Status and oscillation results of the OPERA experiment

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The OPERA experiment, placed 730 km downstream the CERN Neutrino beam to Gran Sasso (CNGS) in the LNGS underground laboratory, is designed to measure muon-neutrino to tau-neutrino oscillations in a direct appearance mode. The hybrid apparatus consists of an emulsion/lead target complemented by electronic detectors. Due to the target structure made of thin lead plates, OPERA is able to detect electromagnetic showers, allowing searches for tau electronic decays and for oscillations from muon-neutrino to electron-neutrino. The experimental set-up and associated facilities used to extract data recorded in the emulsion will be described, with the special procedures aimed to locate interaction vertices and detect short decay topologies. OPERA is taking data since 2008. A first nu-tau interaction candidate was already published in 2010. New results with increased statistics will be presented. In particular, an overview of the studies related to electrons will be shown.

1 Experimental status of neutrino oscillation

An important part of the neutrino physics, in which the OPERA experiment takes part, consists in measuring all parameters driving the oscillation phenomenon to be briefly described later on. The mixing angles, and consequently squared masses differences, in the solar (GALLEX, SNO, KamLAND and Borexino experiments) and in the atmospheric (atmospheric experiments like SuperKamiokande and LBL experiments like K2K or MINOS) sectors have been "easily" determined because of the abundance of neutrino sources and because of the relatively large value of these parameters. However in 2009, θ_{13}, which is the coupling between the two oscillation regimes, was unknown and compatible with a zero value meaning that a two flavours oscillation scheme was a possibility. In addition, the CP phase and the other parameters would be significantly affected depending on the large, small or zero value of θ_{13}. This picture being incomplete, several experiments dedicated to measure the undetermined mixing angle θ_{13} were being built in 2009. On the one hand, LBL experiments like T2K in Japan which aim to measure the appearance of ν_e into a beam of ν_μ with SuperKamiokande detector placed 295km away from the neutrino source. On the other hand, nuclear power plant experiments like Double Chooz in France, Daya Bay in China and Reno in South Korea based on the same principle of the CHOOZ experiment but adding a detector to compare fluxes at near and far positions to reduce the neutrino flux predictions uncertainties. These experiments have recently published a result thus completing the oscillation picture by measuring the value of θ_{13} at 95% C.L. It is now clear that the picture is a 3-flavours oscillation since θ_{13} is not compatible with zero anymore. Finally, there is a summary of all mixing parameters determined by a new global analysis by G.L. Fogli et al., in these proceedings [1]. In the present context the contribution of OPERA is still to validate the oscillation in the atmospheric sector in the appearance mode and provide results in order to confirm the first-octant value of θ_{23}. About θ_{13}, OPERA by measuring $\nu_\mu \rightarrow \nu_e$ oscillation can also confirm the above mentioned results.

2 The OPERA experiment

OPERA[3] is a long-baseline neutrino experiment located at the Gran Sasso Laboratory in Italy, 730 km from CERN, downstream in the CNGS neutrino beam. The OPERA experiment is designed and optimised for a direct appearance search of $\nu_\mu \rightarrow \nu_\tau$ oscillations in the parameter region indicated by Super-Kamiokande[2] to explain the zenith dependence of the atmospheric neutrino deficit. It detects the ν_τ Charged Current (CC) interactions in an almost pure muon neutrino beam produced at the CERN SPS. In addition to $\nu_\mu \rightarrow \nu_\tau$ oscillations, the OPERA detector will also be searching for $\nu_\mu \rightarrow \nu_e$ oscillations thanks to its electron identification capability. OPERA is a large detector made of a VETO plane followed by two identical Super-Modules (SM) each consisting of a target section and a muon spectrometer. The Emulsion Cloud Chamber (ECC), a part of the target section, is made of a modular structure called the "brick" : 56 passive 1 mm plates of lead interleaved with 57 emulsion layers. The brick is completed by two "Changeable Sheets" (CS) emulsion layers, attached downstream to it in order to reduce the emulsion scanning load. By assembling a large quantity of such modules, it has been possible to realize 1.25 kt fine-grained vertex detector optimized for the study of ν_τ appearance. Indeed, the micrometric resolution of nuclear emulsions allows the detection of the kink topology, specific to the short-lived particles such as the tau produced in neutrino interactions. The walls of bricks are alternated with scintillator detectors for event location called Target Tracker (TT). The target part is completed with magnetised iron spectrometers for muon charge and momentum measurements. Finally, two automated systems called Brick Manipulator System (BMS) have been built in order to insert bricks during the construction phase of the detector and extract the ones for which a neutrino interaction is located during the physics runs. Event location is achieved when charged particles from a neutrino interaction in a brick, cross the CS and produce signals in the scintillators of the TT. These signals allow identifying the brick where the interaction occurred. The brick is then extracted, disassembled and developed to be sent to one of the 14 scanning labs in Europe and Japan. After the scanning of the emulsions, tracks and vertices are reconstructed within the entire brick ; a decay topology search is performed to look for ν_τ interactions.

