Search for $\nu_\mu \to \nu_\tau$ appearance in OPERA

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Abstract
OPERA is a unique experiment aimed at the first direct observation of the appearance of ν_τ caused by ν_μ to ν_τ oscillation by detecting the decay topology of the τ induced in the ν_τ CC interactions. The CERN ν_μ CNGS beam has an average optimised energy of 17 GeV. The hybrid detector composed of nuclear emulsion films and electronic detectors is located 1400m underground in the LNGS laboratory, 730km away from CERN. The first physics run with a target partly filled started in spring 2008. The experiment is currently in the phase of its second year of data taking and of data analysis.

1. Introduction

In 1962, Maki, Nakagawa and Sakata proposed that oscillation may exist between massive neutrinos of different flavours [1]. In 1998, the Super-Kamiokande experiment established the deficit in atmospheric ν_μ due to their disappearance through the oscillation mechanism [2]. This has been confirmed later by the K2K [3] and then the MINOS [4] accelerator experiments.

The goal of OPERA is to detect $\nu_\mu \to \nu_\tau$ oscillation in the appearance mode in the CERN CNGS beam by detecting the decay topology of the τ induced in the ν_τCC interactions [5].The CERN ν_μ CNGS beam has an average optimised energy of 17 GeV. The hybrid detector composed of nuclear emulsion films and electronic detectors is located 1400m underground in the LNGS laboratory, 730km away from CERN. The first physics run with a target partly filled started in spring 2008. The experiment is currently in the phase of its second year of data taking and of data analysis.

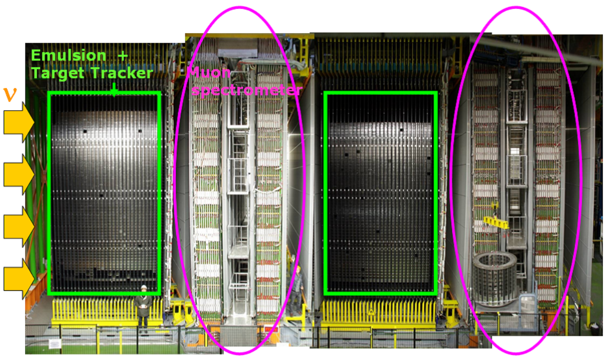

Fig. 1. Side view of the OPERA detector

2. The OPERA detector

The OPERA detector [6] consists of two identical Super-Modules. Each consists of an instrumented target followed by a magnetic muon spectrometer. The targets, for a total mass of 1.25 kton, is composed of 150 000 units called hereafter "bricks" arranged in twice 31 walls. These are interleaved with pairs of planes of orthogonal plastic scintillator strips constituting the Target Tracker (TT) - see Fig.1.). Bricks are fabricated following the so-called Emulsion Cloud Chamber (ECC) technique: 57 nuclear emulsion films and 56 1-mm thick lead plates are stacked alternately (see Fig.2.). This technique is adequate to recognize τ decay topologies as proven by the DONuT experiment [7].

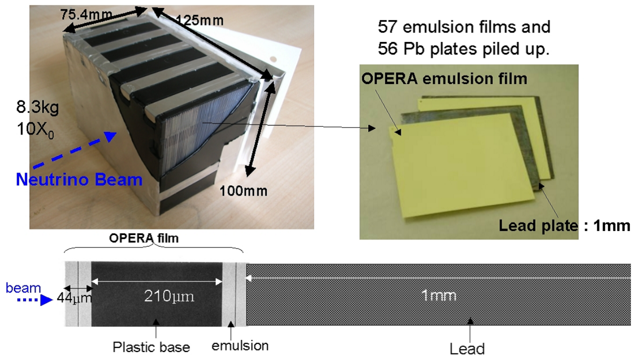

Fig. 2. An ECC brick, OPERA emulsion films and lead plates.

