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# More results from the OPERA experiment

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# More results from the OPERA experiment

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**Abstract.** The OPERA experiment reached its main goal by proving the appearance of tau-neutrinos in the CNGS muon-neutrino beam. A total sample of 5 candidates fulfilling the analysis defined in the proposal was detected with a S/B ratio of about ten allowing to reject the null hypothesis with a significance of 5.1 $\sigma$. The search was extended to $\nu_\tau$-like interactions failing the kinematical analysis defined in the experiment proposal, to obtain a statistically enhanced, lower purity, signal sample. One such interesting neutrino interaction showing a double vertex topology with a high probability of being a tau-neutrino interaction with charm production will be reported. Based on the enlarged data sample the estimation of $\Delta m^2_{23}$ in appearance mode is presented. The search for $\nu_e$ interactions has been extended over the full data set with a more than twofold increase in statistics with respect to published data. The analysis of the $\nu_\mu \to \nu_e$ channel is updated and the implications of the electron-neutrino sample in the framework of the 3+1 sterile model is discussed. An analysis of the $\nu_\mu \to \nu_\tau$ oscillations in the framework of the sterile neutrino model has also been performed.

## 1. The OPERA experiment

The OPERA experiment was designed to observe $\nu_\mu \to \nu_\tau$ flavour appearance in the long baseline CERN Neutrinos to Gran Sasso (CNGS) beam and thus unambiguously prove neutrino oscillations at the atmospheric scale. The OPERA detector [1] was located in the underground Gran Sasso Laboratory (LNGS) and exposed from 2008 to 2012 to the CNGS $\nu_\mu$ beam, 730 km away from the neutrino source. The direct appearance search was based on the detection of $\tau$ leptons produced in Charged Current (CC) $\nu_\tau$ interactions with a signal to noise ratio of $\mathcal{O}(10)$. The observation of the short-lived $\tau$ decay was a demanding experimental challenge requiring a micrometric resolution and a large mass, accomplished using a modular and hybrid apparatus composed by Emulsion Cloud Chambers (ECC) complemented with electronic detectors. The ECC basic unit in OPERA was the "brick", a sandwich made of 56 lead plates, 1 mm thick, interspaced with 57 nuclear emulsion films. The submicrometre spatial resolution of the nuclear emulsion allowed a precise three-dimensional reconstruction of the neutrino vertex as well as of the decay vertex associated with short-lived particles, like the $\tau$ lepton. Moreover, each brick acted as a compact stand-alone detector measuring electromagnetic showers and charged particle momentum through multiple Coulomb scattering [2]. The overall target (150000 bricks, corresponding to 1.25 kton) was segmented into two modules. In each of the two target modules, the bricks were arranged in 29 vertical "walls", transverse to the beam direction, interleaved with Target Tracker walls (TT), planes of horizontal and vertical scintillator strips. The TT triggered the read-out and were used to identify the brick containing the neutrino interaction. Each target section was followed by a magnetic spectrometer. A dipolar iron magnet was instrumented with RPC and drift tube detectors in order to measure the muon charge and momentum.

Bricks expected to contain neutrino interactions were extracted from the modular target and distributed to the scanning laboratories in Europe and in Japan. The emulsion films were analysed by automatic optical microscopes in order to reconstruct the neutrino interaction vertex and a dedicated procedure was applied to search for and identify short-lived particle decay vertices [4]. If a secondary vertex was found, a full kinematic analysis was performed extending the scanning, following the tracks in the downstream bricks, and combining the complementary information provided by emulsions and electronic detectors.

