New results from the OPERA experiment in the CNGS neutrino beam

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Abstract. A new analysis of full OPERA data set was performed, based on looser selection criteria and multivariate approach. Oscillation parameters and tau neutrino cross-section have been determined with a reduced statistical uncertainty, and the discovery of tau neutrino appearance is confirmed at 6.1σ level. Moreover, the search for electron neutrino events has been extended to the full dataset, exploiting an improved method for the electron neutrino energy estimation. New limits have been set in the 3+1 neutrino model.

1. Introduction
The main goal of the OPERA experiment [1] was a confirmation of $\nu_\mu \rightarrow \nu_\tau$ oscillations in the appearance mode through the detection of the $\tau$-leptons in the $\nu_\tau$ charged-current (CC) interactions in the almost pure muon CNGS beam [2] (CERN Neutrinos to Gran Sasso). It was successfully achieved in 2015 and the non oscillation hypothesis was excluded at 5.1σ level [3]. The strategy of this analysis was chosen in order to have a high purity of the $\nu_\tau$ signal. Lately, looser selection criteria and multivariate approach were applied aimed to increase statistics and to perform a first measurement of $\Delta m^2_{23}$ in the appearance mode and $\nu_\tau$ cross-section measurement with less statistical uncertainties [4]. Among the events selected by the new strategy, there is one turned out to be very likely a $\nu_\tau$ CC interaction with charm production.

The tracking capabilities of the OPERA emulsion detector allow to study the $\nu_\mu \rightarrow \nu_e$ oscillations in the appearance mode through the registration of the e.m. shower associated with the track originating in the primary neutrino interaction vertex. The results of the full data set analysis, corresponding to $17.97 \cdot 10^{19}$ protons on target (p.o.t.), allow setting an upper limit on the $\nu_e$ appearance probability. Moreover, the hypothesis of the sterile neutrino existence, as hinted by LSND [5], MiniBooNE [6] and other experiments, is tested and the upper limit on the oscillation parameters in 3+1 model [7] are derived.

2. The OPERA experiment
The detector was located at the Gran Sasso underground laboratory (LNGS) in Italy, at the distance of about 730 km away from the neutrino source, CERN SPS, where CNGS beam was produced. The CNGS beam was a quasi pure muon beam with a small contamination of $\bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ which were 2.1% and 0.87%, respectively, in term of CC interactions at LNGS site.

The detector was composed of the two identical super modules (SM), each containing a target section made of lead-emulsion bricks called ECC (Emulsion Cloud Chamber) arranged in walls and interleaved with the vertical and horizontal planes of the scintillator strips called target
tracker (TT). Each SM was supplemented with a muon spectrometer and a magnet used for the muon charge and momenta determination [8, 1]. The total mass of the target was about 1.25 kt, which included about 150 000 bricks. Each ECC had a size of $12.7 \times 10.2 \times 7.5 \, \text{cm}^3$ and consisted of 57 emulsion plates interleaved with the 56 lead plates. The emulsion plates consisted of 2 emulsion layers, 45 $\mu$m thick each, poured on 200 $\mu$m plastic plates, while the thickness of lead plates was 1 mm. Each brick had an emulsion doublet (CS or Changeable Sheet) used as an interface between the cm-precision of TT and $\mu$m-precision of ECC.

The TT was used for the ontime event reconstruction and classification [9], for neutrino energy reconstruction [8], and for the ECC ranking according to the probability to contain the neutrino interactions [10]. The bricks most probably containing the interaction were extracted from the detector and CS were scanned aiming to reconstruct the tracks related to the TT data such as a muon candidate or other tracks connected to TT hits. In case a connection was found, the whole ECC was developed and the CS tracks were searched in the ECC and followed plate by plate until their origin. Then the volume around the tracks origin was scanned to reconstruct all the tracks attached to the primary vertex. These tracks were carefully investigated to reconstruct the event topology via the dedicated procedure called decay search [11].

During the experiment runs in 2008–2012, corresponding to $19.79 \cdot 10^{19}$ p.o.t., 19505 ontime events were registered in the detector and 6785 events were located and decay search procedure was performed. This data sample was used for the final $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ analysis in appearance mode.

