More results from the OPERA experiment


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received 16 September 2017
Summary. — The OPERA experiment reached its main goal by proving the appearance of $\nu_\tau$ in the CNGS $\nu_\mu$ beam. Five $\nu_\tau$ candidates were detected with a S/B ratio of $\sim 10$, allowing to reject the null hypothesis at 5.1$\sigma$. The search has been extended by loosening the selection criteria in order to improve the statistical uncertainty. One of the $\nu_\tau$ candidates selected with the new strategy shows a double vertex topology and, after a dedicated multivariate analysis, is compatible with being a $\nu_\tau$ interaction with charm production. Based on the enlarged data sample the estimation of $\Delta m_{23}^2$ in appearance mode is being performed. The search for $\nu_e$ interactions has been extended over the full data set with a more than twofold increase in statistics: data are compatible with the non-oscillation hypothesis in the three-flavour mixing model. The implications of the electron neutrino sample in the framework of the 3+1 sterile mode will lead to exclusion limits on $\sin^2 2\theta_{13}$. Finally, the analysis of the annual modulation of cosmic muons is introduced.

1. – The CNGS beam and the OPERA detector

The OPERA experiment was designed to conclusively prove the existence of $\nu_\mu \rightarrow \nu_\tau$ oscillations. The direct appearance search was based on the detection of $\tau$ leptons produced in $\nu_\tau$ charged current interactions (CC). The challenge to detect the short-lived $\tau$ lepton ($c\tau = 87 \mu$m), produced in the CC $\nu_\tau$ interactions, out of almost twenty thousands $\nu_\mu$ interactions was achieved exploiting the nuclear emulsion technique that features micrometric spatial resolution.

The OPERA detector (fig. 1(a)) was located in the underground Gran Sasso Laboratory (LNGS), 730 km away from the neutrino source, in the high energy long-baseline CERN to LNGS beam (CNGS) [1, 2]. The average neutrino energy was about 17 GeV, the $\bar{\nu}_\mu$ contamination 2.1% in terms of interactions, the $\nu_e$ and $\bar{\nu}_e$ together below 1%, while the number of prompt $\nu_\tau$ negligible. The detector was an hybrid apparatus consisting of an emulsion/lead target complemented by electronic detectors. It was made up of two identical super-modules aligned along the CNGS beam direction, each made of a target section and a muon spectrometer. Each target section consisted of a multi-layer array of 31 target walls interleaved with pairs of planes of plastic scintillator strips. Target walls were made of Emulsion Cloud Chamber target units, called bricks (fig. 1(b)). Each brick consists of 57 emulsion films, 300 $\mu$m thick, interleaved with 56 lead plates, 1 mm thick, for a total mass of 8.3 kg. The electronic detectors were used to identify the brick containing the neutrino interaction, for muon identification and its charge and momentum determination.

2. – Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam

Runs with CNGS neutrinos were successfully carried out from 2008 to 2012, with a total CNGS beam intensity of $1.8 \times 10^{20}$ protons on target. Five $\nu_\tau$ candidates were observed, satisfying kinematical selection criteria: three in the $\tau \rightarrow 1h$ decay channel [3-5], one in the $\tau \rightarrow 3h$ [6] and one in the $\tau \rightarrow \mu$ [7] decay channel. In the analysed sample, 0.25 $\pm$ 0.05 background events are expected, coming mainly from charmed events with an undetected primary muon, hadronic re-interactions (for the hadronic decay channels) and large angle muon scattering (for the $\tau \rightarrow \mu$ channel). Taking into
account the background and observed events in each tau-decay channel, the observation of five candidates results in 5.1σ significance for the exclusion of the background-only hypothesis [5].

3. – Extended analysis

After discovering the $\nu_\tau$ appearance in a $\nu_\mu$ beam [5], a new goal has been set: estimate the oscillation parameters in appearance mode and exploit the unique capability of the OPERA experiment to identify all 3 neutrino flavours in order to put constrain the oscillation parameters by a joint oscillation fit of all datasets. A new strategy has been defined with looser kinematical cuts and a multivariate analysis: this allows a larger data sample with a lower purity, in order to decrease the statistical errors on atmospheric oscillation parameters measured in appearance mode.