## 2. $\nu_\mu \to \nu_\tau$ appearance search

The OPERA experiment collected data from 2008 to 2012. During the five years exposure to the CNGS a sample of 19505 neutrino interactions in the emulsion targets was recorded, corresponding to an integrated intensity of $17.97 \times 10^{19}$ protons on target (pot). Five $\nu_\tau$ candidates satisfying the kinematic selection criteria defined in the proposal were observed [5]. Three sources of background, charmed particles decays, hadronic interactions and large-angle muon scattering (LAS), were expected to contribute overall for $0.25 \pm 0.05$ events to the final sample, allowing to exclude the background-only hypothesis with a significance of $5.1\sigma$. The expected background and signal events (assuming $\Delta m^2_{23} = 2.44 \times 10^{-3}$ eV$^2$ [6] and maximal mixing) for the analysed data set with the corresponding uncertainties are summarised in Table 1.

**Table 1.** Expected signal and background events in the analysed data set [5].

| Channel | Exp. Background | | | | Exp. Signal | Observed |
|---|---|---|---|---|---|---|
| | Charm | Hadronic re-int | LAS | Total | | |
| $\tau \to 1h$ | $0.017 \pm 0.003$ | $0.022 \pm 0.006$ | – | $0.04 \pm 0.01$ | $0.52 \pm 0.10$ | 3 |
| $\tau \to 3h$ | $0.17 \pm 0.03$ | $0.003 \pm 0.001$ | – | $0.17 \pm 0.03$ | $0.73 \pm 0.14$ | 1 |
| $\tau \to \mu$ | $0.004 \pm 0.001$ | – | $0.0002 \pm 0.0001$ | $0.004 \pm 0.001$ | $0.61 \pm 0.12$ | 1 |
| $\tau \to e$ | $0.03 \pm 0.01$ | – | – | $0.03 \pm 0.01$ | $0.78 \pm 0.16$ | 0 |
| Total | $0.22 \pm 0.04$ | $0.02 \pm 0.01$ | $0.0002 \pm 0.0001$ | $0.25 \pm 0.05$ | $2.64 \pm 0.53$ | 5 |

In Ref. [5] the number of observed $\nu_\tau$ was used to measure the atmospheric squared mass difference in appearance mode for the first time. In order to improve the $\Delta m^2_{23}$ measurement, the kinematic selection cuts were loosened so to increase the $\nu_\tau$ sample statistics, at the cost of reducing the S/B from $\sim$10 to $\sim$3. A minimum selection, leading to a negligible additional background from $\pi$ and $K$ decays, was used to limit the contribution from hadronic interactions and LAS, and a multivariate analysis was applied. Boosted Decision Trees (BDT) [7] were trained with Monte Carlo to discriminate between $\nu_\tau$ and background events using topological and kinematic variables and their correlations. A cut on the BDT response maximizing the product of selection efficiency and sample purity was defined. In total 10 $\nu_\tau$-like events were selected, with $6.8 \pm 1.4$ expected signal events and an expected total background of $2.0 \pm 0.5$ events.

For the CNGS baseline and energy range the rate of $\nu_\tau$ CC interactions varies as $(\Delta m^2_{23})^2$. Assuming maximal mixing $\sin^2 2\theta_{23} = 1$ and taking into account the CNGS baseline $L = 730$ km and the mean neutrino energy $\langle E \rangle = 17$ GeV, the $\nu_\mu \to \nu_\tau$ oscillation probability $P_{\mu\tau}$ can be approximated to

$$P_{\mu\tau}(E) \approx \sin^2\left(\frac{\Delta m^2_{23}\,L}{4E}\right)^2 \approx \left(\Delta m^2_{23}\right)^2 (L/4E)^2$$

Consequently the number of expected $\nu_\tau$ varies as $(\Delta m^2_{23})^2$. Using different approaches (Feldman-Cousins method, profile likelihood ratio) and assuming full mixing, the 90% C.L. interval for $\Delta m^2_{23}$ is evaluated as $(2.7 \pm 0.6) \times 10^{-3}$ eV$^2$.

