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Neutrino Oscillations in the OPERA experiment

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The OPERA experiment aims to establish neutrino oscillations in direct appearance mode in the $\nu_\mu \to \nu_\tau$ channel, through the detection of the tau lepton produced in ν_τ charged current interactions on event by event basis. The OPERA detector is a hybrid apparatus made of an emulsion/lead target and of electronic detectors. It exploited the CNGS muon neutrino beam from CERN to Gran Sasso, 730 km from the source. The experiment accumulated data for five years from 2008 to 2012.

We report on the large data sample analyzed so far and on $\nu_\mu \to \nu_\tau$ oscillation results. Search for $\nu_\mu \to \nu_e$ transitions and sterile neutrinos are also discussed.

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1. Introduction

The concept of neutrino oscillations was introduced by B. Pontecorvo in 1957 [1]. Later the idea was extended to include mixing between mass and flavor eigenstates and transitions between different neutrino flavors [2]. Neutrino oscillations have been studied by many experiments using solar, atmospheric, reactor and accelerator neutrinos. Most of the existing data coming from those experiments have provided compelling evidence for the existence of neutrino oscillations among three flavor neutrinos, ν_e, ν_μ, ν_τ (and antineutrinos $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) through the mixing of three mass eigenstates [3]. Neutrino oscillations provide the first direct and unambiguous indication for physics beyond the standard model.

Two types of experimental methods have been used to detect neutrino oscillations: (i) observing the appearance of a neutrino flavor initially absent in the beam or (ii) measuring the disappearance rate of the initial neutrino flavor. In the latter case, one has to know precisely the flux of the beam, then explore whether less than the expected number of neutrinos of a produced flavor arrives at a detector or whether the spectral shape changes when observed at various distances from the source. Since the final state is not observed, disappearance experiments cannot determine the flavor of oscillated neutrinos. An appearance experiment searches for possible neutrino flavors not present in the original beam. The identification of the flavor relies on the detection of the lepton produced in neutrino charged current (CC) interactions: $\nu_l N \to l^- X$ with $l = e, \mu, \tau$ and where X denotes the hadronic final state.

Neutrino oscillations have been mainly studied in disappearance mode. The OPERA experiment [4] performs a unique appearance observation of the oscillation products to confirm unambiguously $\nu_\mu \to \nu_\tau$ transition hypothesis in the parameter region indicated by the atmospheric neutrino experiment. Although the neutrino beam is not optimized for it, OPERA performs also a study on sub-leading $\nu_\mu \to \nu_e$ oscillations at atmospheric and large Δm^2.

In the following, the neutrino beam, the OPERA detector with its performances and the event-by-event analysis stream are briefly reviewed. The neutrino oscillation results both on $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ channels are discussed.

2. The neutrino beam and the OPERA detector

The CERN Neutrinos to Gran Sasso (CNGS) neutrino beam [5] was designed and optimized to maximize the number of ν_τ CC interactions at the Gran Sasso underground laboratory (LNGS) in order to study $\nu_\mu \to \nu_\tau$ oscillations in appearance mode in the atmospheric neutrino sector. The average ν_μ beam energy is 17 GeV, higher than the 3.5 GeV kinematic threshold for τ production. The CNGS beam was operated in a neutrino-enhanced mode and provided a high purity ν_μ source with $\bar{\nu}_\mu$ contamination of $\sim 4\%$ in flux, 2.1% in terms of interactions. The ν_e and $\bar{\nu}_e$ contamination were lower than 1%, and the number of prompt ν_τ from D_s decay was negligible, $\mathscr{O}(10^{-6})$. The average L/E_ν ratio was 43 km/GeV, suitable for oscillation studies at atmospheric Δm^2.

The CNGS beam was directed towards the OPERA detector, located 1400 m underground at the LNGS, Italy, 730 km away from the neutrino source. The expected number of ν_τ interactions is small and the measurement is made more challenging by the difficulties of detecting the short

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lived τ^- lepton (cτ=87 μm, decay length $\sim$1 mm at the average CNGS beam energy) produced in the CC interaction of ν_τ.