3. $\nu_\mu \rightarrow \nu_\tau$ analysis

The full OPERA data set was re-analyzed using a new selection strategy, which allowed to increase $\nu_\tau$ candidates statistics with respect to previous analysis [3] giving a possibility to measure $\Delta m_{23}^2$ and $\nu_\tau$ cross-section with decreased systematic uncertainties.

The first step of the analysis is a selection of events showing one of $\tau$-lepton decay typologies. Then, kinematical cuts were applied to refine the selection and to reject background. Decay typologies were identified by the requirements presented in table 1 where $z_{\text{dec}}$ is the distance between the decay vertex and the downstream face of the lead plate containing the primary vertex, $\theta_{\text{kink}}$ is the average angle between the parent and its daughters, $p_{2\text{ry}}$ is a total momentum of the visible tracks originating from the secondary vertex and $(p_{2\text{ry}}^T)$ is a daughter transverse momentum with respect to the parent direction which is applied for 1-prong decays only. Lastly, for the $\tau \rightarrow \mu$ channel only events with negative or unknown charge of the daughter muon were selected.

| Variable         | $\tau \rightarrow 1h$ | $\tau \rightarrow 3h$ | $\tau \rightarrow \mu$ | $\tau \rightarrow e$ |
|------------------|------------------------|------------------------|------------------------|------------------------|
| $z_{\text{dec}}$ (mm) | $< 2.6$               | $< 2.6$               | $< 2.6$               | $< 2.6$               |
| $\theta_{\text{kink}}$ (rad) | $> 0.02$            | $> 0.02$            | $> 0.02$            | $> 0.02$            |
| $p_{2\text{ry}}$ (GeV/c) | $> 1$              | $> 1$              | [1, 15]             | $> 1$              |
| $p_{2\text{ry}}^T$ (GeV/c) | $> 0.15$          | –                  | $> 0.1$             | $> 0.1$             |
| charge$_{2\text{ry}}$ | negative or unknown | negative or unknown | negative or unknown | negative or unknown |

After selection, a multivariate analysis based on a Booted Decision Tree (BDT) algorithm implemented in TMVA was applied. It was trained on Monte Carlo (MC) events selected with
the parameters in table 1. Additional kinematical variables were used as an input for BDT: the missing transverse momentum with respect to the incoming neutrino direction, $p_{miss}^T$, the transverse opening angle between the $\tau$ candidate and the hadronic system, $\phi_{lH}$ and the invariant mass of the parent particle, $m$.

The expected number of $\nu_\tau$ events has been evaluated using the simulated CNGS flux, normalised to the number of observed $\nu_\mu$ CC interactions, assuming a maximal mixing $\sin^22\theta_{23} = 1$, $\Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2$ and the $\nu_\tau$ cross-section as in the default implementation provided by GENIE v2.6 [12]. The systematic uncertainty of the expected signal was conservatively set to 20%. It is mainly dominated by $\nu_\tau$ cross-section and detection efficiency uncertainties. The main background sources are the following: charm background, hadron re-interaction and muons large angle scattering. The total expected signal is $N^{expS} = (6.8 \pm 0.75)$ events, whereas the total background expectation is $N^{expB} = (2.0 \pm 0.4)$, the number of expected background and signal event for each $\tau$-lepton decay channel as well as the number of detected events are reported in table 2.

Table 2. The expected number of signal and background events for the analysed data sample, evaluated assuming $\Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2$, $\sin^22\theta_{23} = 1$ and default implementation for the $\nu_\tau$ cross-section of GENIE v2.6 [4].

| Channel | Charm | Had. re-interaction | Large $\mu$-scat. | Total | $\nu_\tau$ Exp. | Observed |
|---------|-------|---------------------|-------------------|-------|----------------|----------|
| $\tau \rightarrow 1h$ | 0.015 ± 0.003 | 1.28 ± 0.38 | – | 1.43 ± 0.39 | 2.96 ± 0.59 | 6 |
| $\tau \rightarrow 3h$ | 0.44 ± 0.09 | 0.09 ± 0.03 | – | 0.52 ± 0.09 | 1.83 ± 0.37 | 3 |
| $\tau \rightarrow \mu$ | 0.035 ± 0.007 | – | 0.016 ± 0.008 | 0.024 ± 0.008 | 1.15 ± 0.23 | 1 |
| $\tau \rightarrow e$ | 0.035 ± 0.007 | – | – | 0.035 ± 0.007 | 0.84 ± 0.17 | 0 |
| **Total** | 0.63 ± 0.10 | 1.37 ± 0.38 | 0.016 ± 0.008 | 2.0 ± 0.4 | 6.8 ± 0.75 | 10 |

