



The discovery of the appearance of $\nu_\mu - \nu_\tau$ oscillations

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Abstract

Almost 20 years after the first conceptual design of the experiment, five years of running in the Gran Sasso underground laboratory (LNGS), and billions of billions muon-neutrinos sent from CERN along the CNGS beam, in 2015 the OPERA neutrino detector has allowed the long-awaited discovery of the direct transformation (oscillation) of muon-neutrinos into tau-neutrinos. This result unambiguously confirms the interpretation of the so-called atmospheric channel, after the discovery of neutrino oscillations by the Super-Kamiokande Collaboration in 1998.

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1. Introduction

Neutrino oscillations were originally proposed by Bruno Pontecorvo for the neutrino–antineutrino oscillation mode around the end of the fifties of the last century, when only one neutrino flavor was known [1]. A few years later, soon after the discovery of the ν_μ [2] a 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 Shoichi Sakata [3], within the so-called Nagoya Model [4]. Mixing among massive neutrinos occurs as for quarks, as first proposed by Nicola Cabibbo and then extended by Makoto Kobayashi and Toshihide Maskawa. This hypothesis, well supported by the experimental data, led to the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing-matrix [5]. For neutrino mixing we talk today of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix. After the discovery of the second neutrino flavor, partner of the muon, the concept of a third

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family came about with the new charged τ lepton and its corresponding tau-neutrino. It took 25 years to discover the third neutrino with the DONUT experiment conducted by Kimio Niwa and collaborators at Fermilab [6].

The flavor conversion (oscillation) between neutrino weak eigenstates (ν_e , ν_μ and ν_τ) can occur provided the neutrino is a massive particle and non-vanishing, non-degenerate mass eigenstates (ν_1 , ν_2 and ν_3) exist. The two sets of eigenstates mix through the PMNS mixing matrix and one can then obtain a periodic flavor variation during neutrino propagation in space and time. The PMNS matrix includes angles, which appear in the oscillation probability relations experimentally tested between different flavor eigenstates. The original oscillation formalism deals with neutrinos oscillating in vacuum. For matter propagation a different formula should be adopted, as the MSW relations [7], which is applied, in particular, to electron-neutrino propagation in the dense solar matter.

If we restrict ourselves to vacuum oscillations, a reasonable approximation for most terrestrial experiments, we are left with 3 independent mixing angles: θ_{12} experimentally associated to the solar neutrino oscillations, θ_{23} connected to the atmospheric neutrino oscillations, and the θ_{13} angle that constitutes the “link” between the two leading oscillation channels. The fact that the latter angle is larger than zero allows detecting a possible non-vanishing CP violating phase δ in the matrix. Two independent values of the squared mass eigenvalue differences ($m_i^2 - m_j^2$), Δm_{12}^2 and Δm_{23}^2 , respectively associated to the solar and atmospheric sectors, complete the oscillation parameters to be measured by the experiments. We have to finally 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 depends on the Δm^2 parameters and L/E .

After the discovery of the oscillations by the Super-Kamiokande Collaboration with atmospheric neutrinos [8] and relevant experimental results from many more experiments, global fits have been produced including all neutrino oscillation results obtained with natural and artificial neutrinos [9]. The consequent flavor composition of the mass neutrino eigenstates can then be derived for both the possible cases of normal and inverted mass hierarchy: $m(\nu_3) > m(\nu_2) > m(\nu_1)$ and $m(\nu_2) > m(\nu_1) > m(\nu_3)$.

The one just briefly described is the “Standard Neutrino Oscillation Model”. However, some experimental hints accumulated in the last two decades seem to point to the possible existence of another Δm^2 associated to an additional oscillation amplitude, coming from short baseline and reactor oscillation experiments. Obviously, this cannot be accommodated by assuming a simple 3×3 matrix that mixes the three known neutrino flavors. For this reason, one should advocate the existence of at least a fourth neutrino in Nature. Given the fact that no charged current reactions induced by such a neutrino have ever been observed, one postulates that it is a sterile particle, only coupling to the other fermions (standard neutrinos) through the oscillation mechanism. Several experiments are searching for sterile neutrinos with different experimental techniques. As an example, I mention the SBN program at Fermilab [10].

The most general oscillation formula can be approximated for two notable oscillation channels, namely $\nu_\mu - \nu_\tau$ appearance studied by the OPERA experiment, and $\nu_\mu - \nu_e$, explored by the T2K [11] and NOvA [12] experiments:

$$P(\nu_\mu - \nu_\tau) \sim \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2(\Delta m_{23}^2 L/4E)$$

$$P(\nu_\mu - \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta m_{23}^2 L/4E)$$

Although OPERA is particularly sensitive to the atmospheric neutrino oscillation parameters governed by the $\nu_\mu - \nu_\tau$ channel, the search for tau-neutrino appearance can also be attempted by employing atmospheric neutrinos. There, the main limitation is given by the small statistics determined by the very low flux of atmospheric ν_τ (~ 1 per kton year) above the kinematical threshold of ~ 3.5 GeV. In addition, experiments of this type are performed by looking at differences in the kinematical features of ν_τ events as compared to atmospheric ν_μ and ν_e interactions. This determines a small signal to noise ratio limiting the statistical significance. Nevertheless, Super-Kamiokande has got excellent results with this method [13].

