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Latest results from the OPERA experiment

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Latest results from the OPERA experiment

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Abstract. The OPERA experiment has been designed to perform the first detection of neutrino oscillations in the $\nu_\mu \rightarrow \nu_\tau$ channel in direct appearance mode, through the event by event detection of the τ lepton produced in ν_τ charged current interactions. OPERA is a hybrid detector, made of emulsion/lead target elements and of electronic detectors, placed in the CNGS muon neutrino beam from CERN to Gran Sasso, 730 km away from the source. Neutrino interactions from the CNGS neutrino runs were recorded from 2008 until the end of 2012. We report on the data sample analysed so far and give the latest OPERA results on $\nu_\mu \rightarrow \nu_\tau$ oscillation, ν_e analysis and the first ν_μ disappearance study.

1. Introduction

The 3-flavour oscillation framework and the PMNS matrix describe with success the results from solar, atmospheric, reactor and neutrino beam experiments. However most of the results have been obtained from neutrino disappearance phenomena involving muon and electron neutrinos and anti-neutrinos, the only exception being $\nu_\mu \rightarrow \nu_e$ from T2K and NOvA. For the ultimate confirmation of the whole theoretical framework the oscillation picture needs to be proved also in the flavour appearance modes. OPERA [1] was a long baseline neutrino experiment located in the Gran Sasso underground laboratory (LNGS) in Italy. The collaboration is composed of about 140 physicists coming from 26 institutions in 11 countries. The experiment is a massive hybrid detector with nuclear emulsions used as very precise tracking devices and electronic detectors to locate the neutrino interaction events in the emulsions. It was designed to primarily search for ν_τ appearance in the CERN high energy ν_μ beam CNGS [2] at 730 km from the neutrino source, in order to establish unambiguously the origin of the neutrino oscillations observed at the “atmospheric” Δm^2 scale. The preferred hypothesis to describe this phenomenon being $\nu_\mu \rightarrow \nu_\tau$ oscillation.

In addition to the dominant $\nu_\mu \rightarrow \nu_\tau$ oscillation and the ν_μ disappearance, the sub-leading $\nu_\mu \rightarrow \nu_e$ transition occurs as well due to the non zero θ_{13} mixing angle. This process is also investigated by OPERA profiting from its electron identification capabilities. This also allows to study possible non standard oscillation process.

The ν_τ direct appearance search is based on the observation of events produced by charged current (CC) interactions with the τ lepton decaying in leptonic and hadronic modes. The principle of the OPERA experiment is to observe the τ trajectory and its decay products in stacks of lead plates and emulsion films each composed of two thin emulsion layers (44 μm thick) put on either side of a plastic base (205 μm thick). The detector concept combines micrometer tracking resolution with large target mass (Sect 2). This concept allows good lepton



identification and efficient rejection of the main background coming from charm production in ν_μ CC interactions.

2. The CNGS beam and the OPERA detector

The CNGS neutrino beam [2] is a high energy wide band conventional ν_μ beam designed to maximise the ν_τ charged current interactions at Gran Sasso produced by the oscillation mechanism at the atmospheric Δm^2 . The mean neutrino energy is about 17 GeV with a contamination of 2.1% $\bar{\nu}_\mu$, 0.9% ν_e and less than 0.06% $\bar{\nu}_e$. Using the CERN SPS accelerator in a shared mode with fixed target experiment and with LHC, a total intensity of 18×10^{19} protons on target (pot) have been delivered from 2008 to December 2012. The 400 GeV protons were extracted from the SPS accelerator by 2 fast extractions lasting 10.5 μ s each and separated by 50 ms per SPS cycle. With an average of 2×10^{13} protons per extraction the corresponding average beam power over the running period amounts to 160 kW with a maximum of 480 kW achieved [3].

Figure 1 summarizes the performance of the CNGS beam by showing the integrated proton on target intensity as a function of time during the 5 years of physics running. The record performance was achieved in 2011 while in 2012 it was lower, mainly because the proton intensity per extraction was decreased due to radiation limits in the accelerator complex.

