# OPERA

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## 1 The experiment

OPERA [1] has been designed to provide a very straightforward evidence for $\nu_\mu \to \nu_\tau$ oscillations in the parameter region indicated by Super-Kamiokande as the explanation of the zenith dependence of the atmospheric neutrino deficit. It is a long baseline experiment located at the Gran Sasso Laboratory (LNGS) and exploiting the CNGS neutrino beam from the CERN SPS. The detector [2] is based on a massive lead/nuclear emulsion target. The target is made up of emulsion sheets interleaved with 1 mm lead plates and packed into removable "bricks" (56 plates per brick). Each brick is equipped with a detachable emulsion doublet ("Changeable Sheet", CS), which is scanned before the full development of the brick emulsions. The bricks are located in a vertical support structure making up a "wall". These bricks were produced in situ by a "brick assembly machine" (BAM) located near the OPERA experimental Hall; they are inserted into the wall support structure by a dedicated robot (BMS). Nuclear emulsions are used as high resolution tracking devices for the direct observation of the decay of the $\tau$ leptons produced in $\nu_\tau$ charged current interactions. Electronic detectors positioned after each wall locate the events in the emulsions. They are made up of extruded plastic scintillator strips read out by wavelength-shifting fibers coupled with photodetectors at both ends. Magnetized iron spectrometers measure charge and momentum of muons. Each spectrometer consists of a dipole magnet made of two iron walls interleaved with pairs of precision trackers. The particle trajectories are measured by these trackers, consisting of vertical drift tube planes. Resistive Plate Chambers (RPC) with inclined strips, called XPC, are combined with the precision trackers to provide unambiguous track reconstruction in space. Moreover, planes of RPC are inserted between the magnet iron plates. They allow for a coarse tracking inside the magnet to identify muons and ease track matching between the precision trackers. They also provide a measurement of the tail of the hadronic energy leaking from the target and of the range of muons which stop in the iron. A block of 31 walls+scintillator planes, followed by one magnetic spectrometer constitutes a "super-module". OPERA is made up of two super-modules (SM) located in the Hall C of LNGS (see Fig. 1). Since 2008 all bricks have been inserted, for a total of 150036 bricks, corresponding to a target mass of 1.25 kton, now decreased to 1.15 kton after the extraction of the bricks analyzed so far.
OPERA is able to observe the $\nu_\tau$ signal with an impressively low background level. The direct and

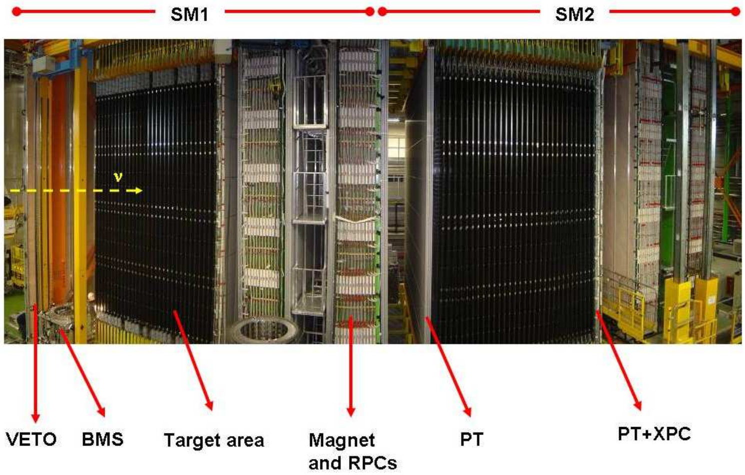


Figure 1: *A fish-eye view of the OPERA experiment. The upper red horizontal lines indicate the position of the two identical super-modules (SM1 and SM2). The "target area" is made up of planes of walls filled with lead-emulsion bricks interleaved with planes of plastic scintillators (TT): the black covers visible in the photograph are the end-caps of the TT. Arrows show also the position of the VETO planes, the drift tubes (PT) followed by the XPC, the magnets and the RPC installed among the magnet slabs. The Brick Manipulator System (BMS) is also visible. The direction of incoming neutrinos from CERN is indicated by the yellow arrow.*

