IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11120-2

Colloquia: LaThuile11

Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in the OPERA experiment

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(ricevuto il 29 Settembre 2011; pubblicato online il 19 Gennaio 2012)

Summary. — The OPERA experiment in the underground Gran Sasso Laboratory (LNGS) has been designed to perform the first detection of neutrino oscillations in direct appearance mode in the muon neutrino to tau neutrino channel. The detector is hybrid, being made of an emulsion/lead target and of electronic detectors. It is placed in the CNGS neutrino beam 730 km away from the neutrino source. Runs with CNGS neutrinos were successfully carried out in 2008, 2009, and 2010. After a brief description of the beam and the experimental setup, we report on event analysis of a sample of events corresponding to 1.89×10^{19} p.o.t. in the CERN CNGS ν_μ beam that yielded the observation of a first candidate ν_τ CC interaction. The topology and kinematics of this candidate event are described in detail. The background sources are explained and the significance of the candidate is assessed.

PACS `13.15.+g` – Neutrino interactions.
PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `29.40.Gx` – Tracking and position-sensitive detectors.
PACS `29.40.Rg` – Nuclear emulsions.

1. – Introduction

Two types of experimental methods can be used to detect neutrino oscillations: observing the appearance of a neutrino flavour initially absent in the beam or measuring the disappearance rate of the initial flavour. In the latter case, one must know the flux of the beam precisely. In this type of experiment one explores whether less than the expected number of neutrinos of a produced flavour arrives at a detector or whether the spectral shape changes if observed at various distances from a source. Since the final state is not observed, disappearance experiments cannot tell into which flavor a neutrino has oscillated. An appearance experiment searches for possible new flavours of neutrino, which does not exist in the original beam, or for an enhancement of an existing neutrino

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flavour. The identification of the flavour relies on the detection of the corresponding lepton produced in its charged current (CC) interactions: $\nu_l N \rightarrow l^- X$ with $l = e$, μ, τ and where X denotes the hadronic final state.

In the past two decades, several experiments carried out with atmospheric and accelerator neutrinos, as well as with solar and reactor neutrinos, have established the picture of a three-neutrino oscillation scenario with two large mixing angles. Atmospheric sector flavor conversion was first established by the Super-Kamiokande [1] and MACRO [2] experiments and then confirmed by the K2K [3] and MINOS [4] longbaseline experiments. The CHOOZ [5] and Palo Verde [6] reactor experiments excluded indirectly the $\nu_\mu \rightarrow \nu_e$ channel as the dominant process in the atmospheric sector. However, the direct observation of flavour transition through the detection of the corresponding lepton has never been observed. Appearance of ν_τ will prove unambiguously that $\nu_\mu \rightarrow \nu_\tau$ oscillation is the dominant transition channel at the atmospheric scale.

The OPERA experiment [7] has been designed to directly observe the appearance of ν_τ in a pure ν_μ beam on an event by event basis. The ν_τ signature is given by the decay topology and kinematics of the short lived τ^- leptons produced in the interaction of $\nu_\tau N \rightarrow \tau^- X$ and decaying to one prong (μ, e or *hadron*) or three prongs, which are [8]:

$$\begin{aligned}
&\tau^- \rightarrow \mu^- \nu_\mu \bar{\nu}_\tau && \text{with} && BR = 17.36 \pm 0.05\%,\\
&\tau^- \rightarrow e^- \nu_e \bar{\nu}_\tau && \text{with} && BR = 17.85 \pm 0.05\%,\\
&\tau^- \rightarrow h^- (n\pi^0) \bar{\nu}_\tau && \text{with} && BR = 49.52 \pm 0.07\%,\\
&\tau^- \rightarrow 2h^- h^+ (n\pi^0) \bar{\nu}_\tau && \text{with} && BR = 15.19 \pm 0.08\%.
\end{aligned}$$

2. – The neutrino beam

The CNGS ν_μ beam produced by the CERN-SPS is directed towards the OPERA detector, located in the Gran Sasso underground laboratory (LNGS) [9] in Italy, 730 km away from the neutrino source at CERN. In order to study $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode as indicated in the atmospheric neutrino sector, the CERN Neutrinos to GranSasso (CNGS) neutrino beam [10] was designed and optimized by maximizing the number of ν_τ CC interactions at the LNGS.

