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Results from the OPERA experiment in the CNGS beam

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Abstract. The OPERA experiment at the Gran Sasso underground laboratory was designed to study $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in the CNGS neutrino beam. In this paper we report the detection of the 5th ν_τ candidate event found in the analysis of an enlarged data sample. Given the number of analysed events and the low background, $\nu_\mu \rightarrow \nu_\tau$ oscillations have been established with a significance of 5.1σ . The analysis of the present electron neutrino sample in the framework of the $3 + 1$ sterile model is also presented. Finally the analysis of the muon charge ratio in the cosmic ray sample is discussed.

1. Introduction

Aiming at the direct detection of the ν_τ appearance in an almost pure ν_μ beam, OPERA can unambiguously prove the $\nu_\mu \rightarrow \nu_\tau$ solution for the atmospheric neutrino oscillation channel supported so far by many experimental evidences. The CNGS [1] is a conventional ν_μ beam with minor contaminations by other neutrino flavors, produced at CERN, 730 km away from the detector location. The mean neutrino energy is about 17 GeV, the energy spectrum maximizing the convolution of oscillation probability and τ production cross section.

An event by event analysis is performed in order to discriminate ν_τ from dominant ν_μ interactions. Being the experimental signature the detection of the short lived τ particle produced in ν_τ CC interactions through the observation of its decay modes, a micrometric spatial resolution is needed in order to accurately reconstruct the submillimeter track of the τ lepton.

2. Detector Overview

The basic unit of the OPERA target is the so called *brick*, a stack of 57, 300 μm thick, nuclear emulsion films interleaved by 1 mm thick lead plates. Downstream of each brick is a tightly packed doublet of emulsion films (called Changeable Sheets, CS). The target is composed by about 150000 such bricks, arranged in 27 vertical planes (*walls*). Downstream of each brick wall is a plane of plastic scintillator strips (TT), oriented along the horizontal and vertical directions, coupled by Wave Length Shifting (WLS) fibers to photomultipliers. The target section is complemented by a magnetic spectrometer instrumented with bakelite resistive plate chambers (RPC) and drift tubes. The target section and the muon spectrometer constitute the so called supermodule (SM): the OPERA apparatus is made of two identical SMs for a total target mass of about 1.3 kton. A detailed detector description can be found in [2].



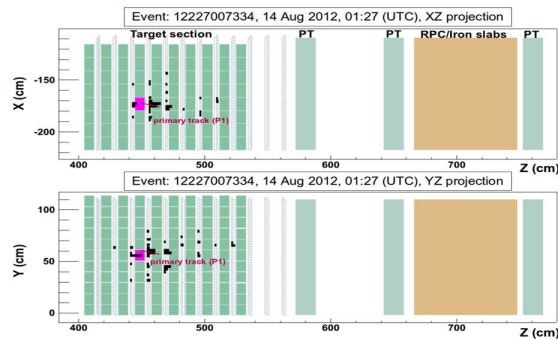


Figure 1. Display of the fifth ν_τ candidate event as seen by the electronic detectors in the x-z (z axis oriented along the beam direction) projection (top panel) and y-z projection (bottom panel). The brick containing the neutrino interaction is highlighted in magenta.

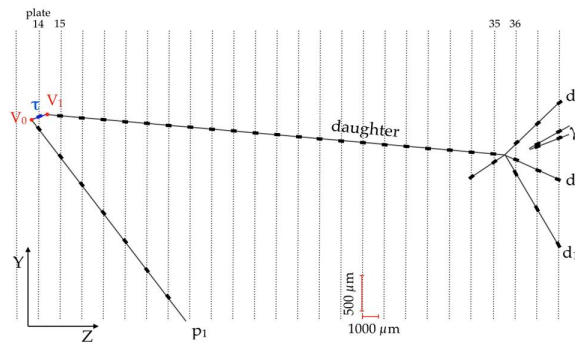


Figure 2. Event display of the fifth ν_τ candidate event in the horizontal projection longitudinal to the neutrino direction. The primary and secondary vertices are indicated as V0 and V1, respectively. The black stubs represent the track segments as measured in the films.

3. Event Reconstruction and analysis status

In five years of data taking, from 2008 to 2012, OPERA integrated 17.97×10^{19} protons on target corresponding to $\sim 80\%$ of the proposed value. 19505 neutrino interactions occurring inside the OPERA target were recorded.

Electronic detector data are processed in order to localise the brick with the highest probability to contain the neutrino interaction vertex. The brick is then removed from the target and the corresponding CS doublet is developed and analysed.

