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Latest results of the OPERA experiment

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Summary. — The OPERA neutrino experiment was designed to perform a unique appearance measurement in the CNGS beam to confirm the oscillation mechanism in the atmospheric sector. Runs were successfully carried out from 2008 to 2012. The status of the analysis is reported and the topology and the kinematics of the first two ν_τ CC candidate events are described. A first result of the $\nu_\mu \to \nu_e$ oscillation search is also presented.

PACS 14.60 – Neutrino oscillations.
PACS 29.40 – Nuclear emulsions.

1. – Introduction

The aim of the OPERA (Oscillation Project with Emulsion-tRacking Apparatus) experiment [1, 2] at the Gran Sasso underground Laboratory (LNGS) is to perform the first direct detection in the appearance mode of $\nu_\mu \to \nu_\tau$ oscillations.

The direct appearance search is based on the detection of τ leptons produced in the charged current interactions of ν_τ. The neutrino beam is an almost pure ν_μ beam produced by protons accelerated in the CERN SPS and injected in the CNGS beam line. The OPERA experiment [3, 4] is installed in the LNGS Hall C, aligned with the CNGS baseline.

2. – The OPERA detector

OPERA is a hybrid apparatus with a modular structure. The detector concept is based on the Emulsion Cloud Chamber (ECC) technique, combined with real-time detection techniques (electronic detectors). The ECC basic unit in OPERA is a brick made of 56 lead plates, providing the necessary mass, interleaved with 57 nuclear emulsion films, providing the necessary spatial and angular resolution. The analysis of the nuclear emulsion films is performed in the OPERA scanning laboratories in Europe and Japan by fast automatic scanning systems developed to reconstruct with sub-micrometric accuracy the neutrino interaction events.

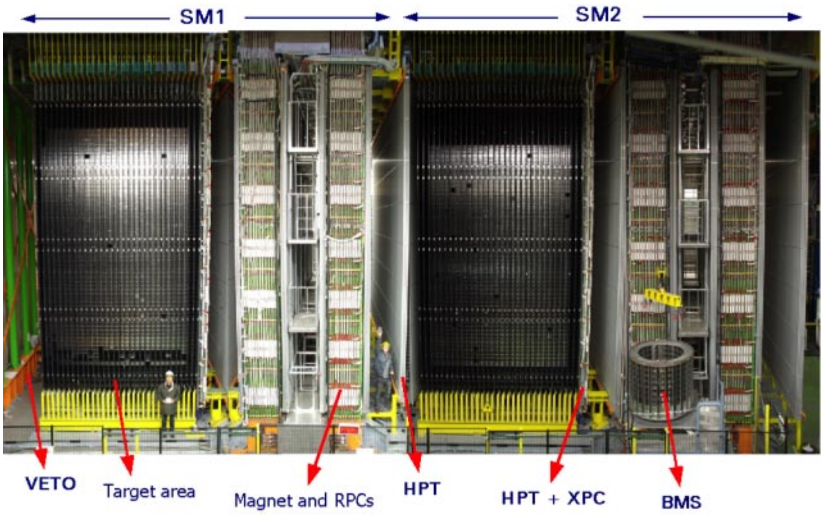

Fig. 1. – View of the OPERA detector. The upper horizontal lines indicate the position of the two identical supermodules (SM1 and SM2). Arrows show the position of a target area (ECC brick walls interleaved with planes of plastic scintillators), the VETO planes, some drift tube detector (HPT) planes, the magnets and the RPC installed between the magnet iron slabs. A part of the Brick Manipulator System (BMS) is also visible.

The detector is composed of two identical parts called supermodules (SM1 and SM2), each consisting of a target section made of arrays of bricks and a scintillator Target Tracker detector (TT) to trigger the read-out and localize neutrino interactions within the target. Each target section is followed by a muon spectrometer, which is a dipole magnet instrumented with resistive plate chambers (RPCs) and drift tubes detectors (HPT), to measure the muon charge and momentum (fig. 1).

3. – Event selection and analysis

In five years of data taking, from 2008 to 2012, OPERA integrated 17.97×10^{19} protons on target (p.o.t.) corresponding to 80% of the initially proposed value.

All electronic detector triggers recorded on-time with the CNGS, are classified as internal or external events by an online algorithm, *i.e.* as interactions inside or outside the OPERA target, respectively. Only internal events are used for oscillation studies. The algorithm further classify the events as charged current (CC) or neutral current (NC) interactions, through the identification of a muon track or the amount of traversed material [5].

