Status of the OPERA experiment

E Medinaceli for the OPERA Collaboration

INFN and University of Padova

E-mail: medinaceli@pd.infn.it

Abstract. The OPERA neutrino detector at the Gran Sasso underground laboratory (LNGS) has been designed to perform the first detection of neutrino oscillations in direct appearance mode, through the study of the $\nu_\mu \rightarrow \nu_\tau$ channel. Tau leptons produced in the charged current interactions are identified by their decay topologies, using nuclear emulsions. After a brief description of the experimental setup, the first two tau candidates found in the runs 2008 to 2010 are reported. The OPERA experiment has measured the velocity of neutrinos sent from the CERN CNGS beam over a baseline of about 730 km. The measurement is based on data taken from 2009 to 2011. An arrival time of CNGS muon neutrinos with respect to the one computed, assuming the speed of light in vacuum, of $(6.5 \pm 7.4^{+3.4}_{-3.3 \text{(stat)}})^{\pm 7.4}_{\text{sys}})$ ns was measured.

1. The CNGS beam and the OPERA detector

The CNGS beam at CERN [1], is a high energy beam ($< E_{\nu_\mu} > \sim 17 GeV$) optimized for the study of the appearance of $\nu_\tau$ starting from a pure beam of $\nu_\mu$. At the CNGS energies, the average $\tau$ decay length is submillimetric, therefore nuclear emulsions are used as high precision tracking devices. In terms of interactions, the $\bar{\nu}_\mu$ contamination is 2.1%, the $\nu_e$ and $\bar{\nu}_e$ contaminations together are smaller than 1%, while the prompt number of $\nu_\tau$ is negligible.

OPERA’s detector basic unit is the so-called “brick”, which is composed of 56 lead layers, 1 mm thick, interleaved with 57 nuclear emulsion layers (0.1 mm accuracy). The submicrometer spatial resolution of the nuclear emulsion allows a precise 3D reconstruction of the neutrino interaction point, and of the decay vertex associated with short-lived particle produced, like the $\tau$ lepton. The overall target is composed of about 150000 bricks for a total mass of 1.25 kton. Each brick is a stand-alone detector used to estimate several kinematical variables of each neutrino interaction, e.g. particle momentum through their multiple Coulomb scattering in the lead plates [2], and the energy of electromagnetic showers. OPERA is a hybrid detector [3] made of a veto plane followed by two identical Super Modules (SM). Each one includes a target section made of arrays of bricks and a scintillator Target Tracker detector (TT) [4] to trigger the read-out and localize neutrino interactions within the target. Each target section is followed by a muon spectrometer [6], which is a dipolar magnet instrumented with resistive plate chambers (RPCs) and drift tubes detectors, to measure the muon charge and momentum. See Fig. 1.

2. Event selection and analysis

All electronic detector triggers recorded on-time with the CNGS, are classified as internal or external events by an online algorithm i.e. as interactions inside or outside the OPERA target (e.g. in material along the beam-line preceding the OPERA target), respectively. Only internal events are used for oscillation studies. The algorithm further classify the events as charged current (CC) or neutral current (NC) interactions, through the spectrometers muon tracks identification or the amount of traversed material [6].
The neutrino vertex position is reconstructed, and the brick with the highest probability of containing it is extracted from the target. After a positive scan result of two “trigger” emulsions (a detachable set of two emulsion films, called Changeable Sheets, or CS doublet) where tracks compatible with TT data are found, the brick is developed and dispatched to a scanning laboratory in Europe or in Japan. Tracks found in the CS doublet are extrapolated to the most downstream film of the brick, then followed upstream using its prediction from the scanning, until they reach their stopping point, i.e., when the track is not found in the next three consecutive films. The vertex confirmation is done by scanning a large volume of \( \sim 2cm^3 \) around the stopping point.