The resulting BDT output distributions are shown in figure 1 for all ten events selected in the following analysis as $\nu_\tau$ CC candidates. The distribution of the visible energy, i.e. the scalar sum of the momenta of charged particles and $\gamma$s is shown in figure 2. One of selected events have 3 vertexes. It was analysed additionally to check whether it is a $\nu_\tau$ CC with a charm production or background. The preliminary results achieved with multivariate analysis confirm the $\nu_\tau$ CC with a charm production at 3.4 $\sigma$ level.

The statistical analysis of the data employs a maximum-likelihood fit jointly across the four channels. The null-hypothesis, implying the background and no signal, was excluded with 6.1$\sigma$ level, more details are in [4].

Assuming maximal mixing and $\nu_\tau$ CC interaction cross section, as for the evaluation of the expected signal, and using the Feldman-Cousins technique first $\Delta m^2_{23}$ measurements were performed in appearance mode:
Figure 2. Stacked plot of visible energy: data are compared to the expectation [14]. Monte Carlo simulation is normalised to the expected number of events reported in table 2.

\[
\Delta m_{23}^2 = (2.7^{+0.7}_{-0.6}) \cdot 10^{-3} \text{ eV}^2 \text{ at 68\% C.L.,} 
\]

which is consistent with the disappearance experiments as well as with the world average [13].

Alternatively to \(\Delta m_{23}^2\) measurement, it is possible to estimate the \(\nu_\tau\) CC cross-section on the lead target, taking the world averaged value of \(\Delta m_{23}^2 (2.50 \cdot 10^{-3} \text{ eV}^2)\) and maximal mixing \(sin^22\theta_{23} = 1\). The result of the observed data analysis is:

\[
<\sigma>_{\text{meas}} = (5.1^{+2.4}_{-2.0}) \cdot 10^{-36} \text{ cm}^2, 
\]

where the error is dominated by statistics. It is a first measurement of \(\nu_\tau\) CC cross-section with a negligible contamination of \(\bar{\nu}_\tau\), which is compatible with the GENIE v2.6 default value, \(<\sigma>_{G} = (4.29 \pm 0.04) \cdot 10^{-36} \text{ cm}^2\).

4. \(\nu_\mu \rightarrow \nu_e\) analysis
The \(\nu_e\) search in the OPERA experiment was based on the reconstruction of the electromagnetic (e.m.) shower associated with the track originating from the primary neutrino vertices [15]. High emulsion granularity allowed to distinguish e-pair tracks from \(\gamma\) conversion separated by 1 \(\mu m\) from each other, thus significantly reducing background. The search was performed among the events located in the 1-st or 2-nd bricks most probably containing neutrino interaction with no reconstructed three-dimensional muon track and less than 20 fired TT/RPC planes, which called 0\(\mu\) sample. In the final sample of 1185 0\(\mu\) events, 35 events with the origin of e.m. shower confirmed as due to a single charged particle associated with the primary vertex were found and classified as \(\nu_e\) candidates.

The expectation of the signal from the CNGS beam was obtained by normalization on the 0l sample (nether \(\mu\) nor electron reconstructed). The detection efficiencies for each sample were obtained from the Monte Carlo applying the full analysis chain. The expected beam contamination amounts to 30.7 ± 0.9(stat.) ± 3.1(syst.) events.

