two main reasons. On the one hand, in order to certify the observation of ν_τ events one should prove the ability of observing charm interactions at the expected rate. On the other hand, since charm decays exhibit the same topology as tau decays, they are a potential source of background if the muon at the primary vertex is not identified. Therefore, searching for charm decays in events with the primary muon correctly detected provides a direct measurement of this background. The distinctive topology of one of the detected 1-prong charm decay events is depicted in fig. 14.

Another potentially important source of background is given by re-interactions of hadrons in muonless events. This scattering process, exhibiting the typical kink topology, could well fake hadronic tau decays, although rather unlikely, given the relatively long interaction length of hadrons in the lead target as compared to the 2 mm allowed decay length for signal events. Similar considerations apply to muon large-angle scattering, a background source to the "gold plated" $\tau \to \mu$ decay mode.

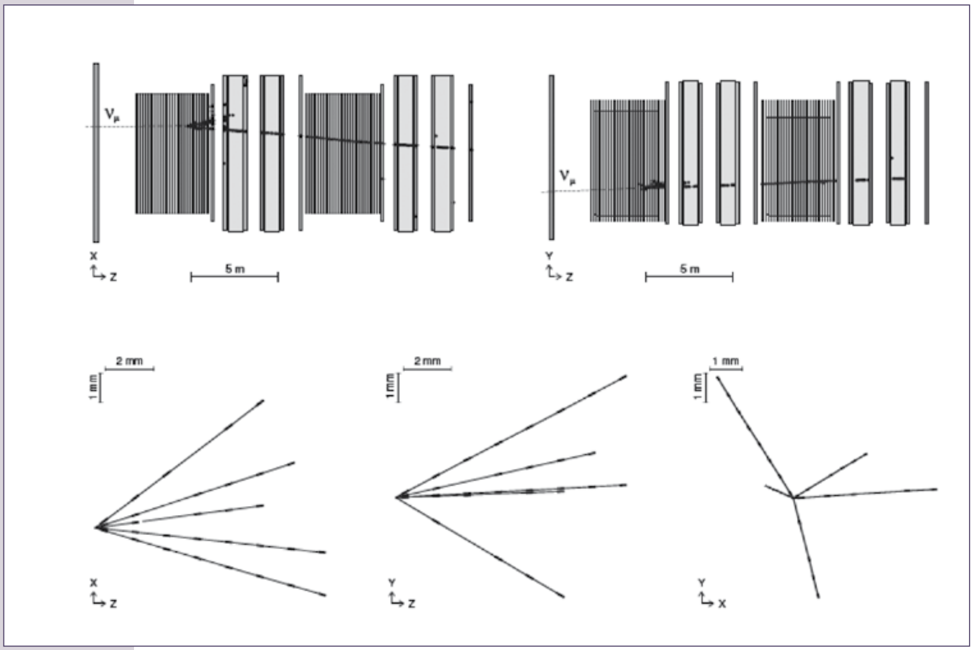

Fig. 13 Display of a charged-current muon-neutrino event produced in the OPERA target. Top: the reconstruction by the electronic detectors (~15 m scale). Bottom: the neutrino interaction vertex region reconstructed by means of the emulsions (millimeter scale).

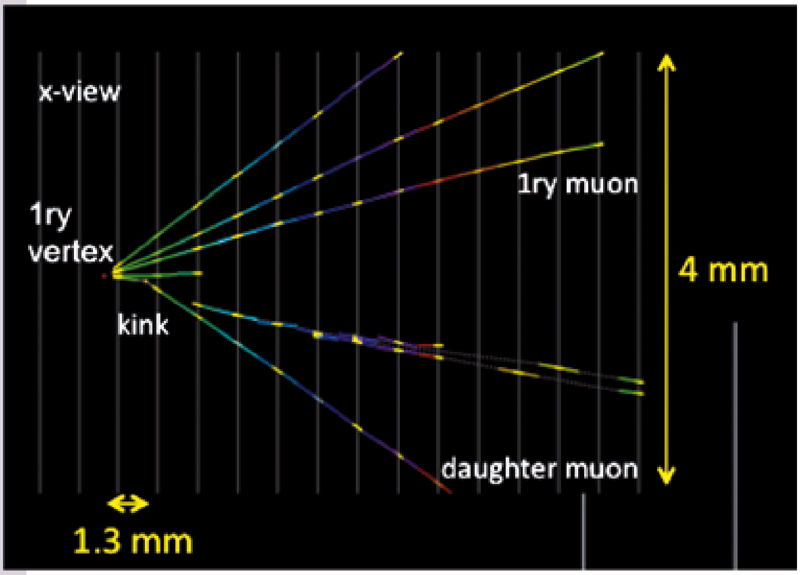

Fig. 14 Charm meson production and decay in the OPERA target. The distinctive kink topology is detected. The presence of an identified prompt muon at the primary vertex excludes the hypothesis of tau production and decay.