A procedure called decay search is applied afterwards, in order to search for: (1) charged or neutral decay topologies, (2) secondary interactions or (3) gamma-ray conversions. If a secondary vertex is found, a full kinematical analysis is performed combining the measurements in the nuclear emulsion with data from the electronic detectors. The momentum of charged particles can be measured in emulsions up to 6 GeV/c. It can be measured up to 12 GeV/c with a resolution better than 33% using position deviations. For muons crossing the spectrometers, the momentum is measured with a resolution better than 22% up to 30 GeV/c, the muon charge is also determined [6]. The hint of a decay topology is the observation of an impact parameter greater than 10 \( \mu m \), defined as the minimum distance between the track and the reconstructed vertex, excluding low momentum tracks.

3. Oscillation results

By applying the procedure, described in section [2], to 4190 events acquired between 2008-2011, two events pass the selection criteria defined for the \( \tau \) lepton decay in two hadronic channels [3, 5].

3.1. First tau candidate

The first \( \nu_\tau \) candidate event was observed in the 2008-2009 dataset, details can be found in [7]. The event, shown in Fig. 2, has seven prongs at the primary vertex: four of them originate from hadrons, three have a probability lower than 0.1% of being caused by a muon, and none of them are left by an electron. The parent track (labeled 4 and displayed in red in Fig. 2) exhibits a kink topology, and the daughter track (shown also in Fig. 2) is identified as produced by a hadron through its interaction. The daughter impact parameter (IP) with respect to the primary vertex

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**Figure 1.** The OPERA detector at the Gran Sasso laboratory. The picture shows both super-modules (SM1 and SM2), and the target and muon spectrometers in each SM.
3.2. Second tau candidate
The second $\nu_\tau$ candidate event was found in the 2011 dataset. The event, displayed in Fig. 3 is a two prongs interaction with production of a short track (by a possible $\tau$ lepton) with a flight length of 1.54 mm, and a track identified as a hadron. One nuclear fragment was associated to the primary vertex. The short track decay vertex (shown in Fig. 3) is located in the plastic base in between the two sensitive layers of an emulsion film. The parent lepton decays in three hadrons (shown in Fig. 3), one that reinteracts producing two charged tracks and four back-scattered nuclear fragments. The charged hadron momentum at the primary vertex is $2.8^{+2.1}_{-2.5}$ GeV/c and the hypothesis of a muon on the basis of consistency between momentum and range is very unlikely. All daughter particles coming from the decay vertex were also identified as hadrons. The kinematical analysis of the event satisfies the specified criteria for the $\tau \rightarrow 3h$ decay channel. Kinematical variables used in the event classification are listed in table 2.

3.3. Charm background
The main background source comes from $\nu_\mu$ interactions with production of a charmed particle. The study of decay vertices of charm particles, that have lifetimes and decay topologies close to

![Figure 2. Left: Sketch of the first $\nu_\tau$ candidate, showing seven tracks attached to the primary vertex. Red track number 4, performing a kink, is the parent of a single prong decay. The daughter and both $\gamma$-rays ($\gamma_1$ and $\gamma_2$) are attached to the secondary vertex. Right: Zoom-in of the event, showing both primary and secondary vertices, displayed with dots. The kink of the parent can be clearly seen.](image)

is $55 \pm 4 \mu m$, while the other tracks have and IP$<7 \mu m$. Two $\gamma$-rays (labeled $\gamma_1$ and $\gamma_2$ in the plot) point to the secondary vertex with probabilities greater than 99% and 90% respectively. The invariant mass of the two $\gamma$-rays is $(120 \pm 20(stat) \pm 35(sys)) MeV/c^2$ compatible with the $\pi^0$ mass. Assuming the secondary hadron is a $\pi^-$, and adding the two $\gamma$-rays, the invariant parent’s mass is compatible with the mass of a $\rho(770)$. The decays mode $\tau \rightarrow \rho \nu_\tau$ branching ratio is about 25%. Different kinematical variables used for the event classification are listed in table 1, as well as the selection criteria applied for the single hadron decay channel.

