Recent results of the OPERA experiment

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OPERA is a long baseline hybrid experiment located in the Gran Sasso underground laboratory designed to study the $\nu_\mu \longrightarrow \nu_\tau$ neutrino oscillations. OPERA is the first experiment searching for ν_τ appearance from a pure high energy ν_μ beam (CNGS) produced at CERN and travelling a distance of 730 km to the OPERA detector. Tau leptons produced in charged current interactions are identified from their decay topology using the technique of nuclear emulsions. After a brief introduction on the physics motivation, on the OPERA hybrid electronic-emulsion detector and the description of the principle of tau detection, the recent results are presented including a topological and kinematical description of the first candidate event.

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 ν oscillation in the atmospheric sector was first established in disappearance mode by Super-Kamiokande [1] and then confirmed by K2K [2] and MINOS [3]. The final proof for neutrino oscillation should be the detection of a ν_τ in a terrestrial (almost) pure ν_μ beam. The OPERA experiment aims at the direct observation of $\nu_\mu \longrightarrow \nu_\tau$ oscillation in the CNGS (CERN Neutrinos to Gran Sasso) neutrino beam produced at CERN.

The OPERA detector is located in the Hall C in the underground laboratories at LNGS and it is a hybrid detector made of two identical Super Modules (SM): each SM is formed by a target section (composed by a large amount of nuclear emulsions and lead piled up into a modular structure called brick), electronic detectors and a muon spectrometer. The electronic detectors 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 ($\langle E_{\nu_\mu} \rangle \approx 17$ GeV) and 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 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. The contamination (in terms of interations in the target) of τ from D_s decay is negligible and the contamination due to $\overline{\nu}_\mu$ is about 2.0%. ν_e ($\overline{\nu}_e$) contamination is low and allows to investigate the sub-dominant oscillation channel.

1.2 The Veto

Following the beam line, the first OPERA detector component is the Veto designed to reduce wrong triggers due to particles produced by neutrino interactions in the rock, in the mechanical structures and in the Borexino detector. Veto is also used to monitor CNGS beam counting muons which pass through it.

1.3 The Target

The target has an overall mass of about 625 ton per Supermodule 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 called Changeable Sheet (CS). 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. Bricks are assembled into walls.

1.4 Target Tracker

Target trackers located after each brick wall, are used to select the brick in which neutrino interactions took place. Plastic scintillator strips equipped with Wave Length Shifting (WLS) fibers coupled to multi-anode PM tubes are chosen to perform this task; they are used to sample hadronic showers energy and contribute to identify and reconstruct high penetrating tracks. Each brick-wall is followed by two orthogonal planes of electronic trackers ($\sim$ 6.7 x 6.7 m^2), each of them contains 256 scintillating strips.

1.5 The Muon Spectrometer

The OPERA 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. Three stations of drift tubes placed in front, behind and in between the two magnet walls provide the high precision measurement of the trajectories [5].

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 classifies in-target events into CC and NC interactions. 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 bricks, developed and analysed with high-speed automatic optical microscopes [9], [10] looking for neutrino-related charged tracks compatible with the ED 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 most downstream films of the brick and, if found, are followed back film by film until they disappears 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 and in the electronic detectors. For charged particles up to 6 GeV/c, the momentum is estimated using the angular deviations generated by multiple Coulomb scattering of tracks in the lead plates [11] 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 [5]. 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. The decay search was applied to a subsample of 1088 neutrino events (187 NC), corresponding to about 35% of the 2008 and 2009 data sample in the analysis of a first data sample [6].

Since charmed particles have lifetimes similar to the τ lepton and decay topologies in common, the study of the production of charmed particles in the OPERA experiment is useful to validate the procedures used for the selection and identification of ν_τ interaction candidates. Charmed particles are produced in about 4% of Charged Current neutrino interactions at the CNGS energy. In the analysed CC interactions of the cited sample, a total of 20 charm decay candidates passing all selection cuts have been observed. This number is well compatible with the expectations coming from the Monte Carlo simulation (16.0 $\pm$ 2.9), and demonstrates that the efficiency of the search for short-lived decay topologies is understood. The background in this charm event sample is about 2 events.

3 Candidate event topological and kinematical analysis

The decay search procedure applied to the data sample reported in [6] yielded one event passing the selection criteria defined for the ν_τ interaction search with the τ lepton decaying into one charged hadron. The cuts used in the analysis are described in details in the experiment proposal [7] and in its addendum [8].