## 3. Peculiar event with 2 decay vertices

Among the observed neutrino events, one without a reconstructed muon and with two secondary vertices within about 1 mm from the interaction point was identified. The observation of events with two secondary vertices had been considered negligible in the experimental proposal and no analysis procedure had been designed for such an observation, consequently a dedicated analysis was performed. Several physical processes can produce this peculiar topology:

- $\nu_\tau$ CC interaction with charm production
- $\nu$ NC interaction with $c\bar{c}$ production
- $\nu_\mu$ CC interaction with a mis-identified muon and two secondary interactions
- $\nu_\mu$ CC interaction with single charm production, a mis-identified muon and one secondary interaction
- $\nu$ NC interaction with two secondary interactions
- $\nu_\tau$ CC interaction with one secondary interaction.

A secondary interaction can be either i) a hadronic interaction of a final state particle, ii) a short decay of a pion or a kaon, or iii) a large-angle Coulomb scattering of a hadron or of a mis-identified muon. In order to establish whether the observed event is a $\nu_\tau$ CC interaction with charm production or has another origin, the expected distributions of kinematic variables for each process were obtained through a dedicated Monte Carlo production and a multivariate analysis was applied. To better discriminate between signal and background, several algorithms were tested: an Artificial Neural Networks (ANN) method [8], two kinds of Boosted Decision Trees [7] and the Fisher Discriminant method [9]. The ANN, whose output variable distribution is shown in Fig. 1, turned out to be the best one, as it provided good signal efficiency and background rejection power.

Using the ANN output variable as observable and the profile likelihood ratio as test statistic, the probability to observe events less likely compatible to the background than the measured one, under the background-only hypothesis, is $(2.6 \pm 0.2) \times 10^{-4}$. This result provides evidence for the first observation of a $\nu_\tau$ CC interaction with charm production. The significance of this observation is $3.5\sigma$.

## 4. Search for $\nu_e$ CC interactions

The nuclear emulsion granularity allows the reconstruction of electromagnetic showers disentangling electrons from photon conversions, and consequently the identification of $\nu_e$ CC interactions. A dedicated procedure [10] was defined to systematically search for $\nu_e$ events. In the 2008-2012 data set a total of 35 $\nu_e$ events was observed. The number is compatible with the $\nu_e$ expected from the 0.9% beam contamination (30.4 $\pm$ 3) plus the two main sources of background: $\pi^0$ misidentified as electron in neutrino interactions without a reconstructed muon (0.5 $\pm$ 0.5) and $\nu_\tau$ CC interactions with $\tau$ decaying into an electron (0.8 $\pm$ 0.2). Using the PDG values for $\theta_{13}$, $\theta_{23}$ and $\Delta m^2_{\text{atm}}$ [6], assuming $\delta_{\text{CP}} = 0$ and neglecting matter effects, 2.7 $\pm$ 0.3 $\nu_e$ CC events were expected from $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the whole energy range. The number of observed events is compatible with the 3-flavour oscillation model.

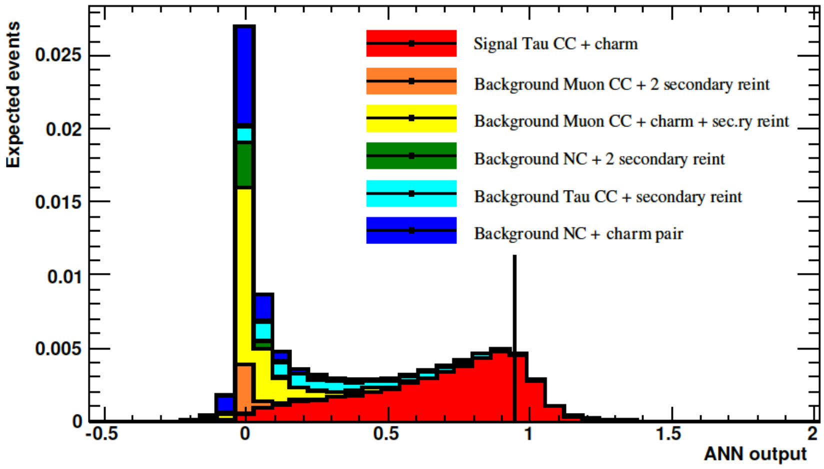


**Figure 1.** Distribution of the ANN output variable. The contribution of each process is shown with a different colour. The vertical black line represents the ANN output for the event taken into account in this analysis.