2. The state of the art

The possibility of neutrino oscillations was considered 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. In 1967 Bruno Pontecorvo proposed this solution [14] after the first results by Ray Davis with the Homestake experiment [15], the first to obtain indications of the disappearance of neutrinos from the Sun. The solar neutrino puzzle formally started in 1964, with the simultaneous publication of two papers on solar neutrinos by John Bahcall [16] and by Ray Davis [17]. In recognition of 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 Koshihba. The latter, with his Kamiokande detector, confirmed Davis’ observations and, even more important, detected neutrinos from the supernova SN1987A explosion in 1987 [18], virtually opening the new field of neutrino astrophysics.

Other radiochemical experiments with a lower energy detection threshold and hence sensitive to a different part of the solar neutrino spectrum were conducted later on by the Gallex [19], GNO [20] and SAGE Collaborations [21]. These radiochemical detectors, together with the real-time detectors Kamiokande [22], Super-Kamiokande [23], Borexino [24] and SNO [25], allowed to confirm the correctness of the solar model worked out by John Bahcall [26] and unambiguously point to the solution of the puzzle. The interpretation is that during the travel from the inner solar core to the Earth, electron-neutrinos oscillate into muon- or tau-neutrinos, not detected by the experiments, following the Mikheev–Smirnov–Wolfenstein (MSW) matter oscillations mechanism [7]. These results were eventually convincingly confirmed by the KamLAND experiment [27], by exploiting the detection of anti-electron-neutrinos from nuclear reactors.

However, the discovery of atmospheric neutrino oscillations had already been reported at the Neutrino98 conference by Takaaki Kajita [9], bringing to maturity a long-standing work pioneered by Masatoshi Koshihba 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 created in the interaction of primary cosmic-rays with the atmosphere. Secondary mesons decay into muon- and electron-neutrinos (and antineutrinos). Super-Kamiokande showed that while the number of detected atmospheric ν_e ’s is what one expects, a statistically significant deficit of ν_μ ’s is observed, function of the neutrino energy E and of its traveled distance from the production point, through the Earth, up to the underground detector.

The results from Super-Kamiokande represented the end point of a long series of other notable contributions: Kamiokande [28], Soudan2 [29], MACRO [30], Chooz [31] and Palo Verde [32]. Eventually, a strong confirmation came from experiments designed for accelerator neutrinos addressing the same oscillation parameter region, namely K2K [33] and MINOS [34]. It is in the

framework of this exciting international competition that the discussion on direct appearance got credit around the end of the nineties of the last century, to support/complement the measurement of neutrino oscillations obtained in disappearance mode. We should note that the SNO experiment, led by Art McDonald, has performed an “indirect appearance” measurement of neutrino oscillations culminated with the outstanding results on the study of neutral-current reactions induced by solar neutrinos [35]. The combination of the muon- and tau-neutrino fluxes extracted from the measurements exactly matched 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 firmly proved the occurrence of the MSW phenomenon inside the solar matter.

The last chapter of the experimental studies on oscillations, settled quite recently, concerned the measurement of the third PMNS angle, θ_{13} . As mentioned above, two oscillation channels can be exploited for this: $\nu_\mu - \nu_e$ and $\bar{\nu}_e - \bar{\nu}_x$ oscillations. The first is studied by the T2K and NOvA experiments, the second by reactor disappearance experiments, such as Daya-Bay in China [36], RENO in Korea [37] and Double Chooz in France [38]. While a first indication of a non-vanishing θ_{13} angle came from T2K [39], the discovery was made with high significance by the Chinese reactor experiment led by Yfang Wang [40]. Last but (definitely) not least, in 2014 the T2K experiment provided the discovery of oscillation appearance with a sensitive $\nu_\mu - \nu_e$ search by the observation of an excess of electron events [41]. This result was followed by the discovery of tau appearance in 2015 by the OPERA experiment, as described in detail in the following.