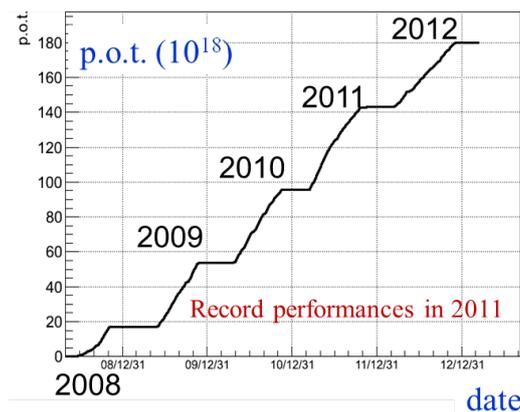


Figure 1. Integrated CNGS delivered proton on target intensity as a function of the time since 2008.

The neutrino produced at CERN arrived at the INFN Gran Sasso underground laboratory (LNGS) in Italy. The laboratory is located at an average rock overburden of 3700 m.w.e. It consists of three large experimental halls with the longest axis oriented towards CERN.

Figure 2 shows a picture of the OPERA detector which is 20 m long with a cross section of about 8×9 m² and composed of two identical parts called super modules (SM). Each SM has a target section and a muon spectrometer. The spectrometer allows a determination of the charge and momentum of crossing muons by measuring their curvature in a bipolar magnet made of 990 tons of iron, and providing a 1.53 T magnetic field transverse to the neutrino beam axis. Each spectrometer is equipped with six vertical planes of drift tubes (Precision Tracker) together with 22 planes (8×8 m²) of RPC chambers reaching a spatial resolution of ~ 1 cm and an efficiency of 96%. The precision tracker planes are composed of 4 staggered layers of 168 aluminium tubes, 8 m long with a 38 mm outer diameter. The spatial resolution of this detector is better than 500 μ m. The physics performance of the complete spectrometer reduces the charge confusion to less than 0.5% [4] and gives a momentum resolution better than 20% for momentum less than 25 GeV. The muon identification efficiency reaches 95% after adding the target tracker information for the cases where the muons stop inside the target.

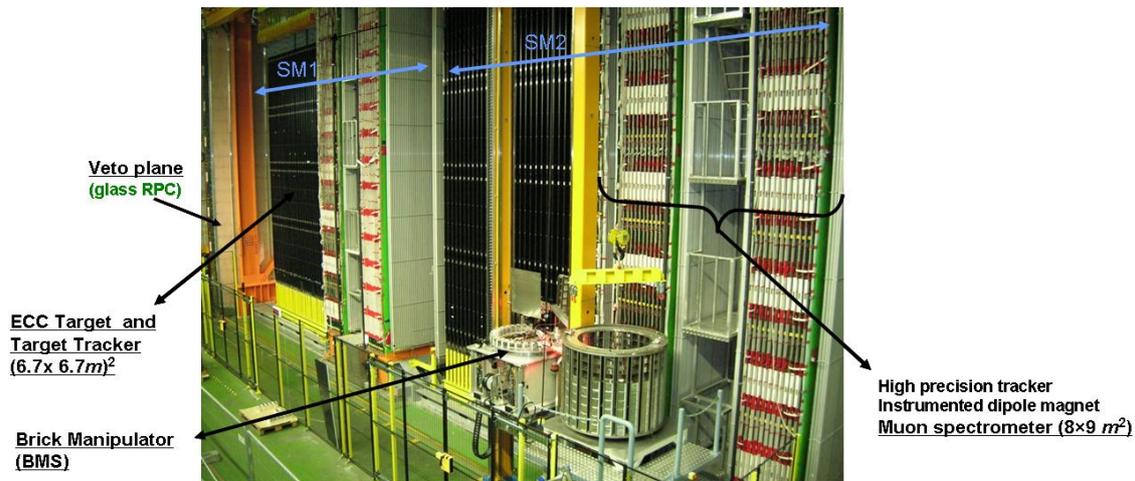


Figure 2. View of the OPERA detector in Hall C of the Gran Sasso Underground Laboratory.

