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# Evidence for $\nu_\mu \to \nu_\tau$ oscillation by appearance mode from OPERA experiment

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The aim of the OPERA experiment is to detect $\nu_\tau$ from $\nu_\mu \to \nu_\tau$ oscillation, via the direct observation of $\nu_\tau$ charge current interactions. A $\nu_\tau$ charged current (CC) interaction is identified by observing a decay topology of the $\tau$ lepton. Taking advantage of the extremely fine spatial resolution of nuclear emulsions, an active target made of nuclear emulsion films interleaved by lead plates (called ECC or bricks hereafter), provides capability both to identify tau lepton decay topologies and fully reconstruct the neutrino interaction.

The OPERA apparatus is a complex of ECC bricks and electronic detectors. Five years of neutrino exposure from 2008 to 2012 to the OPERA detector have been completed. A total of 5272 events were analyzed and three $\nu_\tau$ candidates were observed with $\tau$ decaying into different final states. Features of these events are described in this article. The observation of three $\nu_\tau$ candidates corresponds to establishing $\nu_\mu \to \nu_\tau$ oscillations with a significance of $3.4\sigma$.

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## 1. The OPERA detector

Muon neutrino disappearance has been explained as $\nu_\mu \to \nu_\tau$ oscillation by several experiments [1],[2]. In that context, the OPERA experiment is aiming to provide a conclusive evidence of $\nu_\tau$ appearance due to $\nu_\mu \to \nu_\tau$ oscillation. The detection of $\nu_\tau$ CC interactions, which has a tau lepton at the interaction vertex, will provide the evidence to the appearance of $\nu_\tau$.

The energy of neutrino should be large enough to produce $\nu_\tau$ CC interactions ( »3.5GeV); while the oscillation probability increases at lower neutrino energy values. The neutrino beam energy had a mean value of 17 GeV, in order to maximize the appearance yield at a distance of 730 km from CERN to the Gran Sasso underground laboratory (LNGS). A pure $\nu_\mu$ beam, which had at the origin about 2 % of $\bar{\nu_\mu}$, 1 % of $\nu_e + \bar{\nu_e}$ and negligible prompt $\nu_\tau$ contamination, was provided [3].

The detector should have spatial resolution appropriate to observe the decay topology of the short lived tau lepton (c$\tau \sim 90\mu$m). Nuclear emulsions can provide sub-micrometric spatial resolution, which is suitable for this purpose, and actually they were used for the first observation of $\nu_\tau$ CC events in the DONUT experiment [4].

Assuming oscillation parameter of $\Delta m^2$=2.5$\times$10$^{-3}$ eV$^2$/c$^2$, $sin^2\theta$=1, a kton target mass is required to observe $\nu_\tau$ events. The OPERA experiment combines a large target mass with a good spatial resolution. The basic unit of the OPERA target is an ECC brick made of 57 nuclear emulsion films interleaved with 56 lead plates, 1mm thick. Each ECC has a size of 12 cm$\times$10 cm$\times$8 cm and 8.3 kg weight. A matrix of 50$\times$50 ECC brick constitutes a wall. 36 such walls, each interleaved by plastic scintillator detectors (called Target Tracker and TT hereafter) form a super module equipped downstream with a muon spectrometer. Two such super modules (in total 15,000 ECCs and a mass of 1250 ton) were exposed to the neutrino beam from CERN to Gran Sasso (CNGS) from 2008 to 2012. A total of $17.97 \times 10^{19}$ protons on target were used for the five years of CNGS running.

## 2. The event location

Neutrino events on time with the beam within 1$\mu$s were selected by the TT system. Tagged events are classified into 1$\mu$ and 0$\mu$ categories according to the presence of an identified muon. Most of muons produced at the neutrino interaction penetrate the entire super module and their charge and momentum is measured by the muon spectrometer with the accuracy of $\frac{dP}{P} \sim 0.2$. The majority of tagged events are 1$\mu$ events (about 70%), while $\nu_\tau$ events enrich the 0$\mu$ sample (about 30%) due to decay branching ratios of the $\tau$ lepton (Br(1$\mu$)$\sim$ 17%, Br(0$\mu$)$\sim$ 83%).