unambiguous observation of $\nu_\mu \to \nu_\tau$ appearance will constitute a milestone in the study of neutrino oscillations. Moreover, OPERA has some sensitivity to the sub-dominant $\nu_\mu \to \nu_e$ oscillations [3]. The potential of the experiment for the research of oscillations into sterile neutrinos and non standard interactions has also been investigated [4, 5].
Opera is an international collaboration (Belgium, Croatia, France, Germany, Israel, Italy, Japan, Russia, Switzerland, Tunis and Turkey) and the INFN groups involved are Bari, Bologna, LNF, LNGS (Gran Sasso), Naples, Padova, Rome and Salerno. The Technical Coordinator (A. Paoloni) is a LNF researcher.

## 2 Overview of the OPERA activities in 2012

The CNGS complex ended its operation after the 2012 run, with $4.84 \times 10^{19}$ protons delivered on target, corresponding to 3493 events inside the OPERA bricks, with an overall duty-cycle for the accelerator complex of 81%. The corresponding live-time of the detectors on the beam has been greater than 99%.

Considering all the years of data taking with the bricks inside the target, i.e. from to 2008 to 2012, the CNGS accumulated in total $18.22 \times 10^{19}$ proton-on-target, about 80% of the statistics considered in the OPERA proposal, corresponding to 17330 events inside the OPERA bricks. To speed up the research of tau candidates in the exposed bricks, the collaboration has decided to postpone the analysis of those events in which the neutrino vertex is not localized in the first

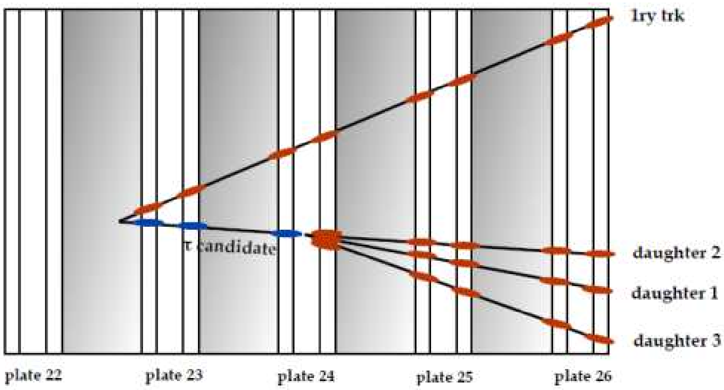


Figure 2: *The second OPERA tau candidate event.*

scanned brick and to give priority to events without muons or with muons of momentum lower than 15 GeV. Up to the end of 2012, about 9000 bricks have been scanned and 5500 events located.

During 2012, the collaboration reported the observation of the second observed tau candidate, interpreted as a 3 prong hadronic decay, whose picture is shown in Fig.2, The expected number of $\nu_{mu}$ into $\nu_\tau$ oscillations is 2.1 with 0.18 background events.

The analysis of the oscillation into electron neutrinos was also completed for the 2008+2009 data sample (corresponding to $5.25 \times 10^{19}$ pot). We observed 19 events, compatible with the non-oscillation expectation of $19.8 \pm 2.8$ events.

The experiment revised the measurement of the neutrino velocity using the electronics detectors data acquired on CNGS beam from 2009 to 2011 [6)] and performed a new measurement with the data acquired during 2012 run. Both measurements show that neutrinos are traveling at the speed velocity within experimental errors.

The analysis of the events in the bricks will continue in the next years.

## 3 Activities of the LNF group

The Frascati group has been responsible for the design and the construction of the dipole magnets and the general support structure of the sub-detectors. It shares responsibility with INFN Padova and LNGS for the construction and running of the bakelite RPC planes. Frascati and Naples also designed and prototyped the wall support structures housing the lead/emulsion bricks and LNF was responsible for their production and installation. The Frascati group has been also involved, with the University of Hamburg, in the trigger of the drift tubes, performed by the Resistive Plate Chambers.