As far as the experiment sensitivity is concerned, we already mentioned that OPERA should be able to discover appearance oscillations already with a handful of candidate events, given its low physics background. The experiment is basically sensitive to all tau decay modes, with about 10 signal events expected for the nominal integrated beam intensity of $\sim 22 \times 10^{19}$ CERN protons on target (the target for the production of the neutrinos), and for less than 0.75 background events, for the current best-fit values of the oscillation parameters.

The experiment has been running since 2006, when a technical run was performed without target bricks [50]. In 2007 the first interactions in the emulsions were detected [51] and, as mentioned above, 2008 and 2009 featured the first two "production runs", with the collection of several thousand neutrino interactions, out of which we detected the expected number of charm events and the first ν_τ candidate event [52], discussed in the previous section.

3 Neutrino oscillation physics appendix

Before concluding, let us make some basic considerations on the physics of neutrino oscillations in order to better frame the case of tau appearance in the current experimental scenario.

The formalism of neutrino oscillations, as previously discussed, is well explained by the 3 × 3 PMNS neutrino-mixing matrix *U*, similar to the CKM quark-mixing matrix. If three Majorana neutrino states exist (neutrino ≡ antineutrino) the matrix then features six independent parameters: three angles and three phases. The matrix can then be conveniently parametrized as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. The first three matrices can be independently explored by different classes of oscillation experiments: the first one is relevant to atmospheric and accelerator neutrino searches (*e.g.*, OPERA), the third one is sensitive to solar and reactor experiments, while the second one represents an "interference" or "linking" term, that as we will see below, can be assessed by testing "sub-leading" ν_μ- ν_e oscillations.

In the case of three Dirac neutrinos (neutrino ≠ antineutrino), the Majorana phases η_1 and η_2 appearing in the fourth matrix can be absorbed in the neutrino states and the number of physical phases becomes one (analogously to the CKM matrix). The mixing matrix *U* then takes the form

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}.$$

It is important to stress that neutrino oscillation experiments are neither sensitive to the so far unknown Majorana or Dirac nature of the neutrino, nor to the actual values of the mass eigenvalues, but only to their squared differences, as shown below.

One can then derive the well-known oscillation probability formula that in the most general case takes the expression

$$P_{\alpha,\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{i=1}^{n} \sum_{j=1}^{n} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle \right|^2 .$$

This describes the oscillatory probability for a neutrino flavour α produced at the time $t = 0$ to be found at the time t as a neutrino of flavour β, the latter able to produce the charged lepton β in a charged-current interaction with the detector. The above relation applies to propagation of the oscillating neutrinos in vacuum and can only occur if the mass eigenvalues are not degenerate. For propagation in matter a more complicated formula must be used; this is the case, *e.g.*, of the above-mentioned electron-neutrinos propagation in the dense solar matter, well described by the MSW formalism [22].

In summary, oscillations are described (take the case of vacuum neutrino propagation as an example) by 3 independent mixing angles: θ_{12}, experimentally associated to the solar neutrino oscillations, θ_{23}, associated to the atmospheric neutrino oscillations, and the still unknown θ_{13} angle that represents as already said a sort of "link" between the two main oscillation channels. This angle directly affects the possibility of detecting a non-vanishing *CP*-violating phase δ, as evident from the above parametrizations of the mixing matrix: a null θ_{13} value would make the dependence of the oscillation probability on δ undetectable.

Two independent values of the squared-mass eigenvalue differences $(m_i^2 - m_j^2)$, Δm^2_{12} and Δm^2_{23}, respectively associated to the solar and atmospheric sectors, complete the oscillation parameters to be determined by the experiments. To the above, unknown parameters we have to add the baseline L and the energy of the neutrinos E, both in principle fixed by the experimental conditions. The oscillation formula amplitude is then a function of the mixing angles, while the frequency of the oscillation (or its length) does depend upon Δm^2 times L/E.