Since the neutrino interaction occurred is well inside the target it is possible to perform a very deep study on this event. Tracks belonging to the primary vertex are followed down through several bricks (until they stop) to assess the muon-less nature of the event (with a confidence level of $\sim$ 99%) and a datailed analysis looking for secondary interactions and electromagnetic shower is performed.

Seven charged tracks are associated with the primary vertex. Two electromagnetic showers induced by gamma rays associated to the event have been located: the event-display of the reconstructed interaction is shown in Fig. 1. Track 4 travels over a distance of 1335 $\pm$ 35 μm before showing a kink topology (kink angle = 41 $\pm$ 2 mrad) satisfying the selection criteria. The daughter track (labelled 8) has an impact parameter with respect to the primary vertex of 55 $\pm$ 4 μm and a momentum of 12^{+6}_{-3} GeV/c well above the selection criterion.

The energy and the pointing probability has been measured. The energy of tgamma ray 1 is 5.6 $\pm$ 1.0 (stat.) $\pm$ 1.7 (syst.) GeV and its converting point is 2.2 mm downstream of the secondary vertex to which the shower points with a probability of $\sim$ 32 %) whereas the probabilty to be attached at the primary is less than 10^{-3}.
The energy of gamma ray 2 is 1.2 $\pm$ 0.4 (stat.) $\pm$ 0.4(syst.) GeV. It is compatible with pointing to both vertexes, with a significantly larger probability ($\sim$ 82%) at the secondary vertex, compared to ($\sim$ 10 %) at the primary vertex. Its longitudinal distance to both vertices is about 13 mm.