The neutrino interaction position is reconstructed and the brick with the highest probability of containing the vertex is extracted from the target. If tracks compatible with TT data are found in the analysis of the set of two emulsion films (called Changeable Sheets or CS doublet) attached externally to the brick, the brick internal films are developed and dispatched to a scanning laboratory in Europe or in Japan. Tracks found in the CS doublet are extrapolated to the most downstream film of the brick where the primary vertex is supposed to be, then followed upstream using its prediction from the

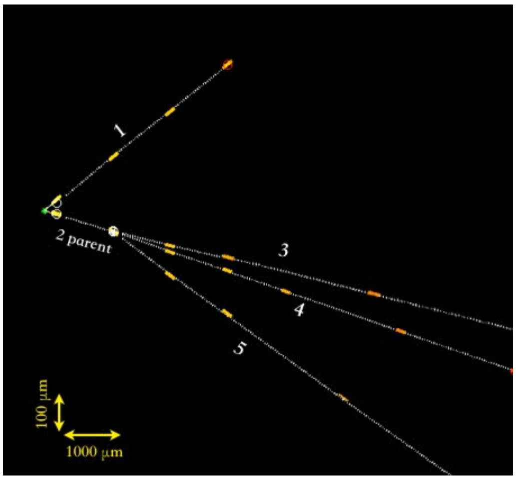

Fig. 2. – Display of the second ν_τ candidate event.

scanning, until they reach their stopping point, *i.e.* when the track is not found in the next three consecutive films. The vertex confirmation is done by scanning a large volume of $\sim 2\,\mathrm{cm}^3$ around the stopping point.

A procedure called decay search is applied afterwards, in order to search for charged or neutral decay topologies, secondary interactions or gamma-ray conversions. If a secondary vertex is found, a full kinematical analysis is performed combining the measurements in the nuclear emulsion with data from the electronic detectors. The momentum of charged particles can be measured in emulsions by the Multiple Coulomb Scattering up to $6\,\mathrm{GeV}/c$ with resolution better than 22% using the angular deviations [6]. It can be measured up to $12\,\mathrm{GeV}/c$ with a resolution better than 33% using position deviations. For muons crossing the spectrometers, the momentum is measured with a resolution better than 22% up to $30\,\mathrm{GeV}/c$, the muon charge is also determined [5]. The hint of a decay topology is the observation of an impact parameter greater than $10\,\mu\mathrm{m}$, defined as the minimum distance between the track and the reconstructed vertex, excluding low momentum tracks.

4. – $\nu_\mu \to \nu_\tau$ oscillation search

The first ν_τ candidate was observed in the 2008-2009 data sample and described in detail in 2010 [7]. The event has seven prongs at the primary vertex. One of these seven tracks exhibits a kink topology and the daughter track is identified as a hadron through its interaction. The impact parameter of the daughter track with respect to the primary vertex is $(55 \pm 4)\,\mu\mathrm{m}$ while the impact parameter is less than $7\,\mu\mathrm{m}$ for the other tracks. Two γ-rays have been found pointing to the secondary vertex.

By computing the invariant mass of the two photons emitted at the decay vertex, a value of $(120 \pm 20(\mathrm{stat.}) \pm 35(\mathrm{syst.}))\,\mathrm{MeV}/c^2$, compatible with the π^0 mass, is found. Combining with the secondary hadron from the decay, assumed to be a π^-, the result is in an invariant mass of $640^{+125}_{-80}(\mathrm{stat.})^{+100}_{-90}(\mathrm{syst.})\,\mathrm{MeV}/c^2$: the decay mode is therefore compatible with $\tau \to \rho(770)\nu_\tau$, whose branching ratio is about 25%.

The second ν_τ candidate was found in the 2011 data sample. As shown in fig. 2 the event is a 2-prong interaction with production of a short track with flight length

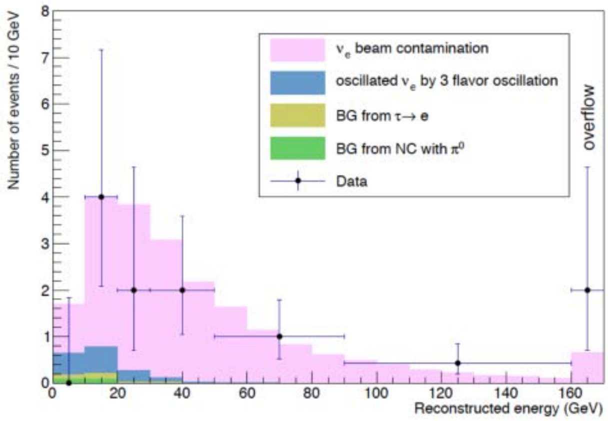

Fig. 3. – Energy distribution of the detected ν_e events comparing to the expectations of beam ν_e and oscillated ν_e.

of 1.54 mm (the assumed τ lepton) and a longer track identified as a hadron. The interaction vertex lies in the lead plate between two emulsion films and one nuclear fragment is associated to the primary vertex. The decay vertex of the τ lepton is in the plastic base in between the two sensitive layers of an emulsion film and no nuclear fragments have been found pointing to the decay vertex. The parent τ lepton decays in three daughter particles, one of them re-interacting four walls downstream and producing two charged tracks and four back-scattered nuclear fragments. The charged hadron at the primary vertex has been followed downstream and has been found to stop after 2 walls: the momentum has been evaluated to be $2.8^{+2.1}_{-2.5}\,\mathrm{GeV}/c$, discarding the hypothesis to be a muon on the basis of the consistency between momentum and range. The daughter particles belonging to the τ decay are also identified as hadrons on the basis of momentum-range consistency. The kinematical analysis of the event finally satisfies all the specified criteria for the $\tau \to 3h$ decay channel.