The analysis of CS doublets is equally shared by two labs hosting a farm of microscopes: the LNGS Scanning Station in Italy and the F-Lab at the Nagoya University in Japan. The CS analysis foresees the scanning of a large emulsion area in order to confirm the electronic detector data: if a signal compatible with the TT prediction is found, then the brick is dismantled and developed. Otherwise the brick is reinserted in the detector, the second most probable brick is extracted and the corresponding CS doublet analysed.

All tracks found in the CS are sought in the most downstream emulsion films of the brick and

Table 1. : Kinematical parameters considered for the $\tau \rightarrow 1h$ decay channel selection: measured values for the new candidate event and predefined cuts are reported in the second and third columns, respectively. Table from [9].

Parameter	Measured Value	Selection criteria
$\Delta\Phi_{\tau H}(\circ)$	151 ± 1	> 90
p_T^{miss} (GeV/c)	0.3 ± 0.1	< 1
θ_{kink} (mrad)	90 ± 2	> 20
z_{dec} (μm)	630 ± 30	[44, 2600]
p_T^{2ry} (GeV/c)	11_{-4}^{+14}	> 2
p_T^{2ry} (GeV/c)	$1.0_{-0.4}^{+1.2}$	> 0.6 (no γ attached)

then followed upstream until they stop, being the stopping point a signature either of a primary or a secondary vertex. Once the vertex has been located in a brick, a surrounding volume of about 2 cm^3 is scanned to detect τ lepton's or other short-lived particle's decays [3]. The details of the event analysis procedure are described in [4].

At the time of this conference about 26115 bricks had been manipulated for event analysis, 3110000 cm^2 of CS surface analysed and 12500 bricks developed. 6932 neutrino events have been localised: among the 6612 fully analysed events, 5 ν_τ candidate events were found.

4. Oscillation search results

The first ν_τ candidate event was reported in 2010 [5]. Since 2013, three more candidate events had been detected allowing us to claim the first observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode with a 4.2 significance [6–8]. A new ν_τ candidate event was recently reported in [9]: here the analysis of first and second bricks in the probability map for all the events was considered, resulting in a 15% increase of the event sample with respect to [8].

The event display of the new ν_τ candidate is shown in Fig. 1: the event is classified as 0μ (i.e. an event without any track tagged as a muon track [9]) with a visible energy of $12 \pm 4 \text{ GeV}$. The CS analysis showed a converging pattern of tracks that were followed upstream inside the brick, allowing the localization of the neutrino interaction vertex. As it is shown in Fig. 2 the primary vertex consists of the τ candidate track, which exhibits a kink topology, and a charged particle track (P1). In addition four forward-going plus two backward-going nuclear fragments pointing to the primary vertex were observed. The τ lepton decays into one charged particle that interacts 22 plates downstream of the primary vertex and can thus be unambiguously identified as a hadron. No nuclear fragments are observed at the decay vertex thus strongly reducing the probability of being due to hadronic interaction. The interaction of the daughter particle produces four charged particles and a photon. The presence of a muon at the primary vertex is ruled out by assessing the hadronic nature of track P1 (which was found interacting in the downstream brick), together with the negative search for large angle tracks at the primary vertex. The measured values of the kinematical parameters and the corresponding predefined selection criteria are summarised in Table 1: all the criteria for the $\tau \rightarrow 1h$ channel are satisfied.

In the considered data sample, the total number of expected events is 2.64 ± 0.53 and 0.25 ± 0.05 for signal and background respectively, assuming $\Delta m_{23}^2 = 2.44 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{23} = 1$.

Charmed particles decays, hadronic interactions and large-angle muon scattering (LAS) are the main processes contributing to the background for the ν_τ appearance search. The corresponding contributions are estimated by simulation studies validated with real data samples. Details are given in [3, 10, 11].

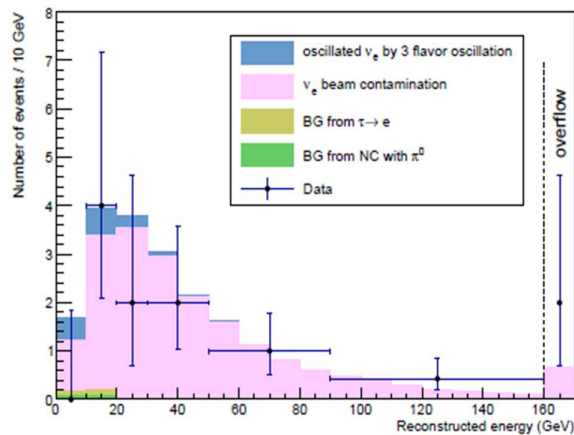


Figure 3. Distribution of the reconstructed energy of the ν_e events, and the expected spectrum from the different sources in a stack histogram, normalized to the number of analysed pot. Figure from [13].

