The OPERA experiment

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1 The experiment

OPERA [1] has been designed to provide a direct evidence for $\nu_\mu \rightarrow \nu_\tau$ 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 τ leptons produced in ν_τ 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 kt.

OPERA is able to observe the ν_τ signal with an impressively low background level. The direct and unambiguous observation of $\nu_\mu \rightarrow \nu_\tau$ appearance constitutes a milestone in the study

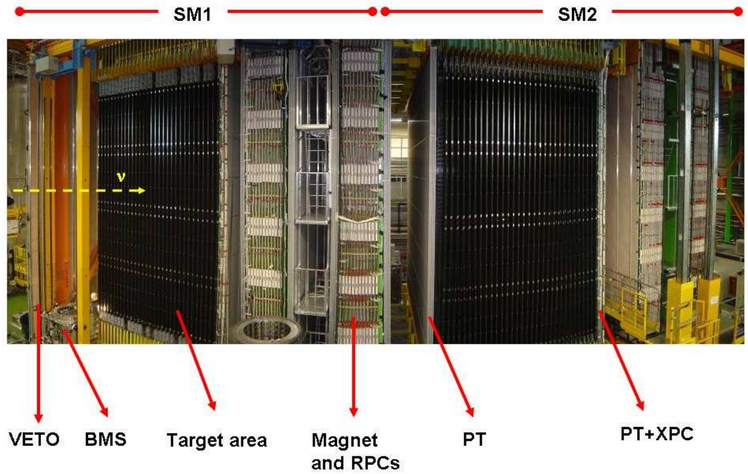

Figure 1: *A fish-eye view of the OPERA experiment. The upper red horizontal lines indicate the position of the two identical super-modules (SM1 and SM2). The "target area" is made up of planes of walls filled with lead-emulsion bricks interleaved with planes of plastic scintillators (TT): the black 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.*

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 and Turkey) and the INFN groups involved are Bari, Bologna, LNF, LNGS (Gran Sasso), Naples, Padova, Rome and Salerno. The Technical Coordinator (A. Paoloni), its deputy (M. Spinetti) and the Physics Coordinator deputy (A. Longhin) are LNF researchers. A. Longhin is also member of the PTB, Publications and Talks Board.

2 Overview of the OPERA activities in 2015

The CNGS complex ended its operation after the 2012 run, collecting, from 2008 to 2012, a total of 17.97×10^{19} proton-on-target (about 80% of the statistics considered in the OPERA proposal), corresponding to 19505 events inside the OPERA bricks. The analysis of the events is almost completed and will continue in parallel to the decommissioning, started in January 2015.

During the last year, the collaboration reported the observation of the fifth ν_τ candidate [6] in the single prong hadron decay channel, whose picture is shown in Fig. 2. The expected number of ν_μ into ν_τ oscillations is 2.64 ± 0.53 (assuming full mixing and $\Delta m^2_{32} = 2.44 \times 10^{-3}\ eV^2$) with 0.25 ± 0.05 background events. The non-oscillation hypothesis is therefore excluded at $5.1\ \sigma$.

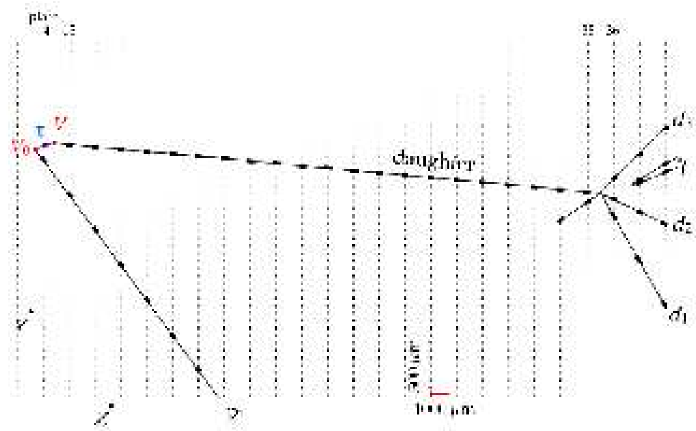

Figure 2: *Event display of the fifth OPERA τ candidate event.*

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 shared 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.

The group is contributing also to data analysis, with particular interest in exotic searches exploiting the $\nu_\mu \rightarrow \nu_\tau$ oscillation channel.