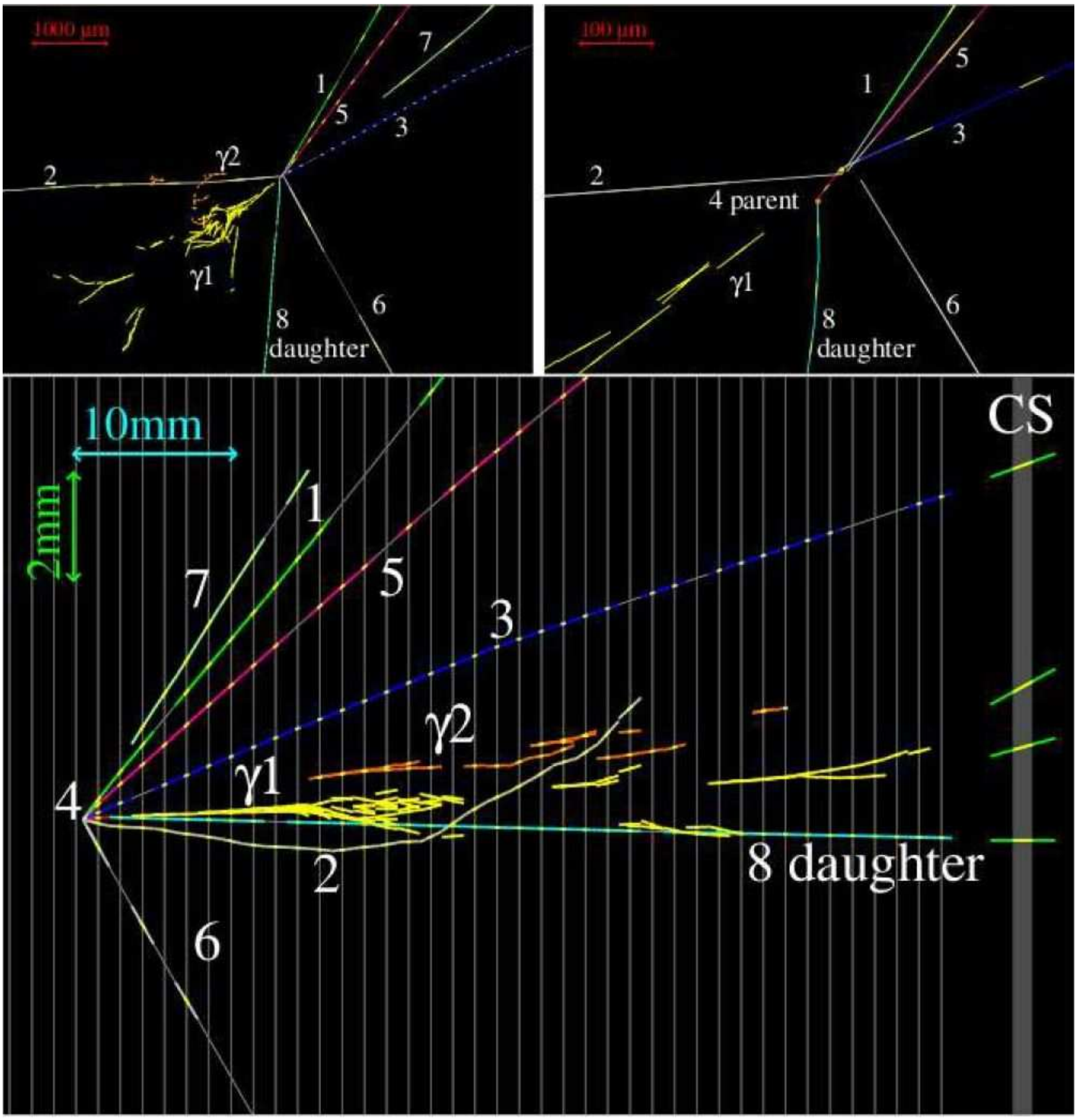

Figure 1: Display of the ν_τ candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

In the most probable hypothesis both gamma rays are emitted at the secondary vertex. The total transverse momentum of the daughter particles with respect to the parent track is $0.47^{+0.24}_{-0.12}$ GeV/c (over the selection cut, 0.3 GeV).

The missing transverse momentum at the primary vertex is $0.57\ ^{+0.32}_{-0.17}$ GeV/c, which is lower than the 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 cut-off fixed at $\pi/2$. The invariant mass estimation of the two-gammas system is compatible with the π^0 mass (120 ± 20 (stat.) $\pm$ 35 (syst.) MeV/c^2). Similarly, the invariant mass of the charged decay daughter assumed to be a π^- plus the two gamma rays is $640\ ^{+125}_{-80}$ (stat.) $^{+100}_{-90}$ (syst.) MeV/c^2, compatible with the $\rho(770)$ mass. The branching ratio of the decay mode $\tau \rightarrow \rho\nu_\tau$ is about 25%.

4 Background estimation

The secondary vertex is compatible with the decay of a τ into $\rho\nu_\tau$. In this channel the main background sources are

- the decays to a single charged hadron of charged charmed particles produced in ν_μ CC interactions where the primary muon is notidenti?ed as well as the c $\bar{c}$ pair production in ν_μ NC interactions when one charm particle is not identi?ed and the other decays to a one-prong hadron channel;
- the one 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.

The charm background in the analysed sample amounts to 0.007 ± 0.004 (syst.) events [6]. The estimation of the charm background is conservative since it is evaluated assuming a single-brick based scanning strategy, and they do not include the additional reduction obtained by following all tracks up to their end points as it was done for this event.

An additional search for hadronic activity looking for nuclear fragments pointing to the secondary vertex was performed and no track is observed.

The probability for a hadronic reinteraction to satisfy the selection criteria of the kink decay topology and its kinematics is (3.8 ± 0.2) x 10^{-5} per NC event, leading to a total of 0.011 ± 0.006 (syst.) background events when adding the misclassification of CC events into NC. By considering the one-prong hadron channel only the probability to observe one event due to a background fluctuation is $\sim$ 1.8 % for a statistical significance of 2.36 σ. Since all the τ decay modes are included in the search, this probability increases to 4.5 % corrisponding to a significance of 2.01 σ.

At Δm^2 = 2.5 x 10^{-3} eV^2 and full mixing, the expected number of observed ν_τ events with the reported event statistics is 0.54 ± 0.13 (syst.), of which 0.16 ± 0.04 (syst.) in the one-prong hadron channel in agreement with the observation of one event.

5 Conclusions

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 where the oscillated nu-tau is unambiguously identified through the identification of the tau lepton produced in its CC interaction. 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 analysis of a sample of events corresponding to 1.89 x 10^{19} p.o.t. in the CERN CNGS ν_μ beam yielded the observation of a first candidate ν_τ CC interaction.

This event is compatible with the production of a τ lepton and the subsequent decay into $\rho\nu_\tau \rightarrow \pi^-\pi^0\nu_\tau$ and more generally to $h^-(n\pi^0)\nu_\tau$ and passes the selection criteria. The observation of a tau candidate in this decay channel has a significance of 2.36 σ of not being a background fluctuation, which becomes 2.01 σ when all decay modes are considered.

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