The neutrino event location begins with the extraction of the ECC brick having the highest probability to contain the tagged neutrino event. A pair of emulsion films, called CS and mounted on the downstream surface of the ECC, is detached from the brick and are developed underground. Developed CS emulsion films are sent to the scanning stations at the LNGS and at the Nagoya University to be measured using automated scanning systems [5], [6].

The position accuracy provided by the TT system is limited by the scintillator segmentation of 2.6 cm and is affected by electromagnetic components from the neutrino interaction. Around the TT predicted position, an area of 5 cm$\times$5 cm to 12 cm$\times$10 cm, depending on the recorded TT hits, are scanned on CS films to search for tracks in angular acceptance within 0.6 rad. If a CS track matches with the TT hits of the event, the corresponding ECC is developed for further analysis. If no track is found in the CS, the ECC is returned to the detector with new CS doublet attached to it and the event next probable ECC is extracted and analyzed following the same procedure.

A track validated in the CS is then connected to the most downstream emulsion film in the ECC to locate the tagged interaction. The position accuracy for track connection between CS and the most downstream emulsion film in ECC is about 100$\mu$m, therefore the scanning area on ECC can be much smaller than on CS. A track connected to the most downstream film is then scanned back on upstream films until no track is found in three consecutive films.

A vertex, either the tagged neutrino interaction or a secondary vertex is assumed to be just upstream of the last emulsion film where the track had been confirmed. This procedure is called Scan Back location [7] [8], and the connected track is called Scan Back track.

In order to validate a vertex, a volume of 1 cm x 1 cm x 15 films around the vertex position is analyzed. Once all tracks in the volume are reconstructed, penetrating tracks and low momentum tracks are rejected. After a vertex is reconstructed an impact parameter analysis is made searching for signature of tau decay and its corresponding daughter track.

Up to now 5272 events were fully analyzed for $\nu_\tau$ search and three $\nu_\tau$ candidate events were observed.



## 3. Observed $\nu_\tau$ candidate events

The important signature of $\nu_\tau$ CC interactions is that no lepton other than $\tau$ is attached to the neutrino interaction vertex. The $\tau$ lepton in OPERA decays after a flight length of about 1mm. The decay topology is categorized by the number of charged decay daughters (prongs), in 85 % of the cases it is 1 prong decay and the remainings are mostly 3 prongs. Charmed particles have similar mass and life time as the $\tau$ lepton. Thus a $\nu_\mu$ CC associated with a charmed particle production looks similar to $\nu_\tau$ CC in its topology, although the existence of a muon at the neutrino interaction vertex discriminates it from a $\nu_\tau$ CC event.

Another important features which discriminate $\nu_\tau$ CC from its background is that the tau candidate direction and the sum of the momentum of the other primary particles are back to back in the plane transverse to the neutrino beam while it has a wide distribution for charmed particle decays.

### 3.1 The first $\nu_\tau$ candidate event

The first $\nu_\tau$ candidate event was reported at the NEUTRINO2010 Conference [9]. The interaction vertex is formed by the candidate tau particle track and six charged hadron tracks (see figure 1). The tau particle flights $1355 \pm 35\mu$m and decays in the downstream lead plate. A charged hadron track and two $\gamma$s form the decay vertex. Charged particle's momentum is determined by Multiple Coulomb scattering (MCS). The hight Z of lead is exploited also to detect $\gamma$s by reconstructing electromagnetic showers. A conversion length of the ECC corresponds to about 7 emulsion films with 6 lead plates interleaved. The invariant mass of two $\gamma$s is $120 \pm 20 \pm 35$ MeV/c$^2$, which is consistent with the mass of $\pi^0$. The daughter hadron and two $\gamma$s have an invariant mass of $640^{+125}_{-80}{}^{+100}_{-90}$ MeV/c$^2$, which is consistent with the $\rho$ particle mass. The angle between the transverse momentum of the hadron system and that of tau is $173 \pm 2$ degree, consistent with the expected back to back topology. All observed kinematic variables satisfy $\nu_\tau$ event criteria.