The results of a global fit including all neutrino oscillation results obtained with natural and artificial neutrinos is shown in fig. 15 [53]. This is a remarkable achievement, although one may notice the different accuracy yielded so far in the measurement of the corresponding mixing parameters in the quark sector: this indicates that the work has just started and more efforts will be needed for the future! Figure 16 shows the consequent flavour composition of the mass neutrino eigenstates in the two (still both) possible hypotheses of normal or inverted mass hierarchy: $m(\nu_3) > m(\nu_2) > m(\nu_1)$ and $m(\nu_2) > m(\nu_1) > m(\nu_3)$. Analogously, each of the neutrino flavour eigenstates has a "specific" composition in terms of mass eigenstates.

Looking at the oscillation parameter values, it turns out that both the atmospheric and solar sectors exhibit small values of Δm^2 and large values (or maximal, as in the case of the atmospheric sector 23) of the corresponding mixing angles. This is "per se" a quite intriguing result, since a rather different situation occurs for the quark-mixing parameters in the CKM matrix.

From the measurements made so far on the oscillation parameters and from the limits set by beta-decay and cosmological measurements, it also very clearly emerges that the neutrino mass eigenvalues are extremely small, when compared to the masses of the other fermions. This is a fundamental question that deserves an answer. The explanation of the neutrino mass smallness is actually a mandatory duty of any theory going beyond the present version of the Standard Model. Among the various proposed interpretation hypotheses, the so-called "see-saw" models predict the existence of a "grand unification mass scale" heavy Majorana neutrino, as counterpart of the physically observed low-mass neutrinos. This is a rather appealing possibility, also because such models predict (as a "by-product") leptogenesis, and therefore a way to account for the supremacy of matter over anti-matter in the present Universe, and ultimately for the fact that we are here talking about neutrinos! For a review of these interesting subjects the reader can refer to, *e.g.*, [53].

The previous considerations on the neutrino mass, in particular, have motivated another category of precision experiments, such as those on the search for neutrinoless double-beta decay, a process that if eventually detected, would at the same time tell us the (average) neutrino mass value, and confirm its Majorana particle nature (for a review see, *e.g.*, [54]).

Back to the oscillation formalism, we can write below two notable examples of oscillation