On the emulsion side, LNF was highly involved in the construction and operation of the Brick Assembly Machine (BAM) and, since 2008, contributes to the emulsion scanning with one dedicated microscope located in Frascati. Finally, since 2007 LNF follows the brick handling of OPERA, with the management of the X-ray marking facilities and the automation of the temperature control of the development tanks.

The group is contributing also to data analysis, with particular interest in electronic detectors (cosmic ray studies, RPC data quality checks, neutrino velocity measurement) and in the statistical significance assessment of the observed $\nu_\mu$ into $\nu_\tau$ oscillations.

### 3.1 Resistive Plate Chambers

After major contributions in the construction of the RPC system, the LNF group has been highly involved in its running during the CNGS data taking. One of the duties of the group is the monitoring of the performances as a function of time. In OPERA, Resistive Plate Chamber with bakelite electrodes are arranged into layers, 22 in each spectrometer, inserted into 2 cm gaps inside the magnetized iron. Two additional layers, called XPCs because of the inclined read-out strips, are placed in each Super-Module between the Target Tracker and the spectrometer. The XPC layers and 7 out of 22 RPC layers in each spectrometer are instrumented with dedicated Timing Boards (TBs) for triggering the drift tubes. A complete description of the OPERA RPC system can be found on [2, 9, 10].

The detectors are operated in streamer mode at 5.7 kV with the gas mixture $Ar/C_2H_2F_4/i-C_4H_{10}/SF_6 = 75.4/20.0/4.0/0.6$ [11]. An automatic correction is applied for the pressure, according to [12]; the temperature is quite stable, between 15 and 18$^o$C, depending on the detectors position. Signals from the vertical strips, measuring the bending coordinate, are discriminated at 40 mV, while the threshold for the horizontal strips is 26 mV, in order to correct for the different impedance matching with the read-out twisted flat cables.

The full RPC system ran smoothly during the 2012 run, with almost no dead-time and with performances similar to those observed in previous years [7], matching the required specifications, with efficiency greater than 90% and time resolutions better than 5 ns.

The main aging effect observed on OPERA RPCs is the progressive increase of electrode resistivity due to the drying of the bakelite. Since the gas mixing is in common between the bakelite RPCs (instrumenting the spectrometers) and the glass ones (instrumenting the VETO system), both detectors are indeed flushed with a dry mixture. The chambers in the spectrometers are disposed in rows of three chambers, with the gas flowing from column 1 to column 3. In figure 3 it is shown the average efficiency measured on cosmic rays as a function of the RPC position along the gas flow. During the years of operation, detector efficiencies have slightly decreased, especially at the entrance of the gas, as expected.

### 3.2 Cosmic rays analysis with OPERA detector

Beside its main goal of neutrino oscillation appearance, the OPERA experiment is perfectly suited as a cosmic ray detector due to its interesting physics capabilities. OPERA is located in the underground Gran Sasso Laboratory, at an average depth of 3800 meters of water equivalent (m.w.e.). The rock overburden naturally selects very energetic muons. The detector observes underground muons with a minimum surface energy of 1 TeV and the mean value of their energy spectrum is about 2 TeV. The analysis of the atmospheric muon charge ratio $R_\mu = N_{\mu^+}/N_{\mu^-}$ in the highest energy region with the whole OPERA statistics over five years is in progress.