| Variable           | Value       | Selection Criteria |
|--------------------|-------------|--------------------|
| kink [mrad]        | $41 \pm 2$  | $>20$              |
| decay length [\mu m] | $1335 \pm 35$ | $\leq 2600$       |
| $P_{\text{daughter}}$ [GeV/c] | $12^{+8}_{-3}$ | $>2$               |
| $P_t$ [MeV/c]      | $470^{+120}_{-129}$ | $>300$ ($\gamma$ attached) |
| missing $P_t$ [MeV/c] | $570^{+320}_{-170}$ | $<1000$           |
| $\phi$ [deg]      | $173 \pm 2$ | $>90$              |

Table 1. Kinematical variables (and selection criteria) for the first $\nu_\tau$ candidate in the $\tau \rightarrow 1h$ decay channel.
Figure 3. Event display of the second $\nu_\tau$ candidate, showing a two prong primary vertex. The red track is the decay vertex parent, with 3 prongs attached.

| Variable | Value       | Selection  |
|----------|-------------|------------|
| kink [mrad] | 87.4±1.5   | $<$500     |
| $P$ at 2$^{nd}$ vertex [GeV/c] | 8.4±1.7 | $>$3.0     |
| $P_t$ at 1$^{st}$ vertex [GeV/c] | 0.31±0.11 | $<$1.0     |
| Min invariant mass [GeV/c$^2$] | 0.96±0.13 | 0.5$<$m$<$2.0 |
| Invariant mass [GeV/c$^2$] | 0.8±0.12 | 0.5$<$m$<$2.0 |
| $\phi(\tau$-hadron) [deg] | 167.8±1.1 | $>$90      |

Table 2. Kinematical variables of the second $\nu_\tau$ candidate satisfying specified criteria for the $\tau \rightarrow 3h$ decay channel.

those of the $\tau$ lepton, offer an opportunity to check $\tau$ efficiency. The number of charm decays found so far in the data taken from 2008 to 2011 is 49. This number is in good agreement with the Monte Carlo expectation of 51±7.5. The statistical significance of the two $\nu_\tau$ candidate event observations is still under evaluation, along with the efficiencies for signal and background, taking into account different sample selections. The preliminary number of expected $\nu_\tau$ in the analysed data sample is 2.1, with background of 0.2 events.

4. Non oscillation results, neutrino velocity
For this analysis the neutrino velocity is defined as the ratio of the measured distance from CERN to OPERA (i.e. the baseline), to neutrinos’ time of flight, $ToF_\nu$, traveling through the Earth’s crust. High statistics data taken by OPERA between 2009 and 2011 is used for the analysis. The systematic uncertainties were reduced to the level of the statistical error, by dedicated upgrades of the timing systems, for time tagging and synchronisation of the CNGS beam at CERN and of the OPERA detector.

4.1. Neutrino time of flight measurement
The neutrino starting time is defined by time tagging the extractions of the SPS beam. The proton time structure is accurately measured by a fast Beam Current Transformer (BCT) detector (400 MHz bandwidth) read out by a 1 GS/s Wave Form Digitizer (WFD) with a 250 MHz bandwidth. The waveforms recorded for each extraction by the WFD are UTC (Universal Time Coordinates) time-stamped with a Symmetricron GPS receiver and stored in the CNGS database. The $ToF_\nu$ is given by the difference between the arrival time in OPERA and the start time at CERN. At LNGS, every millisecond a pulse (PPmsS) is derived from the one second periodic pulse (1PPS) of a ESAT2000 GPS system and is transmitted from the surface laboratory to the OPERA Master Clock in the underground laboratory through 8.3 km of optical fibre. The time base of the Master Clock is transmitted to OPERA detector sensors, by which
neutrino interaction time is defined. The required ns accuracy for relative time tagging between CERN and the OPERA detector is achieved by adopting two identical systems, installed in both sites, composed of a GPS receiver for time-transfer applications operating in common-view mode and a Cs atomic clock. Both systems were calibrated in 2008 by the Swiss Federal Metrology Institute (METAS) and established a permanent time link at the level of 2 ns between $t_{CERN}$ and $t_{OPERA}$ as reference points. This time link was independently verified in 2011 by the German Federal Metrology Institute (PTB) by taking data at CERN and LNGS with a portable time-transfer device. The difference between the time base of the both GPS receivers was measured as $(2.3\pm1.7) \text{ ns}$. A detailed description of these procedures can be found in Ref. [8].

