Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations with the OPERA experiment

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The OPERA experiment at the Gran Sasso Laboratory is aimed at searching for tau-neutrino appearance in the pure CERN-CNGS 17 GeV muon-neutrino beam over a 730 km baseline. Tau leptons produced in charged current interactions are identified from their decay topology in nuclear emulsions. After a brief description of the beam and the experimental apparatus, the status of the search is discussed focusing on the topology and kinematics of so far collected candidate events. The background sources are also presented and the statistical significance is assessed.

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1. The OPERA experiment

Neutrino physics, and in particular neutrino oscillations, is one of the most challenging and important topics in particle physics. There is a convincing evidence for neutrino oscillations provided by many experiments which studied solar and atmospheric neutrinos. The neutrino oscillation in the atmospheric sector was first established in disappearance mode by Super-Kamiokande [1] and then confirmed by K2K[2] and MINOS[3]. A missing piece in our current neutrino oscillation scheme is the detection of a ν_τ in a terrestrial (almost) pure ν_μ beam.

The OPERA experiment aims at the direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in the CNGS (CERN Neutrinos to Gran Sasso) neutrino beam produced at CERN. The OPERA detector is located in the Hall C of the underground laboratories at LNGS and it is a hybrid detector made of two identical Super Modules (SM): each SM is composed by a target section (made of a large amount of nuclear emulsions and lead), electronic detectors and a muon spectrometer. The electronic detectors are used to time-tag the event, select the brick in which the interactions took place and identify the muon determining also its momentum and charge; nuclear emulsions are used to study in detail the neutrino interactions and to identify the daughter particles produced.

1.1 The CNGS beam

The CNGS beam [4] is a high energy beam ($\langle E_\mu \rangle \approx 17$ GeV), it was designed and optimized for the appearance study of ν_τ starting from a pure beam of ν_μ. At the CNGS energies the average 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. The contamination (at the detector place) of τ coming from D_s decay is negligible and the contamination due to anti-ν_μ is about 2.0%. Since also the contamination due to ν_e and anti-ν_e is low it is possible to investigate the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation channel.

1.2 The target

The target has an overall mass of about 625 ton per SM and it has a modular structure whose basic cell is made of a sheet of lead (1 mm thick) and a thin nuclear emulsion. Each emulsion film is made of two layers (each with a nominal thickness 44 μm) separated-out by a plastic base (nominal thickness of 200 μm). An OPERA brick is obtained piling up 56 cells and adding an extra emulsion film. Brick transversal dimensions are 12.7 x 10.2 cm^2, while the total thickness is about 7.5 cm (that means 10 X_0): one brick has a weight of 8.3 kg. A set of two emulsion films called Changeable Sheets (CS) is attached externally to the brick. Bricks are assembled into walls.

1.3 The Target Tracker

Scintillators strips located after each brick wall, are used to select the brick in which neutrino interactions took place. Plastic scintillators coupled with Wave Length Shifting (WLS) fibers are chosen to perform this task. Each wall is followed by two planes of electronic trackers (~ 6.7 x 6.7 m^2), each of them contains 256 scintillating strips.

1.4 The Muon Spectrometer

The spectrometers allow determining the momentum and charge of penetrating charged particles identified as muons by measuring their deflection in the 1.55 T magnetic field of a dipolar magnet instrumented with planes of RPC [5]. Three stations of drift tubes placed in front, behind and in between the two magnet walls provide the high precision measurement of the trajectories.

2. Neutrino event analysis

The selection of neutrino events is done discarding the events occurring in the materials surrounding the target; this operation is done by an offline algorithm that also classifies in-target events into events with and without a muon recognized.

The next step is to build a probability map for bricks to contain the selected event and to extract from the target the brick with the highest probability. The CS films are detached from the brick, developed and analyzed with high-speed automatic optical microscopes [6][7] looking for neutrino-related charged tracks compatible with the electronic detectors data. If such tracks are found, the brick is then unpacked and the emulsion films are developed. All the CS tracks are searched for in the downstream films of the brick and, if found, followed back film by film until they disappear because of a primary or a secondary vertex. In order to study the located vertices and reconstruct the events, a volume of about 2 cm^3 surrounding the vertex point is analyzed.