An emulsion film is made of two layers of nuclear emulsion gel 44 mm thick deposited on each side of a 205 mm thick plastic base of 12.5×9.9 cm^2 [8]. A track of a minimum ionizing particle is shown in Fig.3. The position resolution of the emulsion film is 0.3 micron. A brick weighs 8.3 kg and its thickness, 7.5 cm, corresponds to about 10 radiation lengths. With this structure, it is also possible to measure momentum by Multiple Coulomb Scattering [9] and identify electrons and measure their energy by counting the number of track segments in the electromagnetic showers [10].

A pair of emulsion films called the Changeable Sheets (CS) is packed into a thin box glued on the downstream face of each brick[11]. The films can be removed and if necessary replaced without opening the brick. They serve as interface between the TT and the brick.

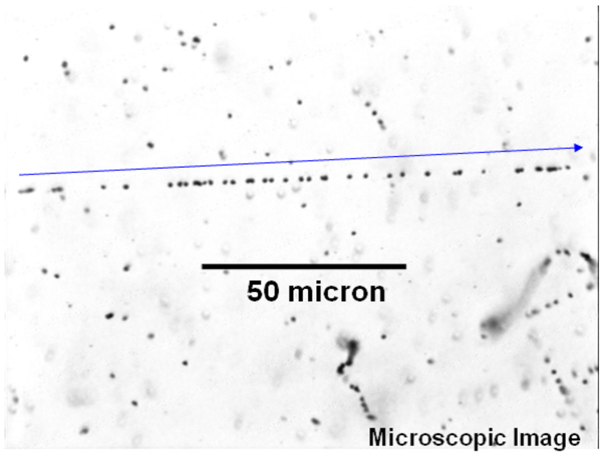

Fig. 3. The microscopic image of a Minimum Ionising Particle (M.I.P.) track in a developed emulsion film.

3. High speed emulsion scanning systems

The scanning area of the OPERA CS measures in cm^2; this is more than 100 times larger than for DONuT, the last experiment having used the ECC technique. Therefore high speed scanning systems were developed in both Japan and Europe. The new Japanese scanning system, the S-UTS (Super Ultra Track Selector, [12]) is shown in Fig.4.-left. Four systems with a scanning speed of 75 cm^2 per hour and one of 20 cm^2 per hour are operational in Japan. The previous generation operated at speeds of about 1 cm^2 per hour[13]; 5 such systems are used for manual verification and subsidiary tasks. The European scanning machine[14], the ESS (European Scanning System) is shown in Fig.4.-right. It operates at a speed of 20 cm^2 per hour. A total of 33 such systems are currently active for OPERA.

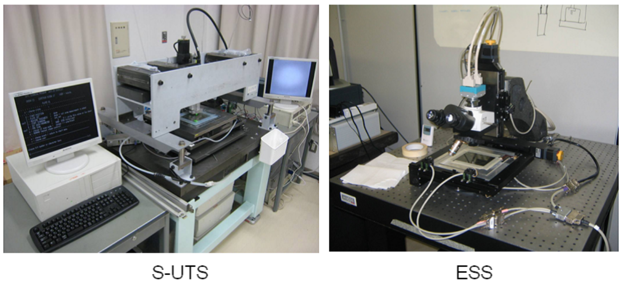

Fig. 4. A photograph of the Japanese(left) and European(right) scanning system.

4. Localisation of the neutrino interaction vertices in the ECC bricks

From the tracks reconstruction in the TT, the brick with the highest probability to contain the interaction vertex is identified and removed from the target by an automaton. The CS is developed underground and scanned at either LNGS and or in Japan. If tracks from the neutrino interaction are found in the CS, the films of the corresponding brick are developed, scanned and analised. The tracks in the CS are extrapolated to the most downstream film of the brick and searched for. They are then followed upstream until they disappear (Fig.5.). A volume scan of about 1 cm^3 around the point of disappearance is performed (Fig.6.). Tracks emerging from a single point are extracted from the data. This localises the position of the vertex inside the brick. In case tracks belonging to the event are not found in the CS, the brick is equipped with a new pair of CS and reinserted into the target. The next most probable brick is then removed and its CS are analised.

