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Recent results of the OPERA neutrino experiment

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The OPERA experiment built in the underground Gran Sasso laboratory (LNGS) was designed to detect neutrino oscillations in direct appearance mode in the mu-neutrino to tau-neutrino channel. The apparatus consisting of 150 000 lead/emulsion modular targets complemented by electronic detectors is placed in the long baseline CERN to Gran Sasso neutrino beam (CNGS) 730 km away from the source. In this paper the running of the detector and the extraction of data from the nuclear emulsions are described, with the special procedures used to locate the interaction vertices and to detect short decay topologies. CNGS neutrino interactions were recorded from 2008 to 2012. Since the report of the two first tau-neutrino candidate events last year, a large amount of additional data has been analyzed. The latest results on oscillations with the increased statistics are presented.

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1. Introduction

Strong evidence in favor of the hypothesis of neutrino oscillations [1] was provided over the past decades by several experiments. In particular, the mixing of neutrino flavor states was confirmed in the atmospheric sector in disappearance mode. A final proof will be set by studying the $\nu_\mu \to \nu_\tau$ oscillation channel in appearance mode.
The Oscillation Project with Emulsion tRacking Apparatus (OPERA) [2] was designed to directly observe tau-neutrino interactions in an almost pure muon neutrino beam.
The CERN Neutrinos to Gran Sasso (CNGS) [3] wide-band, high energy neutrino beam was produced at CERN and delivered at LNGS where the OPERA detector is located. The beam was conceived in order to maximize the number of ν_τ charged current interactions in the target. The mean energy of the beam, about 17 GeV, is indeed well above the tau lepton production energy threshold. The contamination of the beam in terms of $\overline{\nu}_\mu$ CC interactions is about 2%, the contribution coming from ν_e CC and $\overline{\nu}_e$ CC interactions is lower than 1%. For ν_τ CC interactions it is of the order of 10^{-6}. The average L/E_ν ratio is about 43 km/GeV, suitable for oscillation studies at the atmospheric scale.
The CNGS ran for five years and completed its operation in December 2012. A nominal integrated intensity of about 18×10^{19} p.o.t. was delivered.

2. The OPERA experiment

OPERA was designed as a massive detector exploiting the advantages of nuclear emulsion detection technique.
This led to maximize statistics and rely on a very high spatial accuracy that should cope with the peculiar signature of short lived τ lepton produced in ν_τCC interactions (in the millimeter range at the CNGS beam energy). Although the neutrino beam is not optimized for it, OPERA is also able to study the sub-leading $\nu_\mu \to \nu_e$ oscillation channel both at atmospheric and high Δm^2.

2.1 The detector

The OPERA hybrid apparatus consists of two identical Super Modules as shown in Fig. 1. Each Super Module is made up of a target area followed by a muon spectrometer. A single target

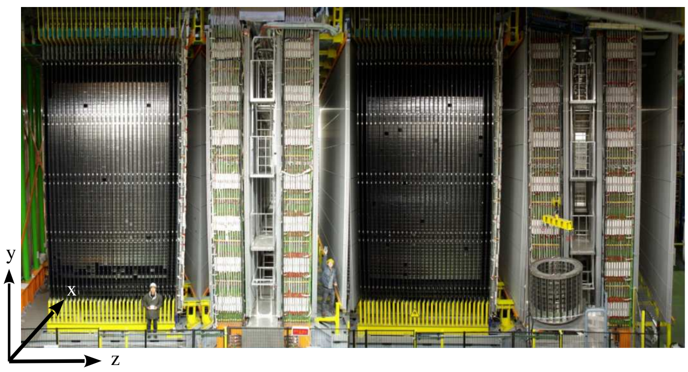

Figure 1: View of the OPERA detector.