The target section is composed of vertical light supporting steel structures, called walls, interleaved with double layered planes of 6.6 m long scintillator strips in the two transverse directions. The main goals of this electronic detector are to provide a trigger for the neutrino interactions, an efficient event pattern recognition together with the magnetic spectrometer allowing a clear classification of the ν interactions and a precise localisation of the event. The electronic target tracker spatial resolution reaches ~ 0.8 cm and has an efficiency of 99%. The walls contain the basic target detector units, called “brick”, which are stacks of 56 lead plates interleaved with 57 emulsion films. This structure provides a massive target coupled to a very precise tracker, as well as a standalone detector to measure electromagnetic showers and charged particle momentum using multiple Coulomb scattering in lead [5]. Tracks segments are reconstructed using automated microscopes with angle and position resolutions of 2 mrad and $0.21 \mu\text{m}$, respectively. Downstream of each brick, an emulsion film doublet, called Changeable Sheet (CS) is attached in a separate plastic envelope. The CS is detached from the brick for analysis to confirm and locate the tracks produced in neutrino interactions.

3. Event Analysis

The OPERA event analysis, detailed in [6], proceeds in several steps starting by the acquisition of events generating a trigger in the electronic detectors in time coincidence with the CNGS spills. An on-line filtering is applied to keep the events with sufficient number of hits in the target tracker planes and to remove background from random noise. Using the target tracker and spectrometer information the events are reconstructed and classified as charged current-like (1μ) or neutral current-like (0μ).

A total of 17.97×10^{19} pot have been collected by OPERA since 2008 which is to 20% less than what was foreseen in the experiment proposal [7].

With a trigger efficiency of 99%, a pure sample of 106422 on time events were recorded: about 60% are from neutrino interactions in the rock surrounding the detector and about 20% are interactions occurring in the spectrometer. The remaining 20% yields 19505 contained events of which 83% are fully reconstructed in the target. Table 1 summarises the characteristics of the collected data sample during the CNGS running years.

3.1. Location of the ν interaction and vertex reconstruction

For contained events, namely those with the neutrino interaction occurring in the emulsion target, a brick finding algorithm based on the energy deposition in the target tracker strips and

Table 1. Summary of the collected data sample, the number of beam days and interactions [6] in the target during the 5 years of run.

year	protons on target	SPS efficiency	beam days	ν interactions
2008	1.74×10^{19}	61 %	123	1931
2009	3.53×10^{19}	73 %	155	4005
2010	4.09×10^{19}	80 %	187	4515
2011	4.75×10^{19}	79 %	243	5131
2012	3.86×10^{19}	82 %	257	3923

on muon track information (if available), is applied to define a three dimensional probability map for the brick vertex localisation. The identified brick is then extracted using automated brick manipulators located on each side of the experiment. The CS film is readout by automated optical microscopes (“scanned”) to confirm the vertex in the corresponding brick. In case of positive feedback, the emulsions in the brick are developed and sent to emulsion scanning laboratories in Europe and Japan hosting high speed automated optical microscopes. This last step is the start of the detailed event analysis for the neutrino vertex location and decay kink topology reconstruction in the vertex region.

In order to optimise the search for $\nu_\mu \rightarrow \nu_\tau$ oscillation, the scanning strategy has evolved with time. The oscillation results shown in this paper are based on the analysis of the complete data sample which takes into account the two most probable bricks [8]. The events are classified in two categories: the NC-like events for which no muon has been identified and the CC-like events with a muon with a momentum less than 15 GeV.

The vertex location is performed by following back the predicted tracks from the CS film doublets inside the brick taking into account multiple Coulomb scattering and measurement error effects. This “scanback” procedure is stopped when the track is not seen in three consecutive films. A detailed volume scan is then performed around the stopping point defined by a transverse area of 1 cm^2 for 5 films upstream and 10 films downstream of it. After rejecting passing through tracks and short tracks, tracks pointing to an interaction vertex are searched for in the corresponding volume. The mean efficiency to locate a neutrino interaction vertex is about 74% for CC-like events and 48% for NC-like events, compatible with the expected values from the Monte Carlo simulation [6].