## 5. Sterile neutrino mixing searches

Some experimental results may hint to possible oscillations involving additional sterile neutrinos with $\Delta m^2 \sim 1$ eV$^2$ [11]. In presence of a fourth sterile neutrino (3+1 model), the oscillation probability is a function of a $4 \times 4$ mixing matrix $U$ and of three squared mass differences. OPERA can constrain combinations of the sterile neutrino parameters, comparing the predictions of the 3+1 model with the observations [12]. The predictions of the 3+1 model was evaluated using the GLoBES software [13]. The solar squared mass difference $\Delta m^2_{21}$ was fixed to the PDG value [6], a Gaussian prior on the atmospheric $\Delta m^2_{31}$ was set, and only positive values of $\Delta m^2_{41}$ were considered as favoured by cosmological limits on the sum of neutrino masses [14]. The profile likelihood ratio was used as test statistic. The 90% C.L. exclusion region on the $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$ and $\Delta m^2_{41}$ plane, shown in Fig. 2, was obtained comparing the number of observed $\nu_\tau$ events with the expected one in an energy range ($E_{rec} < 30$ GeV) which maximizes the sensitivities on the parameters of interest. For $\Delta m^2_{41} \gtrsim 1$ eV$^2$, the 90% C.L. upper limit on $\sin^2 2\theta_{\mu\tau}$ is 0.116, independently of the mass hierarchy of the three standard neutrinos. The OPERA experiment extends the exclusion limits on $\Delta m^2_{41}$ in the $\nu_\mu \to \nu_\tau$ appearance channel down to values of $\sim 10^{-2}$ eV$^2$ for $\sin^2 2\theta_{\mu\tau} < 0.5$.

Furthermore a 90% C.L. exclusion region on the $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ and $\Delta m^2_{41}$ plane, shown in Fig. 3, was evaluated comparing the observed $\nu_e$ energy spectrum with the expected one. At large $|\Delta m^2_{41}|$ values, the 95% C.L. upper limit on $\sin^2 2\theta_{\mu e}$ is 0.022.

## 6. Annual modulation of atmospheric muons

Atmospheric muons reaching the OPERA detector arise mostly from the decay of $\pi$ and $K$ produced by the interaction of primary cosmic rays with the nuclei of the upper atmosphere. During summer, air temperature increases and the average gas density decreases. The less dense medium allows a longer mean free path of the mesons and increases the fraction of them that decay to produce muons before their first interaction, so the atmospheric muon rate ($R_\mu$) varies during the year. The variation was modelled as a sinusoidal function. The fit gives a period and a phase of $(365 \pm 2)$ days and $(176 \pm 4)$ days respectively. The cross-correlation between $R_\mu$ and the effective air temperature ($T_{eff}$) has been evaluated and shows a peak at zero day shift. Muon rate fluctuations are shown to be positively correlated with atmospheric temperature,

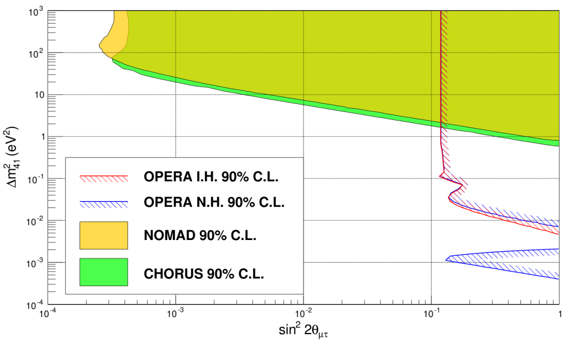


**Figure 2.** 90% C.L. exclusion region on $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$ and $\Delta m^2_{41}$ plane for normal neutrino mass hierarchy (blue) and for inverted one (red). Yellow and green areas are the 90% C.L. exclusion regions obtained respectively by NOMAD and CHORUS experiment.