3.1 Exotic searches in $\nu_\tau \rightarrow \nu_\mu$ oscillation channel [7]

The OPERA experiment has so far detected 5 ν_τ candidates, consistent with the number of events expected in the standard three neutrino framework (2.8 events for $\Delta m^2_{32} = 2.4 \times 10^{-3}\ eV^2$, including 0.25 expected background events). Limits have been derived on the existence of a fourth sterile massive neutrino with mass m_4. The oscillation probability is a function of the 4×4 mixing matrix U and of the squared mass differences. At L/E values of interest for OPERA it can be parametrized as:

$$\begin{aligned} P(E) \;=\; & C^2 \sin^2(\Delta_{31}) \;+\; \sin^2(2\theta_{\mu\tau})\; \sin^2(\Delta_{41}) \\ & +\; 0.5\; C\; \sin(2\theta_{\mu\tau})\; \cos(\phi_{\mu\tau})\; \sin(2\Delta_{31})\; \sin(2\Delta_{41}) \\ & -\; C\; \sin(2\theta_{\mu\tau})\; \sin(\phi_{\mu\tau})\; \sin^2(\Delta_{31})\; \sin(2\Delta_{41}) \\ & +\; 2\; C\; \sin(2\theta_{\mu\tau})\; \cos(\phi_{\mu\tau})\; \sin^2(\Delta_{31})\; \sin^2(\Delta_{41}) \\ & +\; C\; \sin(2\theta_{\mu\tau})\; \sin(\phi_{\mu\tau})\; \sin(2\Delta_{31})\; \sin^2(\Delta_{41}) \end{aligned} \tag{1}$$

where $C = 2|U_{\mu 3}U^*_{\tau 3}|$, $\phi_{\mu\tau} = Arg(U_{\mu 3}U^*_{\tau 3}U^*_{\mu 4}U_{\tau 4})$, $\sin(2\theta_{\mu\tau}) = 2|U_{\mu 4}U^*_{\tau 4}|$ and $\Delta_{ij} = 1.27\Delta m^2_{ij}L/E$. Δm^2_{31} and Δm^2_{41} are expressed in eV^2, L in km and E in GeV. Given the long baseline and the average CNGS neutrino energy, *P(E)* is independent of Δm^2_{21} since $\Delta_{21} \sim 0$. The terms proportional to $\sin(\phi_{\mu\tau})$ are CP-violating, while those proportional to $\sin(2\Delta_{31})$ are sensitive to the mass hierarchy of the three standard neutrinos, normal ($\Delta m^2_{31} > 0$, N.H.) or inverted ($\Delta m^2_{31} < 0$, I.H.). Matter effects have been neglected because the effective potential is identical for ν_μ and ν_τ.

The experiment result likelihood has been defined as

$$L(\Delta m^2_{41}, \phi_{\mu\tau}, \sin^2(2\theta_{\mu\tau}), C^2) = e^{-\mu}\; \mu^n/n! \tag{2}$$

where $n = 5$ is the number of ν_τ candidate events and μ is the expected number of events, obtained convoluting the oscillation probability with the neutrino flux, the ν_τ charged current cross section and the τ selection efficiency, and adding the expected background. The value of $|\Delta m^2_{31}|$ has been fixed to 2.4×10^{-3} eV^2.

The analysis presented here is based on the χ^2 statistics appropriate to small sample sizes:

$$\chi^2 \;= -2\; \ln(\widetilde{L}(\Delta m^2_{41}, \sin^2(2\theta_{\mu\tau}))/L_0), \tag{3}$$

where $L_0 = e^{-n}\; n^n/n!$ is a normalization factor and $\widetilde{L}(\Delta m^2_{41}, \sin^2(2\theta_{\mu\tau}))$ is the profile likelihood obtained by maximizing the likelihood over C^2 and $\phi_{\mu\tau}$. The likelihood profiling (χ^2 minimization) procedure is performed considering the correlation between C^2, $\sin^2(2\theta_{\mu\tau})$ and $\phi_{\mu\tau}$ due to the dependence on the mixing matrix parameters.

In Fig. 3 the 90% Confidence Level (CL) exclusion limits are represented for normal and inverted mass hierarchy in the parameter space Δm^2_{41} vs $\sin^2(2\theta_{\mu\tau})$. For simplicity sake, the sign of Δm^2_{41} is considered to be positive. In the figure, the limits of direct searches for $\nu_\mu \rightarrow \nu_\tau$ oscillations obtained by NOMAD [9] and CHORUS [10] experiments at short baseline are also shown.

Our analysis extends down to $\Delta m^2_{41} \sim 10^{-2}$ eV^2 the limits obtained by the short baseline experiments, for $\sin^2(2\theta_{\mu\tau})$ values above 0.1. An exclusion region at $\Delta m^2_{41} \sim 10^{-3}$ eV^2 is also visible in the case of the direct hierarchy of the three standard neutrino masses, as a consequence of the fact that the expected number of τ events is lower than that expected in the standard three neutrino framework. The exclusion region at $\Delta m^2_{41} \sim 10^{-3}$ eV^2 disappears fixing the number of observed events equal to the number of events expected in the three neutrino framework. For negative values of Δm^2_{41}, similar plots are obtained with the three standard neutrino hierarchies exchanged.