Another important item is the search for coincident events between the LVD and OPERA detectors, respectively located in Hall A and C at LNGS. The idea is to look for shower events

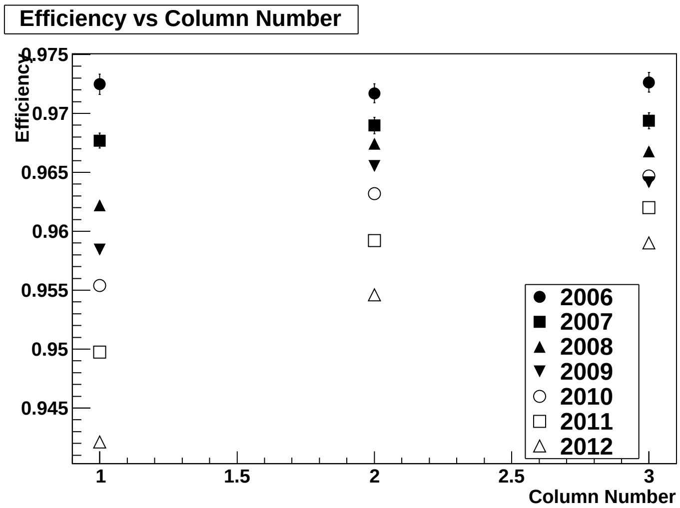


Figure 3: *Average RPC efficiency along the gas flow for the different data taking years.*

intercepted by both detectors as a tool for study high $p_t$ events in cosmic rays. Given the large distance between the two detectors ($d \sim 170$ m) coincident muon bundles would allow to address the boundary region where pQCD gives way to soft physics, a region of particular interest for the modeling of high energy Monte Carlo codes. Possibly CNGS-correlated coincident events would also allow the study of large angle di-muon events from charmed particles produced by charge-current neutrino interaction in the rock upstream the detectors. The analysis was jointly carried out by the two Collaborations after a formal agreement.

A preliminary analysis showed no interesting events related to muon bundles. We observed several events with a large ($\sim$ 600 ns) time difference between the two detectors. After visual scanning these events were identified as single muon events, hitting OPERA first and then LVD, coming from the so called Teramo Valley, a peculiar region in the Gran Sasso orography with large zenith angles ($>$ 80 deg) and modest rock thickness ($\sim$ 2200 m).

After the first release of the neutrino velocity measurement, showing an anomalous anticipation of the neutrino time-of-flight, by continuing the campaign of cross checks, the fiber delay measurement was repeated in December 2011. The result was different from the one obtained in 2007 and quoted in the analysis. The Bologna and LNF groups used the high energy muon beam ($\sim$ 270 GeV) from the Teramo Valley as a probe to cross-calibrate the two detector timing systems.

We extended the OPERA-LVD coincidence analysis to a larger period (2007-2012 Runs' data). We found a discontinuity in the muon time-of-flight around summer 2008 of the same size of the fiber delay anomalous result. The analysis also confirmed the existence of a drift in the OPERA internal clock [13].

This led to a model able to explain all the effects, historicizing when the two issues arose. The coincidence analysis solved the neutrino velocity anomaly and contributed to reassess the measurement eventually presented in Ref. [6].

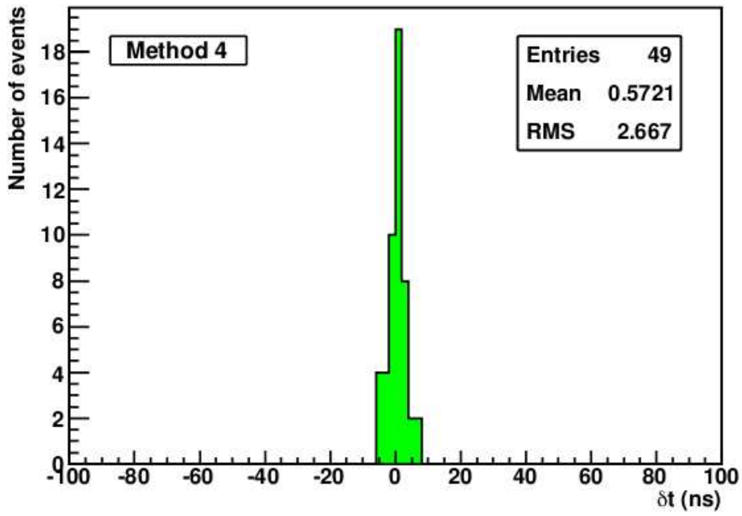


Figure 4: *CNGS neutrinos timeofflight distribution: $\delta t$=L/c-TOF, where L=baseline CERN-LNGS and TOF=measured time-of-flight.*

### 3.3 Neutrino velocity measurement

After the measurement of the CNGS neutrinos velocity with the data acquired from 2009 to 2011, the OPERA experiment performed several improvements on the setup for the 2012 bunched beam run [14].

