OPERA experimental results

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Abstract. The aim of the OPERA experiment is to search for the appearance of the tau neutrino in the quasi pure muon neutrino beam produced at CERN (CNGS). The detector, installed in the Gran Sasso underground laboratory 730 km away from CERN, consists of a lead/emulsion target complemented with electronic detectors. 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 \(1.89 \times 10^{19}\) p.o.t in the CERN CNGS \(\nu_\mu\) beam that yielded the observation of a first candidate \(\nu_\tau\) 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.

1. Introduction

In the last decades solar and atmospheric neutrino experiments observed deficits in the measured fluxes which are all well reproduced in a neutrino oscillations model, implying non vanishing, not degenerate neutrino masses and neutrino mixing. Within such hypothesis weak interactions eigenstates differ from the mass eigenstates. The mixing can be parametrized in an unitary matrix whose parameters (3 angles and 1 or 3 phases depending on the Dirac or Majorana nature of neutrinos) associated to the square masses differences \(\Delta m^2\) drive the amplitude of the disappearance \(P(\nu_\alpha \rightarrow \nu_\beta)\) or survival \(P(\nu_\alpha \rightarrow \nu_\alpha)\) probabilities.

The major experimental results for solar [1, 7], atmospheric [4, 9], reactor [10, 11] or accelerator [12, 13] neutrinos were obtained by observing the disappearance of neutrinos w.r.t. to a close position measurement or a predicted flux.

OPERA [14] has been designed to perform a unique appearance observation of the oscillation products to confirm (or infirm) the neutrino oscillation hypothesis in the atmospheric sector through the \(\nu_\mu \rightarrow \nu_\tau\) channel and also to set limits on the \(\theta_{13}\) angle through the \(\nu_\mu \rightarrow \nu_e\) channel.

2. The OPERA experiment

2.1. The CNGS beam

The CNGS [15] programme of neutrino beam from CERN to Gran Sasso has been approved in 1999. The beam has been optimized to maximize the number of \(\tau\) events in the detector (convolution of the neutrino flux, the appearance probability and the detection efficiency). The neutrino average energy is 17 GeV. Measured in the number of interactions in the detector, the \(\nu_\mu\) contamination is \(\sim 2\%\), the \(\nu_e(\bar{\nu}_e)\) is \(<1\%\) and the number of prompt \(\nu_\tau\) is negligible.

\(^1\) On behalf of the OPERA Collaboration
The beam configuration starts from the SPS protons directed to the target chamber where mainly pions and kaons are produced, which decay then into a 1 km long decay tunnel followed by hadron stops and muon detectors. From CERN to Gran Sasso the escaping neutrinos travel for 2.44 ms and their mean direction w.r.t. the horizontal in Gran Sasso forms a $3^\circ$ angle due to the earth curvature. There are two fast extractions separated by 50 ms in each CNGS cycle (6 s long). These cycles are repeated 3 or 4 times during each SPS supercycle. The goal is to accumulate a statistics of neutrino interactions corresponding to $22.5 \times 10^{19}$ p.o.t. in 5 years. The 2008, 2009 and 2010 runs achieved a total intensity of $1.78 \times 10^{19}$, $3.52 \times 10^{19}$ and $4.04 \times 10^{19}$ 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.

2.2. The detector technique
The challenge of the experiment is to measure the appearance of $\nu_\tau$ from $\nu_\mu$ oscillations through CC $\tau$ interactions. The events induced by the shortlived $\tau$ have a characteristic topology (with a kink due to the presence of undetected neutrinos in the $\tau$ decay) but extends over $\sim$ mm$^3$ typical volumes. The detector should therefore match a large mass for statistics, a high spatial resolution and high rejection power to limit background contamination. These requirements are satisfied using the proven ECC (Emulsion Cloud Chamber) technique which already worked successfully in the DONUT experiment [16].

The passive target consists of lead plates. Particles are tracked in nuclear emulsions films with a sub-micrometric intrinsic resolution. 57 emulsions films are assembled and interspaced with 56 lead plates 1 mm wide in a detector basic cell called brick. An additional doublet of emulsion film (Changeable Sheets, CS) is attached on the downstream face of each brick to guide the tracks predictions inside the brick itself. A brick is a $12.7 \times 10.2$ cm$^2$ object with a thickness along the beam direction of 7.5 cm (about 10 radiation lengths). Bricks are assembled in 31 walls ($52 \times 64$ bricks) separated by electronic detectors planes to trigger the event and identify the brick with the interaction vertex.

The total OPERA target contains 150000 bricks with a total mass of 1.25 ktons. The ECC bricks were assembled underground at an average rate of 700 per day by a dedicated fully automated Brick Assembly Machine (BAM); the OPERA target was filled using two automated manipulator systems (BMS). The passage of a m.i.p. in an emulsion film results, after development, in a set of aligned grains, 35 grains/100 $\mu$m.

2.3. The OPERA electronic detectors
OPERA is a hybrid detector made of two identical Super Modules (SM1 and SM2) consisting of a target section followed by a muon spectrometer (see Figure 1). The target section is made of the already mentioned 31 brick walls each one being followed by a highly segmented scintillator tracker plane. A large VETO plane is placed in front of the detector to further discriminate beam events from horizontal cosmics and beam neutrino interactions in the rock. The construction of the experiment started in Spring 2003.