section is arranged in 31 vertical "walls", across the beam direction.
Every wall is filled with target elementary constituents, the so-called lead/emulsion "bricks" and it is followed by two planes of plastic scintillator strips, one per transverse direction, called Target Trackers (TT). The TT were designed to locate, on a centimetric scale, the brick where neutrino interactions occured.
The brick structure is such to reconstruct neutrino interactions and short-lived particles decays with a sub-micron accuracy. It also allows charged particles momenta evaluation by Multiple Coulomb Scattering, μ/π identification by *dE/dx* measurements and electromagnetic shower reconstruction. It consists of 57 nuclear emulsion films, interleaved with 1 mm thick lead plates, with a total volume of 7.9x10.2x12.8 cm^3 and mass of 8.3 kg. OPERA emulsion films are made of two 45 μm-thick sensitive layers deposited on each side of a 205 μm plastic base.
An additional tightly packed doublet of emulsion films (Changeable Sheets, CS) is glued to the downstream face of the brick, in order to connect the electronic detectors predictions to the brick.
The overall target mass is about 1.2 kt.
Each spectrometer consists of a dipolar magnet instrumented with planes of Resistive Plate Chambers (Inner Tracker) and drift tubes (Precision Tracker) detectors in order to identify muons mainly from ν_μCC interactions and measure their momentum and charge. The charge-sign misidentification probability was estimated to be of about 0.3% up to 50 GeV/c; the momentum resolution is about 20% in the same kinematical range. A veto system, consisting of planes of glass Resistive Plate Chambers, is placed in front of the first Super Module in order to tag the interactions occurring in the upstream rock.
The apparatus is equipped with an automatic machine (Brick Manipulator System, BMS), allowing the online removal of bricks from the detector, together with some ancillary facilities devoted to the emulsion films' handling. Specially designed and dedicated European and Japanese scanning stations perform the nuclear emulsion film measurement. The experimental apparatus and measurement techniques are described in more details in [4].

2.2 Event location

The events triggered by the neutrino beam, in coincidence with the two 10.5 μs long CNGS spills 50 ms distant ("*on-time*" events), are those used for neutrino oscillation studies. Every time a charged particle belonging to "on-time" events produces a signal in the TT, a brick finding algorithm selects the bricks with the highest probability to contain the neutrino interaction. The efficiency of this procedure is 83% in a sub-sample where up to 4 bricks per event are processed.
The selected brick is removed from the target by the BMS and the corresponding CS doublet is detached from it and developed in a dedicated underground facility. The two emulsion films are scanned in one of the dedicated scanning stations of the Collaboration. The measurement of emulsion films is performed through fast automated microscopes with a scanning speed greater than 20 cm^2/h. The tracking efficiency was evaluated to be about 90%, the position resolution being at the sub-micron level. The angular resolution is of the order of one milliradian. The residuals between electronic detectors' predictions and CS tracks are $\sim$ 1 cm.
If any track originating from the interaction is detected in the CS, the brick is brought to the surface laboratory and exposed to high-energy cosmic rays for alignment purposes and then unpacked. Its emulsion films are developed and sent to the scanning laboratories of the Collaboration for event

location studies and decay search analysis.
All CS tracks are searched for in the most downstream film of the brick. The CS to brick connection is achieved with a position accuracy smaller than 100 μm and a slope accuracy of the order of 10 mrad. Tracks that have been successfully located in a CS doublet are followed upstream through the corresponding brick (*scan-back*) until they stop. This is interpreted as a signature of either a primary or a secondary vertex.
A general scanning (no angular pre-selection) is then performed in a 2 cm^3 volume around the stopping points in order to reconstruct the vertex topology with micrometric precision.
In order to detect decay topologies, every located vertex is carefully investigated by means of a dedicated procedure.

2.3 Decay search

The ν_τ appearance search is based on τ decay topology detection inside the OPERA target. Tau decays inside a brick may be classified in two categories, *short* or *long*, depending on the τ decay length. A decay is defined as *short* if it occurs in the same lead plate as the ν_τ CC interaction or in the first 45 μm-thick emulsion layer downstream of it. Otherwise, the decay is defined as *long*.
At first, interesting topologies are selected by means of topological criteria. The main signature of a τ candidate is the observation of a track with a significant impact parameter (*ip*) relative to the neutrino interaction vertex. Therefore, a check on impact parameters of all the reconstructed primary tracks is mandatory. Only tracks showing an *ip* value smaller than 10 μm are confirmed as primary tracks. All tracks not verifying this selection, have to be further investigated to find whether they are due to scattering in the traversed lead thickness, decay daughter, etc.
The so-called "*in-track*" decay search is then applied to tracks confirmed to belong to the primary vertex, to identify possible small kink angles ($\theta_{kink} > 15$ mrad), which are signatures of decaying particles to be analyzed in more detail.
Extra tracks originated from neutral decays, interactions and gamma ray conversions are searched for inside the measured volume, too. The selected tracks are visually inspected in order to reject electron-positron pairs from gamma-conversion and then investigated as short decays' daughter candidates or long decays' daughter/parent candidates.
Once an interesting secondary vertex topology is found, it is analyzed through kinematical criteria which depend on the decay channel under investigation and are based on particle angles and momenta measured in the emulsion films.