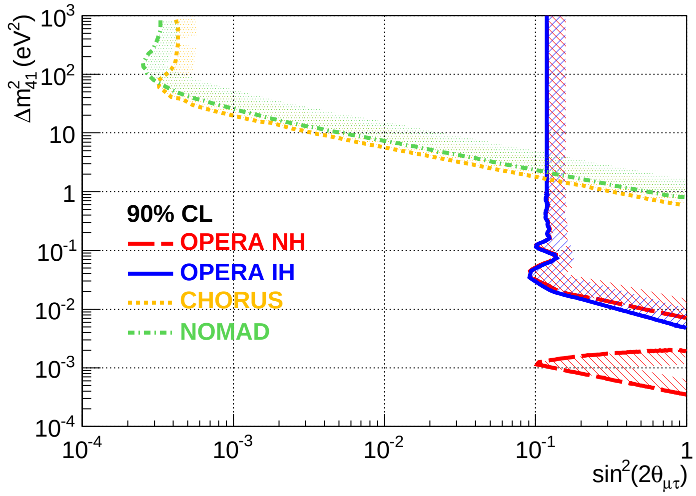

Figure 3: 90% *CL exclusion limits in the* Δm^2_{41}, $\sin^2(2\theta_{\mu\tau})$ *parameter space for normal (red) and inverted hierarchy (blue). Bands are drawn to indicate the excluded sides.*

An alternative exotic mechanism that can induce $\nu_\mu \to \nu_\tau$ oscillations is the Neutral Current (NC) neutrino Non-Standard Interaction (NSI). The Hamiltonian operator describing the NC neutrino NSI is given [5] by:

$$H = V \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \tag{4}$$

where $V = \sqrt{2} G_F N_e$. Since at OPERA neutrino energies and baseline $\Delta m^2_{31} L/2E << 1$ and $VL << 1$, the flavor evolution matrix S can be approximated as $S = exp(-iHL) \sim I - iHL$ and the oscillation probability $P_{\mu\tau} = |S_{\mu\tau}|^2 \sim |H_{\mu\tau} L|^2$. OPERA experiment is sensible to $\epsilon_{\mu\tau}$. The oscillation probability at the first orders in L can be approximated by:

$$P_{\mu\tau} = |\cos^2\theta_{13} \sin 2\theta_{23} \frac{\Delta m^2_{31}}{4E} + \epsilon^*_{\mu\tau} V|^2 L^2 + o(L^3). \tag{5}$$

In case of anti-neutrinos, V and $\epsilon_{\mu\tau}$ must be replaced by $-V$ and $\epsilon^*_{\mu\tau}$ respectively.

In the analysis described here:

- Δm^2_{31} and $\cos^2\theta_{13}$ have been fixed to 2.44×10^{-3} eV^2 and 1 respectively.
- The normal neutrino mass hierarchy ($\Delta m^2_{31} > 0$) has been assumed; results for the inverse hierarchy can be derived by flipping the sign of $Re(\epsilon_{\mu\tau})$.
- possible NSI effects in Charged Current (CC) interactions of muon neutrinos have been neglected. Similarly to NC interactions, they are described by the complex parameter $\epsilon^{CC}_{\mu\tau}$, on which limits of the order of 10^{-2}, more stringent of those obtainable from OPERA, can be derived from CHORUS and NOMAD results [9, 10].

In figure 4 the 90% allowed region is shown in the parameter space $Im(\epsilon_{\mu\tau})$ vs $Re(\epsilon_{\mu\tau})$. The results are consistent with the absence of NSI interactions ($Re(\epsilon_{\mu\tau}) = Im(\epsilon_{\mu\tau}) = 0$).

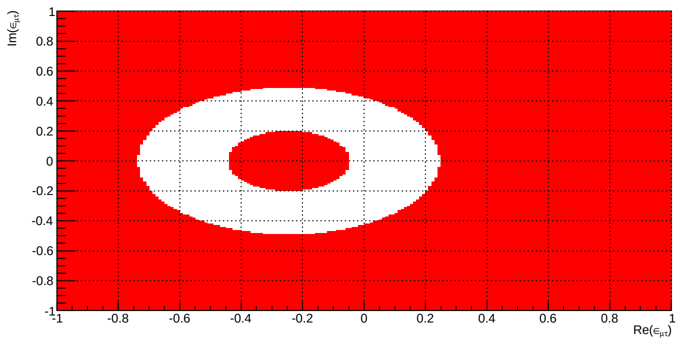

Figure 4: 90% CL allowed region (white) in the $Im(\epsilon_{\mu\tau})$, $Re(\epsilon_{\mu\tau})$ parameter space.