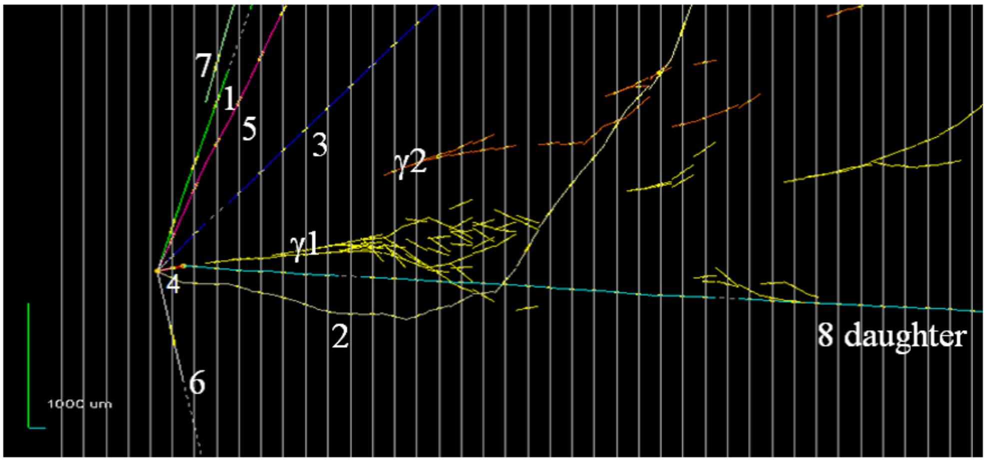


**Figure 1:** The first $\nu_\tau$ candidate event. The $\tau$ particle (track 4) decays into a hadron (track 8) and two $\gamma$s ($\gamma$1, $\gamma$2). The candidate decay mode is $\tau \to \rho + \nu_\tau$. Primary track 2 is identified as a proton from its MCS and dE/dx.

### 3.2 The second $\nu_\tau$ candidate event

A second $\nu_\tau$ candidate event was reported at NEUTRINO2012 Conference [10]. A hadron track and a $\tau$ lepton form the primary interaction vertex with an associated nuclear fragment. The $\tau$ decays into three hadrons in the plastic base of the downstream emulsion film (see figure 2). The plastic base is the lowest density material in the ECC where most unlikely a hadron interaction would occur. The hadron and the $\tau$ tracks are back to back forming an angle of $167.8 \pm 1.1$ degree. The invariant mass of three decay daughters is $0.8 \pm 0.12$ GeV/c$^2$. Other kinematic variables satisfy the $\nu_\tau$ event criteria.

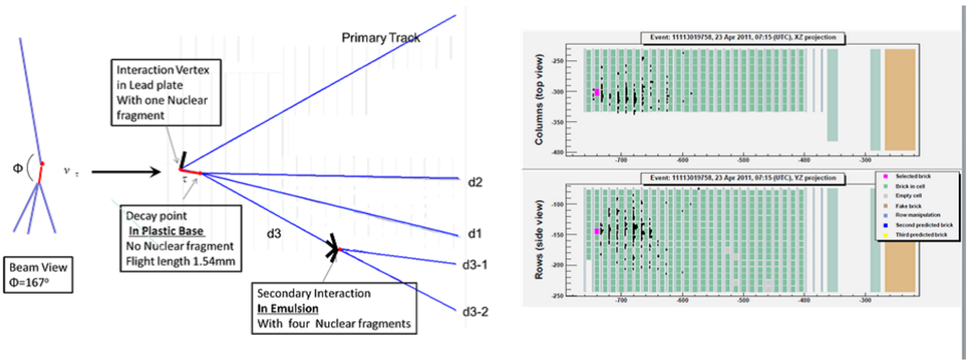


**Figure 2:** The second $\nu_\tau$ event. $\tau$ decays into three charged daughters, d1, d2, d3 in the plastic base of emulsion film. d3 makes an interaction in the same ECC.

