Latest results of the OPERA experiment on nu-tau appearance in the CNGS neutrino beam

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Abstract

OPERA is a long-baseline experiment designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode. It was based at the INFN Gran Sasso laboratory (LNGS) and took data from 2008 to 2012 with the CNGS neutrino beam from CERN. After the discovery of ν_τ appearance in 2015, with 5.1σ significance, the criteria to select ν_τ candidates have been extended and a multivariate approach has been used for events identification. In this way the statistical uncertainty in the measurement of the oscillation parameters and of ν_τ properties has been improved. Results are reported.

Contents

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 of neutrino oscillations was provided by the Super-Kamiokande experiment, showing the disappearance of atmospheric muon neutrinos [1]. This result was consistent with the transition of 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.

The OPERA experiment [2] was designed to conclusively prove the existence of $\nu_\mu \rightarrow \nu_\tau$ oscillations. It was operated underground at the Gran Sasso INFN Laboratory (LNGS), 730 km away from the muon neutrino source at CERN, and collected data from 2008 to 2012. The direct search for ν_τ appearance was based on the detection of τ leptons produced in ν_τ charged current interactions (CC). The challenging detection of the short-lived τ lepton (cτ = 87 μm), out of almost twenty thousands ν_μ interactions, was achieved exploiting the nuclear emulsions sub-micrometric spatial resolution.

2 The CNGS beam and the OPERA detector

The OPERA detector was located at the underground Gran Sasso Laboratory (LNGS), 730 km away from the neutrino source, in the high energy CERN to LNGS beam (CNGS) [3,4]. The average neutrino energy was ~ 17 GeV, the $\bar{\nu}_\mu$ contamination was 2.1% in terms of interactions, the ν_e and $\bar{\nu}_e$ together were below 1%, while the number of prompt ν_τ was negligible. The detector was a 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.The target total mass was 1.25 ktons. The electronic detectors were used to identify the brick containing the neutrino interaction, for muon identification and its charge and momentum determination.

3 Event selection and analysis

Once a neutrino interaction was reconstructed in the electronic detectors, the bricks most probably containing the interaction vertex was identified by a dedicated offline algorithms and extracted from the walls. The nuclear emulsions were eventually developed and scanned to search for τ decays. The scanning was performed with automated optical microscopes installed in Laboratories in Europe and in Japan. If a secondary vertex was found, a full kinematic analysis was performed combining the nuclear emulsion data with those from the electronic detectors. The momentum of charged particles in emulsions was determined by Multiple Coulomb Scattering [5]. For muons crossing the spectrometers, the momentum was measured with a resolution better than 22% up to 30 GeV/c, and the charge sign determined [6].

The appearance of the τ lepton was identified by the detection of its characteristic decay topologies, either in one prong (electron, muon or hadron) or in three prongs. A first hint of a decay topology was the observation of an impact parameter larger than 10 μm, defined as the minimum distance between the track and the reconstructed vertex, excluding low momentum tracks. Kinematic selection criteria were then applied according to the decay channel.

4 First phase of the OPERA experiment

In the first phase of the OPERA experiment, very stringent kinematical selection criteria for ν_τ candidate selection were applied, allowing a signal-to-background ratio of ~ 10.

Five ν_τ candidates were observed: three in the $\tau \to 1h$ decay channel [7–9], one in the $\tau \to 3h$ [10] and one in the $\tau \to \mu$ [11] decay channel. In the sample analysed up to 2015, corresponding to 5408 neutrino interactions, 0.25 ± 0.05 background events were expected, coming mainly from events with an undetected primary muon, hadronic re-interactions and large angle muon scattering. The observation of five candidates results in 5.1σ significance for the exclusion of the background only hypothesis [9].

5 Second phase of the OPERA experiment

A new goal has been set. In order to estimate the oscillation parameters with reduced statistical uncertainty a new analysis procedure was implemented.

Given the validation of the Monte Carlo simulation of ν_τ events, based on different control data samples [12–14], a new analysis strategy was developed, fully exploiting the features of expected 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. The new selection was applied to the complete data sample, corresponding to 5603 ν interactions. Details about the new selection method are reported in [15]. The total expected signal is (6.8 ± 1.4) events, whereas the total background expectation is (2.0 ± 0.4) events.