3. The history of the tau appearance quest

The proposal and the design of an accelerator neutrino beam directed towards LNGS started in 1995 at CERN. LNGS is still the largest underground laboratory in the world and had been conceived and realized under the leadership of Antonino Zichichi as president of INFN. Already several years before the project of a CERN long baseline neutrino beam, the idea of the orientation of the large experimental halls towards CERN was envisioned to welcome a future long baseline neutrino beam. In 1997 I joined the Technical Committee jointly mandated by CERN and INFN, initially led by Kurt Hubner and later on by Konrad Elsener, with the duty of designing the new beam facility. With the support of both institutions, it was soon decided that the beam had to be dedicated to ν_τ appearance from ν_μ oscillations. Luciano Maiani (CERN director general), Enzo Iarocci (INFN president) and Sandro Bettini (LNGS director) contributed to the decision. The main impact of that choice was on its (high) intensity and on the energy of the neutrinos, required to be high to match the kinematical threshold for the production of the tau lepton in the charged current interactions of the ν_τ .

The largest fraction of the cost of the facility was covered by the Italian INFN, with additional contributions from Belgium, France, Germany, Spain and Switzerland and also from the Italian Compagnia di San Paolo. An in kind contribution was provided by Russia. The CNGS beam (CERN Neutrinos to Gran Sasso) was eventually approved in 1999 [42]. In a speech to 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*”.

Following the final approval of the CNGS project, two experiments were considered for the physics exploitation, namely OPERA [43] and, later on, ICARUS [44]. Both experiments proposed the search for $\nu_\mu - \nu_\tau$ oscillations in appearance mode, although with complementary

experimental approaches. OPERA aimed at the direct observation of the tau with a large nuclear emulsion detector, while ICARUS featured the kinematical reconstruction of the events produced in a liquid argon TPC. In both cases, the technology was that of an active, large-mass target. This choice reflected what had been done with the previous generation of CERN experiments, CHORUS [45] and NOMAD [46]. OPERA and ICARUS were finally approved in 2001 and 2003, and named as CERN experiments CNGS1 and CNGS2, respectively. This was the first time that CERN projects were located outside the boundaries of the laboratory.

The procedure that led to the choice of the detectors started in 1996. At that time, in parallel to the initial work on the CNGS beam, the first Kamiokande results on atmospheric neutrinos were clearly pointing to an anomaly. At the same time, the idea of exploring $\nu_\mu - \nu_\tau$ oscillations at short baseline, in the small mixing-angle and large Δm^2 parameter region, was also getting momentum. In this context, with the objective to extend by an order of magnitude the reach of CHORUS and NOMAD, we developed the conceptual design of a very high-sensitivity experiment (TENOR) [47], featuring nuclear emulsions to be used in a novel implementation. Eventually, this design converged into the TOSCA proposal to CERN [48]. However, the case of the atmospheric anomaly was (correctly) considered more compelling and the interest of the community moved to long baseline searches in the parameter region of large mixing-angle and small Δm^2 . With a paper that we wrote in 1997 [49], the idea of possible experiments for the direct detection of ν_τ appearance with an ECC (Emulsion Cloud Chamber) detector was proposed. This was the birth of OPERA, an Oscillation Project with an Emulsion tRacking Apparatus.

The ECC is a rather old detector technology originally developed in Japan (see e.g. [50]). Emulsions are employed in the ECC as high-resolution micro-tracking devices with three-dimensional reconstruction features, by sandwiching emulsion and passive material layers made of plastic or metal. The detector allows to reconstruct all tracks from charged particles originating from primary interactions with very high spatial accuracy, even better than $\sim 1 \mu\text{m}$. This detector was successfully used for the study of cosmic-rays [50]. An outstanding example is the discovery of the so-called X-particle in 1971 by Kiyoshi Niu [51]. That event was the first evidence of a charmed meson production and decay, obtained three years before the detection of the J/Ψ particle by Richter and Ting.

Kiyoshi Niu and his successor in Nagoya, Kimio Niwa further refined the concept of the ECC. Niwa introduced for the first time automatic emulsion scanning with computer driven microscopes and substantially contributed to the genesis of the conceptual design of the OPERA experiment [52]. Kimio Niwa and collaborators obtained an outstanding result by using an ECC detector when in the year 2000 they discovered the tau-neutrino with the DONUT beam dump experiment at Fermilab [6].

The OPERA Collaboration was initially created around the groups from Nagoya, Napoli, Salerno, Toho and Utsunomiya that submitted a Letter of Intent to CERN and LNGS [53]. The Collaboration soon increased with the arrival of more groups, in parallel to the conduction of preliminary studies and the definition of the experiment technical design. The Collaboration arrived to count about 200 colleagues from more than 30 institutions. In 1999 I presented the OPERA concept at the CERN SPS Scientific Committee. After approval, the experiment moved to the construction phase. The cost of the detector was mainly covered by INFN and LNGS, and by the Nagoya group, which provided the more than 10 million industrial emulsion films produced by Fuji-Film. Other contributions came from Belgium, France, Germany and Switzerland. Croatian, Korean, Russian, Tunisian and Turkish colleagues took part in many detector construction and operation activities. Last but not least, several Japanese and European groups were also involved