The average ν_μ beam energy is 17 GeV, well above tau production energy treshold. The $\bar{\nu}_\mu$ contamination is $\sim 4\%$ in flux, 2.1% in terms of interactions. The ν_e and $\bar{\nu}_e$ contaminations are lower than 1%, while the number of prompt ν_τ from D_s decay is negligible. The average L/E_ν ratio is 43 km/GeV, suitable for oscillation studies at atmospheric Δm^2. Due to the Earth's curvature neutrinos from CERN enter the LNGS halls with an angle of about 3° with respect to the horizontal plane.

With a nominal CNGS beam intensity of 4.5×10^{19} protons on target (p.o.t.) per year, and assuming $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\text{eV}^2$ and full mixing, about 10 ν_τ 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 goal is to accumulate a statistics of neutrino interactions correspomding to 22.5×10^{19} p.o.t. in 5 years. The 2008, 2009 and 2010 runs achieved a total intensity of 1.78×10^{19}, 3.52×10^{19} and 4.04×10^{19} p.o.t. respectively. Within these three years, neutrinos produced 9637 beam events. The processing of these events, particularly the scanning of emulsion films, is continuously going on. The 2011 run started on May 2011 and is still in progress.

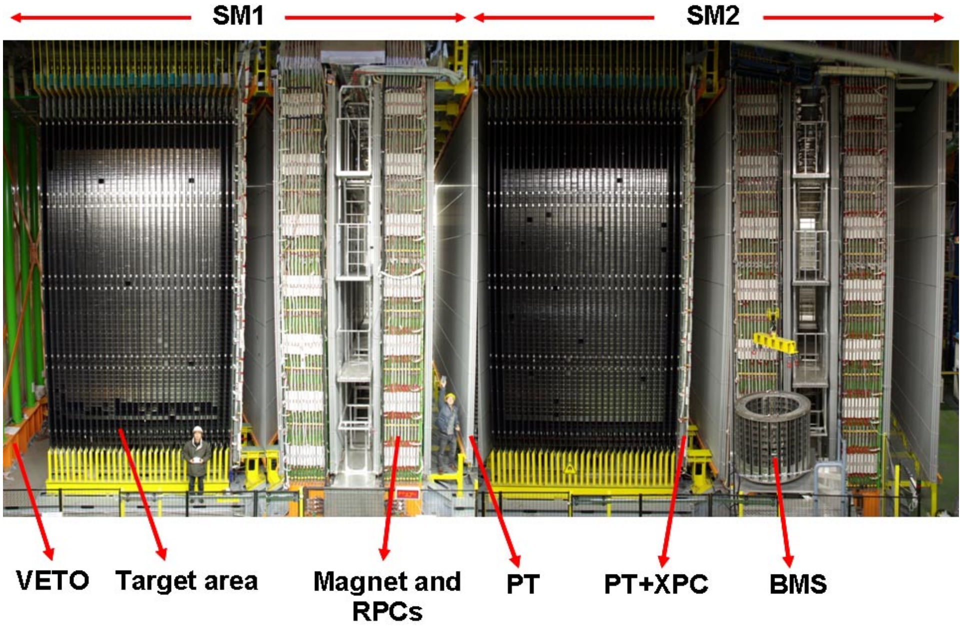

Fig. 1. – View of the OPERA detector; the neutrino beam enters from the left. Arrows show the position of detector components, the VETO planes, the target and TT, the drift tubes (PT) laid out along the XPC, the magnets and the RPC installed between the magnet iron slabs. The Brick Manipulator System (BMS) is partly shown.

