

# OPERA: A first tau-neutrino appearance candidate

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**Abstract.** OPERA is a long-baseline neutrino experiment dedicated to the study of muon-neutrino to tau-neutrino oscillation. Using the high-energy CERN neutrinos to Gran Sasso beam (CNGS), it is the first experiment directly searching for tau-neutrino appearance from oscillation of muon-neutrinos. Since 2008 runs with CNGS neutrinos have been successfully accomplished. After a brief introduction on the OPERA hybrid detector and the main parameters of the experiment, recent results are presented. A first candidate for a tau-neutrino charged-current event is described in detail. The background and the corresponding significance of the event is evaluated.

## 1. Introduction

In the past two decades, experimental results from various sources have established the picture of a three-neutrino oscillation scenario with two large mixing angles. Most of these results are based solely on disappearance analyses, with the lack of observed neutrinos explained by oscillation. However, from the SNO results, it is clear that the total flux of active neutrinos remains constant for solar neutrinos [1], while the flavour of the appearing oscillation partners still has not been directly observed. In addition, indirect methods on a statistical basis have been applied by Super-Kamiokande, strongly favouring the hypothesis that the oscillation partner of the atmospheric  $\nu_\mu$  is the  $\nu_\tau$  [2]. On the other hand, recent MiniBooNE data [3], as well as the preceding LSND data [4], seem to include an excess of  $\bar{\nu}_e$ , that, if interpreted as an oscillation effect, is incompatible with the three-flavour solution. Furthermore, the first anti-neutrino data of the MINOS experiment suggest some slight tension with respect to the oscillation parameters measured with neutrinos [5]. However, these last observations require confirmation with significantly more statistic.

Thus, it is of the utmost importance to unambiguously answer as many questions as possible. The OPERA experiment [6] is specially designed to address one of these questions. Its goal is to directly observe the appearance of  $\nu_\tau$  in a pure  $\nu_\mu$  beam by identifying the  $\tau$  leptons produced in their CC interaction.

The OPERA detector is located in the Gran Sasso underground laboratory (LNGS) in Italy, 732 km away from its neutrino source at CERN. The CNGS [7, 8] is a high-energy  $\nu_\mu$ -beam with an average neutrino energy ( $\bar{E}_{\nu_\mu} \approx 17$  GeV) well above the production threshold for  $\tau$  leptons. The  $\bar{\nu}_\mu$  beam contamination in terms of interactions is about 2.1 %, while  $\nu_e$  and  $\bar{\nu}_e$  together contribute less than 1 %, and the prompt  $\nu_\tau$  production is negligible. With a nominal CNGS beam intensity of  $4.5 \times 10^{19}$  protons on target (p.o.t.) per year, and assuming  $\Delta m_{23}^2 = 2.5 \times 10^{-3}$  eV<sup>2</sup> and full mixing, about 10  $\nu_\tau$  events are expected to be observed in OPERA in 5 years of data taking, with selection criteria reducing the background to 0.75 events.

The  $\nu_\tau$  signature is given by the decay topology of the short-lived  $\tau$  lepton produced in  $\nu_\tau$  Charged Current (CC) interactions, decaying after typically 1 mm (at CNGS energies) to one charged particle (electron, muon or hadron) or three charged hadrons. In order to resolve this topology, a very fine spatial resolution is needed. In addition, the detector has to provide the interaction target for the neutrinos, and thus has to be massive. The technology chosen for this challenge are emulsion films interleaved with lead plates, historically called Emulsion Cloud Chamber (ECC).

## 2. The OPERA detector

The OPERA ECC are arranged into small light-tight packages called bricks. Each brick consists of 57 thin nuclear emulsion films, interspaced with 56 lead plates, 1 mm in thickness, with the dimensions of  $10.2 \times 12.7 \times 7.5$  cm<sup>3</sup>. The processing of events in these bricks is a complex and time-consuming task. Therefore further information is needed to reduce the scanning area as much as possible. For this reason, the OPERA detector has a hybrid structure, combining ECC-bricks with electronic detectors. The latter act as a kind of trigger for the bricks in the sense that they allow to locate the interaction vertex. Furthermore, they provide kinematical information and identify muons. Two additional emulsion films, packed in a removable box, are attached to the downstream face of each brick. These so-called Changeable Sheets (CS) are used for a first cross-check between the electronic detector data and the brick and help to reduce the scanning area in the brick films.

The detector consists of two super modules (SM1 and SM2), each of them made up of a target section and a muon spectrometer. The target section contains the bricks. In total, around 150000 bricks are used, amounting to a target mass of 1.25 kton. The bricks are arranged in walls, separated by planes of horizontal and vertical scintillator strips composing the target tracker (TT). The TT strips have a width, perpendicular to the beam direction, of 2.63 cm, allowing the identification of bricks containing an interaction vertex with a high probability.

