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Final results of the OPERA experiment on ν_τ appearance and the OPERA “legacy”

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Abstract. OPERA (Oscillation Project with Emulsion tRacking Apparatus) was a long-baseline experiment at the INFN Gran Sasso laboratory (LNGS) designed to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode. It took data from 2008 to 2012 with the CNGS neutrino beam from CERN. In 2015, after the detection of five ν_τ candidates with a signal-to-background ratio of ~ 10 , the discovery of ν_τ appearance in the CNGS beam was announced with 5.1σ significance. After having reached the experiment main goal, the selection of ν_τ candidates has been extended by loosening the selection criteria and applying a multivariate approach for events identification, in order to improve the statistical uncertainty in the measurement of the oscillation parameters and of ν_τ properties. Future experiments that will take advantage of the improvements done by OPERA in the use of nuclear emulsions will also be described.

1. Introduction

Originated by the neutrino mass and the mixing between flavour and mass eigenstates, neutrino oscillations are now established thanks to intense experimental efforts. In 1998, the first evidence for neutrino oscillations was provided by the Super-Kamiokande experiment, showing the disappearance of muon neutrinos produced in the atmosphere [1]. This result was interpreted as a possible transition from ν_μ to ν_τ or to a new type of neutrino, still not known. At that time, moreover, the ν_τ neutrino had not been observed yet. Therefore, OPERA (Oscillation Project with Emulsion tRacking Apparatus) was conceived to demonstrate unambiguously the transition from ν_μ to ν_τ by directly observing the τ lepton produced in charged-current (CC)



ν_τ interactions in a pure ν_μ beam [2]. It was operated underground in the Gran Sasso INFN Laboratory (LNGS), 730 km away from the muon neutrino source.

The challenge of the OPERA experiment to detect the short-lived τ lepton ($c\tau = 87 \mu\text{m}$), produced in the CC ν_τ interactions, was achieved using the nuclear emulsion technique that features micrometric spatial resolution.

2. The CNGS beam and the OPERA detector

Runs with the CNGS neutrino beam [3, 4] were successfully carried out from 2008 to 2012, with a total beam intensity of $17.97 \cdot 10^{19}$ protons on target (p.o.t.). The average neutrino energy was about 17 GeV, the contamination from $\bar{\nu}_\mu$ interactions was 2.1%, the one from ν_e and $\bar{\nu}_e$ together below 1%, while the number of prompt ν_τ negligible. The detector was an hybrid apparatus consisting of an emulsion/lead target complemented by electronic detectors. It was made up of two identical super-modules aligned along the CNGS beam direction, each made of a target section and a muon spectrometer. Each target section consisted of a multi-layer array of 31 target walls interleaved with pairs of planes of plastic scintillator strips. Target walls were made of Emulsion Cloud Chamber target units, called bricks, which were, in total, 150000. Each brick consists of 57 emulsion films, 300 μm thick, interleaved with 56 lead plates, 1 mm thick, for a total mass of 8.3 kg. The electronic detectors were used to identify the brick containing the neutrino interaction, for muon identification and its charge and momentum determination.

The appearance of the τ lepton was identified by the detection, in the nuclear emulsions, of its characteristic decay topologies, either in one prong (electron, muon or hadron) or in three prongs. Kinematic selection criteria were then applied according to the decay channel.

3. First phase of the OPERA experiment

In 2015, five ν_τ candidates [5–9] had been observed, satisfying stringent kinematical selection criteria as reported in [6]. The observation of these five ν_τ candidates with a background of 0.25 ± 0.05 events, allowed to exclude the absence of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a 5.1σ significance, as reported in the paper [9].

4. Second phase of the OPERA experiment

After discovering the ν_τ appearance in the ν_μ CNGS beam [9], a new goal has been set: estimate the oscillation parameters in appearance mode and exploit the unique capability of the OPERA experiment to identify all three neutrino flavours in order to put constraints on the oscillation parameters by a joint oscillation fit of all datasets.

Given the validation of the Monte Carlo simulation of ν_τ events, based on different control data samples, a new analysis strategy was developed, fully exploiting the features expected for ν_τ events. A multivariate approach to improve signal to noise separation was applied to candidate events selected by means of moderately tight topological and kinematical cuts.

