Updated results of the OPERA long baseline neutrino experiment

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Abstract. The OPERA neutrino detector built in the underground Gran Sasso Laboratory is designed to detect \( \nu_\mu \rightarrow \nu_\tau \) oscillations in direct appearance mode. The hybrid apparatus consists of an emulsion/lead target complemented by electronic detectors. It is placed in the long-baseline CERN to Gran Sasso neutrino beam (CNGS) 730 km away from the source.

The experimental setup and ancillary facilities used to extract data recorded in the emulsion will be described, with the special procedures used to locate the interactions vertices and detect short decay topologies. OPERA is taking data since 2008. A first \( \nu_\tau \) interaction candidate was already published in 2010. An improved analysis scheme associated with a more detailed simulation has been developed and new results with increased statistics will be presented.

1. Introduction
OPERA [1] is a hybrid experiment based on electronic detectors and nuclear emulsions. It is exposed to the long-baseline CNGS beam [2] from CERN to the Gran Sasso underground laboratory (LNGS) 730 km away from the neutrino source. The main purpose of the experiment is the observation of \( \nu_\mu \rightarrow \nu_\tau \) oscillations in the direct appearance mode. The \( \nu_\tau \) are identified through the measurement of the \( \tau \) leptons produced in their Charged Current (CC) interactions.

The neutrino runs started in 2008 and a first \( \nu_\tau \) candidate has recently been observed [3]. The beam is mainly composed of \( \nu_\mu \); interactions due to the \( \bar{\nu}_\mu \), \( \nu_e \) and \( \bar{\nu}_e \) contamination amount to 2.1%, 0.80% and 0.07% of the \( \nu_\mu \) CC event rate.

2. The OPERA detector
The challenge of the OPERA experiment is to achieve the very high spatial accuracy required for the detection of \( \tau \) leptons (whose decay length is of the order of 1 mm in this experiment) inside a large-mass active target. The hybrid detector [4] is composed of two identical super modules, each consisting of an instrumented target section of a mass of about 625 tons followed by a magnetic muon spectrometer (Fig. 1). A target section is a succession of walls filled with units called bricks, interleaved with planes of scintillator strips, the Target Tracker (TT). The TT allows the initial localization of neutrino interactions and provides also their time stamp. A brick is an Emulsion Cloud Chamber (ECC) module consisting of 56 1 mm thick lead plates interleaved with 57 nuclear emulsion films. It weighs 8.3 kg and its thickness corresponds to 10 radiation lengths along the beam direction. Tightly packed removable doublets of emulsion films called Changeable Sheets (CS) are glued to the downstream face of each brick. They serve as interfaces between the TT planes and the bricks to facilitate the location of neutrino...
interactions. Complex brick handling ancillary facilities are used to bring emulsion films from the target up to the automatic scanning microscopes [5].

An emulsion film is made of two layers of nuclear emulsion gel 44 $\mu$m thick deposited on each side of a 205 $\mu$m thick plastic base of $12.5 \times 9.9cm^2$ [6]. Emulsion records charged particles as 3D tracks with submicron resolution. The ECC technique is adequate to recognize $\tau$ decay topologies as proven by the DONuT experiment [7].

3. Location of neutrino interactions

The expected number of neutrino events registered in the target volume is 850 per $10^{19}$ protons on target (p.o.t.) per 1000 tons. A 10% error is assigned to this number resulting from uncertainties on the neutrino flux and interaction cross-sections. During the 2008 and 2009 runs the average target mass was 1290 tons, of which 8.6% of dead material other than lead plates and emulsion films, for a total number of $1.78 \times 10^{19}$ p.o.t in 2008 and $3.52 \times 10^{19}$ p.o.t. in 2009.

Data from the electronic detectors associated with the 5255 events reconstructed to have occurred inside the target volume were processed by a software algorithm that selects the brick with the highest probability to contain the neutrino interaction vertex. The brick so designated is removed from the target, the CS is detached and its films are searched for tracks compatible
with the electronic data to verify the brick selection. In case this search is unsuccessful, the brick is equipped with a fresh CS and reinserted into the target. A second brick is then extracted according to its probability to contain the vertex complemented by a visual inspection of the event display. In case the search is successful the brick is dismounted and the emulsion films are developed and dispatched to the scanning laboratories. All tracks measured with high precision in the CS films are sought for in the most downstream films of the brick. These tracks are then followed back until they are not found in three consecutive films. A volume is then scanned around their stopping point in order to localize the interaction vertex. When a secondary vertex is found the kinematical analysis of the whole event is performed. This analysis makes use of the angles measured in the emulsion films, the momenta determined by multiple Coulomb scattering as measured in the brick, the momenta measured by the magnetic spectrometers, and the total energy deposited in the instrumented target acting as a calorimeter [3, 8, 9]. The energy of γ-rays and electrons is estimated by a Neural Network algorithm that uses the combination of the number of track segments in the emulsion films and the shape of the electromagnetic shower, together with the multiple Coulomb scattering of the leading tracks.