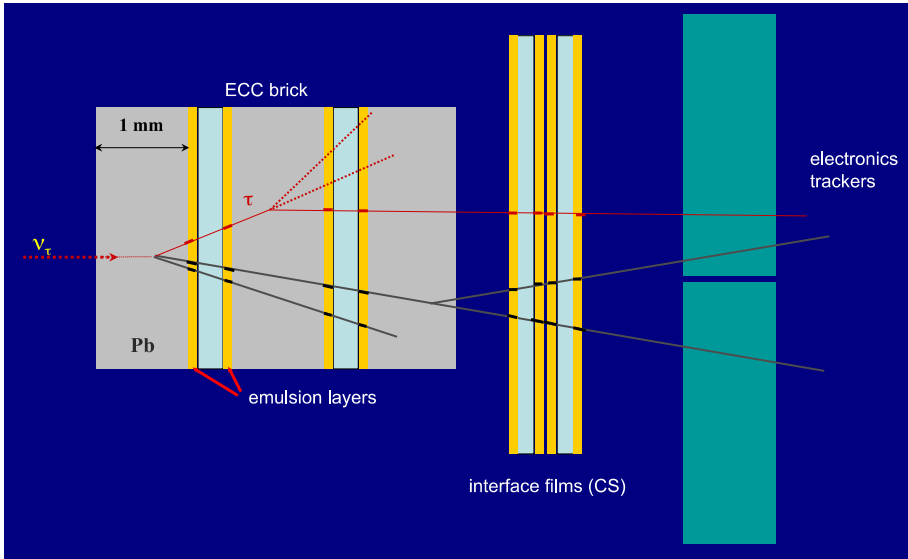


Fig. 1. The detection principle of OPERA. Electronic trackers predict the brick “hit” by the neutrino with the help of emulsion interface films (Changeable Sheets: CS). The interaction vertex is found by a “scan back” scanning procedure on those tracks identified by the CS.

in the successful development of the two automatic emulsion scanning-systems, the S-UTS and the ESS, required to analyze the unprecedented amount of emulsion film data.

The building up of detector and infrastructure at LNGS was carried out under the leadership of Yves Declais who was leading the Collaboration at the moment of the very first data collected in 2006. In 2008 I was elected as successor of Yves Declais, in the exciting time of the first neutrino data in the emulsions and of the first tau candidate event.

4. Experiment and methods

The OPERA experiment is a typical long baseline neutrino experiment, featuring an underground location, a large neutrino-target mass, and an intense ν_μ beam with negligible contamination of other neutrino flavors [54]. In order to achieve the detection of the appearance of ν_τ from ν_μ oscillations, one has to identify the short-lived tau lepton produced in the charged current interaction of ν_τ 's. Two conflicting requirements have to be fulfilled, namely the realization of a large target mass to collect enough event statistics, at the same time providing an extremely high spatial accuracy to measure the tau lepton. The latter is identified by the detection of its decay topologies in one-prong (electron, muon or hadron) or in three-prongs; its short track (<2 mm) is detected by thin nuclear emulsion films assembled in the ECC structure. The OPERA detection principle is depicted in Fig. 1.

The experimental setup (Fig. 2) is a large mass hybrid detector composed of two Super-Modules each consisting of a target section made of emulsion/lead ECC units called bricks. Scintillator trackers allow to trigger the read-out and pre-localize neutrino interactions in the ECC bricks. A muon spectrometer complements each Super-Module for muon identification. The total number of bricks is 150 000, composing a neutrino active target mass weighing 1250 t. Each of the two spectrometers consists of an iron magnet instrumented with plastic Resistive



Fig. 2. The OPERA detector in the LNGS underground Hall C.

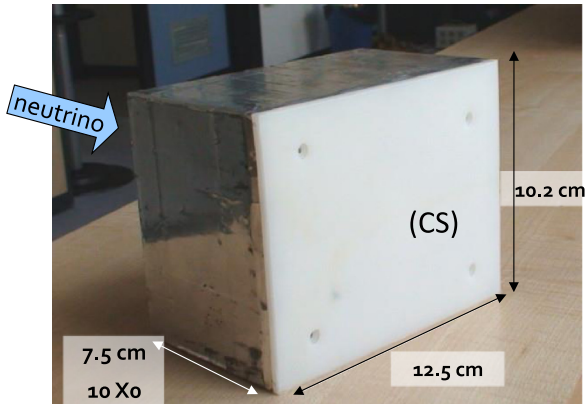


Fig. 3. One of the 150 000 ECC target units (bricks) that constitute the OPERA neutrino target. The interface downstream emulsion film doublet (CS) attached to the brick is also shown.