The statistical significance of the observation of 5 ν_τ candidate events is evaluated as the probability that the background can produce a fluctuation greater than or equal to the observed data. Two test statistics were performed, one based on the Fisher’s method, the second one based on the one-sided profile likelihood ratio taking into account the observed and expected number of signal and background events in each channel. Both methods give a significance of 5.1σ .

4.1. Search for $\nu_\mu \rightarrow \nu_e$ oscillation.

By exploiting the tracking capabilities of nuclear emulsions and the high efficiency in the reconstruction of electromagnetic showers in the bricks, ν_e CC interactions can be identified, allowing to search for $\nu_\mu \rightarrow \nu_e$ oscillations. In [13] we reported the search for the appearance of ν_e in the CNGS neutrino beam using the data collected in 2008 and 2009, corresponding to an integrated intensity of 5.25×10^{19} pot. In that data sample, 19 ν_e candidate events had been observed. The expected number of ν_e interactions from the ν_e and $\bar{\nu}_e$ beam contamination was 19.8 ± 2.8 events: the result is compatible with the non-oscillation hypothesis; an upper limit on $\sin^2(2\theta_{13}) < 0.44$ was derived at the 90% C.L. In Figure 3 the reconstructed energy distribution of the ν_e candidate events and the expected spectrum from the different background sources is shown. An update of the analysis with larger statistics is in preparation.

5. Non-oscillation physics: cosmic muon charge ratio measurement.

The OPERA detector is located in a privileged site to study TeV-scale cosmic rays. Between 2008 and 2012 OPERA collected charge-separated cosmic ray data for a total amount of 3 million atmospheric muon events, among which about 110000 multiple muon bundles. This data sample was used to measure the atmospheric muon charge ratio ($R_\mu \equiv N_{\mu^+}/N_{\mu^-}$) in the TeV region, exploiting the inversion of the magnet polarity, performed on purpose during the 2012 Run and allowing minimizing systematic uncertainties and reaching an accurate determination of R_μ . The observed behaviour of R_μ as a function of the surface energy from ~ 1 TeV up to 20 TeV (about 200 TeV/nucleon for the primary particle) indicates no deviations from a simple parametric model including only pion and kaon contributions to the muon flux, showing no significant contribution of the prompt component. The energy independence supports the validity of Feynman scaling in the fragmentation region up to 200 TeV/nucleon primary energy. The analysis is reported in detail in [14].

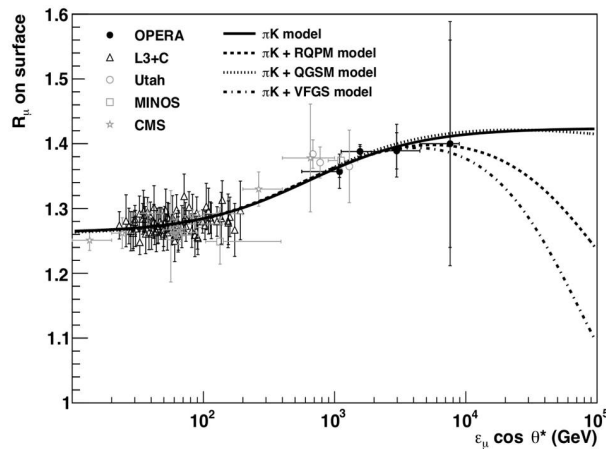


Figure 4. The muon charge ratio measured by OPERA as a function of the vertical surface energy $\epsilon \cos \theta^*$ (black points). Figure from [14].

6. Conclusion

The OPERA experiment, taking data from 2008 to 2012, successfully detected all the three active flavor neutrinos ν_μ , ν_τ , ν_e . The analysis of an enlarged data sample, including the first and the second most probable bricks for all runs, led to the detection of the 5th ν_τ candidate. Thanks to the low background level achieved and to the observed number of ν_τ candidate events, the discovery of ν_τ appearance in the CNGS neutrino beam with a significance of 5.1 σ could be established [9].

The $\nu_\mu \rightarrow \nu_\tau$ oscillation result has been exploited to derive limits on the mixing parameters of a fourth massive sterile neutrino. Details on the analysis has been reported at this Conference [12]. Results have been reported also for the $\nu_\mu \rightarrow \nu_e$ oscillation channel. Updates of the analysis for the non-standard oscillation scenario both in the $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ channels are in preparation.

A further extension of the data sample to the 3rd and 4th brick of the probability map is currently under completion. Moreover a re-analysis of the full data sample with a likelihood approach and less tight (kinematical) selection criteria is planned.

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