By applying this procedure, the first $\nu_\tau$ candidate event was observed in 2010, as reported in detail in [3].

4. Signal detection efficiencies and physics background

Charged charmed particles own lifetimes similar to that of the $\tau$ lepton and share analogous decay topologies. The finding efficiency of the decay vertices is therefore also similar for both types of particles. Comparing the observed charm event sample in size, decay topologies and kinematics with expectations from simulations constitutes a direct way to verify prompt-decay selection criteria and their corresponding efficiencies as well as backgrounds evaluations. Recently published cross-sections by the CHORUS experiment [10] have been used in the simulation.

The expected numbers of events in the various $\tau$ channels for the nominal number of $22.5 \times 10^{19}$ p.o.t. and for the fraction of the 2008 and 2009 runs analysed so far are shown in Table 1. Full mixing and $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$ are assumed. The total number of signal events expected to be eventually detected has decreased from 10 as quoted in the experiment proposal [11] to 8. This reduction is essentially due to the lower efficiency in location of the interaction vertex resulting from a more reliable knowledge of the detector and of the analysis procedures.

The main source of background to all $\tau$ decay channels is constituted by charged charmed particles that decay into similar channels and are produced in $\nu_\mu$ CC interactions where the primary muon is not identified.

The second main source of background in the $\tau \rightarrow h$ decay channel comes from one-prong inelastic interactions of primary hadrons produced in NC interactions, or in CC interactions where the primary lepton is not identified, and in which no nuclear fragments can be associated with the secondary interaction. This has been evaluated with Monte Carlo Simulation and cross-checked with measurements.

The expected background in the muon decay channel caused by large angle muon scattering has been evaluated in [11].

All background sources are summarized in Table 2. Systematic errors of 25% on charm background and of 50% on hadron and muon backgrounds are assumed. Errors arising from the same source are combined linearly, otherwise in quadrature.
Table 1. Expected numbers of observed signal events for $22.5 \times 10^{19}$ p.o.t. and for the analysed sample of the data accumulated in the 2008 and 2009 runs.

| Decay channel | Number of signal events expected for $22.5 \times 10^{19}$ p.o.t. | Analysed sample |
|---------------|-------------------------------------------------|-----------------|
| $\tau \rightarrow \mu$ | 1.79 | 0.39 |
| $\tau \rightarrow e$ | 2.89 | 0.63 |
| $\tau \rightarrow h$ | 2.25 | 0.49 |
| $\tau \rightarrow 3h$ | 0.71 | 0.15 |
| Total | 7.63 | 1.65 |

Table 2. Expected numbers of observed background events from different sources for the nominal number of $22.5 \times 10^{19}$ p.o.t. and for the analysed sample of the data accumulated in the 2008 and 2009 runs. The quoted errors are systematic ones.

| Decay channel | Number of background events expected for $22.5 \pm 10^{19}$ p.o.t. | Analysed sample |
|---------------|-------------------------------------------------|-----------------|
| | Charm | Hadron | Muon | Total | Charm | Hadron | Muon | Total |
| $\tau \rightarrow \mu$ | 0.025 | 0.00 | 0.07 | 0.09 ± 0.04 | 0.00 | 0.00 | 0.02 | 0.02 ± 0.01 |
| $\tau \rightarrow e$ | 0.22 | 0.00 | 0.00 | 0.22 ± 0.05 | 0.05 | 0.00 | 0.00 | 0.05 ± 0.01 |
| $\tau \rightarrow h$ | 0.14 | 0.11 | 0.00 | 0.24 ± 0.06 | 0.03 | 0.02 | 0.00 | 0.05 ± 0.01 |
| $\tau \rightarrow 3h$ | 0.18 | 0.00 | 0.00 | 0.18 ± 0.04 | 0.04 | 0.00 | 0.00 | 0.04 ± 0.01 |
| Total | 0.55 | 0.11 | 0.07 | 0.73 ± 0.15 | 0.12 | 0.02 | 0.02 | 0.16 ± 0.03 |

5. Signal statistical significance
One $\nu_\tau$ candidate event is observed in the $\tau \rightarrow h$ decay channel that passes all the selection cuts where $0.49 \pm 12$ events are expected for this decay mode in the currently analysed sample assuming full mixing and $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$. The background in this channel is estimated to $0.05 \pm 0.01$ (syst.) event. The probability for the event not to be due to a background fluctuation and thus the statistical significance of the observation is 95%. Considering all decay channels, the numbers of expected signal and background events are respectively $1.65 \pm 0.41$ and $0.16 \pm 0.03$ (syst.).

6. Conclusion
The OPERA experiment has completed the study of 92% of the data accumulated during the first two years of operation in the CNGS beam (2008-2009) with the aim of the first detection of neutrino oscillations in direct appearance mode.

The observation so far of a single candidate event is compatible with the expectation of 1.65 signal events. The significance of the observation of one decay in the $\tau \rightarrow h$ channel is 95%.

The analysis of the large event samples collected in the 2010 and 2011 CNGS runs and corresponding to $6.90 \times 10^{19}$ p.o.t. at the moment of writing is in progress.

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