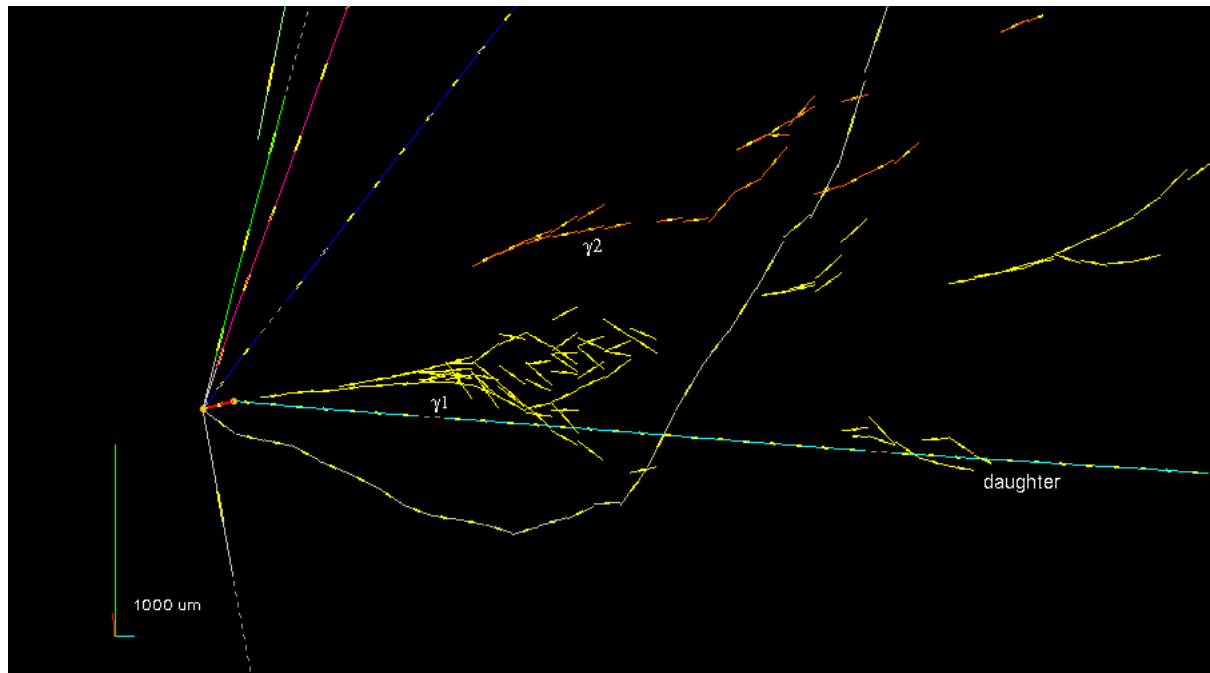
The main component of the muon spectrometers, one behind each target, is a dipole magnet, operated at 1.52 T. The iron slabs of its core are interleaved with resistive plate chambers (RPC), used as inner trackers. In addition, the spectrometer is equipped with high-resolution drift tube chambers, the precision tracker (PT), allowing the measurement of muon momenta up to 50 GeV/c with a resolution of better than 20 % and the charge determination with an efficiency of better than 98 %. In order to remove ambiguities in the reconstruction of particle trajectories, in particular in multi-track events, each spectrometer is further instrumented with additional RPC planes in front of the magnet, with two crossed strip planes rotated by  $\pm 42.6^\circ$  with respect to the horizontal (XPC). Together with the TT the spectrometer allows the identification of  $\mu$  leptons with an efficiency of 95 %.

Another two RPC planes (VETO) are placed in front of the detector, acting as a veto for charged particles originating from interactions in the upstream material (mainly muons from neutrino interactions in the rock).

A detailed description of the complete detector can be found in [9]. The event processing and analysis procedures are described in [10] and [11].

## 3. A $\nu_\tau$ appearance candidate

OPERA has been collecting data from beam neutrinos since several years now. After a short commissioning run in 2007, with 38 beam-induced events inside the detector target, three years of physics runs have been successfully accomplished until 2010. Within these three years, neutrinos produced by a total of  $9.34 \times 10^{19}$  p.o.t. have been sent in the CNGS beam towards the Gran Sasso, and 9637 beam events have been collected within the OPERA target until November 23rd, 2010. The processing of these events, particularly the scanning of emulsion films, is continuously going on. Even though the event processing is very time-consuming and complex,



**Figure 1.** Side view of the  $\nu_\tau$  candidate event. The short yellow markings indicate the measured tracks in the emulsions. All other lines are extrapolations. The red track is the  $\tau$  candidate, with its decay daughter in light blue. Two electromagnetic showers  $\gamma_1$  and  $\gamma_2$  are visible, pointing in the direction of the primary and secondary vertex.

at the beginning of 2010 the analysis of an unbiased sub-sample of 1088 events had been finalised, out of which 901 have been classified as CC interactions. Taking into account a combined brick finding and vertex location efficiency of about 60%, the total sub-sample corresponds to 1813 interactions occurring in the target. Considering the energy spectrum of the beam, this number of interactions is expected for an integrated beam intensity of  $1.89 \times 10^{19}$  p.o.t., which is about 35% of the 2008 and 2009 statistics. Assuming  $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{eV}^2$  and full mixing, the expected number of observed  $\nu_\tau$  events with these statistics is  $0.54 \pm 0.13$  (syst.). This subsample, including 2008 and 2009 data, has been fully analysed in order to be able to extract first results.