One of these improvements is the duplication of the DAQ for the resistive plate chambers with a new VME based system, in order to perform cross-checks on eventual data anomalies. The key element of the new system is a custom VME board receiving through an optical fiber the synchronization signal of the Gran Sasso atomic clock (PPmS), reading its UTC time (coded with ms precision) and distributing it to the readout electronics in standard NIM logic. The module, originally designed for the NAUTILUS experiment by the LNF electronic workshop, has been adapted for the operation in the underground Gran Sasso laboratory, with the addition of large bandwidth amplifier to compensate for the light attenuation over the 8 km optical fiber connecting the module to the atomic clock located in the external laboratory.

The repeated PPmS and the OR signals of the 14 RPC layers instrumented with the Timing Boards are acquired by a VME TDC with 800 $\mu$s range and 1 ns precision; their time difference is the sub-ms component of the corresponding UTC times. The custom VME PPmS receiver module provides also a reference 5 kHz frequency for calibrating and verifying the stability of the internal TDC frequency.

The measured time of flight is consistent with the neutrinos traveling at the speed of light, while the rms of the distribution, shown in figure 4, is 2.7 ns, the best among all the experiments at GranSasso. The systematic error on the measurement is around 3 ns, dominated by the knowledge of the RPC detector intrinsic response delay.

This delay has been measured on purpose in the external LNGS laboratories triggering cosmic rays with a time-calibrated detector (a scintillator read-out by a photomultiplier), acquiring the analog signals by means of a 5 GSample/sec digitizer. We have found that the intrinsic delay in the response of OPERA RPCs (gas gap=2mm, operated in streamer mode) is $24 \pm 2$ ns.

### 3.4 Analysis of the OPERA emulsion detectors at the LNF scanning station

The OPERA brick is based on the Emulsion Cloud Chamber (ECC) detector concept, fulfilling the requirements of high granularity and micrometric resolution necessary to distinguish the $\tau$ decay vertex from the primary $\nu_\tau$ interaction. Each ECC can act as a standalone detector that can be selectively removed from the target, developed and analyzed after the interaction took place.

A detailed description of the automatic microscopes developed for the analysis of OPERA ECCs can be found in Ref. [15]. The ECC (or "brick") dimensions and length are optimized to contain the primary as well the decay vertex and to provide particle identification and kinematical reconstruction. The use of passive material, combined with high accuracy tracking devices, allows for momentum measurement of charged particles via multiple Coulomb scattering (MCS) and for electromagnetic shower identification [16].

The bricks selected by the electronic detectors as containing a neutrino interaction vertex are extracted from the OPERA target and equally shared between Japan and Europe for the scanning. The CS doublet acts as a confirmation of the trigger provided by the Target Tracker: the brick is developed only if the prediction is confirmed, otherwise the CS is replaced and the brick is put back in the target. For events assigned to the European community the CS doublets are analyzed at the LNGS scanning station and the scanning load is shared among a group of specialised shifters. Since 2008 the LNF group contributes to the CS doublets scanning performing shifts at the LNGS station, in addition to the work load at the home scanning laboratory. The LNF scanning station [18] is part of the network of italian scanning groups including Bari, Bologna, LNGS, Napoli, Padova and Roma1 to which the emulsions developed at LNGS are sent for the final analysis.

The LNF emulsion scanning station (Building 29) is hosted in a climatised environment to ensure good conditions for emulsion storage. The station is equipped with a motorized optical microscope instrumented with a system for the emulsion plates loading on the microscope stage (Plate Changer). The whole chain for brick scanning at LNF is fully operational since 2008. It consists of three phases: the brick scanning, the event reconstruction and the data publication on the central database.