The target tracker covers a total area of 7000 m$^2$ and is built of 32000 scintillator strips, each 7 m long and of 25 mm $\times$ 15 mm cross section. The muon spectrometer consists of a large $8 \times 8$ m$^2$ dipolar magnet delivering a magnetic field of 1.55 T and instrumented with RPCs and drift tubes. Each magnet arm consists of twelve 5 cm thick iron slabs, alternating with RPC planes. This sandwich structure allows the tracking in the magnetic field to identify the muons and to determine their momentum and sign. In addition the precision tracker measures the muon track coordinates in the horizontal plane. It is made of 8 m long drift tubes with an outer diameter of 38 mm. The charge misidentification is expected to be 0.1% - 0.3% in the relevant momentum range which is efficient enough to minimize the background originating from
Figure 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.

the charmed particles produced in $\nu_\mu$ interactions. With the muon spectrometer a momentum resolution of $\Delta p/p < 0.25$ for all muon momenta $p$ up to a maximum of $p = 25$ GeV/c can be achieved.

3. 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 [17, 18] 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 1×1 cm² 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%.

4. 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 interaction) 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 [19] 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.

5. Data analysis
In the following, the analysis results [20] of about 35% of the 2008 and 2009 data sample, corresponding to the 1.89×10¹⁹ 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. 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 νₑ-induced events have also been observed.

Moreover, a first CC ντ candidate has been detected. The expected number of ντ events detected in the analysed sample is about 0.54±0.13(syst.) at ∆m² = 2.5 × 10⁻³ eV² and full mixing.

6. The first tau neutrino candidate
In this section, the first tau neutrino candidate [20] 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 ± 2 mrad after a path length of 1335 ± 35 µm. The kink daughter momentum is estimated to be 12⁺6⁻³ GeV/c by MCS measurement and its transverse momentum to the parent direction is 470⁺230⁻120 MeV/c. The event is displayed in Figures 2 and 3.
Figure 2. Display of the $\nu_\tau$ candidate event. Left: view transverse to the neutrino direction. Right: same view zoomed on the vertices. The short track named $4$ parent is the $\tau^-$ candidate.

Figure 3. Longitudinal view of the $\nu_\tau$ candidate.

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 $\nu_\mu$ CC event, with a possibly undetected large angle $\mu$ 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 $\gamma$-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 [21] and its addendum [22]. All the kinematical variables of the event and the cut applied are given in Table 1.
Table 1. Kinematical variables of \( \nu_\tau \) candidate event.

| Variable                  | Measured     | Selection criteria |
|---------------------------|--------------|--------------------|
| Kink angle (mrad)         | 42+2         | > 20               |
| Decay length (\( \mu \)m) | 1335+35      | Within 2 plates    |
| \( P_{\text{daughter}} \) (GeV/c) | 12+6−3   | > 2                |
| \( P_t \) daughter (MeV/c) | 470+230−120 | > 300 (\( \gamma \) attached) |
| Missing \( P_t \) (MeV/c)  | 12+320−170  | < 1000             |
| Angle \( \phi \) (deg)   | 1335±35      | > 90               |

The invariant mass of the two observed \( \gamma \)-rays is \( 120\pm20(\text{stat.})\pm35(\text{syst.}) \) MeV/c, supporting the hypothesis that they are emitted in a \( \pi^0 \) decay. The invariant mass of the charged decay daughter assumed to be a \( \pi^- \) and of the two \( \gamma \)-rays amount to \( 640^{+125}_{-80}(\text{stat.})^{+100}_{-90}(\text{syst.}) \) MeV/c, which is compatible with the \( p(770) \) 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%).

7. Background estimation

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

- the decays of charmed particles produced in \( \nu_\mu \) CC interactions where the primary muon is not identified as well as the \( c\bar{c} \) pair production in \( \nu_\mu \) 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 \( \nu_\mu \) CC interactions where the primary muon is not identified or in \( \nu_\mu \) NC interactions and in which no nuclear fragment can be associated with the secondary interaction.

The Monte Carlo expectation of the first background source is \( 0.007\pm0.004(\text{syst.}) \) event, the fraction produced in \( \nu_\tau \) CC interactions is less than \( 10^{-3} \) events. The second type of background amounts to \( 0.011\pm0.006(\text{syst.}) \) event. The total background in the decay channel to a single charged hadron is \( 0.018\pm0.007(\text{syst.}) \) events. The probability that this background events fluctuate to one event is \( 1.8\% \) (2.36 \( \sigma \)). As the search for \( \tau^- \) decays is extended to all four channels, the total background then becomes \( 0.045\pm0.023(\text{syst.}) \).

The probability that this expected background to all searched decay channels of the \( \tau^- \) fluctuates to one event is 4.5\% (2.01 \( \sigma \)). At \( \Delta m^2 = 2.5 \times 10^{-3} eV^2 \) and full mixing, the expected number of observed \( \tau^- \) events with the present analyzed statistics is \( 0.54 \pm 0.13(\text{syst.}) \) of which \( 0.16\pm0.04(\text{syst.}) \) in the one-prong hadron topology, compatible with the observation of one event.

8. Conclusions

During 2008, 2009 and 2010 runs, a total intensity of \( 1.78\times10^{19}, 3.52\times10^{19} \) and \( 4.04\times10^{19} \) 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 \( \nu_\tau \) CC interaction in the OPERA detector at LNGS was detected after analysis of a sample of events corresponding to \( 1.89\times10^{19} \) p.o.t. in the CERN CNGS \( \nu_\mu \) beam. The expected number of \( \nu_\tau \) events in the analysed sample is \( 0.54\pm0.13(\text{syst.}) \).
The candidate event passes all selection criteria, it is assumed to be a $\tau^-$ lepton decaying into $h^-(n\pi^0)\nu_{\tau}$. The observation of one possible tau candidate in the decay channel $h^-(n\pi^0)\nu_{\tau}$ has a significance of 2.36$\sigma$ of not being a background fluctuation.

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