The next phase of the analysis is called decay search procedure and is applied to vertices to detect decay topologies, secondary interactions and gamma-ray conversions. If a secondary vertex is found in the event, a kinematical analysis is performed using particle angles and momenta measured in the emulsion films. For charged particles up to 6 GeV/c, the momentum is estimated using the angular deviations due to multiple Coulomb scattering (MCS) of tracks in the lead plates (with a resolution better than 22%) while for higher momentum particles the measurement is based on position deviations (with a resolution better than 33% up to 12 GeV/c). The momentum of muons reaching the spectrometer is measured with a resolution better than 20% up to 30 GeV/c and the sign of their charge is also measured. The gamma-ray energy is estimated by a Neural Network algorithm. Due to the position and angle resolution provided by the emulsion, the impact parameter (defined as the minimum distance between one track and the reconstructed vertex) of tracks attached to the primary vertex is below 10 μm excluding low momentum tracks. The detection of decay topologies is based on the observation of tracks with impact parameter greater than this value.

3. Background sources

There are several background sources for the ν_τ candidate search. Since charmed particles have similar lifetimes to the tau lepton, the decays of charm can mimic the τ decay topology in all the channels whenever the primary muon is not detected or is misidentified. A particular background to the $\tau \rightarrow \mu$ channel is the large angle Coulomb scattering of muons coming from ν_μ CC. Another source of background affecting the $\tau \rightarrow h$ and $\tau \rightarrow hhh$ channels is the hadronic re-interaction background. Hadrons coming from ν_μ interactions scatter hadronically off nuclei sometimes resulting in a kink-like topology. Most backgrounds are identified and discarded using kinematic variables, such as the flight length of the candidate, the missing p_T at the primary vertex or the ϕ angle. The latter, a powerful discriminating variable, is defined as the angle in the transverse plane between the τ candidate and the hadronic shower.

4. Candidate events topological and kinematical analysis

The decay search procedure has been applied to 5497 events (a subsample of the runs 2008 $\rightarrow$ 2012) resulting in 3 ν_τ candidates identified. The cuts used in the analysis are described in details in the experiment proposal [8] and in its addendum [9].

The first candidate was observed in the 2008-2009 data sample and described in detail in 2010 [10]. Since the neutrino interaction occurred in the first super module it is possible to perform a very deep study on this event. Tracks belonging to the primary vertex are followed down through several bricks to assess the muon-less nature of the event (with a confidence level of ~99%) and a detailed analysis looking for secondary interactions and electromagnetic shower is performed. The tau candidate track exhibits a kink with an angle of 41±2 mrad. Two electromagnetic showers induced by gamma rays associated to the event have been located; in the most probable hypothesis both gamma rays are emitted at the secondary vertex and the measured invariant mass is compatible with a neutral pion, $m_{\gamma\gamma} = 120 \pm 20$ (stat) ± 35 (syst) MeV/c^2. The total transverse momentum of the daughter particles with respect to the parent track is $0.47^{+0.24}_{-0.12}$ GeV/c. The missing transverse momentum at the primary vertex is $0.57^{+0.32}_{-0.17}$ GeV/c, which is lower than the upper cut at 1 GeV/c. The angle ϕ in the transverse plane between the parent track and the momentum of hadronic shower is equal to 3.01 ± 0.03 rad, well above the lower selection cutoff fixed at $\pi/2$.

The event is therefore consistent with the interaction of a ν_τ in the OPERA target producing a τ lepton that decays through the channel $\tau^- \rightarrow \rho^- \nu_\tau$ with $\rho^- \rightarrow \pi^- \pi^0$ and $\pi^0 \rightarrow \gamma\gamma$.