3.2 Analysis of the OPERA emulsion detectors at the LNF scanning station

The LNF scanning station [13] 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 climatized 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.

The OPERA brick is based on the Emulsion Cloud Chamber (ECC) detector concept, fulfilling the requirements of high granularity and micro-metric resolution necessary to distinguish the τ decay vertex from the primary ν_τ 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. [11]. 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 [12]. 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 specialized shifters.

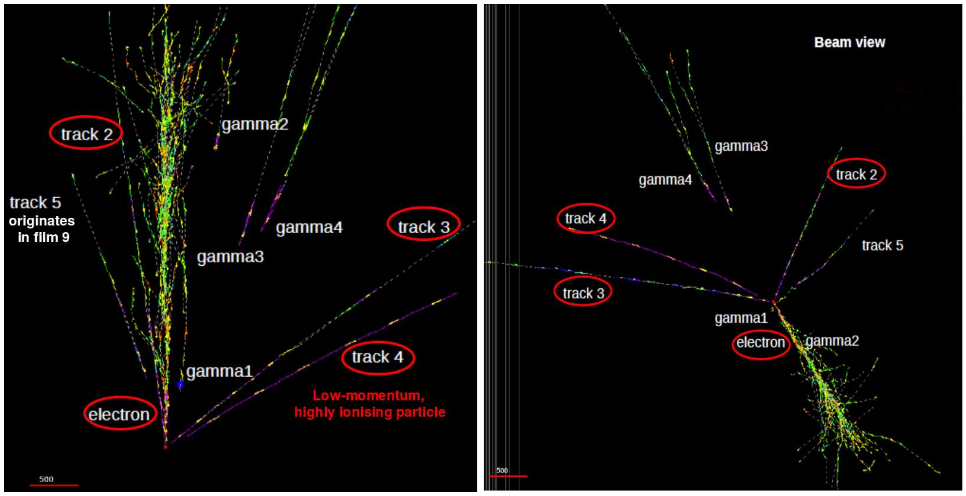

Figure 5: A ν_e interaction detected in the LNF scanning laboratory in 2015.

The 2015 activity of the LNF scanning station was addressed to the completion of the assigned data sample, in order to fit with the dismounting operations and the brick removal from the OPERA target. In total about 37 events have been treated at the LNF scanning station during the last year, with an overall location efficiency of $\sim 68\%$, well compatible with expectations. The activity of this year required a particular effort to complete the analysis of all the assigned bricks including the most difficult cases. These include those neutrino interactions with a lack of "predictions" to trigger the scanning due to an anomalous noise level on the CS doublet. LNF contributed to the systematic search of ν_e interactions with a dedicated analysis of an event sub-sample, selected by the presence of a shower-like topology in the related CS films. The emulsion reconstruction of a particularly beautiful ν_e charged current event located by the LNF facility is shown in Fig. 5. The electron at the primary vertex develops a large electromagnetic shower extending through the complete ECC ($\sim 10\ X_0$). Two γ from a π^0 converting to e^+e^- pairs inside the ECC are also visible. 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. Besides the scanning activity we are also deeply involved in the development of the simulation and the global analysis of the emulsion data.

4 List of Conference Talks by LNF Authors in Year 2015

1. A. Paoloni, "Latest results from the OPERA experiment", XVI International Workshop on Neutrino Telescopes, Venezia, Italia, 2-6 Marzo 2015.

2. F. Pupilli "Update on OPERA results", IX International Conference on Interconnections between Particle Physics and Cosmology (PPC 2015), Deadwood, South Dakota, USA, 29 June - 3 July 2015.

5 Publications

1. N. Agafonova *et al.* [OPERA Collaboration], "Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam", JHEP06 (2015) 069.

2. N. Agafonova *et al.* [OPERA Collaboration], "Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment", Phys. Rev. Letters 115 (2015) 121802.

3. A. Longhin, A. Paoloni, F. Pupilli, Large-Angle Scattering of Multi-GeV Muons on Thin Lead Targets, IEEE Transactions on Nuclear Science, vol. 62, NO.5, OCTOBER 2015 2216-2225.

4. A. Paoloni on behalf of the OPERA collaboration, "Results from the OPERA experiment", PoS NEUTEL2015 (2015) 010.

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`http://www.lnf.infn.it/esperimenti/opera/scanning/figs/animation_54105.gif`