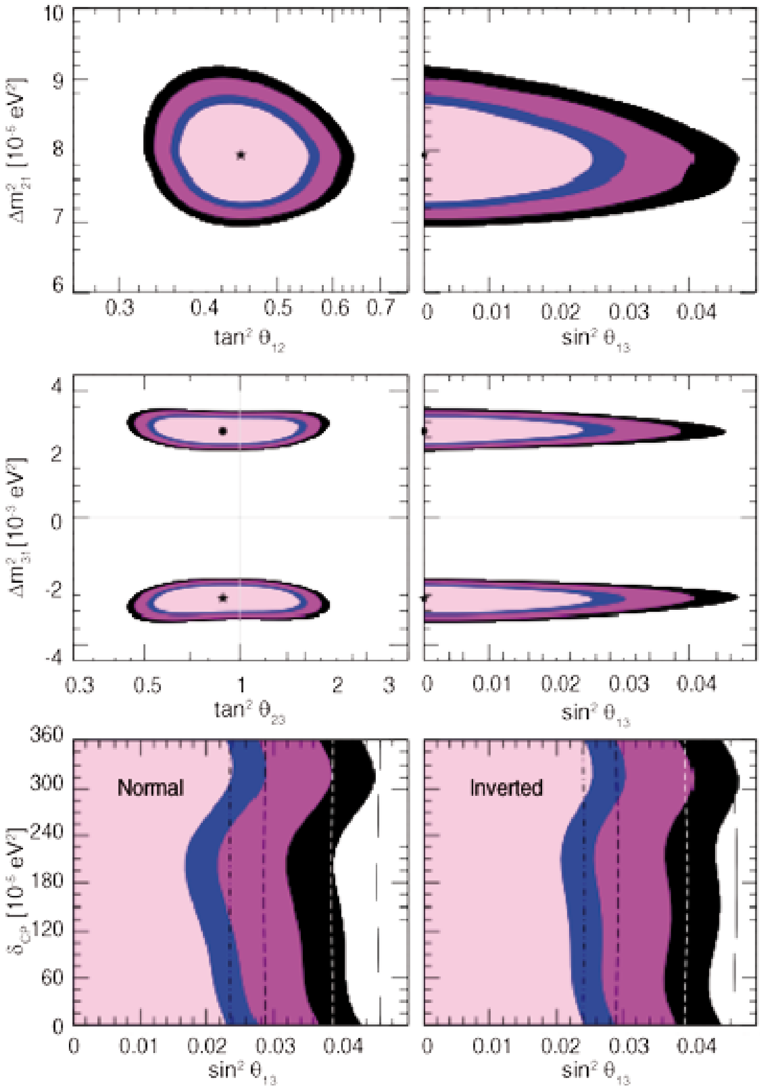

Fig. 15 An example of a global fit of all oscillation data, to infer the oscillation parameters in the general 3-flavour mixing scheme [53].

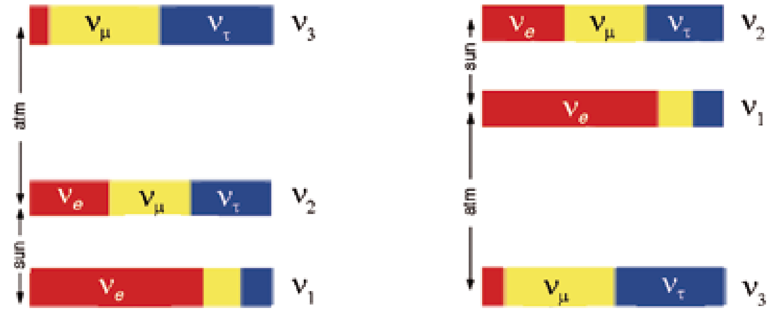

Fig. 16 Flavour composition of the neutrino mass eigenstates as indicated by all neutrino oscillation experiments, for the two possible hierarchy schemes.

probability formulae in a simplified expression of the general oscillation formula, respectively for the ν_μ- ν_τ mode (*i.e.* tau-neutrino appearance oscillations, studied by OPERA) and the ν_μ-ν_e (electron neutrino appearance, currently addressed, *e.g.,* by the T2K experiment [55], aimed at the measurement of the θ_{13} angle):

$$P\left(\nu_\mu\text{-}\nu_\tau\right) \sim \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\Delta m^2_{23}L/4E\right) ,$$

$$P\left(\nu_\mu\text{-}\nu_e\right) \sim \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\Delta m^2_{23}L/4E\right) .$$

From the above relations, it is clear that OPERA is well sensitive to the atmospheric neutrino oscillation parameters (sector 23), while, in order to achieve a good sensitivity to the “interference” sector 13, one should better exploit the ν_μ - ν_e oscillation channel, given the presumably very small value of the so far unknown θ_{13} angle. This is straightforward, given the $\cos^4$ dependence of P (ν_μ- ν_τ) on θ_{13}. For completeness, from one (of the several available) global fits of all oscillation data we know that $\sin^2\theta_{13} < 0.035$ at the 90% CL [24].

It is worth stressing that the appearance of ν_τ can be in principle also attempted with atmospheric neutrinos, without the use of a high-energy accelerator beam as done by OPERA. In that case, the strong limitation is the rather low number of events that can be detected by an (even large) underground detector, due to the extremely low flux of atmospheric ν_τ (~ 1 per kton year) that are above the high-energy kinematical threshold of ~3.5 GeV that is required to produce a tau-lepton. In addition, such a measurement can only be (realistically) performed on a statistical basis, by exploiting the differences in the kinematical features of ν_τ events as compared to ordinary atmospheric ν_μ and ν_e interactions. This implies a rather unfavourable signal-to-noise ratio that eventually will limit the achievable statistical significance of the measurement. Despite these strong experimental difficulties, the Super-Kamiokande Collaboration has got an interesting result with this method, “*disfavouring the absence of tau appearance*” [56].

4 What next?

After the final confirmation of OPERA on ν_τ appearance with the adequate statistical significance, we should be able to shed light on the alternative hypothesis to standard 3-flavour neutrino oscillations, such as additional sterile neutrinos, decoherence or decay models, etc.

In order to achieve its goal OPERA will have to run at least two more years in the CNGS beam, with the hope that the continuous improvements of the beam intensity and stability, as well as of the performance of detector and related facilities, will continue.

We will have then to move on towards the next generation of measurements. The precise determination of the above-mentioned θ_{13} angle by accelerator and nuclear-reactor–based experiments will allow the assessment of the full 3 × 3 nature of the mixing matrix and open the way to an even further step, namely the measurement of a possible *CP*-violating phase in the leptonic sector, a major issue in particle physics. For such a goal, a complete new generation of beam facilities and detectors will be required to cope with the complexity of the measurements and with the smallness of the expected signal.