Plate Chambers (RPC) and of drift tubes used to accurately measure the deflection of particles inside the magnet iron. Two glass RPC planes placed in front of the most upstream target allow the rejection of particles from neutrino interactions in the surrounding rock material.

Each brick is made of 56 lead plates with 1 mm thickness sandwiched with 57 emulsion films. The plate material is a lead alloy with a small calcium content needed to improve the mechanical properties. The transverse dimensions of a brick, shown in Fig. 3, are $12.8 \times 10.2 \text{ cm}^2$ for a thickness along the beam direction of 7.9 cm. Bricks are enclosed in a stainless-steel support structure placed between consecutive target tracker walls. The detector is equipped with two robots taking care of the automatic removal of bricks from the target. Ancillary facilities are used



Fig. 4. The emulsion scanning station of the Bern OPERA group equipped with 5 automatic microscopes.

for the handling, the development and the scanning of the emulsion films. Emulsion scanning is performed with two different types of automatic microscopes independently developed by the European and the Japanese groups of the Collaboration [55,56] (Fig. 4).

The use of Changeable Sheets (CS) film interfaces, previously applied to the CHORUS and DONUT experiments, was extended to OPERA on a much larger scale with the aim of reducing the emulsion scanning-load. Doublets of emulsion films are glued to the downstream face of each brick and are removed without opening the brick itself following a trigger. Charged particles from a neutrino interaction in one lead plate can cross the CS and hence produce a signal in the target tracker scintillators. A selection algorithm provides high-efficiency in identifying the brick hit by the neutrino. The selected brick is extracted and its CS developed and scanned in one of the dedicated scanning facilities at LNGS and Nagoya. 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 defined 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 is shown in Fig. 5.

As far as the experimental background is concerned, production and decay of charmed particles has the highest quantitative relevance in OPERA. However, charm events are also important to support the observation of ν_τ events. In fact, one has to prove that charm interactions, topologically similar to signal events, are detected at the expected rate. This is shown in Fig. 6 where a reconstructed neutral charm decay is shown together with two examples of kinematical distributions plotted for data and simulated events [57].

Another relevant source of background is given by hadron re-interactions in events without muons. This scattering process features the same kink topology as the signal and could fake hadronic tau decays. However, this background is relatively suppressed by the long interaction length of hadrons in the lead target as compared to the 2 mm allowed decay-length for signal events. Analogous considerations apply to muon large-angle scattering, which is a potential

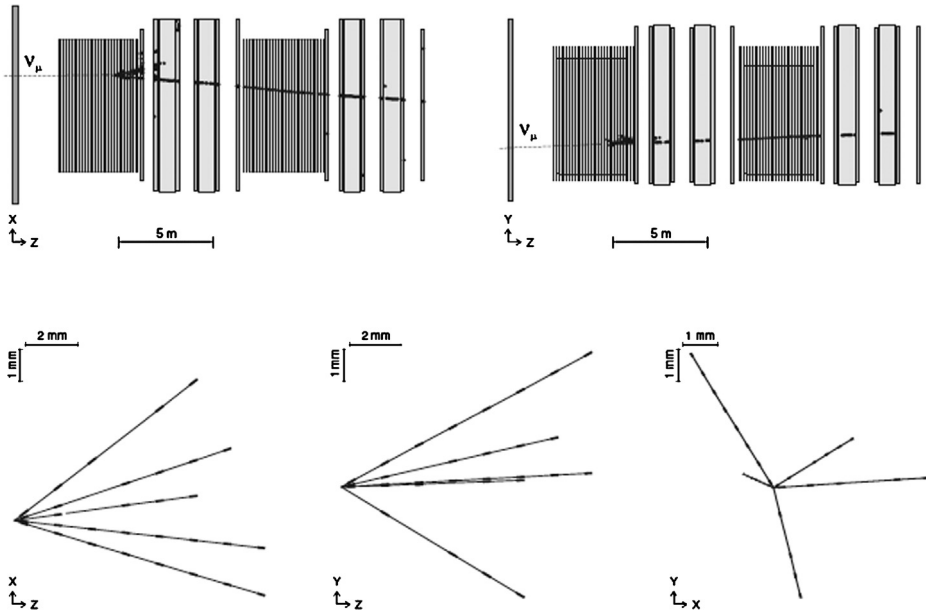


Fig. 5. Display of a charged current muon-neutrino event produced in the OPERA target. Top: the reconstruction by the electronic detectors (~ 15 m scale). Bottom: the neutrino interaction vertex region reconstructed by means of the emulsions (millimeter scale).

background to the clean $\tau \rightarrow \mu$ decay mode. The small estimated background of the experiment allows to obtain a sensitive result already with the detection of few signal candidate events. This is another distinctive feature of the experiment.