The OPERA apparatus is designed as a hybrid detector made of two identical supermodules, each one formed by a target section and a muon spectrometer. The spectrometer is used to reconstruct and identify muons and measure their momentum and charge. Each target section is organized in 31 vertical walls, transverse to the beam direction. Walls are filled with emulsion cloud chamber units (ECC), or *bricks* consisting of 56 lead plates, 1 mm thick, interleaved with 57 nuclear emulsion films. An emulsion film is made of two 44 μm thick sensitive layers separated by 205 μm plastic base. Each ECC weighs 8.3 kg for a total target mass of around 1.25 ktons.The lead plates serve as target and the emulsion films as three-dimensional (3D) tracking detectors. An automated system is used to extract the bricks identified by the target tracking system (TT) from the detector. The measurement of emulsion films is performed through high-speed automated microscopes with a sub-micrometric spatial resolution and an angular resolution of the order of 1 mrad. The high position resolution allows to reconstruct the tau decay topology, to measure the momentum of charged particles by Multiple Coulomb Scattering (MCS) and to separate of low energy pions and muons by dE/dx measurements. Electromagnetic showers can be detected in ECC and unambiguously attributed to electrons, γs or π^0.

The ECC technique was successfully used in the DONUT experiment [6] for the first direct observation of the ν_τ. To date, 9 ν_τ CC interactions have been observed by DONUT. In the following the procedure implemented in OPERA to observe ν_τ interactions originate from the $\nu_\mu \rightarrow \nu_\tau$ oscillations are briefly recalled. The experimental apparatus and techniques are described in detail in [4].

3. Event Analysis

All events in OPERA in time coincidence with the two 10.5 μs long spills separated by 50 ms, ("on time" events) are considered for neutrino oscillation studies. Charged particle tracks produced in a neutrino interaction generate signals in the TT section and in the muon spectrometer. Events are classified as CC-like or neutral current (NC)-like interactions based on the presence of at least a 3D reconstructed track identified as a muon in the event. Furthermore, an automatic algorithm is applied in order to select the events contained in the emulsion target. A brick finding algorithm is used to select the brick with the maximum probability to contain the neutrino interaction. Two emulsion films, Changeable Sheets (CS), attached downstream of the brick, are then analyzed in order to validate the brick. In case of positive signal, the brick is exposed to cosmic rays (for alignment purposes) and then depacked. The emulsion films are developed and sent to the scanning laboratories of the Collaboration for event location studies and decay search analysis.

All track information from the CS analysis is used for a precise prediction of the tracks in the most downstream film of the brick (with an accuracy of about 100 μm) [7]. Tracks are then followed back from film to film. The procedure is stopped when no track candidate is found in three consecutive films; the lead plate just upstream the last detected track segment is defined as the vertex plate. A general scanning is performed in a volume around the stopping point. After rejection of the passing through tracks (mostly related to cosmic rays) and of those due to low energy particles, the tracks produced by the neutrino interaction are selected and reconstructed.

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A decay search procedure is applied to detect possible short/long decays or secondary interactions on tracks attached to the primary vertex [8]. The main signature of a τ candidate is the observation of a track with a significant impact parameter relative to the neutrino interaction vertex. When secondary vertices or kink topologies are found, a kinematical analysis is performed based on particle angles and momenta measured in the emulsion films. The following kinematical parameters are considered to distinguish the τ signal from the background: the missing transverse momentum at the primary vertex (p_T^{miss}), the transverse momentum at the decay vertex (p_T^{2ry}), the momentum of daughter track (p_{2ry}), the momentum of muon (p_μ, used in $\tau \to \mu$ channel), the average kink angle ($< \theta_{kink} >$), the angle between the τ candidate direction and the primary hadronic shower in the plane perpendicular to the CNGS axis (ϕ_{lH}), the flight length, the invariant mass (m_{inv}) and the minimal invariant mass (m_{min}).

4. Neutrino Oscillations results

The OPERA detector was exposed to the CNGS beam from 2008 to 2012 corresponding to 17.97×10^{19} protons on target (pot). A sample of 19505 neutrino interactions contained in the OPERA target was collected. For runs 2008-2009, all events were searched for in the two most probable bricks while for runs 2010-2012 only the first most probable brick have been analyzed so far. The analysis will be extended to the second most probable bricks for runs 2010-2012. A muon momentum cut at 15 GeV/c was introduced. At the time of this conference, 4685 (979 NC-like events and 3706 CC-like events) neutrino interactions had been fully analyzed looking for decay topologies. Additonal of 835 CC-like events with a muon momentum larger than 15 GeV/c from runs 2008-2009 had been analyzed in order to probe understanding of the beam spectrum and the detector response. The selection criteria of ν_τ interactions and the evaluation of efficiencies are described in detail in [9].

4.1 $\nu_\mu \to \nu_\tau$ oscillations

The ν_τ signature is given by the decay topology and kinematics of the short lived τ^- leptons produced in the interaction of $\nu_\tau N \to \tau^- X$ and decaying to one prong (μ, e or $hadron$) or three prongs. Four ν_τCC interaction candidates have been detected and reported in [9-12].