One  $\nu_\tau$  candidate event has been found, fulfilling all the selection criteria determined in the experiment proposal [6]. To reject background, and for the right choice of cuts, it is very important to verify whether there are any muons attached to the primary neutrino vertex or the secondary vertex, being the possible decay vertex. Considering the range of the tracks involved as well as scattering and ionisation in the emulsions, no muon track could be found in this event. However, to verify the muonless nature of the event, three of the tracks that do not end in the interaction brick have been followed through the emulsions of the downstream bricks, up to their endpoint. For two of those, an interaction at the endpoint could be confirmed, ruling out the possibility of muons. The last track has only a short range, resulting in a probability of about  $10^{-3}$  to be left by a muon.

The procedure to follow down tracks to check their possibility of being muons is an upgrade with respect to the procedures taken into account within the proposal. With this new procedure, the residual probability of an event for being a  $\nu_\mu$  CC interaction with an undiscovered large angle low momentum muon can be reduced from  $\sim 5\%$ , as was assumed in the proposal, to  $\sim 1\%$ . However, for the calculations of background and sensitivity given below, the nominal value of the proposal has been used.

Another distinctive feature of this event are the two  $\gamma$  showers that have been found to belong to it, clearly visible in figure 1. One of the selection criteria for the decay of a  $\tau$  to a single charged hadron is that the total transverse momentum ( $P_T$ ) of the decay products is larger than 0.6 GeV/c if there are no photons emitted at the decay vertex, and 0.3 GeV/c otherwise. Since  $P_T$  has a relative small expectation value of  $\lesssim 100$  GeV in pion interactions, this cut rejects most of the hadronic reinteractions mimicking the decay topology. The cut is lower if at least one gamma shower could be attached to the decay vertex, because MC studies have shown that the expected background is reduced if a  $\pi_0$  is emitted at the decay vertex [12]. The probability of the gamma showers to point to the secondary vertex has been calculated to be 32 % for the first shower, and 82 % for the second. Their probability to be attached to the primary vertex is less than 0.1 %, and 10 %, respectively. For the most probable hypothesis of both showers being attached to the secondary vertex, the total transverse momentum  $P_T$  of the daughter particles is  $(0.47_{-0.12}^{+0.24})$  GeV/c. If the second  $\gamma$  shower is instead attached to the primary vertex, this number is changed by no more than 50 MeV/c. Thus, in both cases the  $P_T$  cut criteria mentioned above is satisfied.

The invariant mass of both  $\gamma$  is  $(120 \pm 20(\text{stat.}) \pm 35(\text{syst.}))$  MeV/c<sup>2</sup>, supporting the hypothesis that they originate from a  $\pi^0$  decay. Similarly, the invariant mass of the charged decay product, assumed to be a  $\pi$ , and of the two  $\gamma$  amounts to  $(640_{-80}^{+125}(\text{stat.})_{-90}^{+100}(\text{syst.}))$  MeV/c<sup>2</sup>, being compatible with the  $\rho(770)$  mass. The branching ratio of the decay mode  $\tau \rightarrow \rho\pi^0$  is about 25 % [13].

The two dominant sources of background for a 1-prong hadronic  $\tau$  decay are decays of charmed particles, produced at the primary vertex, and 1-prong inelastic interactions of primary hadrons. In both cases,  $\nu_\mu$  NC and CC interactions contribute. The latter can efficiently be rejected if the primary muon is identified. Following the experiment proposal [6],  $0.007 \pm 0.004(\text{syst.})$  charm background events are expected in the analysed sample and  $0.011 \pm 0.006(\text{syst.})$  background events from hadronic reinteractions. However, the current estimations of charm background are conservative, since they are based on the original scanning strategy. If all decay channels of the  $\tau$  are considered, the total background, including large-angle muon scattering, amounts to  $0.045 \pm 0.02(\text{syst.})$  events.

The probability that the total expected background of  $0.018 \pm 0.007(\text{syst.})$  events to the 1-prong hadronic decay channel of the  $\tau$  fluctuates to 1 event is 1.8 % ( $2.36\sigma$ ) while for all decay channels the probability is 4.5 % ( $2.01\sigma$ ).

A detailed description of the event can be found in [14]. Further information regarding the analysis procedures and the background can be found in [11].

#### 4. Conclusions

The OPERA experiment searches for  $\nu_\tau$  appearing at a distance of 732 km in the CNGS  $\nu_\mu$  beam. A complete analysis of a subsample corresponding to  $1.89 \times 10^{19}$  p.o.t. has been performed. One muonless event with a  $\tau \rightarrow$  1-prong hadron decay topology has been detected that passes the selection criteria. It is the first candidate event for  $\nu_\mu \rightarrow \nu_\tau$  appearance.

The observation of one possible  $\nu_\tau$  candidate in the 1-prong hadronic decay channel has a significance of  $2.36\sigma$  of not being a background fluctuation. If one considers all decay modes included in the search, the significance of the observation is  $2.01\sigma$ .

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