At the CNGS energies the average τ^- decay length is submillimetric, so OPERA uses nuclear emulsion films as high precision tracking device in order to be able to detect such short decays. Emulsion films are interspaced with 1 mm thick lead plates, which act as neutrino target and form the largest part of the detector mass. This technique is called Emulsion Cloud Chamber (ECC). It was successfully used to establish the first evidence for charm in cosmic rays interactions [11] and in the DONUT experiment [12] for the first direct observation of the ν_τ. To date, nine ν_τ CC interactions have been observed by DONUT produced by a fixed target 800 GeV proton beam configuration.

3. – The OPERA detector

OPERA is a hybrid detector made of two identical Super Modules (SM1 and SM2), each one formed by a target section and a muon spectrometer as shown in fig. 1. Each target section is organized in 31 vertical "*walls*", transverse to the beam direction. Walls are filled with "*ECC bricks*" with an overall mass of 1.25 kton. They are followed by double layers of scintillator planes acting as Target Trackers (TT) that are used to locate neutrino interactions occurred within the target. A target brick consists of 56 lead plates of 1 mm thickness interleaved with 57 emulsion films. The lead plates serve as neutrino interaction target and the emulsion films as 3-dimensional tracking detectors providing track coordinates with a sub-micron accuracy and track angles with a few mrad accuracy. The material of a brick along the beam direction corresponds to about 10 radiation length and 0.33 interaction length. The brick size is 10 cm × 12.5 cm × 8 cm and its weight is about 8.3 kg.

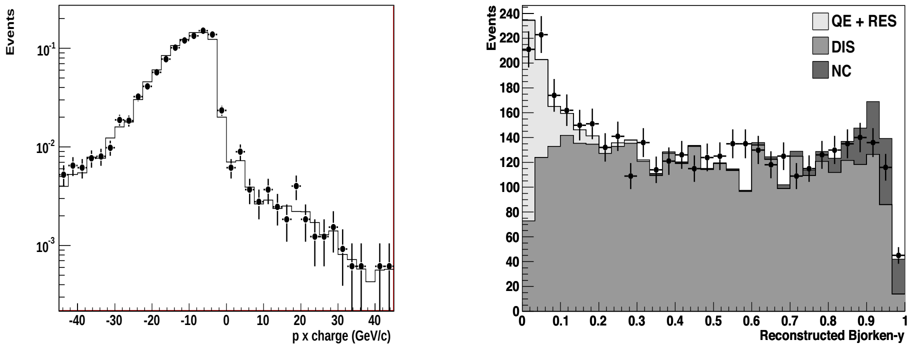

Fig. 2. – Right: Muon charge comparison (momentum×charge): data (black dots with error bars) and MC (solid line) are normalised to one. Left: Bjorken-y variable reconstructed in data (dots with error bars) and MC (shaded areas). The MC distributions are normalised to data. The different contributions of the MC are shown in different colours: QE + RES contribution in light grey, DIS contribution in grey and the NC contamination in dark grey.

In order to reduce the emulsion scanning load, Changeable Sheets (CS) [13] film interfaces have been used. They consist in tightly packed doublets of emulsion films glued to the downstream face of each brick. Charged particles from a neutrino interaction in a brick cross the CS and produce signals in the TT that allow the corresponding brick to be identified and extracted by an automated Brick Manipulator System (BMS).

The spectrometers consist of a dipolar magnet instrumented with active detectors, planes of RPCs (Internal Tracker, IT) and drift tubes (Precision Tracker, PT). Tasks of the spectrometers are muon identification and charge measurement in order to minimize the background. For muon momenta between $2.5\,\mathrm{GeV}/c$ and $45\,\mathrm{GeV}/c$, the fraction of events with wrong charge determination is 1.2%. The μ^+ to μ^- events ratio, within the selected momentum range, obtained from data can be directly compared with predictions based on Monte Carlo simulations: $3.92 \pm 0.37(\mathrm{stat.})\%$ for data, $3.63 \pm 0.13(\mathrm{stat.})\%$ for MC. Figure 2 left-side shows the momentum and momentum times charge distribution for data and MC.

In fig. 2 right side, Bjorken-y distribution is shown for the events with at least a muon track. The agreement between data and MC simulation is reasonable. The sum of the QE and RES processes can be clearly seen as a peak at low y values. The NC contribution shows up at values of Bjorken-y close to one. The NC contribution becomes negligible when a track with its momentum measured by the spectrometer is required.