Certainly many years of studies, investments, construction work and experimental struggle will be needed and, hopefully, new unexpected results will motivate even more neutrino physicists in their work. This subject, however, goes beyond the scopes of the present paper. More information could be found elsewhere (look for example at the papers presented at the recent CERN Workshop on Future Neutrino Physics [57]).

As a conclusion, I believe that the positive achievements reported here, obtained by the OPERA experiment, constitute an important result among those that in the last two decades came from the various projects and that contributed to our comprehension of neutrino oscillation physics. The first OPERA ν_τ candidate is a key milestone towards the discovery of the appearance of neutrino oscillations, more than 50 years after their first hypothesis. Obviously, more work will be needed, but I am confident that the OPERA Collaboration will be definitively able to accomplish its task, given the by now proven ability in reconstructing CNGS neutrino interactions and in identifying decay topologies with low physics background.

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References

[1] A. Ereditato (on behalf of the OPERA Collaboration), Observation of events with decay topologies in the OPERA experiment, seminar given at LNGS, 31 May 2010 and at CERN, 4 June 2010.

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

[3] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.,* 33 (1957) 549 (*Sov. Phys. JETP,* 6 (1957) 429); B. Pontecorvo, *Zh. Eksp. Teor. Fiz.*, 34 (1957), 247 (*Sov. Phys. JETP,* 7 (1958) 172).

[4] G. Dandby *et al., Phys. Rev. Lett.,* 9 (1962) 36.

[5] Z. Maki, M. Nakagawa and S. Sakata, *Prog. Theor. Phys.,* 28 (1962) 870.

[6] Z. Maki, M. Nakagawa, Y. Ohnuki and S. Sakata, *Prog. Theor. Phys.,* 23 (1960) 1174.

[7] N. Cabibbo, *Phys. Rev. Lett.* 10 (1963) 531; M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.,* 49 (1973) 652.

[8] M. Bernardini *et al.*, INFN/AE-67/3, 20 March 1967; C.S. Wu *et al.*, *"The origin of the third family"*, World Scientific Series in 20th Century Physics, vol. 20 (1998).

[9] M. Perl *et al., Phys. Rev. Lett.,* 35 (1975) 1489.

[10] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.,* 53 (1967) 1717 (*Sov. Phys. JETP,* 26 (1968) 984).

[11] R. J. Davis, D. S. Harmer and K. C. Hoffman, *Phys. Rev. Lett.,* 20 (1968) 1205.

[12] J. N. Bahcall , *Phys. Rev. Lett.,* 12 (1964) 300.

[13] R. J. Davis, *Phys. Rev. Lett.,* 12 (1964) 303.

[14] K.S. Hirata *et al.* (Kamiokande II Collaboration), *Phys. Rev. D,* 38 (1988) 448.

[15] W. Hampel *et al.* (GALLEX Collaboration), *Phys. Lett. B,* 447 (1999) 127.

[16] M. Altmann *et al.* (GNO Collaboration), *Phys. Lett. B,* 616 (2005) 174.

[17] J. N. Abdurashitov *et al.* (SAGE Collaboration), *J. Exp. Theor. Phys.,* 95 (2002) 181 (*Zh. Eksp. Teor. Fiz.,* 122 (2002) 211).

[18] Y. Fukuda *et al.* (Kamiokande Collaboration), *Phys. Rev. Lett.,* 77 (1996) 1683.

[19] M. B. Smy *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. D,* 69 (2004) 011104.

[20] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.,* 87 (2001) 071301.

[21] J. N. Bahcall, A. M. Serenelli and S. Basu, *Astrophys. J.,* 621 (2005) L85.

[22] L. Wolfenstein, *Phys. Rev. D,* 17 (1978) 2369; S. P. Mikheev and A. Y. Smirnov, *Sov. J. Nucl. Phys.* 42, 913 (1985) (*Yad. Fiz.,* 42 (1985) 1441).

[23] T. Araki *et al.* (KAMLAND Collaboration), *Phys. Rev. Lett.,* 94 (2005) 081801.

[24] Th. Schwetz, M. Tortola and J. W. F. Valle, *New J. Phys.,* 10 (2008) 113011.