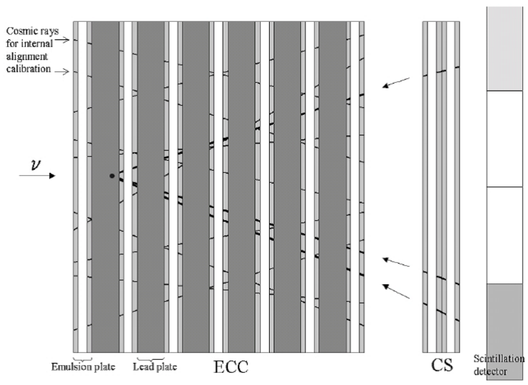

Fig. 5. Event localisation of neutrino interaction vertices.

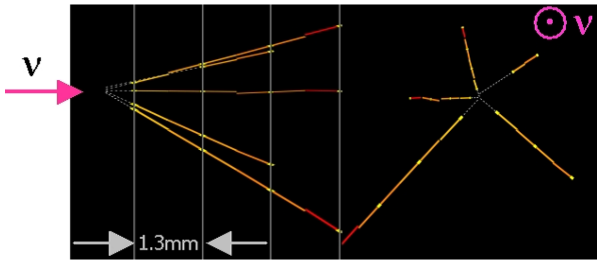

Fig. 6. An example of neutrino interactions reconstructed from the volume scanning data.

5. Separation of the vertices of the neutrino interaction and of the τ decay

The four main decay channels of the τ lepton are given in Table 1. Topologically, they are classified as "kink" "trident" if they have one or three charged daughters. Charm particles have similar lifetime and decay topologies as the τ lepton. Understanding their detection rate is therefore a direct verification of the expected detection efficiency of the τ lepton.

Table 1. Decay modes, topologies and branching ratios of the τ lepton. About 85and neutrals(kink).

decay mode	topology	ratio
$\tau \to \mu$	kink	$\sim$ 17 %
$\tau \to e$	kink	$\sim$ 18 %
$\tau \to h$	kink	$\sim$ 49 %
$\tau \to hhh$	trident	$\sim$ 15 %

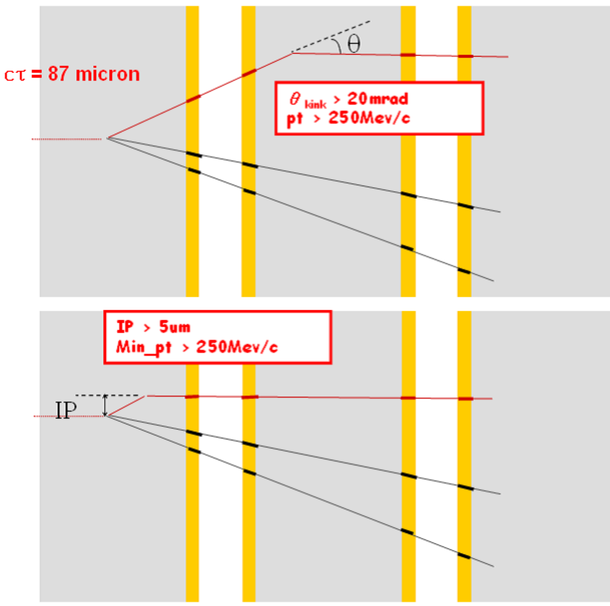

Fig. 7. Detection methods of the tau decay. For 60% of the events(bottom), the decay products are identified by their IP with respect to the primary vertex. For 30% of the events(top), the candidates are identified by the observation of a kink.

Single prong events fall into three categories. For 60% of the events(Fig.7.-bottom) , the decay occurs inside the vertex lead plate and the parent traverses no emulsion layer. The decay products are identified by their large impact parameter (IP) with respect to the primary vertex. For 30% of the events (Fig.7.-top) , the parent traverses at least one film. In this case, the trajectory of both the parent and the decay product may be reconstructed inside at least one plastic base from data registered in the two emulsion layers, the two micro-tracks, to form a base-track. The candidates are identified by the observation of a kink between both trajectories. For 10% of the events, the parent traverses only one emulsion layer and decays in the film base. There is no base track on the parent trajectory but a single micro-track. Whether the presence of this micro-track will is sufficient to identify the candidates by the observation of a kink or will it be identified by the IP method is under study.