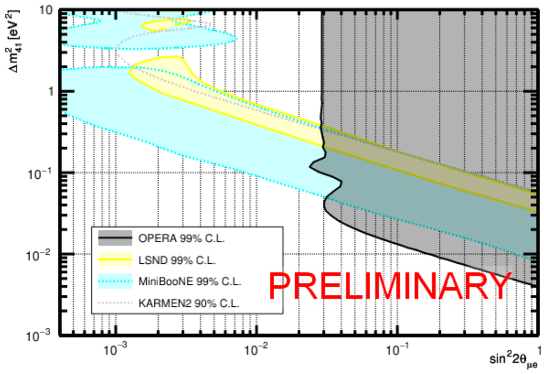


**Figure 3.** 90% C.L. exclusion region on $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ and $\Delta m^2_{41}$ plane (grey area). Yellow and cyan areas are 90% C.L. allowed regions obtained by the LSND and MiniBooNE experiments, the grey dotted line is the 90% C.L. exclusion region obtained by KARMEN2.

with a coefficient $\alpha_T = \Delta R_\mu / \Delta T_{eff} = 0.94 \pm 0.04$.

## 7. Conclusions

The OPERA experiment has been taking data from 2008 to 2012. Five $\nu_\tau$ candidates have been observed allowing to assess the discovery of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode with a significance greater the $5\sigma$. In order to improve the $\Delta m^2_{32}$ measurement the $\nu_\tau$ sample statistic was increased loosening the selection criteria and applying a multivariate analysis. A peculiar event with two secondary vertices has been found. A dedicated analysis allowed identifying it as a $\nu_\tau$ CC interaction with charm production with a significance of $3.5\sigma$. The results on $\nu_\mu \to \nu_e$ search, compatible with the standard $3\nu$ model, have been used to constrain the parameter space of oscillations induced by a massive sterile neutrino. Limits on the sterile neutrino mixing have also been derived in the $\nu_\mu \to \nu_\tau$ appearance channel, given the number of observed $\nu_\tau$ events. Moreover, the OPERA detector was exploited to study the annual modulation of atmospheric muons. The unique feature of the OPERA experiment to identify all 3 flavours will be exploited to put constraints on the oscillation parameters by doing a joint oscillation fit of all datasets.

## References

[1] Acquafredda R *et al.* (OPERA Collaboration), 2009 *JINST* **4** P04018
[2] Agafonova N *et al.* (OPERA Collaboration), 2012 *New J. Phys.* **14** 013026
[3] Agafonova N *et al.* (OPERA Collaboration), 2013 *JHEP* **11** 036, Erratum: 2014 ibidem **04** 014
[4] Agafonova N *et al.* (OPERA Collaboration), 2014 *Eur. Phys. J.* C **74** 2986
[5] Agafonova N *et al.* (OPERA Collaboration), 2015 *Phys. Rev. Lett.* **115** 121802
[6] Patrignani C *et al.* [Particle Data Group], 2016 *Chin. Phys.* C **40** no.10, 100001
[7] Freund Y and Schapire R E, 1997 *J. Comput. Syst. Sci.* **55** no.1, 119
[8] Hocker A, Speckmayer P, Stelzer J, Tegenfeldt F and Voss H, CERN-2008-001
[9] Fisher R A, 1936 *Annals Eugen.* **7** 179
[10] Agafonova N *et al.* (OPERA Collaboration), 2013 *JHEP* **07** 004
[11] Abazajian K N *et al.*, "Light sterile neutrinos: a White Paper", arXiv:1204.5379
[12] Agafonova N *et al.* (OPERA Collaboration), 2015 *JHEP* **06** 069
[13] Huber P, Lindner M and Winter W, 2005 *Comput. Phys. Commun.* **167** 195
[14] Ade P A R *et al.* (Planck Collaboration), 2016 *Astron. Astrophys.* **594** A13