The first ν_τ candidate was observed in the 2008-2009 data sample [10]. The tau candidate track exhibits a visible kink with two electromagnetic showers induced by gamma rays. As shown in Table 1, measured kinematical parameters satisfy the selection criteria established for one prong hadronic decay of the tau lepton. The invariant mass of the two observed γ-rays is $120 \pm 20(stat) \pm 35(syst)$ MeV/c^2 supporting the hypothesis that they are emitted in a π^0 decay. Assuming the charged decay daughter to be a π^- with two γ-rays, the invariant mass becomes $640^{+125}_{-80}(stat)^{+100}_{-90}(syst)$ MeV/c^2, which is compatible with the $\rho(770)$ mass. So the event is consistent with the interaction of a ν_τ in the OPERA target producing a τ lepton that decays in $\tau^- \to \rho^- \nu_\tau$ and $\rho^- \to \pi^- \pi^0$ and $\pi^0 \to \gamma\gamma$.

The second ν_τ candidate is fully described in detail in [9]. The τ candidate track decays into three charged hadrons in the plastic base of the emulsion film, just between the two emulsion film layers, without any nuclear fragment pointing to it. The ranges of the three decay daughters are

Variable	Selection ($\tau \to 1h$)	1^{st} candidate	4^{th} candidate
$< \theta_{kink} >$ (mrad)	> 20	41 ± 2	137 ± 4
Decay Length (μm)	< 2600	1335 ± 35	406 ± 30
p_{2ry} (GeV/c)	> 2	12^{+6}_{-3}	$6.0^{+2.2}_{-1.2}$
p_T^{2ry} (GeV/c)	> 0.6 (0.3^*)	$0.47^{+0.24}_{-0.12}$	$0.82^{+0.30}_{-0.16}$
p_T^{miss} (GeV/c)	< 1	$0.57^{+0.32}_{-0.17}$	$0.55^{+0.30}_{-0.20}$
$\Delta\phi_{\tau H}$ (degrees)	> 90	172.5 ± 1.7	166^{+2}_{-31}

Table 1: Selection criteria for ν_τ interaction search in the $\tau \to 1h$ decay channel and the values measured for the first and fourth ν_τ candidate events. Cut marked with * is applied if there is at least one γ-ray originating from the decay vertex.

Variable	Selection ($\tau \to 3h$)	2^{nd} candidate
$< \theta_{kink} >$ (mrad)	< 50	87.4 ± 1.5
Decay Length (μm)	-	1446 ± 10
p_{2ry} (GeV/c)	> 3	8.4 ± -1.7
p_T^{miss} (GeV/c)	< 1	0.31 ± 0.11
$\Delta\phi_{\tau H}$ (degrees)	> 90	167.8 ± 1.1
m_{min} (GeV/c^2)	$>$ 0.5 and $<$ 2	960 ± 130
m_{inv} (GeV/c^2)	$>$ 0.5 and $<$ 2	800 ± 120

Table 2: Selection criteria for ν_τ events in the $\tau \to 3h$ decay channel along with the values measured for the candidate event. Variables are defined in the text.

Variable	Selection ($\tau \to \mu$)	3^{rd} candidate
$< \theta_{kink} >$ (mrad)	> 20	245 ± 5
Decay Length (μm)	< 2600	151 ± 10
p_μ (GeV/c)	[1, 15]	2.8 ± 0.2
p_T^{2ry} (MeV/c)	> 250	690 ± 50

Table 3: Selection criteria for ν_τ events in the $\tau \to \mu$ decay channel along with the values measured for the candidate event. Variables are defined in the text.

consistent with the hadron hypothesis. The kinematical variables of the event are compatible with the expectation for the $\tau \to 3h$ decay as shown in Table 2.

The third ν_τ candidate was found in the $\tau \to \mu$ channel. The τ decay length is 370 ± 10 μm and the kink angle is $\theta_{kink} = 245 \pm 5$ mrad. The sign of the muon charge was determined to be negative with a 5.6 σ significance. The event satisfies all the kinematical requirements summarized in Table 3 for the $\tau \to \mu$ decay channel. The main background source of this event is the large angle scattering of the muon track. It is highly disfavored since the decay occurs in the plastic base which is made of low density and low-Z material, with $p_T^{2ry} = 690 \pm 50$ MeV/c. More discussions on the event can be found in [11].

The fourth ν_τ candidate was found in the $\tau \to 1h$ decay channel. The detail of the event is reported in [12]. The kinematical variables for this event are summarized in Table 1.