One of background contributions is \(\nu_\tau\) CC interactions with \(\tau \rightarrow e\) decays, where the \(\tau\)-lepton and its daughter electron track can not be distinguished and estimated by MC simulation assuming the 3 flavour \(\nu_\mu \rightarrow \nu_\tau\) oscillation scheme and oscillation parameters from [13]. It amounts to 0.7 ± 0.2(syst.) events. Another background source are 0\(\mu\) events with \(\pi^0 \rightarrow \gamma\gamma\) decay with prompt \(\gamma\) conversion in the first plate downstream the vertex, and the e-pair
Figure 4. The reconstructed energy distribution of the observed $\nu_e$ candidates, the expected background and beam $\nu_e$ and $\bar{\nu}_e$ components: (a) assuming no oscillations; (b) in case of 3 neutrino flavour mixing with the parameters from [13].

misidentified as an electron. The expectation of this background for the full statistics is $0.5 \pm 0.5 \text{(stat.)}$ events. Summarising, the expected number of $\nu_e$ events together with background is $31.9 \pm 1.0 \text{(stat.)} \pm 3.1 \text{(syst.)}$ for no oscillation case. For 3 neutrino flavour mixing the expected number of $\nu_e(\bar{\nu}_e) \to \nu_e(\bar{\nu}_e)$ and $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$, together with background was evaluated as $34.3 \pm 1.0 \text{(stat.)} \pm 3.4 \text{(syst.)}$. The reconstructed energy distributions for both cases are shown in figure 4. The observed 35 $\nu_e$ candidates are in agreement with both theories and allow to set up an upper limit on $\sin^22\theta_{13}$ as 0.43 at 90% C.L. using the expected and observed events number with the reconstructed energies up to 40 GeV.

The $\nu_e$ data was used to test the hypothesis of the presence of light $O(1 \text{ eV/c}^2)$ sterile neutrino by comparing the observed $\nu_e$ energy spectrum with that predicted from 3+1 neutrino mixing model. Analysis was based on profile likelihood ratio, the resulting 90% C.L. exclusion region is shown in figure 5. An upper limit on $\sin^2(2\theta_{\mu e}) = 0.021$ was set for $\Delta m^2_{41} > 0.1 \text{ eV}^2$ in 3+1 model. Moreover, OPERA contributes to limit the effective mixing for low $\Delta m^2_{31}$ and excludes $\Delta m^2_{41} > 4 \times 10^{-3} \text{ eV}^2$ for maximal mixing.

5. Summary

The OPERA experiment reports final results of $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ analysis in the full data set collected during 2008–2012 experimental runs.

The usage of the multivariate techniques allowed to extend the sample of $\nu_\tau$ candidates and to perform the first measurement of $\Delta m^2_{23}$ in appearance mode. This data sample also allowed to measure $\nu_\tau$ cross-section with a negligible contamination of $\bar{\nu}_\tau$. The exclusion of the no oscillation hypothesis is confirmed by the analysis at 6.1 $\sigma$ level. One of found $\nu_\tau$ candidates was classified as $\nu_\tau$ with charm production at 3.4$\sigma$ C.L..

The analysis of $\nu_e$ sample allowed to set an a limit on oscillation parameters in 3+1 model in appearance mode. It must be stressed that, for small $\Delta m^2_{31}$ values, OPERA is the only experiment having collected data in appearance mode.

Unique possibility of the OPERA detector to identify all types of neutrinos with a high efficiency allows to perform combined 3-flavour neutrino oscillation analysis which is ongoing. Furthermore, the OPERA data was used for other non oscillation analysis, such as the study of
Figure 5. The 90% C.L. exclusion plot in the \( \Delta m_{41}^2 \) and \( \sin^2 2\theta_{\mu e} \) plane is shown (black line) together with the 90% C.L. allowed region obtained by LSND [5] (cyan) and MiniBooNE [6] (yellow and green for \( \nu \) and \( \bar{\nu} \) mode, respectively). The blue, red and green lines represent the 90% C.L. exclusion regions obtained by NOMAD [16], KARMEN [17] and the MINOS and DayaBay/Bugey-3 joint analysis [18], respectively.

The charged hadron multiplicity in CC neutrino-lead interactions aid in tuning the models used in MC generators [19]. The electronic detectors data analysis provided the interesting results related to the atmospheric muons analysis at the TeV energy range scale: the muons charge ratio measurement [20] and the measurement of the single muon flux modulation and its correlation with the seasonal variation of the atmospheric temperature.

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