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Status of the OPERA experiment

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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 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 732 km away from the neutrino source. Runs with CNGS neutrinos were successfully carried out in 2008, 2009, and 2010. The analysis of a sample of events corresponding to 1.89×10^{19} p.o.t. in the CERN CNGS ν_μ beam yielded the observation of a first candidate ν_τ CC interaction. The topology and kinematics of this candidate event is described in detail. The background sources are explained and the significance of the observation of the first ν_τ event candidate is assessed.

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1. The detector

In the past two decades several experiments have provided strong evidences supporting the neutrinos oscillation hypothesis. The ν oscillation in the atmospheric sector was first established by the Super-Kamiokande experiment [1], and then confirmed by K2K [2] and MINOS [3]. Nevertheless, neutrino oscillations in this sector have been studied so far only in disappearance mode, and an unambiguous proof of the oscillation mechanism through the direct observation of $\nu_\mu \rightarrow \nu_\tau$ is still missing. The OPERA experiment [4] has been designed to observe the ν_τ appearance in the CNGS ν_μ beam [5].

The OPERA detector is located in the Gran Sasso underground laboratory (LNGS) in Italy, 732 km away from the neutrino source at CERN. The CNGS is a high energy neutrino beam ($< E > \approx 17 GeV$), optimized to maximize the number of detectable ν_τ interactions at LNGS.

With a nominal CNGS beam intensity of 4.5×10^{19} proton on target (pot) per year and assuming a $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and full mixing, about 10 events are expected to be observed in OPERA in 5 years of data taking.

The ν_τ signature is given by the decay topology of the short-lived τ leptons produced in the ν_τ Charged Current (CC) interactions decaying to one prong (electron, muon or hadron) or three prongs.

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).

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. The target sections (total mass 1.25 kt) are highly modular, being made of small units called bricks. A brick consists of 57 0.3 mm thick nuclear emulsion films interleaved with 56, 1 mm thick, lead plates. The brick transverse dimensions are $12.5 \times 10 cm^2$, ans the thickness along the beam direction is 7.9 cm, corresponding to about 10 radiation lenghts.

Two additional films, called Changeable Sheets (CS), are attached downstream of each brick. CS films are used to validate the result of the algorithm for the selection of bricks were ν interaction occurred, and to provide predictions for the event location inside the brick with submillimetric precision. Bricks are arranged in vertical structures, called walls. Each wall is followed by a pair of tracker planes (TT) providing bi-dimensional information used to identify the bricks where the neutrino interactions occurred, to perform muon identification and to generate the trigger. They are made of plastic scintillator strips 1 cm thick, 2.6 cm wide and 6.9m long.

2. Neutrino event analysis

The selection of neutrino events is performed off-line. Neutrino interactions occurring in the materials surrounding the target sections material are rejected by an algorithm that classifies in-target events into CC and NC interactions. For each event a probability map for the bricks to contain the neutrino interaction is built. The brick with the highest probability is then extracted from the target, and the CS films are developed and analysed by means of high-speed automatic

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microscopes [9, 10] in order to search for neutrino-related charged tracks. If such tracks are found, the brick is then unpacked and the emulsion films are developed.

All CS tracks are searched for in the most downstream film of the brick and then followed back film by film. The track is followed until it stops in a plate where either a primary or a secondary vertex has occurred. In order to study the located vertices and reconstruct the events, a volume of about $3cm^3$ surroundind the vertex point is analyzed.

A further phase of analysis, called decay search procedure, is applied to vertices to detect charged or neutral secondary interactions and decay topologies. It is also searched for γ-ray conversions.

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 6 GeV/c, momenta are estimated using the angular deviations produced by Multiple Coulomb Scattering (MCS) of tracks in the lead plates [11]. This method gives a resolution better than 22% for charged particles. For higher momentum particles, the measurement is based on position deviations. In this case the resolution is better than 33% up to 12 GeV/c for particles passing through an entire brick. Momenta of muons reaching the spectrometer are measured with a resolution better than 20% up to 30 GeV/c and the sign of their charge is also measured [12].

The γ-ray energy is estimated by a Neural Network algorithm that uses as input a list of variables describing the longitudinal development of the electromagnetic shower and the multiple Coulomb scattering of the leading tracks.

The detection of decay topologies is based on the observation of tracks with large impact parameters with respect to the primary vertices. The IP of primary tracks is smaller than 10 μm after excluding tracks produced by low momentum particles.

The first analysis of a large data sample was reported in [6], where the decay search was applied to a sample of 1088 ν events of which 901 classified as CC interactions, corresponding to about 35% of the 2008 and 2009 data sample.

Charmed particles are produced in about 4% of Charged Current neutrino interactions at the CNGS energy. They have lifetimes similar to that of the τ lepton and have most of the decay topologies in common. These considerations show how 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.