3. Oscillation physics results

At the time of this talk, the data analysis up to the 2010 run events was completed (the rest still being under way). The total amount of fully analysed neutrino interactions was 4969.
Taking into account the sample of decay searched events from 2008 up to 2010 runs, OPERA observed 50 charm decay candidates. Fig. 2 shows good agreement of their characteristics with expectations.

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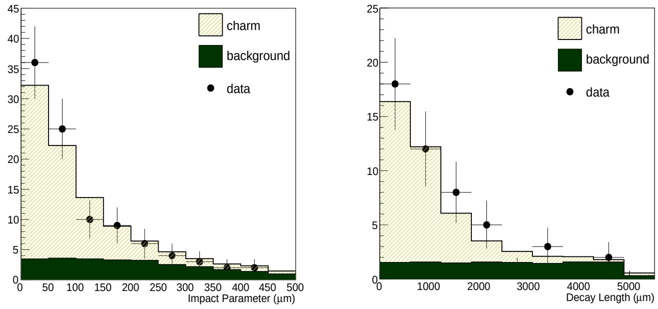

Figure 2: Comparison between observed ν_μ interactions with candidate charm decays and MC expectations. Left: distributions of the impact parameter of the daughter particles with respect to the neutrino interaction vertex; Right: distributions of the decay length of the candidate charmed particle.

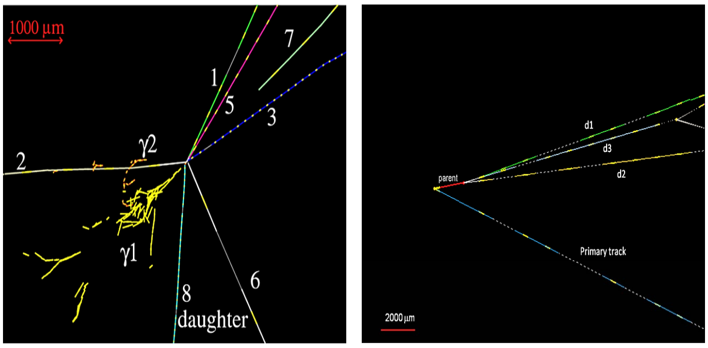

Figure 3: Display of the first (left) and second (right) ν_τCC candidate events.

Moreover, three charged current tau neutrino candidates were detected [5][6], showing three different decay topologies. The first two candidates together with recent interesting results in the sub-leading $\nu_\mu \to \nu_e$ oscillation channel are summarized in the following.

3.1 $\nu_\mu \to \nu_\tau$ oscillation

The first ν_τ CC candidate, from 2009 data sample, is shown in Fig.3. The primary neutrino interaction is reconstructed as seven prong vertex: four tracks are identified as originating from a hadron and three have a probability lower than 0.1% of being a muon. One track exhibits a visible kink. Every kinematical variable satisfies the selection criteria established for hadronic kinks. None of the charged particles at the primary and secondary vertex is identified as electron. Two electromagnetic showers induced by γ-rays associated with the event, were located and studied. Their emission at the secondary vertex is the favored hypothesis and the evaluation of their invariant mass ((120 $\pm$ 20 (stat.) $\pm$ 35 (syst.)) MeV/c^2) supports the hypothesis that they originate from a π^0 decay. The secondary vertex is compatible with the tau one-prong hadronic decay mode $\tau^- \to h(n\pi^0)\nu_\tau$.