4.1.1 Background and statistical significance

The main source of background to all τ decay channels is constituted by charged charmed particles produced in ν_μCC interactions where the primary muon is not detected or is misidentified. A specific background to the $\tau \to \mu$ channel arises from large angle muon scattering. A source of background affecting the hadronic decay channel comes from one-prong inelastic interactions of primary hadrons produced in NC interactions, or in CC interactions where the primary lepton is not identified, and in which no nuclear fragments can be associated with the secondary interaction.

The estimated signal and background for the observed ν_τ candidates are reported in [9-12] and summarized in Table 4. The systematic uncertainties are: 20% on the signal, 20% on the charm background, 30% on the hadronic background and 50% on the large-angle muon scattering background. The number of expected ν_τ in the analyzed data sample is 2.11 ± 0.42 in all decay channels, with an overall background of 0.233 ± 0.041 events.

The probability for the observed four candidates to be a background fluctuations is 1.24×10^{-5}. This corresponds to a significance of 4.2 σ for the exclusion of the null hypothesis.

Decay channel	Expected signal	Observed	Expected background			
			Total	Charm decays	Hadronic re-interactions	Large-angle muon scattering
$\tau \to 1h$	0.41 ± 0.08	2	0.033 ± 0.006	0.015 ± 0.003	0.018 ± 0.005	/
$\tau \to 3h$	0.57 ± 0.11	1	0.155 ± 0.030	0.152 ± 0.030	0.002 ± 0.001	/
$\tau \to \mu$	0.52 ± 0.10	1	0.018 ± 0.007	0.003 ± 0.001	/	0.014 ± 0.007
$\tau \to e$	0.62 ± 0.12	0	0.027 ± 0.005	0.027 ± 0.005	/	/
Total	2.11 ± 0.42	4	0.233 ± 0.041	0.198 ± 0.040	0.021 ± 0.006	0.014 ± 0.007

Table 4: Estimated signal and background for the analyzed sample and the number of observed events.

4.1.2 Measurement of Δm^2_{23}

With four observed ν_τ candidate, 0.233 ± 0.041 background events, and assuming maximal mixing, the confidence interval of Δm^2_{23} is estimated by using both Feldman-Cousins and Bayesian methods. The systematic uncertainties on the signal and the background discussed in the previous section, have been taken into account. The 90% confidence interval for Δm^2_{23} is $[1.8, 5.0] \times 10^{-3}$ eV^2. Using a Bayesian approach with a flat prior on Δm^2_{23}, a confidence interval of $[1.9, 5.0] \times 10^{-3}$ eV^2 have been found [12].

4.2 $\nu_\mu \to \nu_e$ oscillations

The good capability of electron identification and the small contamination of ν_e in the CNGS neutrino beam allows the experiment to perform a $\nu_\mu \to \nu_e$ oscillation search [13]. The appearance of ν_e has been searched using the data collected in 2008 and 2009, corresponding to an integrated intensity of 5.25×10^{19} pot. A systematic search for ν_e events was applied to 505 NC-like events. 19 ν_e candidates were found, in agreement with the expectation of 19.8±2.8 (syst) events (19.4 events from the intrinsic ν_e beam component, 0.3 events from $\tau \to e$ and 0.2 events from π^0 decay). The dominant component is due to the ν_e beam contamination, therefore in the three flavour oscillation scenario (1.4 events expected from $\nu_\mu \to \nu_e$ oscillations assuming PDG values [3] for three neutrino oscillations), the number of observed events are compatible with a non-oscillation hypothesis. This allows to set limit to $sin^2 2\theta_{13} < 0.44$ (90% C.L.).

OPERA set an upper limit for a non-standard ν_e appearance in the parameter space suggested by the results of the LSND [14] and MiniBooNE [15] experiments. 9.4±1.3 $(syst)$ events were expected below 30 GeV neutrino energy, while 6 events were found in the data. Given the underfluctuation of the data, a Bayesian statistical approach was followed to determine the upper limit and the exclusion plot shown in Figure 1. For large Δm^2_{new} values, the 90% C.L. upper limit on $sin^2 2\theta_{new}$ reaches 7.2×10^{-3}, while the sensitivity corresponding to the analyzed statistics is 10.4×10^{-3}.