Details about the new selection method are reported in [10]. The total expected signal, after selection criteria application, is (6.8 ± 1.4) events, whereas the total background expectation is (2.0 ± 0.4) events. Ten events have been observed [10].

Different multivariate techniques have been considered and their performances for signal to background discrimination compared. The one with the best discrimination power was the Boosted Decision Tree (BDT).

4.1. Results

The statistical analysis used to re-evaluate the significance for the ν_τ appearance is based on an extended likelihood constructed as the product of a probability density function given by the BDT response, a Poisson probability term which takes into account the number of observed events and the expected background in each decay channel, and a Gaussian term which accounts for systematics. The discovery significance of ν_τ appearance is expressed in terms of a hypothesis test where the background only hypothesis plays the role of the null hypothesis and the signal-plus-background hypothesis is the alternative one. The null hypothesis is now excluded with the improved significance of 6.1σ [10].

The number of observed ν_τ candidates after background subtraction is a function of the product of ν_τ CC cross-section ($\sigma_{\nu_\tau}^{CC}$) and the oscillation parameter Δm_{23}^2 . Δm_{23}^2 has been evaluated for the first time in appearance mode: assuming the other oscillation parameter $\sin^2 2\theta_{23} = 1$, $|\Delta m_{32}^2|$ is equal to $(2.7_{-0.6}^{+0.7}) \cdot 10^{-3} \text{eV}^2$. The result is consistent within 1σ with the measurements performed in disappearance mode by other experiments and with the Particle Data Group best fit [11].

ν_τ CC cross-section on the lead target has been estimated to be equal to $(5.1_{-2.0}^{+2.4}) \cdot 10^{-36} \text{cm}^2$, when $|\Delta m_{32}^2| = 2.50 \cdot 10^{-3} \text{eV}^2$. This result is the first measurement of the ν_τ CC cross-section with a negligible contamination from $\bar{\nu}_\tau$.

The lepton number of ν_τ has never been observed. In the muonic channel, the OPERA experiment can distinguish neutrinos from anti-neutrinos looking at the charge of the muon produced in τ decays, which was measured to be negative at 5.6σ level for the $\tau \rightarrow \mu$ candidate. Performing a dedicated BDT analysis which included also the background due to the 2% $\bar{\nu}_\mu$ beam contamination, we obtained the first direct evidence for the leptonic number of τ neutrinos with a significance of 3.7σ . All these results have been reported in [10]

5. The OPERA legacy

The improvements achieved for the OPERA experiment in the use of nuclear emulsions and in the scanning systems to analyse them make this kind of detector still attractive in a wide range of scientific fields and applications. Hereafter some of the future experiment will be briefly outlined.

5.1. The SHiP experiment at CERN

The Standard Model provides an explanation for many subatomic processes, but fails to explain some observed phenomena such as the so-called dark matter, the neutrino oscillation and masses and the matter/antimatter asymmetry in the Universe. The SHiP experiment, a multi-purpose facility proposed at CERN, is aimed at searching for very weakly interacting long lived particles including Heavy neutral leptons. Moreover, the facility is also suited to study ν_τ and $\bar{\nu}_\tau$ interactions with a nuclear emulsion detector [12].

5.2. The Nuclear Emulsions for WIMP Search with directional measurement (NEWSdm)

The NEWSdm experiment aims at the direct detection of WIMP dark matter candidates by measuring the direction of WIMP-induced nuclear recoils in the nuclear emulsions. For this challenge, the detector exploits new generation nuclear emulsions with nanometric grains and microscopes that can overcome the diffraction limit, reaching a resolution of 10 nm [13].

5.3. The FOOT (FragmentatiOn Of Target) experiment for hadron therapy

Particle therapy uses proton or C¹² beams for the treatment of deep-seated solid tumors. Nuclear fragmentation of both beam and patient nuclei must be carefully taken into account, but this process is not known with enough precision at present. The FOOT experiment, thanks also to the nuclear emulsions in its detector, will provide an accurate description of nuclear interactions taking place between the beam and the patient tissues during the treatment [14].

5.4. Muon Radiography

Muon Radiography is a technique that uses cosmic ray muons to generate three-dimensional images of volumes using information contained in the Coulomb scattering of muons. Nuclear emulsions are a very portable detector, since they do not need electric supply, therefore they are used to obtain radiography of volcanoes [15], pyramids [16] and other archeological sites of interest.

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