3 The status of OPERA

The CNGS beam started running in 2006. After two years of commissioning, the physics run started in 2008 and is still ongoing. The status of the CNGS in terms of number of p.o.t. is summarized in the table 1.

Table 1: The CNGS neutrino beam status in 2012. In 2012, 4.0×10^{19} p.o.t. are expected to be collected by the end of the run in december. The last column reports the number of events contained in the OPERA dectector per run.

Year	Number of p.o.t.	$\frac{Int.\ p.o.t.}{Exp.\ p.o.t.}$ over 5 years	Contained events
2008	1.78×10^{19}	7.9%	1698
2009	3.52×10^{19}	23.6%	3557
2010	4.04×10^{19}	41.5%	3912
2011	4.84×10^{19}	63.0%	4210
2012 (on going)	$\sim 4.0 \times 10^{19}$	$\sim$ 80%	$\sim$ 4000

Table 2: The 2008-2009 analyzed data sample.

2008-2009 : 5.3×10^{19} p.o.t.	0μ.	1μ	All
Events predicted by the electronic detectors	1503	3752	5255
Interactions located in ECC bricks	519	2280	2799
Located in dead material	54	245	299
Decay search performed	494	2244	**2738**

OPERA aims to collect 22.5×10^{19} protons on target (p.o.t) during the life of the experiment, corresponding to about 23000 interactions in the bricks. At the end of the 2012 run, a total of $\sim 18.0 \times 10^{19}$ p.o.t. will be collected. The analysis reported here uses data collected in 2008 and 2009, corresponding to 5.3×10^{19} p.o.t and 5255 candidate neutrino interactions in the bricks, described the 2012 OPERA collaboration publication[4]. After the event location and tagging (0μ or 1μ) with the TT scintillators and the other electronic detectors, interactions are sought in the ECC bricks, where tracks and vertices are reconstructed and a decay topology search is performed. Table 2 summarizes the performance of these different steps of the analysis for the 2008-2009 data sample.

4 Oscillation results

As presented in the previous sections, OPERA is an experiment designed to measure oscillations in the atmospheric sector in the appearance mode $\nu_\mu \to \nu_\tau$. Although the ν_μ beam is optimized for ν_τ appearance, OPERA remains sensitive to the $\nu_\mu \to \nu_e$ oscillation. Performance in τ detection will be reported and I will then come to the work I have done on the the reconstruction and the analysis of electromagnetic showers in OPERA bricks using Monte-Carlo studies of both $\tau \to e$ appearance channel and the $\nu_\mu \to \nu_e$ oscillation.

4.1 $\nu_\mu \to \nu_\tau$ oscillation signal

The charm sample offers the opportunity to benchmark the efficiency thanks to the similar topologies and thanks to a significant expected rate with respect to the ν_τ events. the OPERA decay search performance has been thus assessed and applied to the 2008-2009 data sample. This is summarized in the table 3 which is also given in the 2012 OPERA collaboration publication[4]. First and second columns of table 3 show the expected numbers of observed signal events for the design intensity of 22.5×10^{19} p.o.t. and for the 2008 and 2009 analyzed data sample corresponding to 5.3×10^{19} p.o.t.. The third and the last columns show the expected numbers of observed background events, from sources like charm production in the ν_μ CC interactions, hadronic reinteractions and large angle muon scattering which all mimick the kink topology, for the design intensity and for the 2008-2009 analyzed data sample. Errors quoted are systematic : 25% on charm background and 50% on hadron and muon backgrounds are assumed, these errors are combined linearly if they arise from the same source, quadratically otherwise.