Ten events (N^{obs}) survived all the topological and kinematical cuts. The distribution of their visible energy, i.e. the scalar sum of the momenta of charged particles and γs, is shown in Fig. 1, where it is compared to Monte Carlo simulation.

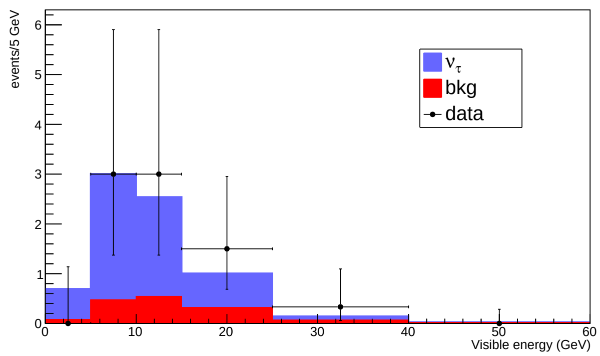

Figure 1: Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalised to the expected number of events [15].

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).

5.1 ν_τ appearance statistical significance

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 was excluded with the improved significance of 6.1 σ [15].

5.2 First measurement of $|\Delta m^2_{23}|$ in appearance mode and of ν_τ CC cross-section on Lead

The number of observed ν_τ candidates after background subtraction is a function of the product of ν_τ CC cross-section ($\sigma^{CC}_{\nu_\tau}$) and the oscillation parameter Δm^2_{23}.

The squared mass difference Δm^2_{23} was evaluated for the first time in appearance mode: assuming $\sin^2 2\theta_{23} = 1$, $|\Delta m^2_{23}|$ is equal to $(2.7^{+0.7}_{-0.6}) \cdot 10^{-3}\mathrm{eV}^2$. The result is consistent with the measurements performed in disappearance mode by other experiments and with the Particle Data Group best fit [16].

The ν_τ CC cross-section on the OPERA lead target was also estimated: it is equal to $(5.1^{+2.4}_{-2.0}) \cdot 10^{-36}\mathrm{cm}^2$, assuming $|\Delta m^2_{23}| = 2.50 \cdot 10^{-3}$ eV^2. It is the first measurement of the

ν_τ CC cross-section with a negligible contamination from $\bar{\nu}_\tau$.

5.3 ν_τ lepton number

The OPERA experiment allowed to distinguish neutrinos from anti-neutrinos by the charge of the muon in τ muonic decays. This charge was determined as negative at 5.6 σ level for the $\tau \to \mu$ candidate. Performing a dedicated BDT analysis which included also the background from 2% $\bar{\nu}_\mu$ beam contamination, the first direct evidence for the leptonic number of τ neutrinos with a significance of 3.7σ was obtained.

Conclusions

OPERA claimed the discovery at 5.1σ of $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam from the detection of five ν_τ events, with a background of 0.25 events. A new analysis strategy was applied for the selection of additional ν_τ candidates, in order to measure the oscillation parameters with reduced statistical error.

With the identification of five additional ν_τ candidates, an overall sample of ten ν_τ candidates was collected, with 2.0 ± 0.4 expected background events. The discovery of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode is confirmed with an improved significance of 6.1 σ.

Assuming $\sin^2 2\theta_{23} = 1$, the first measurement of $|\Delta m^2_{23}|$ in appearance mode yields $(2.7^{+0.7}_{-0.6}) \cdot 10^{-3}\mathrm{eV}^2$, while the measured ν_τ CC cross-section on the lead OPERA target is $(5.1^{+2.4}_{-2.0}) \cdot 10^{-36}\mathrm{cm}^2$, assuming $|\Delta m^2_{23}| = 2.50 \cdot 10^{-3}$ eV^2.

Furthermore, a dedicated BDT analysis in the $\tau \to \mu$ channel allows claiming for the first direct observation of the ν_τ lepton number with a significance of 3.7 σ.

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