Once a vertex has been identified, a “decay search” procedure aiming at detecting the decay topologies of τ leptons or charm hadrons is performed. A decay signature can be associated to a daughter track with a large impact parameter or with a significant kink with respect to a primary track. The number of decay searched events in the full data set amounts to 1144 NC-like and 4264 CC-like events [8].

3.2. Charm hadron production

The charm hadron production is an important process to control the performance and the efficiencies of the analysis for identifying τ decays and validate the decay search procedure. The charm topology is similar to the τ lepton one for what concerns the mass, the decay modes and the lifetime with the exception of the muon produced at the primary interaction vertex in the case of charm ν_μ CC. By analysing the 2008 to 2010 data sample, a total of 50 charm events have been observed with an expectation of 54 ± 4 events [9]. Table 2 summarises the observed and expected events in the different charm decay channels. The background events originate mostly from hadronic interactions (87%), the rest coming from long lived hadron decays (K_S^0 and Λ).

Table 2. Summary of the observed and expected charm events in the different decay channels [9].

topology	observed events	MC expected events		
		charm	background	total
Charged 1-prong	19	21 ± 2	9 ± 3	30 ± 4
Neutral 2-prongs	22	14 ± 1	4 ± 1	18 ± 2
Charged 3-prongs	5	4 ± 1	1.0 ± 0.3	5 ± 1
Neutral 4-prongs	4	0.9 ± 0.2	< 0.1	0.9 ± 0.2
Total	50	40 ± 3	14 ± 3	54 ± 4

Figure 3 shows the comparison of the data with the MC prediction for the charm impact parameter distribution, the decay length and the angle in the transverse plane between the muon track and the parent track. The agreement is very good for both the shapes and the total yields of charm events.

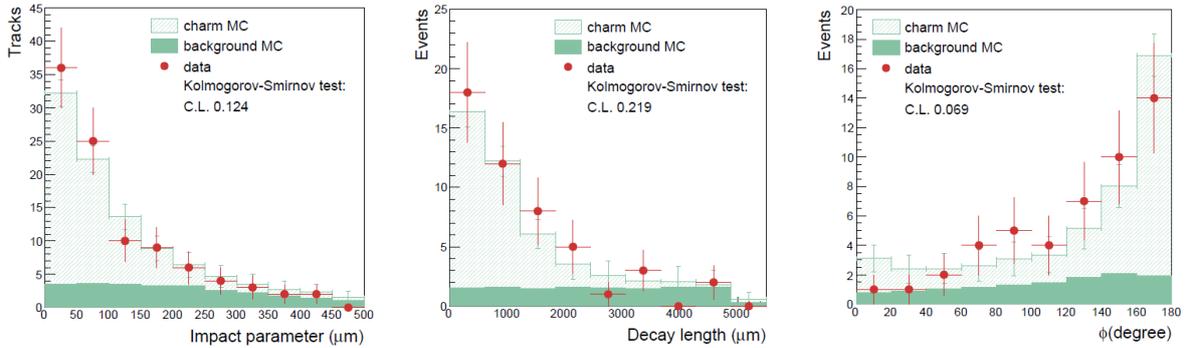


Figure 3. Distributions of the impact parameter (left), decay length (middle) and angle in the transverse plane between the muon and the parent (right) of the charm events. The dots are the OPERA data and the histograms are Monte Carlo predictions for the charm and background events.

This result validates the procedures of the τ search analysis chain with a systematic uncertainty on efficiencies not exceeding 20%.

4. $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

The three main background sources are the ν_μ CC charm production (4% of CC) with missing or mis-identified primary μ ; the nuclear interactions of hadrons (0.2% of NC) and the large angle coulomb scattering of μ .

The kinematical variables used to reduce the background sources are the flight length, the total transverse momentum of τ daughters with respect to the τ direction, the missing transverse momentum at the primary vertex and the ϕ angle of the τ with respect to the hadronic shower in the beam transverse plane.

Applying the kinematical selection criteria described in [6] five ν_τ candidate events have been observed in the analysed data sample with an expected background of 0.25 dominated by the charm in the electron, muon and 3-prong decay channels.