In the minimum bias (M.B.) selection, which is reported in table I, compared with the previous selection criteria (PREV.), decay topologies are searched for requiring: the average 3D angle between the parent and its daughters $\theta_{\text{kink}} > 0.02$ rad and the $z$-coordinate of the decay vertex with respect to the downstream face of the lead plate containing the primary vertex $z_{\text{dec}} < 2600 \mu m$ for all decay channels. The total momentum of the visible tracks coming out from the secondary vertex ($p_{\text{2ry}}$) has been lowered to 1 GeV, with an upper limit of 15 GeV only for $\tau \rightarrow \mu$ decay channel, in order to reduce the background from the decay of charmed hadrons decay. Moreover, to reduce the background from hadron re-interactions and large angle scattering for 1-prong decays, the cut on the transverse component of daughter momentum with respect to the parent direction ($p_{\text{T2ry}}$) was optimised in order to minimise the uncertainty on the number of expected $\nu_\tau$ events taking into account the background contribution. Therefore, since the number of expected $\nu_\tau$ is proportional to $\Delta m_{23}^2 \cdot \sigma_{\nu_\tau}$, the uncertainty on the measurement of these parameters is minimised as well. All remaining selection cuts have been removed to enhance the signal sample.

Among the minimum bias observed events there is a $\tau \rightarrow 1h$ candidate showing a very peculiar topology, with two secondary vertices about 1 mm from the primary one, as shown in fig. 2. Possible interpretations include $\nu_\tau$ CC interaction with charm production or $\nu$ NC interaction with double charm production. Given the peculiar topology, a dedicated analysis was performed using multivariate analysis methods. The event turned out to be likely a $\nu_\tau$ CC interaction with charm production [8, 9].
### Table I. Comparison between the selection cuts used to establish the $\nu_\tau$ appearance (PREV.) and the minimum bias ones (M.B.). Cuts marked with ⋆ are not applied for Quasi-Elastic event. $p_{T_{\gamma}}$ cut is 0.3 in the presence of $\gamma$ particles associated to the decay vertex.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\tau \rightarrow 1h$</th>
<th>$\tau \rightarrow 3h$</th>
<th>$\tau \rightarrow \mu$</th>
<th>$\tau \rightarrow e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_{\text{dec}}$ (\mu m)</td>
<td>[44, 2600) &lt; 2600</td>
<td>&lt; 2600</td>
<td>[44, 2600) &lt; 2600</td>
<td>&lt; 2600</td>
</tr>
<tr>
<td>$\theta_{\text{kin}}$ (rad)</td>
<td>&gt; 0.02</td>
<td>&lt; 0.5 &gt; 0.02</td>
<td>&gt; 0.02</td>
<td>&gt; 0.02</td>
</tr>
<tr>
<td>$p_{T_\gamma}$ (GeV/c)</td>
<td>&gt; 2 &gt; 1</td>
<td>&gt; 3 &gt; 1</td>
<td>[1, 15] &gt; 1</td>
<td></td>
</tr>
<tr>
<td>$p_{T_{\gamma}}$ (GeV/c)</td>
<td>&gt; 0.6 (0.3) &gt; 0.15</td>
<td>–</td>
<td>&gt; 0.25 &gt; 0.1</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>$p_{\text{miss}}$ (GeV/c)</td>
<td>&lt; 1* –</td>
<td>&lt; 1* –</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$\phi_{lH}$ (rad)</td>
<td>&gt; $\pi/2*$ –</td>
<td>&gt; $\pi/2*$ –</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m, m_{\text{min}}$ (GeV/c$^2$)</td>
<td>– [0.5, 2] –</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.1. Multivariate analysis.

To improve the significance evaluation and perform signal to background separation, a multivariate analysis was implemented. Different techniques have been considered and their performances for signal to background discrimination compared. The one with the best discrimination power is the Boosted Decision Tree (BDT). In the $\tau \rightarrow 1h$ decay channel, in particular, where the background sharply increases due to the looser cuts, the BDT method helps rejecting it. A sample of signal and background Monte Carlo events surviving the minimum bias requests in table I has been used as input for the BDT. As an example, the distribution of one of the variables used, the angle in the transverse plane between the parent track and the hadron shower direction ($\phi_{lH}$), is shown in fig. 3.

The BDT output for the $\tau \rightarrow 1h$ decay channel is shown in fig. 4.

As already mentioned, OPERA is the first experiment that can measure $\Delta m_{23}^2$ in appearance mode. The number of expected events, indeed, is proportional to the oscillation probability $P_{\nu_\mu \rightarrow \nu_\tau}$ and the $\nu_\tau$ cross-section: $N_{\nu_\tau} \propto P_{\nu_\mu \rightarrow \nu_\tau} \cdot \sigma_{\nu_\tau}$.