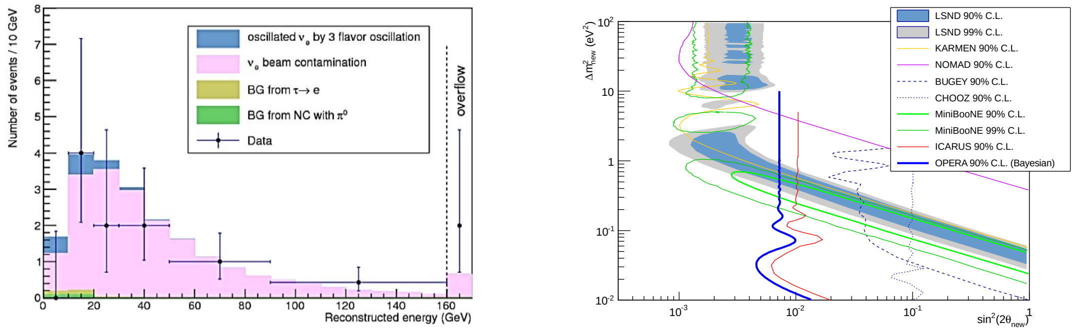

Figure 1: Left: Distribution of the reconstructed energy of the ν_e events and expected spectrum from different sources, normalized to the number of pots analyzed. Right:The exclusion plot for the parameters of the non-standard $\nu_\mu \rightarrow \nu_e$ oscillation.

5. Conclusions

The status of neutrino oscillations in the OPERA experiment has been discussed. The physics run of the OPERA experiment started in 2008 and ended on December 2012. In total 17.97×10^{19} pots were delivered. Four ν_τ candidates have been observed in the analyzed sample corresponding to a 4.2 σ statistical significance for the observation of the ν_τ appearance. Using the observed number of ν_τ candidates, confidence intervals of Δm^2_{23} have been estimated for the first time in $\nu_\mu \rightarrow \nu_\tau$ appearance.

A search for ν_e was performed with the data collected in the first two years of data taking. The analyzed sample provides a competitive bound on non-standard oscillations at large Δm^2. The upper limit on the new possible mixing angle $sin^2 2\theta_{new}$ is 7.2×10^{-3} at 90% C.L. in the large Δm^2 region. By increasing the statistics, OPERA can access the parameter region $sin^2 2\theta_{new} > 5.0 \times 10^{-3}$.

References

[1] B. Pontecorvo, *Mesonium and anti-mesonium*, Sov. Phys. JETP **6** (1957) 429 and Sov. Phys. JETP **7** (1958) 172.

[2] Z. Maki, M. Nakagawa, and S. Sakata, *Remarks on the unified model of elementary particles*, Prog. Theor. Phys. **28** (1962) 870.

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[3] K. A. Olive *et al.* [Particle Data Group], *The review of particle physics*, Chin. Phys. C **38** (2014) 090001.

[4] R. Acquafredda *et al.* [OPERA collaboration], *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, JINST **4** (2009) P04018.

[5] CNGS *project*, http://proj-cngs.web.cern.ch/prj-cngs/.

[6] K. Kodama *et al.* [DONUT Collaboration], *Final ν_τ results from the DONUT experiment*, Phys. Rev. D **78** (2008) 052002.

[7] J. Yoshida *et al.*, *Development and utilization of 'Plate Changer' system for neutrino interaction location in OPERA emulsion target*, JINST **8** (2013) P02009.

[8] N. Agafonova *et al.* [OPERA Collaboration], *Procedure for short-lived particle detection in the OPERA experiment and its application to charm decays*, Eur. Phys. J. C **74** (2014) 2986.

[9] N. Agafonova *et al.* [OPERA Collaboration], *New results on $\nu_\mu \to \nu_\tau$ appearance with the OPERA experiment in the CNGS beam* , JHEP **11** (2013) 036 and Erratum-ibid. **04** (2014) 014.

[10] N. Agafonova *et al.* [OPERA Collaboration], *Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam* , Phys. Lett. B **691** (2010) 138.

[11] N. Agafonova *et al.* [OPERA Collaboration], *Evidence for $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam with the OPERA experiment*, Phys. Rev. D **89** (2014) 051102(R).

[12] N. Agafonova *et al.* [OPERA Collaboration], *Observation of tau neutrino appearance in the CNGS beam with the OPERA experiment*, Prog. Theor. Exp. Phys. (2014) 101C01.

[13] N. Agafonova *et al.* [OPERA Collaboration], *Search for $\nu_\mu \to \nu_e$ oscillations with the OPERA experiment in the CNGS beam*, JHEP **07** (2013) 004 and Addendum-ibid. **07** (2014) 085.

[14] A. Aguilar-Arevalo *et al.* [LSND Collaboration], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049].

[15] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration] [arXiv:1207.4809 [hep-ex]].