OPERA has been running since 2006, when a technical run was performed without target bricks [58]. In 2007 the first interactions in the emulsions were detected [59] and, as mentioned above, 2008 and 2009 featured the first two “production runs”, with the collection of several thousand neutrino interactions. Out of them we detected the expected number of charm events and the first ν_τ candidate event [60], discussed below. Additional runs took place from 2010 and 2012, when data taking successfully ended.

5. Discovery of tau appearance

The first OPERA tau candidate event was born on August 22nd, 2009 at 19:27 (UTC), with the serial number 9234119599. Until then, several 10^{19} muon-neutrinos had been sent from CERN towards the detector in the Hall C of LNGS. The signals from the electronic trackers allowed predicting which one of the 150 000 bricks of the target was likely hit. The CS films of that brick were extracted and scanned. Three tracks were found in the CS and they were compatible with the signals of the downstream electronic detectors. This gave clearance for the cosmic-ray exposure of the brick to perform the precision alignment of its emulsion films. The latter were then developed and shipped to one of the scanning labs of the Collaboration. Starting from the most downstream film, track predictions from the CS films were searched for and extrapolated upstream until a neutrino interaction vertex was eventually found. A 40-mrad kink was detected on a track coming from the neutrino interaction in one of the 56 lead plates, after a flight length of 1.3 mm. All other tracks were found to match within a few micron impact parameter. An

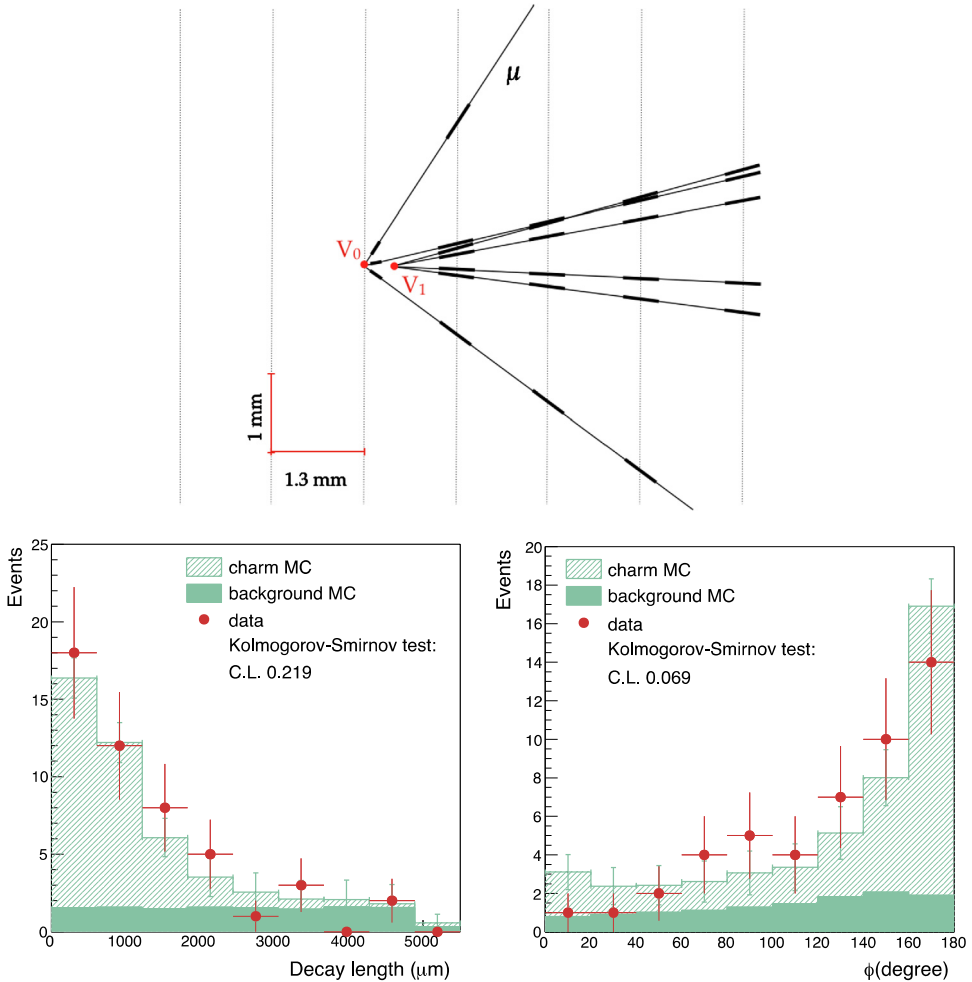


Fig. 6. Top: display of a neutral charm event reconstructed in OPERA. Bottom: examples of kinematical variables distributions relative to charm events (data and simulated events); left histogram: decay length of the charmed particle; right histogram: angle between the charmed hadron direction and that of the primary muon in the plane transverse to the incoming neutrino direction.

emulsion volume scan around the vertex region allowed finding 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 ($120 \pm 20 \pm 30$ MeV).

