Latest results of the OPERA experiment on nu-tau appearance in the CNGS neutrino beam

N. Agafonova[1], A. Alexandrov[2], A. Anokhina[3], S. Aoki[4], A. Ariga[5], T. Ariga[5,6], A. Bertolin[7], C. Bozza[8], R. Brugnera[7,9], A. Buonaura[2,10], S. Buontempo[2], M. Chernyavskiy[11], A. Chukanov[12], L. Consiglio[2], N. D'Ambrosio[13], G. De Lellis[2,10], M. De Serio[14,15], P. del Amo Sanchez[16], A. Di Crescenzo[2,10], D. Di Ferdinando[17], N. Di Marco[13], S. Dmitrievsky[12], M. Dracos[18], D. Duchesneau[16], S. Dusini[7], T. Dzhatdoev[3], J. Ebert[19], A. Ereditato[5], J. Favier[16], R. A. Fini[15], F. Fornari[17,20], T. Fukuda[21], G. Galati[2,10,*], A. Garfagnini[7,9], V. Gentile[22], J. Goldberg[23], S. Gorbunov[11], Y. Gornushkin[12], G. Grella[8], A. M. Guler[24], C. Gustavino[25], C. Hagner[19], T. Hara[4], T. Hayakawa[21], A. Hollnagel[19], K. Ishiguro[21], A. Iuliano[10,2], K. Jakovcic[26], C. Jollet[18], C. Kamiscioglu[24,27], M. Kamiscioglu[24], S. H. Kim[28], N. Kitagawa[21], B. Klicek[29], K. Kodama[30], M. Komatsu[21], U. Kose[7], I. Kreslo[5], F. Laudisio[7,9], A. Lauria[2,10], A. Longhin[9,7], P. Loverre[25], M. Malenica[26], A. Malgin[1], G. Mandrioli[17], T. Matsuo[31], V. Matveev[1], N. Mauri[17,20], E. Medinaceli[7,9], A. Meregaglia[18], S. Mikado[32], M. Miyanishi[21], F. Mizutani[4], P. Monacelli[25], M. C. Montesi[2,10], K. Morishima[21], M. T. Muciaccia[14,15], N. Naganawa[21], T. Naka[21], M. Nakamura[21], T. Nakano[21], K. Niwa[21], S. Ogawa[31], A. Olchevsky[12], N. Okateva[11], K. Ozaki[4], A. Paoloni[33], L. Paparella[14,15], B. D. Park[28], L. Pasqualini[17,20], A. Pastore[15], L. Patrizii[17], H. Pessard[16], C. Pistillo[5], D. Podgrudkov[3], N. Polukhina[11,34], M. Pozzato[17,20], F. Pupilli[7], M. Roda[7,9], T. Roganova[3], H. Rokujo[21], G. Rosa[25], O. Ryazhskaya[1], A. Sadovsky[12], O. Sato[21], A. Schembri[13], I. Shakiryanova[1], T. Shchedrina[11], E. Shibayama[4], H. Shibuya[31], T. Shiraishi[21], S. Simone[14,15], C. Sirignano[7,9], G. Sirri[17], A. Sotnikov[12], M. Spinetti[33], L. Stanco[7], N. Starkov[11], S. M. Stellacci[8], M. Stipcevic[29], P. Strolin[2,10], S. Takahashi[4], M. Tenti[17], F. Terranova[35], V. Tioukov[2], S. Tufanli[5], A. Ustyuzhanin[36,2], S. Vasina[12], P. Vilain[37], E. Voevodina[2], L. Votano[33], J. L. Vuilleumier[5], G. Wilquet[37], B. Wonsak[19] and C. S. Yoon[28]