The second ν_τ CC candidate was found in the 2011 data sample. The primary neutrino interaction is a two-prong vertex (see Fig.3), one identified as a hadron and the other one, with flight length of about 1.5 mm, as τ lepton. The latter particle decays in three charged particles, one of them re-interacting in emulsion after 10 lead plates. All the decay daughters are identified as hadrons on the basis of momentum-range consistency checks. Moreover, one nuclear fragment is associated to the primary vertex, while no fragment has been found pointing to the decay vertex. Since there are no muons at the primary vertex, satisfying all the defined criteria, the event is compatible with a $\tau \to 3$ hadrons decay channel candidate.

The third candidate event will be described in detail in a coming paper.
The statistical significance of the observation of three ν_τ candidate events is 3.4 σ, the probability being associate to a background fluctuation is equal to $7 \cdot 10^{-4}$.

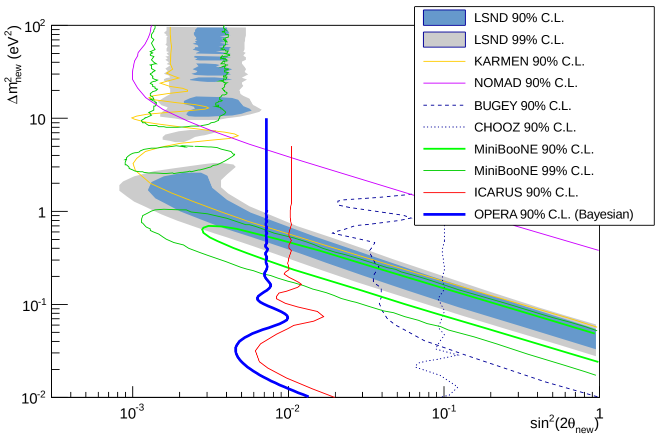

Figure 4: Exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillation. The other limits shown are from KARMEN ($\overline{\nu}_\mu \to \overline{\nu}_e$ [9]), BUGEY ($\overline{\nu}_e$ disappearance [10]), CHOOZ ($\overline{\nu}_e$ disappearance [11]), NOMAD ($\nu_\mu \to \nu_e$ [12]) and ICARUS ($\nu_\mu \to \nu_e$ [13]). The regions corresponding to the positive indications reported by LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ [7]) and MiniBooNE ($\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ [8]) are also shown.

3.2 $\nu_\mu \to \nu_e$ oscillation

A systematic search for ν_e interactions was applied to 505 neutral current located neutrino events from 2008 and 2009 runs data sample. The number of ν_e candidate events is 19, in agreement with the expectation of 19.8±2.8 (syst). To increase the signal to background ratio, event selection with an energy lower than 20 GeV was applied. Within this cut, we observed 4 events with an expectation of 4.6. The number of observed events is compatible with the non-oscillation hypothesis and yields an upper limit of $\sin^2 2\theta_{13} < 0.44$ (90% C.L.).
OPERA has also set an upper limit for non-standard ν_e appearance in the parameter space suggested by the LSND [7] and MiniBooNE [8] experiments in the one mass scale dominance approximation with oscillation parameters θ_{new} and large Δm^2_{new} (>0.1eV^2). An expectation of 9.4±1.3 (syst) events was obtained for neutrino energy lower than 30 GeV (optimal cut on the reconstructed energy in terms of sensitivity), while 6 events were found in the data. The corresponding exclusion

plot is shown in Fig.4. For large Δm^2_{new} values, the 90% C.L. upper limit on $\sin^2 2\theta_{new}$ reaches $7.2{\cdot}10^{-3}$. For comparison, results from other experiments, working at different L/E regimes, are also reported in this figure.

4. Conclusions

The OPERA experiment has ran on the CNGS neutrino beam from 2008 to 2012, collecting about $18 \cdot 10^{19}$ protons on target.
Three tau candidate events have been detected up to now, corresponding to 3.4 σ significance level. From the systematic search for sub-leading $\nu_\mu \to \nu_e$ oscillations in 2008-2009 data sample 19 electron neutrino candidates detected while 19.8 ± 2.8 (syst) were expected. This result is compatible with the non-oscillation hypothesis. The analysis of these data allowed OPERA set an upper limit for a non-standard ν_e appearance in the parameter space indicated by the LSND and MiniBooNE Collaborations.

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