Additional bricks were removed and scanned to follow down all the event tracks and to measure their momentum by the Multiple Coulomb Scattering method. The films of the brick with the neutrino vertex were then sent to a different laboratory to conduct an independent measurement of the track parameters. A detailed visual inspection of the kink region allowed to exclude the presence of micro-tracks that could be potentially attributed to a hadronic re-interaction. 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 interpreted as a $\nu_\tau \rightarrow \tau \rightarrow \pi^0 + \text{charged hadron} + \nu_\tau$ candidate. The display of the event

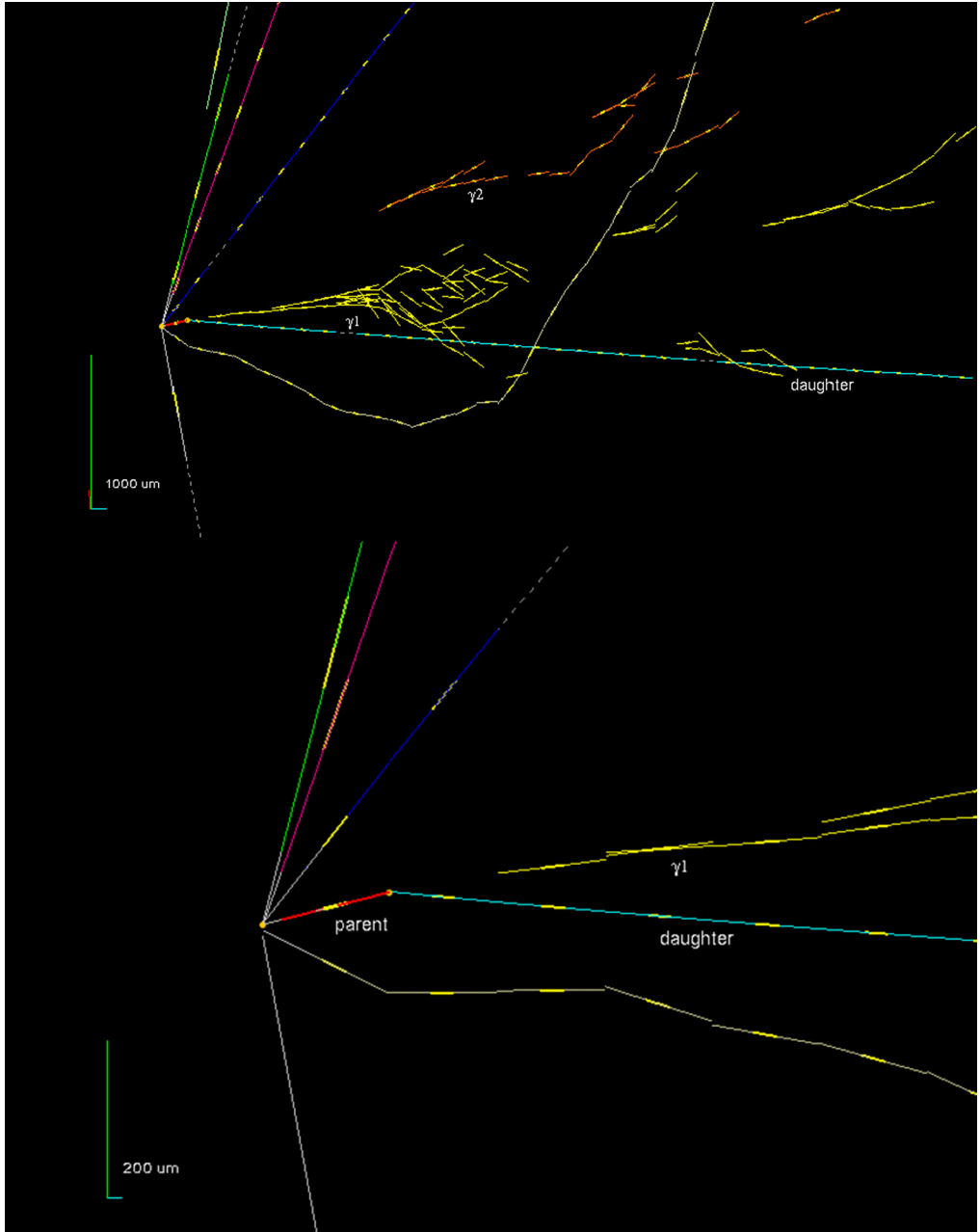


Fig. 7. Top: display of the first OPERA ν_τ candidate event. The tau (red short track) decays into a hadron (light blue track) with the characteristic kink topology; bottom: a zoom of the vertex region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is shown in Fig. 7. The estimate of the residual background gave 0.018 ± 0.007 events. The probability of explaining the single detected event in terms of a background fluctuation is 1.8%,

Channel	Expected background				Expected signal	Observed
	Charm	Had. reinterac	Large μ scat.	Total		
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01			0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

Fig. 8. Signal event statistics and background estimate for the OPERA measurement [59].