### 3.3 The third $\nu_\tau$ event

A third $\nu_\tau$ candidate event was reported in March 2013 [11]. The remarkable feature of this event is its $\tau^- \to \mu^-$ decay topology and kinematics (see figure 3). The daughter muon's charge is negative at 5.6 $\sigma$ significance (see figure 4). It is the first time the charge sign of $\tau$ decay daughter is measured in $\nu_\mu \to \nu_\tau$ candidate events.

The interaction vertex is formed by the $\tau$ particle track and a hadron track. The angle between the hadron and the $\tau$ particle in the transverse plane is $154.5 \pm 1.5$ degree. The decay position is in the plastic base and the decay transverse momentum is $690 \pm 50$ MeV/c which allow to reject muon scattering hypothesis.

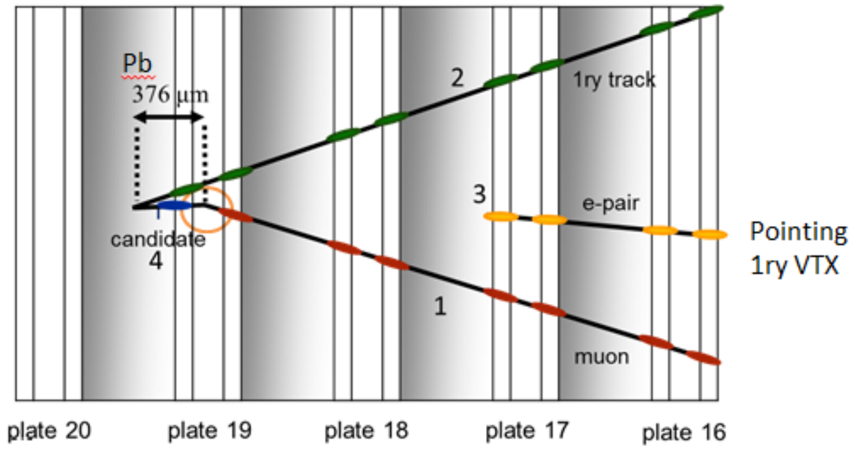


**Figure 3:** The third OPERA $\nu_\tau$ candidate event. The $\tau^- \to \mu^-$ decay in the plastic base of emulsion film was confirmed by the analysis.

### 3.4 The significance of the $\nu_\mu \to \nu_\tau$ observation

The sources of background events are categorized into three physics processes. In the first category are charmed particle decays associated with $\nu_\mu$ CC interactions with the muon not identified. In the second category are hadron interactions occurring at a short distance in $\nu_\mu$ NC interactions. In the third category (and only for the $\tau \to \mu$ decay mode) are muons from $\nu_\mu$ CC forming a kink by scattering at a short distance. These three sources are called Charm BG , Hadron BG and Mu Scattering BG, respectively. In table.1 the numbers of expected background events are indicated for each category.

The decay search efficiency was checked by detecting charm associated $\nu_\mu$ CC interactions. Charm particles have similar decay life time and mass as the tau lepton and thus they constitute a good control sample to validate the decay search efficiency. If a muon is attached to the vertex, the event is identified as a charm associated $\nu_\mu$ CC interaction. Another difference is that a charmed particle can be either charged or neutral, therefore the number of decay daughters can be either even or odd. In a data sub-sample, 49 charm associated $\nu_\mu$ CC events were collected with $51 \pm 7.5$ expected from Monte Carlo simulation.