In the sample of CC interactions reported in [6], 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 ± 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 track kinematical analysis

The decay search procedure applied to the data sample reported in [6] yielded one event satisfying 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 were those described in detail in the experiment proposal [7] and its addendum [8].

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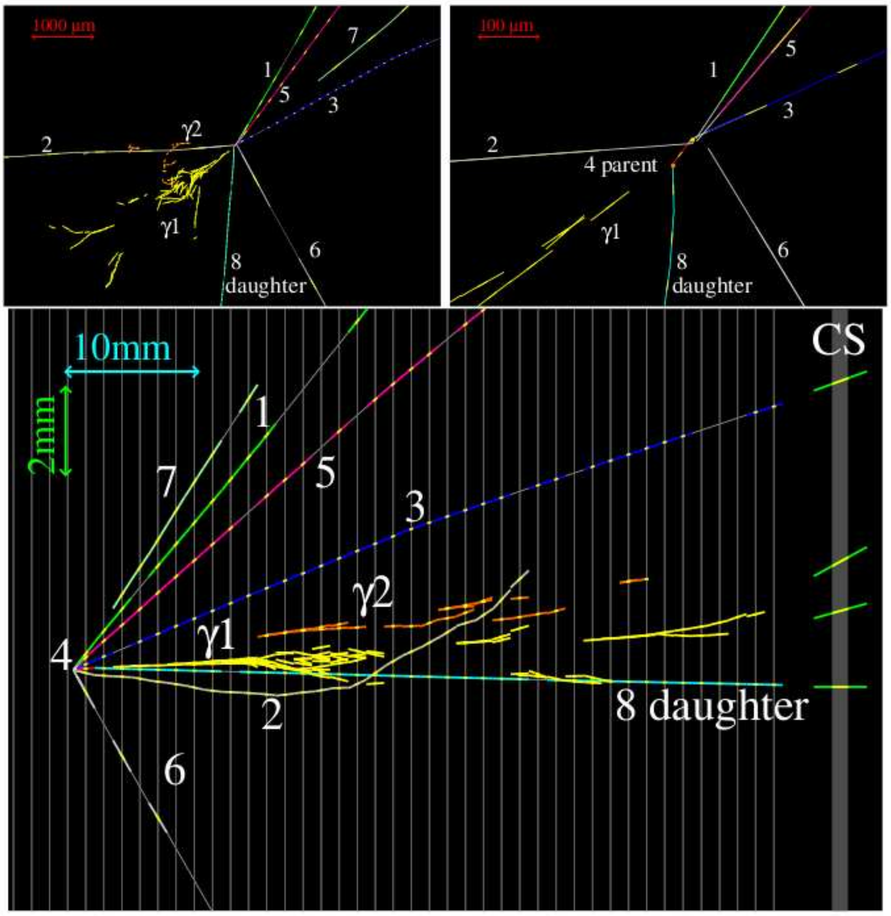

Figure 1: Display of the ν_τ candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

This neutrino interaction occurred well inside the first Super Module, thus allowing a detailed study of the event: tracks were followed in brick modules until they stop, and a search for secondary vertices and electromagnetic showers was performed. Such kind of analysis allowed to reject the hypothesys of charged tracks produced at the primary vertex being a muon at a high confidence level (i.e., about 99.9%). The probability of a soft muon with a slope larger than 1, undetectable in the emulsion films, is 1.5%.

The primary neutrino interaction consists of 7 charged tracks of which one shows a clear kink. Two electromagnetic showers induced by γ-rays and associated to the ν event have been located. The display of this event is shown in Fig.1.

Track 4 in the figure exhibits a kink topology with an angle of (41 ± 2)mrad after a path length of $(1335 \pm 35)\mu m$. Both the kink angle and the path length satisfy the selection criteria. The track labeled 8, the charged daughter of the kink, is associated to a particle with momentum (12^{+6}_{-3})GeV/c, well above the 2 GeV/c selection cut-off. Its IP with respect to the primary vertex is $(55 \pm 4)\mu m$).

The gamma ray 1 has an energy of $(5.6 \pm 1.0(stat.) \pm 1.7(syst.))$ GeV: it converted 2.2 mm downstream of the secondary vertex and the shower points to it with a probability of 32%; the probability to be attached to the primary vertex is less than 10^{-3}.

The gamma ray 2 has an energy of $(1.2 \pm 0.4(stat.) \pm 0.4(syst.))GeV$. It is compatible with pointing to either vertex, with a significantly larger probability of 82% at the secondary vertex, compared to 10% at the primary vertex. Its longitudinal distance to both vertices is about 13 mm.