1 INR - Institute for Nuclear Research of the Russian Academy of Sciences, RUS-117312 Moscow, Russia
2 INFN Sezione di Napoli, I-80126 Napoli, Italy
3 SINP MSU - Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, RUS-119991 Moscow, Russia
4 Kobe University, J-657-8501 Kobe, Japan
5 Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), University of Bern, CH-3012 Bern, Switzerland
6 Faculty of Arts and Science, Kyushu University, J-819-0395 Fukuoka, Japan
7 INFN Sezione di Padova, I-35131 Padova, Italy
8 Dipartimento di Fisica dell'Università di Salerno and "Gruppo Collegato" INFN, I-84084 Fisciano (Salerno), Italy
9 Dipartimento di Fisica e Astronomia dell'Università di Padova, I-35131 Padova, Italy
10 Dipartimento di Fisica dell'Università Federico II di Napoli, I-80126 Napoli, Italy
11 LPI - Lebedev Physical Institute of the Russian Academy of Sciences, RUS-119991 Moscow, Russia
12 JINR - Joint Institute for Nuclear Research, RUS-141980 Dubna, Russia
13 INFN - Laboratori Nazionali del Gran Sasso, I-67010 Assergi (L'Aquila), Italy
14 Dipartimento di Fisica dell'Università di Bari, I-70126 Bari, Italy
15 INFN Sezione di Bari, I-70126 Bari, Italy
16 LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
17 INFN Sezione di Bologna, I-40127 Bologna, Italy
18 IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France

19 Hamburg University, D-22761 Hamburg, Germany

20 Dipartimento di Fisica e Astronomia dell'Università di Bologna, I-40127 Bologna, Italy

21 Nagoya University, J-464-8602 Nagoya, Japan

22 GSSI - Gran Sasso Science Institute, I-40127 L'Aquila, Italy

23 Department of Physics, Technion, IL-32000 Haifa, Israel

24 METU - Middle East Technical University, TR-06800 Ankara, Turkey

25 INFN Sezione di Roma, I-00185 Roma, Italy

26 Ruđer Bošković Institute, HR-10002 Zagreb, Croatia

27 Ankara University, TR-06560 Ankara, Turkey

28 Gyeongsang National University, 900 Gazwa-dong, Jinju 660-701, Korea

29 Center of Excellence for Advanced Materials and Sensing Devices,
Ruđer Bošković Institute, HR-10002 Zagreb, Croatia

30 Aichi University of Education, J-448-8542 Kariya (Aichi-Ken), Japan

31 Toho University, J-274-8510 Funabashi, Japan

32 Nihon University, J-275-8576 Narashino, Chiba, Japan

33 INFN - Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati (Roma), Italy

34 MEPhI - Moscow Engineering Physics Institute, RUS-115409 Moscow, Russia

35 Dipartimento di Fisica dell'Università di Milano-Bicocca, I-20126 Milano, Italy

36 HSE - National Research University Higher School of Economics,
RUS-101000, Moscow, Russia

37 IIHE, Université Libre de Bruxelles, B-1050 Brussels, Belgium

⋆ giuliana.galati@na.infn.it

Abstract

OPERA is a long-baseline experiment designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode. It was based at the INFN Gran Sasso laboratory (LNGS) and took data from 2008 to 2012 with the CNGS neutrino beam from CERN. After the discovery of ν_τ appearance in 2015, with 5.1σ significance, the criteria to select ν_τ candidates have been extended and a multivariate approach has been used for events identification. In this way the statistical uncertainty in the measurement of the oscillation parameters and of ν_τ properties has been improved. Results are reported.

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1 Introduction

Originated by the neutrino mass and the mixing between flavour and mass eigenstates, neutrino oscillations are now established thanks to intense experimental efforts. In 1998, the first evidence of neutrino oscillations was provided by the Super-Kamiokande experiment, showing the disappearance of atmospheric muon neutrinos [1]. This result was consistent with the transition of ν_μ to ν_τ or to a new type of neutrino, still not known. At that time, moreover, the ν_τ neutrino had not been observed yet.

The OPERA experiment [2] was designed to conclusively prove the existence of $\nu_\mu \rightarrow \nu_\tau$ oscillations. It was operated underground at the Gran Sasso INFN Laboratory (LNGS), 730 km away from the muon neutrino source at CERN, and collected data from 2008 to 2012. The direct search for ν_τ appearance was based on the detection of τ leptons produced in ν_τ charged current interactions (CC). The challenging detection of the short-lived τ lepton (cτ = 87 μm), out of almost twenty thousands ν_μ interactions, was achieved exploiting the nuclear emulsions sub-micrometric spatial resolution.