A detailed description of the complete detector can be found in [7]. Event reconstruction procedures and a performances of the OPERA electronic detectors can be found in more detail in [14].

4. – Neutrino interaction location

Neutrino event analysis starts with the pattern recognition in the electronic detectors. Charged particle tracks produced in a neutrino interaction generate signals in the TT and in the muon spectrometer. A brick finding algorithm is applied in order to select the brick which has the maximum probability to contain the neutrino interaction. The brick with the highest probability is extracted from the detector for analysis. The efficiency of this procedure reaches 83% in a subsample where up to 4 bricks per event were processed.

After extraction of the brick predicted by the electronic detectors, its validation comes from the analysis of the CS films. The measurement of emulsion films is performed through high-speed automated microscopes [15, 16] with a sub-micrometric position resolution and angular resolution of the order of one milliradian. If no expected charged track related to the event is found in the CS, the brick is returned back to the detector with another CS doublet attached. If any track originating from the interaction is detected in the CS, the brick is exposed to cosmic rays (for alignment purposes) and then depacked. The emulsion films are developed and sent to the scanning laboratories of the Collaboration for event location studies and decay search analysis.

All the track information of the CS is then used for a precise prediction of the tracks in the most downstream films of the brick (with an accuracy of about 100 μm). When found in this films, tracks are followed upstream from film to film. The scan-back procedure is stopped when no track candidate is found in three consecutive films and the lead plate just upstream the last detected track segment is defined as the vertex plate. In order to study the located vertices and reconstruct the events, a general scanning volume is defined with a transverse area of $1 \times 1\,\mathrm{cm}^2$ for 5 films upstream and 10 films downstream of the stopping point. All track segments in this volume are collected and analysed. After rejection of the passing through tracks related to cosmic rays and of the tracks due to low energy particles, the tracks produced by the neutrino interaction can be selected and reconstructed.

The present overall location efficiency averaged over NC and CC events, from the electronic detector predictions down to the vertex confirmation, is about 60%.

5. – Decay search

Once the neutrino interaction is located, a decay search procedure is applied to detect possible decay or interaction topologies on tracks attached to the primary vertex. The main signature of a secondary vertex (decay or nuclear inetaraction) is the observation of a track with a significant impact parameter (IP) relative to the neutrino interaction vertex. The IP of primary tracks is smaller than 10 μm after excluding tracks produced by low momentum particles. When secondary vertices are found in the event, a kinematical analysis is performed, using particle angles and momenta measured in the emulsion films. For charged particles up to about 6 GeV/c, momenta can be determined using the angular deviations produced by Multiple Coulomb Scattering (MCS) of tracks in the lead plates [17] with a resolution better than 22%. For higher momentum particles, the measurement is based on the position deviations. The resolution is better than 33% on 1/p up to 12 GeV/c for particles passing through an entire brick.

A γ-ray search is performed in the whole scanned volume by checking all tracks having an IP with respect to the primary or secondary vertices lower than 800 μm. The angular acceptance is ±500 mrad. The γ-ray energy is estimated by a Neural Network algorithm that uses the number of segments, the shape of the electromagnetic shower and also the MCS of the leading tracks.

6. – Data analysis

In the following, the analysis results [18] of about 35% of the 2008 and 2009 data sample, corresponding to the 1.89×10^{19} p.o.t are presented. The decay search procedure was applied to a sample of 1088 events of which 901 were classified as CC interactions.