The histogram in red in Fig.8. shows the minimum distance between pairs of tracks from neutrino interactions in lead plates computed from the data recorded in the emulsion films immediately downstream of the vertex plate. Only tracks with a momentum larger than 1 GeV/c are considered. The uncertainty of the position of vertices in the lead plates results from Multiple Coulomb Scattering, the angular resolution and the position resolution of the tracks. The blue histogram shows the Monte Carlo simulation of the distribution of the impact parameter (IP) of the decay daughters of τ produced in CC ν_τ interactions. The comparison between the two plots demonstrates that the vertices of the neutrino interaction and of the τ decay are separable. The 1 mm thickness of the lead plates does not affect significantly the τ decay search. This is confirmed by the detection of several charm decay candidates with topologies similar to that of τ decays. An example of such event is shown in Fig.8.

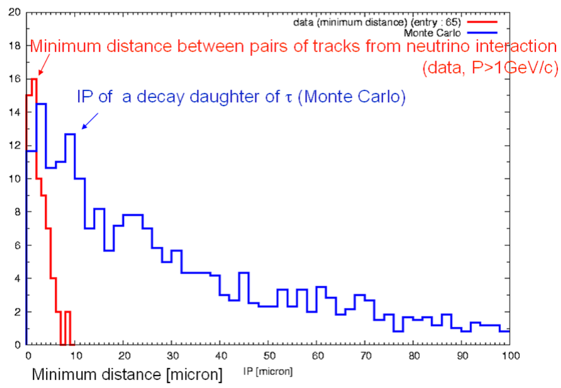

Fig. 8. Experimental data of minimum distance of track pairs from neutrino interactions(red) and the IP of the decay daughters of tau generated by MC(blue).

6. Summary of the run status and future prospects

During the run of 2008 [15], the CNGS provided 1.782×10^{19} protons on target (p.o.t.) and 1690 neutrino events have been registered in the OPERA target. This corresponds to an expectation of 0.7 detected ν_τ CC interactions for $\Delta m^2 = 2.43 \times 10^{-3} eV^2$ and full mixing. Up to now, 797 vertices of neutrino interactions have been localised in the bricks. No τ candidate has been detected yet. However, several charm decay candidates have been observed, in particular charged charm decays into one and three prongs with topologies similar to τ decay topologies. It is verified from the data that the lead plates are thin enough and the spatial resolution of the films is good enough to allow efficiently separating the vertices of the neutrino interaction and the τ decay. For the 2009 run which has started on June 1, we requested 4.5×10^{19} p.o.t. About 2.5 ν_τ CC interactions would then be expected to be detected at the end of this run.

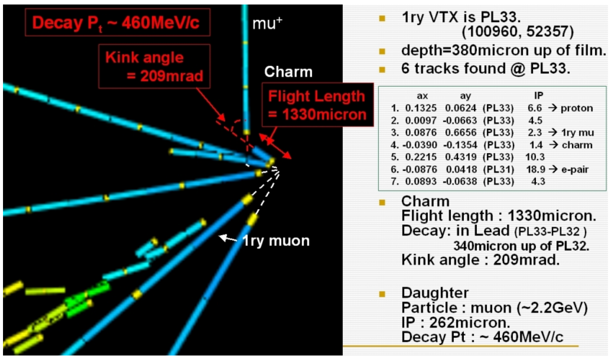

Fig. 9. A charm candidate observed in the 2008 run. Two muons are detected in this event. One is emitted from the neutrino interaction vertex and the other is a daughter of a D^+ decay candidate The flight length of the D^+ candidate is 1330 μm and its kink angle is 209mrad. The momentum of the daughter muon is determined to be 2.2GeV/c by the range measurement. Therefore, the decay P_T is 460MeV/c.

Table 2. Status of the event location for the 2008 run data as of August 2009.

	NC	CC	Total
ECCs received in the labs	218	959	1117
Scanning started	195	895	1090
Vertex located	119	678	797

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