The first ν_τ candidate was published [10] in 2010 based on the analysis of 35% of 2008/2009 data sample. The event characteristics are compatible with a τ decaying into a ρ meson ($\tau^- \rightarrow \rho^- \nu_\tau$ with subsequent $\rho^- \rightarrow \pi^- \pi^0$). The τ decay length is $1335 \pm 35 \mu\text{m}$ with a kink angle of $41 \pm 2 \text{ mrad}$.

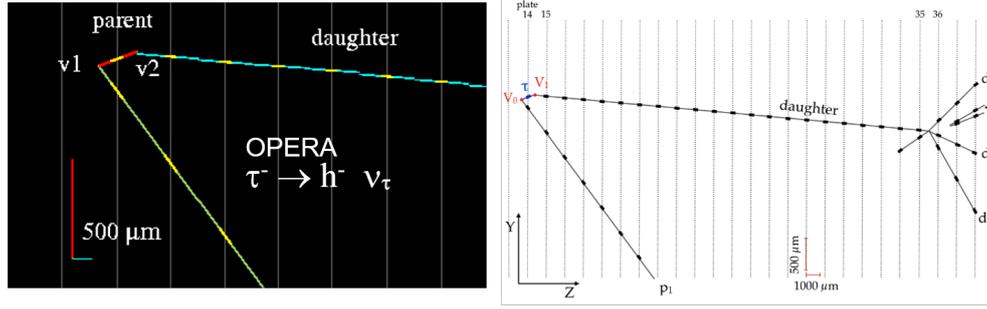


Figure 4. Two different views of the event display of the fifth tau candidate observed in OPERA

The second ν_τ candidate was collected in 2011 [6]; the topology is compatible with a 3-prong τ decay ($\tau^- \rightarrow h^+ h^- h^- \nu_\tau$) with a flight length of $1446 \pm 10 \mu\text{m}$. The third ν_τ candidate, recorded in 2012 [11], shows a topology compatible with a leptonic τ decay ($\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$) with a flight length of $376 \pm 10 \mu\text{m}$ and a kink angle of $245 \pm 5 \text{ mrad}$. The fourth ν_τ candidate was recorded in 2012 [12]; it shows a topology compatible with a 1-prong τ decay ($\tau^- \rightarrow h^- \nu_\tau$) with a flight length of $1090 \pm 30 \mu\text{m}$ and a kink angle of $137 \pm 4 \text{ mrad}$.

The fifth ν_τ candidate which allowed to claim the discovery of ν_τ appearance in a ν_μ beam [8] shows a topology compatible with a 1-prong τ decay ($\tau^- \rightarrow h^- \nu_\tau$) with a flight length of $634 \pm 30 \mu\text{m}$ and a kink angle of $90 \pm 2 \text{ mrad}$. Figure 4 shows the event display of this candidate event. The display on the right side shows an hadronic interaction of the daughter hadron after traversing about 20 lead plates. The distributions of the kink angle and the angle ϕ of the τ with respect to the hadronic shower in the beam transverse plane are shown in Figure 5. The histograms represent the MC expectation for the $\tau \rightarrow h^- \nu_\tau$ channel after selection. The vertical line shows the measured values of the observed event.

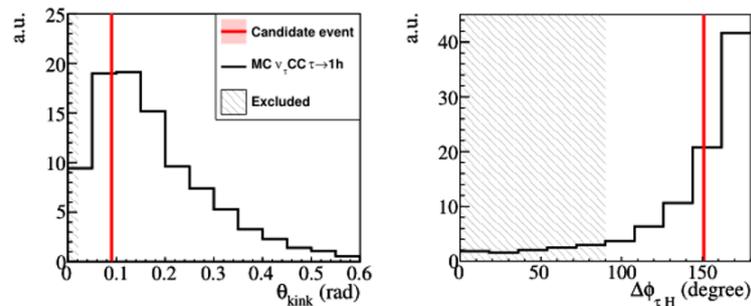


Figure 5. Distributions of the kink angle (left) and the ϕ angle of the τ with respect to the hadronic shower in transverse plane to beam (right) for the $\tau^- \rightarrow h^- \nu_\tau$ channel. The vertical lines show the measured values of the fifth ν_τ candidate.