2 The CNGS beam and the OPERA detector

The OPERA detector was located at the underground Gran Sasso Laboratory (LNGS), 730 km away from the neutrino source, in the high energy CERN to LNGS beam (CNGS) [3,4]. The average neutrino energy was $\sim$ 17 GeV, the $\bar{\nu}_\mu$ contamination was 2.1% in terms of interactions, the ν_e and $\bar{\nu}_e$ together were below 1%, while the number of prompt ν_τ was negligible. The detector was a hybrid apparatus consisting of an emulsion/lead target complemented by electronic detectors. It was made up of two identical super-modules aligned along the CNGS beam direction, each made of a target section and a muon spectrometer. Each target section consisted of a multi-layer array of 31 target walls interleaved with pairs of planes of plastic scintillator strips. Target walls were made of Emulsion Cloud Chamber target units, called bricks, which were, in total, 150000. Each brick consists of 57 emulsion films, 300 μm thick, interleaved with 56 lead plates, 1 mm thick. The target total mass was 1.25 ktons. The electronic detectors were used to identify the brick containing the neutrino interaction, for muon identification and its charge and momentum determination.

3 Event selection and analysis

Once a neutrino interaction was reconstructed in the electronic detectors, the bricks most probably containing the interaction vertex was identified by a dedicated offline algorithms and extracted from the walls. The nuclear emulsions were eventually developed and scanned to search for τ decays. The scanning was performed with automated optical microscopes installed in Laboratories in Europe and in Japan. If a secondary vertex was found, a full kinematic analysis was performed combining the nuclear emulsion data with those from the electronic detectors. The momentum of charged particles in emulsions was determined by Multiple Coulomb Scattering [5]. For muons crossing the spectrometers, the momentum was measured with a resolution better than 22% up to 30 GeV/c, and the charge sign determined [6].

The appearance of the τ lepton was identified by the detection of its characteristic decay topologies, either in one prong (electron, muon or hadron) or in three prongs. A first hint of a decay topology was the observation of an impact parameter larger than 10 μm, defined as the minimum distance between the track and the reconstructed vertex, excluding low momentum tracks. Kinematic selection criteria were then applied according to the decay channel.

4   First phase of the OPERA experiment

In the first phase of the OPERA experiment, very stringent kinematical selection criteria for ν_τ candidate selection were applied, allowing a signal-to-background ratio of ~ 10.

Five ν_τ candidates were observed: three in the $\tau \rightarrow 1h$ decay channel [7–9], one in the $\tau \rightarrow 3h$ [10] and one in the $\tau \rightarrow \mu$ [11] decay channel. In the sample analysed up to 2015, corresponding to 5408 neutrino interactions, 0.25 ± 0.05 background events were expected, coming mainly from events with an undetected primary muon, hadronic re-interactions and large angle muon scattering. The observation of five candidates results in 5.1σ significance for the exclusion of the background only hypothesis [9].

5   Second phase of the OPERA experiment

A new goal has been set. In order to estimate the oscillation parameters with reduced statistical uncertainty a new analysis procedure was implemented.

Given the validation of the Monte Carlo simulation of ν_τ events, based on different control data samples [12–14], a new analysis strategy was developed, fully exploiting the features of expected ν_τ events. A multivariate approach to improve signal to noise separation was applied to candidate events selected by means of moderately tight topological and kinematical cuts. The new selection was applied to the complete data sample, corresponding to 5603 ν interactions. Details about the new selection method are reported in [15]. The total expected signal is (6.8 ± 1.4) events, whereas the total background expectation is (2.0 ± 0.4) events.