After concentrating on the specific task of studying the event kinematics in the emulsions (see the report for 2011), since February 2012, the LNF scanning station has resumed the vertex location activities on a signal enriched sample of NC-like interactions registered by the detector in 2011 and 2012 with the aim of exploring as much as possible the occurrence of new $\tau$ candidates. In 2012 a total number of about 40 bricks has been treated. The event display of a remarkable event with a high-energy electromagnetic shower identified with our microscopes during this campaign is shown in Fig. 5. The scanning and analysis flow is smoothly running on-time with the brick assignment. The LNF scanning laboratory shows good performances with a 75% location efficiency, in agreement with the expectations.

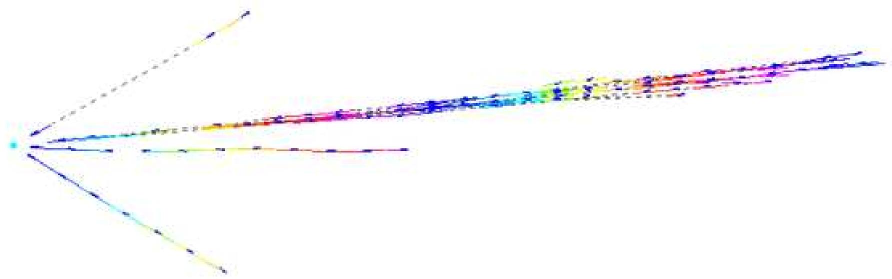

Figure 5: *A neutrino interaction in an OPERA brick found at the LNF scanning station. An animated 3D view is available at* [18].

Besides the scanning activity we are also deeply involved in the development of the simulation and the global analysis of the emulsion data in view of upcoming publications.

## 4 List of Conference Talks by LNF Authors in Year 2012

1. A. Longhin "Results from OPERA", Moriond EWK, La Thuile, Italy, 04 March 2012.
2. A. Paoloni, "Performance and aging of OPERA bakelite RPCs", XI Workshop on Resistive Plate Chambers and Related Detectors, LNF, Italy, 6-10 February 2012.
3. N. Mauri, "Highlights from the OPERA experiment" ICFP 2012, International Conference on New Frontiers in Physics Kolymbari, Crete, Greece, 10-16 June 2012.

## 5 Publications


1. N. Agafonova *et al.* [ LVD and OPERA Collaborations ], "Determination of a time-shift in the OPERA set-up using high energy horizontal muons in the LVD and OPERA detectors" Eur. Phys. J. **127**, 71 (2012).
2. A. Paoloni *et al.*, "Long term performances of OPERA bakelite RPC system.", Nucl. Instrum. Meth., **A661**, S60 (2012).
3. N. Agafonova *et al.* [ OPERA Collaboration ], "Search for $\nu_\mu \Rightarrow \nu_\tau$ oscillation with the OPERA experiment in the CNGS beam", New J.Phys. **14**, 033017 (2012).
4. N. Agafonova *et al.* [ OPERA Collaboration ], "Momentum measurement by the Multiple Coulomb Scattering method in the OPERA lead emulsion target.", New J.Phys. **14**, 013026 (2012).

5. T. Adam *et al.* [ OPERA Collaboration ], "Measurement of the neutrino velocity with the OPERA detector in the CNGS beam", JHEP **10**, 093 (2012).
6. A. Paoloni *et al.*, "Performance and aging of OPERA bakelite RPCs", PoS (RPC2012), 010 (2012).

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13. N. Agafonova *et al.*, Eur. Phys. J. **127**, 71 (2012).
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15. N. Armenise *et al.*, Nucl. Instrum. Meth. **A551**, 261 (2005).
16. L. Arrabito *et al.*, JINST **2**, P05004 (2007).
17. A. Anokhina et al. [OPERA Coll.], JINST **3**, P07005 (2008).
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