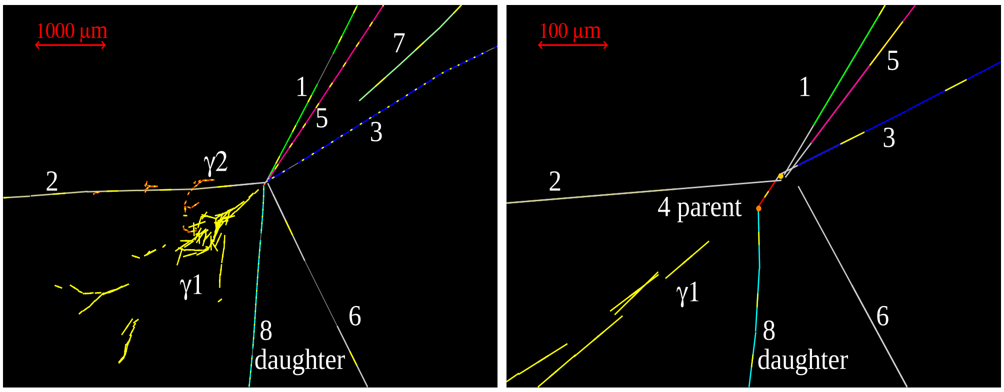

Fig. 3. – Display of the ν_τ candidate event. Left: view transverse to the neutrino direction. Right: same view zoomed on the vertices.The short track named "4 parent" is the τ^- candidate.

In the sample of CC interactions, 20 charm decay candidates were observed, in good agreement with the expectations from the Monte Carlo simulation, 16 ± 2.9. Out of them 3 have a 1-prong topology where 0.8 ± 0.2 was expected. The background for the total charm sample is about 2 events. Several ν_e-induced events have also been observed.

Moreover, a first CC ν_τ candidate has been detected. The expected number of ν_τ events detected in the analysed sample is about $0.54 \pm 0.13(\text{syst.})$ at $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\text{eV}^2$ and full mixing.

7. – The first tau neutrino candidate

In this section, the first tau neutrino candidate [18] will be described. The location and decay search procedure yielded a neutrino interaction vertex with 7 tracks. One track exhibits a visible kink with an angular change of $41 \pm 2\,\text{mrad}$ after a path length of $1335 \pm 35\,\mu\text{m}$. The kink daughter momentum is estimated to be $12^{+6}_{-3}\,\text{GeV}/c$ by MCS measurement and its transverse momentum to the parent direction is $470^{+230}_{-120}\,\text{MeV}/c$. The event is displayed in figs. 3 and 4.

All the tracks from the neutrino interaction vertex were followed until they stop or interact. The probability that one of them is left by a muon is estimated to be less than 10^{-3}. The residual probability for being a ν_μ CC event, with a possibly undetected large angle μ track, is about 1%; a nominal value of 5% is assumed. None of the tracks is compatible with being an electron.

Two electromagnetic showers caused by γ-rays, associated with the event, have been located and studied. The energy of $\gamma 1$ is $(5.6 \pm 1.0(\text{stat.}) \pm 1.7(\text{syst.}))$ GeV and it is clearly pointing to the decay vertex. The $\gamma 2$ has an energy of $1.2 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV and it is compatible with pointing to either vertex, with a significantly larger probability to the decay vertex.

All the selection cuts used in the analysis were those described in detail in the experiment proposal [19] and its addendum [20]. All the kinematical variables of the event and the cut applied are given in table I.

The invariant mass of the two observed γ-rays is $120 \pm 20(\text{stat.}) \pm 35(\text{syst.})$ supporting the hypothesis that they are emitted in a π^0 decay. The invariant mass of the charged decay daughter assumed to be a π^- and of the two γ-rays amount to