[25] T. Kajita, talk given at the NEUTRINO98 Conference in Takayama, `http://www-sk.icrr.u tokyo.ac.jp/nu98/`

[26] Y. Fukuda *et al.* (Kamiokande Collaboration), *Phys. Lett. B,* 335 (1994) 237.

[27] M. C. Sanchez *et al.* (Soudan 2 Collaboration), *Phys. Rev. D,* 68 (2003) 113004.

[28] M. Ambrosio *et al.* (MACRO Collaboration), *Phys. Lett. B,* 517 (2001) 59.

[29] M. Apollonio *et al.* (CHOOZ Collaboration), *Phys. Lett. B,* 466 (1999) 415.

[30] A. Piepke (Palo Verde Collaboration), *Prog. Part. Nucl. Phys.,* 48 (2002) 113.

[31] S. H. Ahn *et al.* (K2K Collaboration), *Phys. Lett. B,* 511 (2001) 178.

[32] D. G. Michael *et al.* (MINOS Collaboration), *Phys. Rev. Lett.,* 97 (2006) 191801.

[33] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.,* 89 (2002) 011301.

[34] Ed. K. Elsener, CERN 98-02, INFN/AE-98/05; R. Bailey *et al.*, Addendum to report CERN 98-02, INFN/AE-98/05, CERN-SL/99-034(DI), INFN/AE- 99/05.

[35] M. Guler *et al.* (OPERA Collaboration), CERN-SPSC-2000-028, LNGS P25/2000.

[36] P. Aprili *et al.* (ICARUS Collaboration), CERN/SPSC 2002-027 (SPSC-P-323), LNGS-EXP 13/89 add.2 /01.

[37] E. Eskut *et al.* (CHORUS Collaboration), *Phys. Lett. B,* 497 (2001) 8.

[38] P. Astier *et al.* (NOMAD Collaboration), *Nucl. Phys. B,* 611 (2001) 3.

[39] A. Ereditato, G. Romano and P. Strolin, *Nucl. Phys. B,* 54 (1997) 139.

[40] A. S. Ayan *et al.* (TOSCA Collaboration), CERN-SPSC/97-05 SPSC/I 213.

[41] A. Ereditato, K. Niwa and P. Strolin, INFN/AE-97/06, DPNU-97-07.

[42] G. De Lellis, A. Ereditato and K. Niwa, *"Nuclear Emulsions"*, in *The Handbook of Particle Physics*, edited by H. Shopper, *Landoldt-Boernstein*, vol. II (Springer Verlag, Heidelberg), to be published.

[43] K. Niu, E. Mikumo and Y. Maeda, Prog. Theor. Phys., 46 (1971) 1644.

[44] K. Niwa, contribution to the *"Snowmass 94"* Conference on *"Particle and Nuclear Astrophysics and Cosmology in the Next Millennium"*, 29 June – 14 July, Snowmass, Colorado.

[45] K. Kodama *et al.* (DONUT Collaboration), *Phys. Lett. B,* 504 (2001) 218.

[46] H. Shibuya *et al.* (OPERA Collaboration), CERN-SPSC-97-24, LNGS-LOI-8-97.

[47] R. Acquafredda *et al.* (OPERA Collaboration), *JINST,* 4 (2009) P04018.

[48] N. Armenise *et al.*, *Nucl. Instrum. Methods. A*, 551 (2005) 261; M. De Serio *et al.*, *Nucl. Instrum. Methods. A*, 554 (2005) 247; L. Arrabito *et al.*, *Nucl. Instrum. Methods. A*, 568 (2006) 578.

[49] K. Morishima and T. Nakano, *JINST,* 5 (2010) P04011.

[50] R. Acquafredda *et al.* (OPERA Collaboration), *New J. Phys.,* 8 (2006) 303.

[51] N. Agafonova *et al.* (OPERA Collaboration), *JINST,* 4 (2009) P06020.

[52] N. Agafonova *et al.* (OPERA Collaboration), arXiv: 1006.1623v1, to be published in *Phys. Lett. B*.

[53] M. C. Gonzales-Garcia and M. Maltoni, arXiv 0704.1800.v1.

[54] S. M. Bilenky, arXiv:1001.1946v1.

[55] `http://jnusrv01.kek.jp/public/t2k/index.html`

[56] K. Abe *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.,* 97, (2006) 171801.

[57] `http://indico.cern.ch/contributionListDisplay.py?confId=69984`

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