A second ν_τ candidate was announced at the Neutrino 2012 conference, compatible with a τ decaying into 3 charged hadrons. It is fully described in [11].The fact that the decay happens in the plastic base of the emulsion film, just between the two emulsion layers, helps reducing the probability of the event being a hadronic reinteraction: no highly ionizing tracks emitted in nuclear processes have been found in the emulsions close to the decay vertex. The ranges of the three decay daughters are consistent with the hadron hypothesis. The measured decay length is

1.54 mm, and the observed momenta yield $\phi = (167.8 \pm 1.1)°$ as well as values of other kinematic variables are compatible with the expectations for a τ decay.

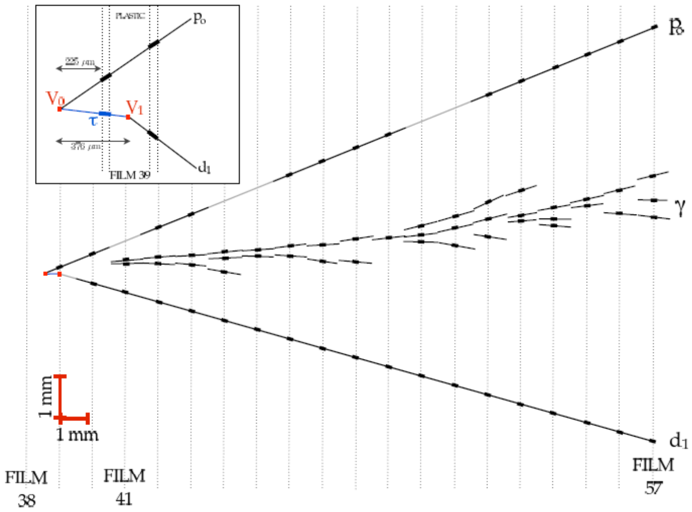

Fig. 1: Display of the $\tau \rightarrow \mu$ candidate event in the xz projection: tracks τ and p_0 come from the primary vertex; the τ candidate decays in the plastic base of film 39, track d_1 is the τ decay daughter identified as a muon.

The third ν_τ candidate is in the $\tau \rightarrow \mu$ channel (a sketch of the event is shown in fig. 1) [11]. Again the decay vertex is located in the plastic base, just between the two emulsion layers. The measured kink angle is 245 ± 5 mrad with a decay length of 376 ± 10 μm. In this case the main background source is the large angle scattering of the muon: a simulation show that kink angle greater than 20 mrad occurs in $O(10^{-6})$ in lead and even less in the emulsion base $O(10^{-7})$.

In Tab. 1 are summarized the expected tau events in the analyzed sample for each decay channel together with the expected backgrounds.

	Signal	Background	Charm	μ-scattering	had. Int.
$\tau \rightarrow h$	0.31	0.027	0.011		0.016
$\tau \rightarrow 3h$	0.43	0.12	0.11		0.0021
$\tau \rightarrow \mu$	0.54	0.021	0.0044	0.017	
$\tau \rightarrow e$	0.46	0.02	0.02		
Total	1.74	0.188	0.145	0.017	0.018

Tab 1: Expected signals and background for the analyzed subsample of the 2008 – 2012 runs assuming $\Delta m_{23}^2 = 2.32 \cdot 10^{-3}$ eV^2.

By a simple counting method the probability that the three observed events in the three channels can be explained as background is $2.9 \cdot 10^{-4}$ leading to a 3.4 σ significance of non-null observation.

5. Summary

The OPERA experiment has been designed to perform the first detection of neutrino oscillations in direct appearance mode in the muon to tau neutrino channel. OPERA is a large scale hybrid apparatus equipped with electronic detectors and a highly segmented target section made of Emulsion Cloud Chamber (ECC) units.

The OPERA experiment has successfully recorded events from 2008 to 2012 exploiting the $18.0 \cdot 10^{19}$ protons on target delivered by the CNGS beam. The analysis of the data sample is ongoing and about 50% of it is completed. The search for $\nu_\mu \rightarrow \nu_\tau$ oscillations has so far identified three τ candidates ($\tau \rightarrow h$, $\tau \rightarrow hhh$, $\tau \rightarrow \mu$) in good agreement with the expectation. The probability that the three observed events in the three channels can be explained as background is $2.9 \cdot 10^{-4}$. This leads to a 3.4 σ significance of non-null observation.

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