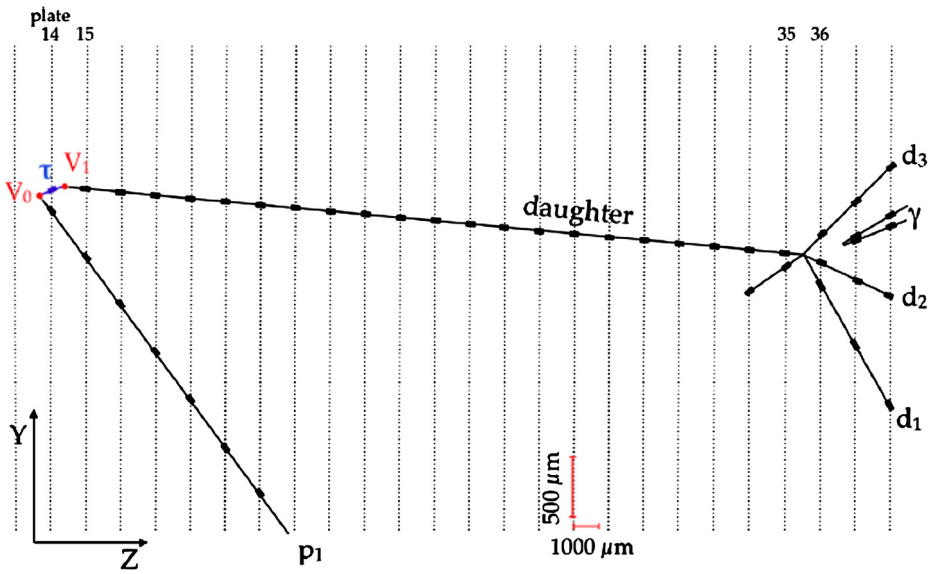


Fig. 9. Event display of the fifth OPERA signal event. The tau (red track) decays into 1 charged hadron that eventually interacts downstream producing a third vertex in the event [59]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for a 2.36σ statistical significance for the observation of the first ν_τ candidate event from ν_μ oscillations in the OPERA experiment.

A seminar was then given at LNGS on May 31st, 2010 [61], repeated a few days later at CERN, Fermilab and Nagoya. The first OPERA ν_τ candidate event had been a key milestone for the Collaboration. After that first event, the detector took data for an integral exposure corresponding to 18×10^{20} protons on the CNGS neutrino production target. The total number of detected events in the target fiducial volume was 19505. The long journey of OPERA towards the discovery of tau appearance ended in 2015 with the publication of an article presenting 5 detected tau events, corresponding to a statistical significance exceeding 5 standard deviations [62]. The final signal event statistics and the corresponding estimated backgrounds are shown in Fig. 8. Three signal events belong to the 1-hadron tau decay mode, one to the 3-pion channel and one to a muonic decay, which features a very low background. The number of tau candidates is in agreement with the expected number events of 2.64 ± 0.53 , for an estimated overall background of 0.25 ± 0.05 events. In Fig. 9 it is shown the display of the fifth OPERA tau candidate event.

The statistical significance of the observed ν_τ event samples is computed by estimating the probability that the background can fluctuate more than the observed data by means of generating pseudo-experiments. With its observed signal OPERA has been able to determine the 90% confidence interval for Δm_{23}^2 by three different statistical approaches, the profile likelihood ratio, the Feldman–Cousins method and the Bayesian statistics. Assuming full mixing, the best fit is $\Delta m_{23}^2 = 3.3 \times 10^{-3} \text{ eV}^2$ with a 90% C.L. interval of $[2.0, 5.0] \times 10^{-3} \text{ eV}^2$ and with a negligible difference between the three methods.

The achievement of this milestone constituted a big reward for the many years of efforts of all people and institutions involved in the CNGS program and in OPERA, in particular. In perspective, we should stress that the detection technology successfully adopted for OPERA could well be considered for future studies, e.g. for the high statistics measurement of tau-neutrino cross section in beam dump experiments. The OPERA results were also recognized, together with those from other collaborations, in the extended motivation of the 2015 Nobel Prize awarded to Kajita-san and Art McDonald: *”Super-Kamiokande’s oscillation results were later confirmed by the detectors MACRO and Soudan, the long-baseline accelerator experiments K2K, MINOS and T2K and more recently also by the large neutrino telescopes ANTARES and IceCube. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN.”*

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