4. Kinematical analysis of the candidate event

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 $(0.47^{+0.24}_{-0.12})GeV/c$, above the lower selection cut-off at 0.3 GeV/c.

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 between the parent track and the momentum of the rest of the hadronic shower in the transverse plane is equal to $(3.01 \pm 0.03)rad$, well above the lower selection cut-off fixed at $\pi/2$.

The invariant mass of the two gamma rays is $(120 \pm 20(stat.) \pm 35(syst.))MeV/c^2$, supporting the hypothesis that they come from the decay of a π^0. Similarly, the invariant mass of the charged decay daughter plus the two gamma rays is $(640^{+125}_{-80}(stat.)^{+100}_{-90}(syst.))MeV/c^2$, which is compatible with the $\rho(770)$ mass. The branching ratio of the decay mode $\tau \to \rho \nu_\tau$ is about 25%.

5. Background estimation

The secondary vertex is compatible with the decay of a τ into $\rho \nu_\tau$. The main sources of background to this channel are the decays of charmed particles produced in ν interactions into a single charged hadrond and the one-prong inelastic interactions of primary hadrons produced in ν interactions classified as NC.

The charm background produced in ν_μ CC interactions where the primary muon is misidentified in the analysed sample amounts to $0.007 \pm 0.004(syst.)$ events [7, 8]. That produced in ν_e interactions is less than 10^{-3} events. These estimates of charm background are conservative since they are obtained 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 was done for this event.

A search was performed also for hadronic activity seeking for nuclear fragments pointing to the secondary vertex, and no such track is observed. The probability for a hadronic reinteraction to satisfy the selection criteria of the kink decay topology and its kinematics is $(3.8 \pm 0.2) \times 10^{-5}$ per NC event, leading to a total of $0.011 \pm 0.006(syst.)$ background events when misclassified CC events are also included. The total background in the decay channel to a single charged hadron is therefore $0.018 \pm 0.007(syst.)$.

Finally, the expected number of events due to prompt ν_τ background from D_s decays is much smaller than any other background source ($\approx 10^{-7}$ per CC event).

The probability for the expected $(0.018 \pm 0.007(syst.))$ background events to the $h^-(n\pi^0)\nu_\tau$ decay channel of the τ fluctuate to one or more events is 1.8% (2.36σ). As the search for the

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τ decays is extended to all the decay channels, the total background then becomes $(0.045 \pm 0.023(syst.))$. The probability that this expected background to all searched decay channels of the τ fluctuate to one or more events is 4.5% (2.01σ).

At $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and full mixing, the expected number of observed ν_τ events with the event statistics reported in [6] is $0.54 \pm 0.13(syst.)$, of which $0.16 \pm 0.04(syst.)$ in the one-prong hadron topology, in agreement with the observation of one event.

6. 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. The analysis of a sample of events corresponding to 1.89×10^{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 and subsequent decay of a τ lepton into $h^-(n\pi^0)\nu_\tau$ and passes the selection criteria [7, 8]. This observation of a tau candidate in the decay channel $h^-(n\pi^0)\nu_\tau$ has a significance of 2.36 σ of not being a background fluctuation, which becomes 2.01 σ when all decay modes are considered.

References

[1] Y. Fukuda, et al., Phys. Rev. Lett. 81 (1998) 1562.

[2] M.H. Ahn, et al., Phys. Rev. D 74 (2006) 072003.

[3] D.G. Michael, et al., Phys. Rev. Lett. 101 (2008) 131802.

[4] R. Acquafredda, et al., JINST 4 (2009) 04018.

[5] CNGS project. http://proj-cngs.web.cern.ch/proj-cngs/.

[6] OPERA Collaboration, "Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam." Published in Phys.Lett.B691:138-145,2010.

[7] OPERA collaboration, M. Guler et al., An appearance experiment to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the CNGS beam: experimental proposal, CERN-SPSC-2000-028, LNGS P25/2000

[8] OPERA collaboration, M. Guler et al., Status Report on the OPERA experiment, CERN/SPSC 2001-025, LNGS-EXP 30/2001 add. 1/01

[9] N. Armenise et al., Nucl. Instrum. Meth. A 551 (2005) 261; M. De Serio et al., Nucl. Instrum. Meth. A 554 (2005) 247; L. Arrabito et al., Nucl. Instrum. Meth. A 568 (2006) 578.

[10] K. Morishima and T. Nakano, JINST (2010) 5 P04011.

[11] M. De Serio at al., Nucl. Instrum. Meth. 512 (2003) 539; M. Besnier, PhD thesis (2008) Universit de Savoie, LAPP-T-2008-02

[12] R. Zimmermann et al., Nucl. Instrum. Meth. A 555 (2005) 435; R. Zimmermann et al., erratum, Nucl. Instrum. Meth. A 557 (2006) 690.