4.2. Neutrino baseline measurement

The neutrino baseline is defined as the distance between the point where the proton time-structure is measured (by the BCT at CERN) and the origin of the OPERA reference frame ORF. The travel path of protons from the BCT to the focal point of the CNGS target has been measured with millimetric accuracy, $L_{\text{BCT-target}} = (743.391 \pm 0.002) \text{ m}$. When these positions are transformed into the global geodesy reference frame (ETRF2000) by relating them to the external GPS benchmarks at CERN, they are known within 2 cm accuracy. The coordinates of the ORF origin were measured in 2010 by establishing GPS benchmarks at the both sides of the 10 km long Gran Sasso highway tunnel, and by transporting their positions with a terrestrial traverse down to OPERA. A common analysis in the ETRF2000 for 3D coordinates of OPERA origin and of the target focal point allowed their distance determination, $L_{\text{target-OPERA}} = (730534.61 \pm 0.20) \text{ m}$. The 20 cm uncertainty is dominated by a long underground link between the outdoor GPS and the OPERA detector benchmarks. Then the baseline considered for measuring $ToF_{\nu}$ is the sum of the distance between CNGS target focal point and the origin of the OPERA detector reference frame, $L_{\text{target-OPERA}}$, and the distance between BCT and the focal point, $L_{\text{BCT-target}}$, i.e. $(731278.0 \pm 0.2) \text{ m}$.

4.3. Data analysis and results

Neutrinos $ToF_{\nu}$ from the standard CNGS beam can not be treated at the single interaction level, due to the 10.5 $\mu$s pulse duration of the SPS extraction. Any extracted proton may produce a neutrino detected by OPERA. Therefore for each neutrino interaction measured in OPERA its corresponding proton extraction waveform is considered. Those waveforms were individually normalized to unity and summed up in order to build a PDF $w(t)$ of neutrinos’ emission time. The neutrino interaction time is defined as the time of the earliest hit in the TT. $ToF_{\nu}$ is obtained by comparing the distribution of protons crossing the BCT with neutrino events detected by OPERA.

Assuming a propagation at the speed of light of protons over the baseline $ToF_c$, the deviation of $ToF_{\nu}$ with respect to $ToF_c$, $(\delta t = ToF_{\nu} - ToF_c)$, can be obtained by a maximum likelihood analysis of the time tags of OPERA events, with respect to the PDF as a function of $\delta t$. For the analysis 15223 events (7235 NC and CC events contained inside the detector, and 7988 external CC events) were used, corresponding to $\sim 10^{20} \text{ p.o.t.}$ The arrival time of neutrinos with respect to the time evaluated considering the speed of light for the propagation is:

$$\delta t = ToF_{\nu} - ToF_c = 6.5 \pm 7.4(\text{stat})^{+8.3}_{-8.0}(\text{sys}) \text{ ns}$$

(1)

In order to exclude possible biases affecting the statistical analysis based on the neutrino emission PDF, the neutrino velocity was measured using a dedicated CNGS beam generated by an special proton beam set-up, from October 22 to November 6, 2011. The modified SPS super-cycle consisted of a single extraction including bunches $\sim 3$ ns long (FWHM) separated by 524 ns, yielding a total of $1.1 \times 10^{12}$ protons per cycle. Given the short bunch length and the relatively long inter-bunch distance one could unambiguously associate each neutrino event to its corresponding proton bunch. The average time difference for 20 events (6 contained plus 14
Figure 4. Distribution of the time difference $\delta t$ between the light and the neutrino times of flight. Neutrino time distribution. First row: selected events for the TT analysis using the first hit (Method 1), and using muon hits only (Method 2). Second row: events selected for the RPC analysis using muon hits (Method 3), and events analyzed using a dedicated timing board (Method 4).

external) measured with the TT is $\delta t = -1.9 \pm 3.7(stat) +8.3(stat) -8.0(sys) ns$, in agreement with previous analysis. At first order, systematic uncertainties related to the bunched beam operation are equal or smaller than those affecting the result with the nominal CNGS beam. Further details can be found in Ref. [8].