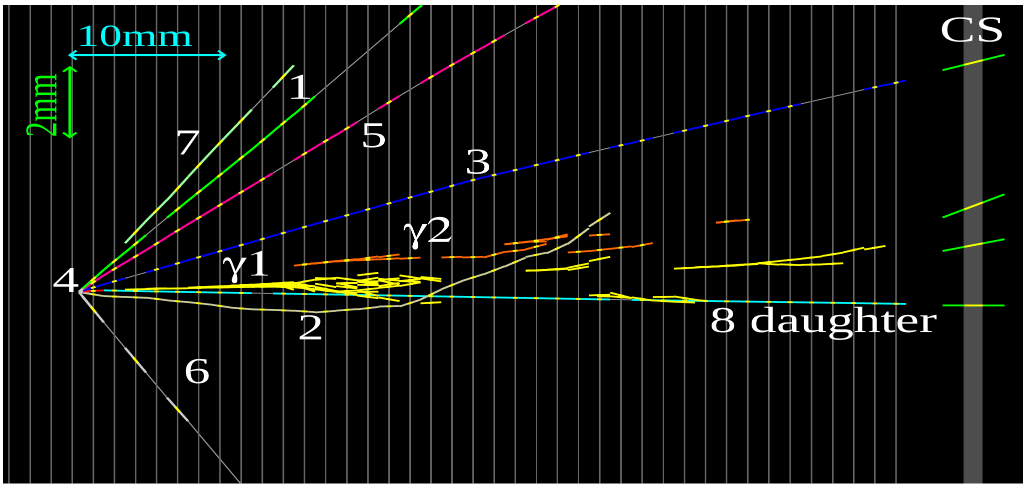

Fig. 4. – Longitudinal view of the ν_τ candidate event.

640^{+125}_{-80}(stat.)$^{+100}_{-90}$(syst.) MeV/c, which is compatible with the $\rho(770)$ mass. So the decay mode of the candidate is consistent with the hypothesis $\tau^- \to \rho^- \nu_\tau$ (where the branching ratio is about 25%).

8. – Background estimation

The two main sources of background to the $\tau^- \to h(n\pi^0)\nu_\tau$ channel where a similar final state may be produced are:

- the decays of charmed particles produced in ν_μ CC interactions where the primary muon is not identified as well as the $c\bar{c}$ pair production in ν_μ NC interactions where one charm particle is not identified and the other decays to a 1-prong hadron channel;
- the 1-prong inelastic interactions of primary hadrons produced in ν_μ CC interactions where the primary muon is not identified or in ν_μ NC interactions and in which no nuclear fragment can be associated with the secondary interaction.

TABLE I. – *Kinematical variables of ν_τ candidate event.*

Variable	Measured	Selection criteria
Kink angle (mrad)	42 ± 2	> 20
Decay length (μm)	1335 ± 35	Within 2 plates
P daughter (GeV/c)	12^{+6}_{-3}	> 2
PT daughter (MeV/c)	470^{+230}_{-120}	> 300 (γ attached)
Missing PT (MeV/c)	570^{+320}_{-170}	< 1000
Angle ϕ (deg)	173 ± 2	> 90

The Monte Carlo expectation of the first background source is 0.007 ± 0.004(syst.) event, the fraction produced in ν_e CC interactions is less than 10^{-3} events, The second type of background amounts to 0.011 ± 0.006(syst.) event. The total background in the decay channel to a single charged hadron is 0.018 ± 0.007(syst.) events. The probability that this background events fluctuate to one event is 1.8% (2.36σ). As the search for τ^- decays is extended to all four channels, the total background then becomes 0.045 ± 0.023(syst.). The probability that this expected background to all searched decay channels of the τ^- fluctuates to one event is 4.5% (2.01σ). At $\Delta m^2 = 2.5 \times 10^{-3}\,\text{eV}^2$ and full mixing, the expected number of observed τ^- events with the present analyzed statistics is 0.54 ± 0.13(syst.) of which 0.16 ± 0.04(syst.) in the one-prong hadron topology, compatible with the observation of one event.

9. – Conclusions

During 2008, 2009 and 2010 runs, a total intensity of 1.78×10^{19}, 3.52×10^{19} and 4.04×10^{19} p.o.t. respectively, was achieved. Within these three years, 9637 beam events have been collected within the OPERA target. The neutrino interaction location and decay search are going on.

A first candidate ν_τ CC interaction in the OPERA detector at LNGS was detected after analysis of a sample of events corresponding to 1.89×10^{19} p.o.t. in the CERN CNGS ν_μ beam. The expected number of ν_τ events in the analysed sample is 0.54 ± 0.13(syst.). The candidate event passes all selection criteria, it is assumed to be a τ^- lepton decaying into $h^-(n\pi^0)\nu_\tau$. The observation of one possible tau candidate in the decay channel $h^-(\pi^0)\nu_\tau$ has a significance of 2.36σ of not being a background fluctuation.

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