Ten events (N^{obs}) survived all the topological and kinematical cuts. The distribution of their visible energy, i.e. the scalar sum of the momenta of charged particles and γs, is shown in Fig. 1, where it is compared to Monte Carlo simulation.
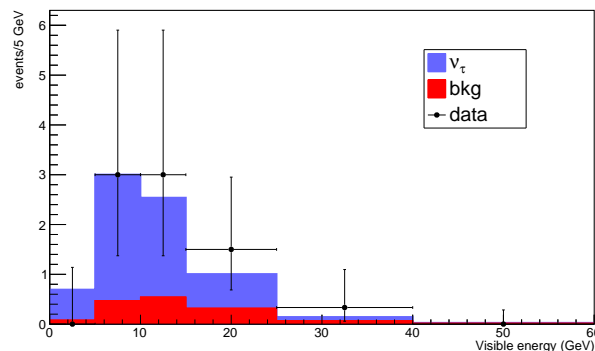

Figure 1: Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalised to the expected number of events [15].

Different multivariate techniques have been considered and their performances for signal to background discrimination compared. The one with the best discrimination power was the Boosted Decision Tree (BDT).

5.1 ν_τ appearance statistical significance

The statistical analysis used to re-evaluate the significance for the ν_τ appearance is based on an extended likelihood constructed as the product of a probability density function given by the BDT response, a Poisson probability term which takes into account the number of observed

events and the expected background in each decay channel, and a Gaussian term which accounts for systematics. The discovery significance of ν_τ appearance is expressed in terms of a hypothesis test where the background only hypothesis plays the role of the null hypothesis and the signal-plus-background hypothesis is the alternative one. The null hypothesis was excluded with the improved significance of 6.1 σ [15].

5.2 First measurement of $|\Delta m_{23}^2|$ in appearance mode and of ν_τ CC cross-section on Lead

The number of observed ν_τ candidates after background subtraction is a function of the product of ν_τ CC cross-section ($\sigma_{\nu_\tau}^{CC}$) and the oscillation parameter Δm_{23}^2.

The squared mass difference Δm_{23}^2 was evaluated for the first time in appearance mode: assuming $\sin^2 2\theta_{23} = 1$, $|\Delta m_{23}^2|$ is equal to $(2.7_{-0.6}^{+0.7}) \cdot 10^{-3} \text{eV}^2$. The result is consistent with the measurements performed in disappearance mode by other experiments and with the Particle Data Group best fit [16].

The ν_τ CC cross-section on the OPERA lead target was also estimated: it is equal to $(5.1_{-2.0}^{+2.4}) \cdot 10^{-36} \text{cm}^2$, assuming $|\Delta m_{23}^2| = 2.50 \cdot 10^{-3}$ eV^2. It is the first measurement of the ν_τ CC cross-section with a negligible contamination from $\bar{\nu}_\tau$.

5.3 ν_τ lepton number

The OPERA experiment allowed to distinguish neutrinos from anti-neutrinos by the charge of the muon in τ muonic decays. This charge was determined as negative at 5.6 σ level for the $\tau \to \mu$ candidate. Performing a dedicated BDT analysis which included also the background from 2% $\bar{\nu}_\mu$ beam contamination, the first direct evidence for the leptonic number of τ neutrinos with a significance of 3.7σ was obtained.

Conclusions

OPERA claimed the discovery at 5.1σ of $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam from the detection of five ν_τ events, with a background of 0.25 events. A new analysis strategy was applied for the selection of additional ν_τ candidates, in order to measure the oscillation parameters with reduced statistical error.

With the identification of five additional ν_τ candidates, an overall sample of ten ν_τ candidates was collected, with 2.0 ± 0.4 expected background events. The discovery of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode is confirmed with an improved significance of 6.1 σ.

Assuming $\sin^2 2\theta_{23} = 1$, the first measurement of $|\Delta m_{23}^2|$ in appearance mode yields $(2.7_{-0.6}^{+0.7}) \cdot 10^{-3} \text{eV}^2$, while the measured ν_τ CC cross-section on the lead OPERA target is $(5.1_{-2.0}^{+2.4}) \cdot 10^{-36} \text{cm}^2$, assuming $|\Delta m_{23}^2| = 2.50 \cdot 10^{-3}$ eV^2.

Furthermore, a dedicated BDT analysis in the $\tau \to \mu$ channel allows claiming for the first direct observation of the ν_τ lepton number with a significance of 3.7 σ.

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