PoS(KMI2013)016

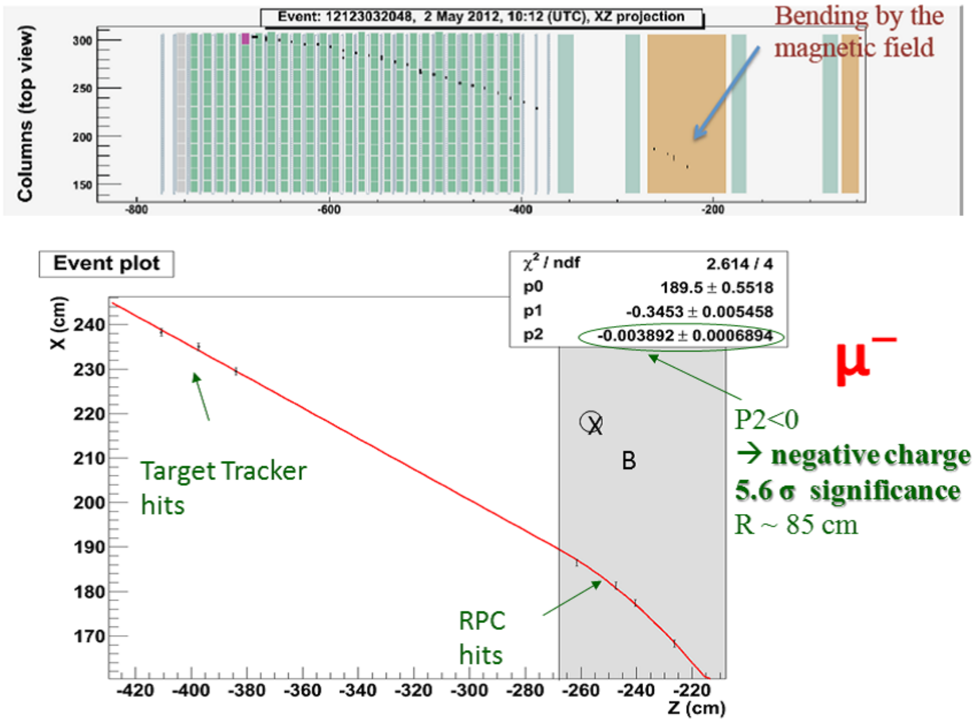


**Figure 4:** The daughter muon track. A negative muon charge was measured in the magnet spectrometer with 5.6 $\sigma$ significance. The muon momentum measured in the ECC is 2.8 GeV/c.

| Channel | $N_{obs}$ | Signal | Background | Charm | Hadron | Mu Scattering |
|---|---|---|---|---|---|---|
| $\tau \to \mu$ | 1 | 0.31 | 0.027 | 0.011 | 0.016 | 0 |
| $\tau \to 3h$ | 1 | 0.43 | 0.117 | 0.114 | 0.002 | 0 |
| $\tau \to h$ | 1 | 0.50 | 0.021 | 0.004 | 0 | 0.017 |
| $\tau \to e$ | 0 | 0.46 | 0.020 | 0.020 | 0 | 0 |
| total | 3 | 1.7 | 0.185 | 0.145 | 0.018 | 0.017 |

**Table 1:** Number of observed $\nu_\tau$ candidate events $N_{obs}$ and expected signal and background events for each decay mode.

By taking into account the difference in the background expectation for the tau candidates' decay channels, the probability of a background fluctuation is $2.9 \times 10^{-4}$. This corresponds to $3.4\sigma$ significance for the exclusion of the null hypothesis, allowing to set an evidence for appearance of $\nu_\tau$ events due to $\nu_\mu \to \nu_\tau$ oscillation.

## 4. Summary

A five years exposure, from 2008 to 2012 of the OPERA detector to the CNGS neutrino beam has been completed. About 80% of protons on target expected according to the proposal [12] were delivered. Neutrino interactions recorded during runs 2008-2009 have been fully analyzed including the second most probable ECC bricks. The first $\nu_\tau$ candidate event was found in the sample and reported at NEUTRINO2010. The analysis of the most probable ECC brick for runs 2010-2012 will be completed in a few months. So far a total of 5272 events have been analyzed and three $\nu_\tau$ candidate events have been found. By the observation three $\nu_\tau$ candidate events, null oscillation hypothesis is excluded with 3.4 $\sigma$ significance.

By the analysis of all remaining first most probable bricks and of all the second most probable ones, an increase of about 30% in analyzed statistics will be achieved.

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