CERN provided in 2012 a new narrow-bunch short-spacing beam between $10^{th}$ and $24^{th}$ of May. In each 13.2 s CNGS cycle, a single extraction delivers 16 proton bunches. Each 2.8 ns long bunch contained $\sim 10^{11}$ protons, giving an intensity a factor 6 higher than the 2011 bunched beam run. During this two week period $1.8 \times 10^{17}$ p.o.t. were delivered. In OPERA 104 on-line events were detected using TT (67 events) and RPC (62 events). An independent analysis was performed for each detector type [9].

For the analysis using TT data, two methods were used to compute neutrinos' interaction time. “Method 1” relies on the information of the earliest hit. While “Method 2” exploits the information of all hits of the reconstructed 3D muon track only. In the second method NC-like events are therefore not considered. On the top row of Fig. 4 are plotted the distributions of $\delta t$ for Method 1 (left) yielding $\delta t = -2.1 \pm 1.1(stat) \pm 4.4(sys) ns$, and for Method 2 (right) yielding $\delta t = 1.2 \pm 1.0(stat) \pm 3.3(sys) ns$. The analysis using RPC data was performed using the standard OPERA DAQ “Method 3”. In this case only neutrino interactions producing a clear muon track in the RPC’s are used. The corresponding $\delta t$ distribution is shown in Fig. 4 (bottom left), the final result is $\delta t = -2.5 \pm 1.8(stat) \pm 5.3(sys)$. “Method 4” uses RPC data taken with a dedicated timing board TB which gives complementary information to events acquired using the standard OPERA DAQ. Details about this timing system can be found in Ref. [9]. The $\delta t$ distribution for this method is shown in Fig. 4 (bottom right), the final result is $\delta t = 0.6 \pm 0.4(stat) \pm 3.6(sys)$. Methods 1 and 2 are statistically correlated since they use the same DAQ system and sub-detector. For the same reason they are also correlated with Method 3. Method 4 is almost uncorrelated with the other methods because of the different timing system used. Residual correlation arises from the systematic error of the common part of the timing chain. In order to obtain a single combined result, Methods 2 and 4 were used since they have the smallest statistical and systematical error, and because they are almost completely uncorrelated.
thus providing maximum information. Values obtained with Method 1 were used when Method 2 could not be used because of the absence of a muon track. Summing in quadrature systematic errors, separately for $\nu$ and $\bar{\nu}$ contributions, leads to $\delta t_{\nu} = (0.6 \pm 0.4(stat) \pm 3.0(syst))$ ns and $\delta t_{\bar{\nu}} = (1.7 \pm 1.4(stat) \pm 3.1(syst))$ ns.

5. Conclusions

The OPERA experiment started collecting data in 2008, with the aim to make the first direct observation of neutrino oscillations in appearance mode. In the $\nu_\mu \rightarrow \nu_\tau$ channel two events were observed in the data from 2008 to 2010 and part of 2011. The significance of this observation is still under evaluation; the preliminary expectancy is 2.1 $\nu_\tau$ events with 0.2 background events.

The OPERA experiment measured the neutrino velocity over the CNGS baseline ($\sim 730$ Km). After correcting and updating its timing system [10, 8], it was able to confirm the results obtained from standard CNGS data from 2009 to 2011 with data from two dedicated bunched beam runs performed in 2011 Ref. [8] and 2012 Ref. [9]. A limit on the speed of light deviation was derived $\frac{\pm 1.6 \times 10^{-6}}{\pm 1.4 \times 10^{-6}} < \frac{v_\nu - c}{c} < \frac{2.3 \times 10^{-6}}{3.1 \times 10^{-6}}$ showing no significant difference between neutrino and antineutrino velocities and speed of light.

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