Since the publication of the first τ candidate in 2010 several improvements were introduced in the analysis in order to reduce the background and improve the signal finding efficiency. In particular, several efforts were done in the study of the ν_μ CC interactions with production of a charmed particle. Charm particles have mass and lifetime close to those of τ lepton and show similar decay topologies; therefore the study of their decay vertex offer the opportunity to benchmark the τ efficiency. The observed events for the 2008–2009 data sample (41 events) are in agreement with Monte Carlo expectations (51.0 ± 7.5 events).

5. – $\nu_\mu \to \nu_e$ oscillation search

A systematic search for ν_e events was applied to the 505 NC like events located in 2008 and 2009 data sample [8]. The number of observed ν_e interactions (19 events) is compatible with the expected ν_e from the beam contamination (19.8 ± 2.8).

Figure 3 shows the reconstructed energy distribution of the 19 ν_e candidates, compared with the expected reconstructed energy spectra from the ν_e beam contamination, the oscillated ν_e from the three-flavour oscillation and the background.

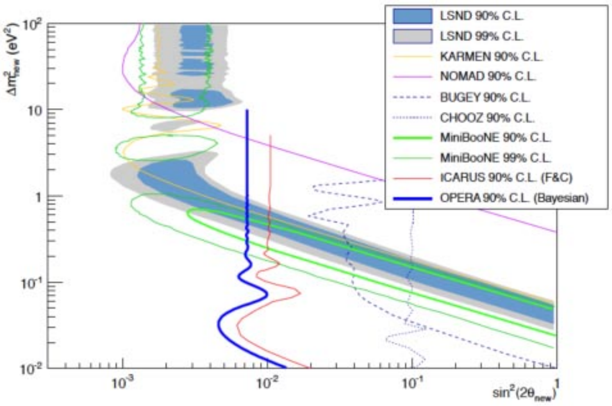

Fig. 4. – The exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillation, obtained from this analysis using the Bayesian method, is shown. Limits from other experiments are also shown.

To increase the signal to background ratio a cut $E < 20\,\text{GeV}$ is applied on the reconstructed energy of the event. As result of the energy cut, 4.2 events from ν_e beam contamination and 0.4 events from the backgrounds are expected, while 4 events are observed. The number of observed events is compatible with the non-oscillation hypothesis and an upper limit $\sin^2(2\theta_{13}) < 0.44$ is derived at the 90% Confidence Level (CL).

OPERA data were used to set an upper limit on non-standard $\nu_\mu \to \nu_e$ oscillations. The $\nu_\mu \to \nu_e$ oscillation probability was expressed in terms of new oscillation parameters θ_{new} and Δm^2_{new}:

$$P_{\nu_\mu \to \nu_e} = \sin^2(2\theta_{new}) \sin^2(1.27 \Delta m^2_{new} L(km)/E(\text{GeV})).$$

The optimal cut on the reconstructed energy in terms of sensitivity is found to be 30 GeV. Six events were observed below $E < 30\,\text{GeV}$, while the expected number of events from background is $9.4 \pm 1.3(\text{syst})$.

Given the under fluctuation of the data, the curve with the Bayesian upper limit was chosen for the exclusion plot shown in fig. 4. For convenience, results from the other experiments, working at different L/E regimes, are also reported in this figure. For large Δm^2_{new} values the OPERA 90% upper limit on $\sin^2(2\theta_{new})$ reaches the value 7.2×10^{-3}, while the sensitivity is 10.4×10^{-3}.

6. – Conclusions

The physics run of the OPERA experiment started in 2008 and ended on December 2012. In total 17.97×10^{19} p.o.t. were collected, corresponding to about 80% foreseen value. The two ν_τ candidate events observed so far have been described.

A systematic search for ν_e CC interactions was performed searching for sub-leading $\nu_\mu \to \nu_e$ oscillations. Using the located NC-like events from 2008–2009 data, 19 ν_e candidates have been detected with an expectation of 19.8 ± 2.8 (syst), a result compatible with the non-oscillation hypothesis. Using the same data sample, OPERA set an upper limit in the parameter space available for a non-standard ν_e appearance.

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