The probability for the 5 candidate events to be explained by background fluctuation was estimated to be 1.1×10^{-7} . From the latter the no-oscillation hypothesis is excluded at 5.1σ . Assuming full mixing a best fit value of $\Delta m_{23}^2 = 3.3 \times 10^{-3} \text{ eV}^2$ with a 90% C.L. interval of $[2.0, 5.0] \times 10^{-3} \text{ eV}^2$ is obtained.

5. ν_μ disappearance analysis

A new analysis is being developed in OPERA to study the possibility of observing and measuring the ν_μ disappearance despite the fact that CNGS is a high energy beam optimised for ν_τ appearance therefore far from the oscillation maximum. The disappearance effect is expected to be only a few percent. The analysis relies on the energy of the neutrino interactions measured

with the scintillator planes of the target tracker. In the absence of a near detector and to reduce the systematics due to flux uncertainties the chosen variable is the ratio of the energy distribution of the NC-like events to the CC-like events shown in Figure 6 (left).

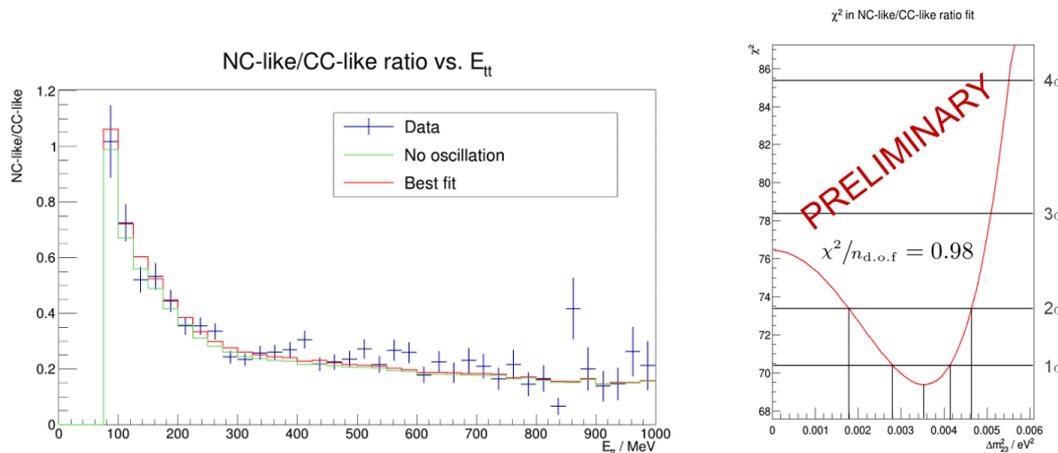


Figure 6. Left: Distribution of the ratio of the energy deposited in the electronic detector of the NC-like events to the CC-like events. Right: χ^2 distribution of the fit to Δm_{23}^2 .

The red and green lines show the expectation with and without oscillation respectively. The difference is larger at low energy. By performing a fit of the prediction to the measured ratio as a function of the deposited energy in the target scintillators and fixing all the parameters but Δm_{23}^2 one obtains the χ^2 distribution of Figure 6 (right). It gives a preliminary estimate of Δm_{23}^2 consistent with the world average and the internal OPERA appearance result.

6. ν_e appearance search

The good electron identification and tracking capabilities of emulsions allow to study the ν_e charged current interactions and therefore to search for ν_e appearance from $\nu_\mu \rightarrow \nu_e$ oscillations. Given the long baseline and the high energy of the ν_μ beam, OPERA can investigate possible exotic processes modifying the number of expected ν_e candidates (sterile neutrinos, non standard interactions). The analysis reported here uses the full data set corresponding to 18×10^{19} pot. A total of 34 ν_e candidate events were found. The expected number of events consists of 36.7 ± 5 events from ν_e beam contamination and 1.2 ± 0.1 background events from $\tau \rightarrow e$ and from mis-identified π^0 .

In the 3-flavour oscillation scenario an additional 2.9 events is expected from $\nu_\mu \rightarrow \nu_e$ oscillation. Figure 7 shows the reconstructed energy distribution of these events compared to the expected reconstructed energy spectra from the various sources described above.