One ν_τ candidate event has been found with a significance of 95%, i.e. the probability of not being a fluctuation of the background. More possible candidates are under scrutiny and news results will be announced during NEUTRINO2012 conference in Kyoto, Japan.

4.2 $\nu_\mu \to \nu_e$ oscillation channel

Looking for oscillated ν_e from the ν_μ produced by the CNGS beam is a complicated task since only a few events are expected. Any channel that has an electron in the final state will be a background. In addition, channels with photon and no other hint identifying clearly the

Table 3: Expected numbers of observed signal events for the design intensity of 22.5×10^{19} p.o.t. and for the 2008 and 2009 analyzed data sample.

Decay channel	Number of signal events expected		Number of background events expected	
	22.5×10^{19}p.o.t.	4.88×10^{19} p.o.t.	22.5×10^{19}p.o.t.	4.88×10^{19} p.o.t.
$\tau \to \mu$	1.79	0.39	0.09±0.04	0.02±0.01
$\tau \to$ e	2.89	0.63	0.22±0.05	0.05±0.01
$\tau \to$ h	2.25	0.49	0.24±0.06	0.05±0.01
$\tau \to$ 3h	0.71	0.15	0.18±0.04	0.04±0.01
Total	7.63	1.65	0.73±0.15	0.16±0.03

interaction type, such as a muon track in a ν_μ CC interaction for instance, will be also considered as a background to the oscillated ν_e search. The different contributions to the background are the following :

- ν_e from the contamination of the beam, this background is the most statistically significant. The two energy spectra are overlapping which means this background is irreducible.
- The $\tau \to e$ decay channel, which becomes a background in this context.
- NC neutrino interactions, are producing hadrons and photons in the final state.
- CC interaction where the muon track is missing.

The crucial point in the $\nu_\mu \to \tau \to e$ channel and the $\nu_\mu \to \nu_e$ oscillation is the electron search and identification. Two different methods have been pursued and showed similar efficiencies when the number of scanned films is sufficient. The first method starts the search from CS looking for shower hint in a cluster of tracks, the second one follows down the reconstructed tracks in the brick and reconstructs an electromagnetic shower. The latter has to be identified as an electron. I worked on the second method, where a neural network "NN" is used in a Monte Carlo (MC) simulation. In the MC simulation, an electromagnetic shower is reconstructed with specific criteria used in the NN training. The reconstructed variables of the shower are input in the NN where the electron identification variable is the output. If electromagnetic shower is identified as an electron, the energy estimation is applied. The electron identification efficiency is also estimated. With this procedure, it has been possible to estimate the signal and background expectations for the 2008-2009 . Thus, for the $\nu_\mu \to \nu_e$ oscillation channel with electron appearance, 1.5 signal events, 18.2 events from the beam contamination, 0.8 from $tau \to e$ and 0.4 from the other sources are expected. In the data, shower hints have triggered 86 events out of 505 and the electron identification algorithm has confirmed 19 events.

If additional cuts or a multi-variable analysis are performed a better signal over background is expected. This analysis is in progress and will deliver its results soon.

References

1. Fogli, G.L. *et al.*, *Phys. Rev.* D **86**, 013012 (2012).
2. Fukuda, Y. *et al.*, *Phys. Rev. Lett.* **85**, 1562 (1998).
3. M. Guler *et al.*, CERN-SPSC-2000-028 (2000).
4. N. Agafonova *et al.*, The OPERA collaboration,*New J.Phys.* **14**, 03017 (2012).
5. M. Komatsu and P. Migliozzi and F. Terranova,JP **G29**, (2003)
6. G.L. Fogli *et al.*, *Phys. Rev.* D **D78**, 033010 (2008)