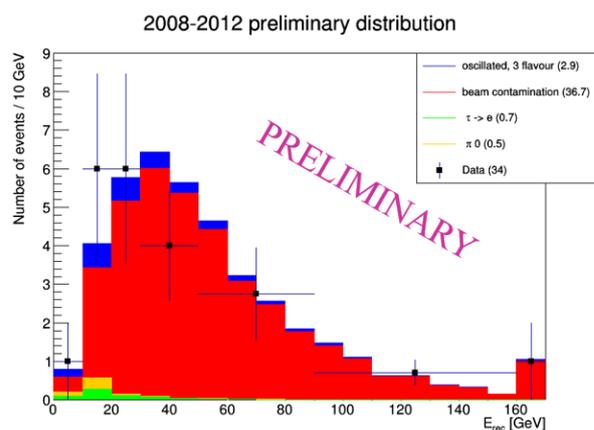


Figure 7. Distribution of the reconstructed energy of the ν_e events and the expected spectra from the various sources discussed in the text.

Applying an additional cut on the electron energy < 30 GeV results in 13 observed events with 10.6 background events and 1.4 events from $\nu_\mu \rightarrow \nu_e$ oscillation expected.

7. Sterile neutrino search

Beyond the three-neutrino paradigm the observation of this number of events allows to set upper limits on $\nu_\mu \rightarrow \nu_e$ oscillations induced by additional sterile neutrinos. Work is in progress to extract those exclusion limits on sterile search in the (3+1) scheme. In the same scheme a specific analysis has been performed to get constraints from ν_μ to ν_τ oscillation results. The appearance probability is modified by the addition of oscillation and interference terms from the new sterile state. A detailed description of this analysis is given in [13]. Here we present an update of the results with the final observation of 5 ν_τ events for 0.25 background expected. It allows to draw the OPERA exclusion contours shown in Figure 8 in the $(\Delta m_{41}^2, \sin^2(2\theta_{\mu\tau}))$ parameter space together with existing limits from previous experiments.

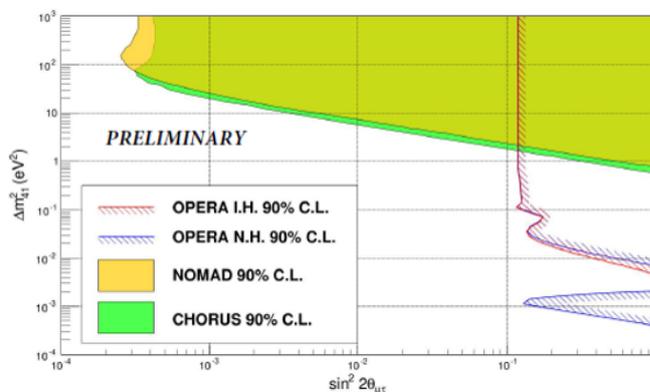


Figure 8. OPERA 90% CL exclusion limits in the Δm_{41}^2 vs $\sin^2(2\theta_{\mu\tau})$ parameter space for the normal (NH, dashed red) and inverted (IH, solid blue) hierarchy of the three standard neutrino masses. Details can be found in [13].

8. Summary and conclusions

OPERA has recorded events corresponding to 18×10^{19} pot delivered by the CNGS beam from 2008 to 2012 which is about 80% of the nominal expected intensity.

The latest results obtained with the full data set analysed have been reviewed. In the $\nu_\mu \rightarrow \nu_\tau$ channel 5 candidates were observed with 2.64 signal + 0.25 background expected, giving a 5.1σ significance to reject the null oscillation hypothesis. The $\nu_\mu \rightarrow \nu_e$ oscillation search resulted in 34 ν_e events observed with 36.7 expected. The analysis to update the OPERA bound on non standard sterile neutrino oscillation in the (3+1) scheme with $\nu_\mu \rightarrow \nu_e$ is on going. An update of the sterile neutrino search from ν_τ appearance has been given as well as a first look at the ν_μ disappearance analysis.

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