The $\nu_\tau$ cross-section has been measured so far only by the DONuT experiment, which observed 9 $\nu_\tau$CC interactions, out of a total of 578 observed neutrino interactions, but could not separate $\nu_\tau$ from $\bar{\nu}_\tau$ [10]. Based on the observed $\nu_\tau$ interactions, assuming best fit values for $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$, OPERA can determine $\sigma_{\nu_\tau}$.

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Fig. 2. Schematic drawing of the muon-less $\nu$ interaction with three vertices.
Fig. 3. – Distribution of the $\phi_{tH}$ angle for signal (blue) and background (red) for the $\tau \to 1h$ decay channel.

Fig. 4. – BDT output for the $\tau \to 1h$ decay channel.

4. $\nu_\mu \to \nu_e$ oscillations

The tracking capabilities of nuclear emulsions also allow to identify electrons from $\nu_e$ CC interactions, and therefore to search for $\nu_\mu \to \nu_e$ oscillations [11]. In the final sample, 34 $\nu_e$ candidate events have been observed. This number is compatible with what expected from the beam contamination, $33 \pm 5$, and $1.2 \pm 0.1$ events from the two main sources of background, i.e. $\pi^0$’s misidentified as electrons in neutrino interactions without a reconstructed muon and $\nu_\tau$ CC interactions with $\tau$ decaying into an electron. With $\sin^2(2\theta_{13}) = 0.098$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{32} = \Delta m^2_{31} = 2.5 \times 10^{-3}eV^2$, assuming $\delta_{CP} = 0$ and neglecting matter effects, $2.9 \pm 0.4$ oscillated $\nu_e$ CC events are expected in the whole energy range. The number of observed events is compatible with the 3-flavour oscillation model, as shown in fig. 5.
Fig. 5. – Comparison between the \( \nu_e \) expected events and data.

OPERA \( \nu_e \) appearance results have been used to derive limits on the mixing parameters of a massive sterile neutrino. In presence of a fourth sterile neutrino with mass \( m_4 \), the oscillation probability is a function of the \( 4 \times 4 \) mixing matrix \( U \) and of the three squared mass differences. Observed neutrino oscillation anomalies, if interpreted in terms of one additional sterile neutrino, suggest \( |\Delta m_{41}^2| \) values at the eV\(^2\) scale. We extend the exclusion limits on \( \sin^2 2\theta_{\mu\tau} = 4|U_{\mu4}|^2|U_{e4}|^2 \) below 0.1 at 95% C.L.

5. – Study of charged particle multiplicity distributions

The study of multiplicity distributions of charged particles in neutrino interactions is important to improve models of particle production in Monte Carlo event generators. A dedicated analysis was performed on a sub-sample of \( \nu_\mu \) CC interactions in the OPERA target.

The results are the object of a forthcoming publication.

Fig. 6. – Upper panel: measured cosmic muon signal as a function of time. Lower panel: effective temperature. Daily binning is used. The curves show the sinusoidal fit to the data.
6. – Annual modulation of atmospheric muons

Underground muons arise mostly from the decay of $\pi$ and $K$ produced in the interaction of primary cosmic rays with the nuclei of the upper atmosphere. During summer air temperature increases and the average gas density decreases. The less dense medium allows a longer mean free path of the mesons, thus the fraction of those decaying to muons before interacting increases. As a result, an annual modulation is expected in the rate of atmospheric muons detected in OPERA at the underground Gran Sasso Laboratory. The observed modulation has a phase of $(176 \pm 4)$ days, as shown in fig. 6. Muon rate fluctuations are shown to be positively correlated with atmospheric temperature, in good agreement with expectations.

7. – Conclusions

After the discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam with a significance of $5.1\sigma$, a new analysis strategy has been applied for the selection of $\nu_\tau$ candidates, in order to measure the oscillation parameters in appearance mode. The measurement of $\Delta m^2_{23}$ based on $\nu_\tau$ appearance can be obtained with an accuracy of about 20%.

The update of $\nu_\mu \rightarrow \nu_e$ oscillation search is also being carried out: the number of observed events is in agreement with the expected background and the 3-neutrino flavour framework oscillation. This agreement can be turned into an upper limit to the mixing with a fourth sterile neutrino.

The multiplicity distribution of charged hadron particles in neutrino-lead interactions has been studied to help tuning interaction models of the Monte Carlo event generators.

Moreover, OPERA cosmic muon data set is used to determine the annual modulation of atmospheric muons flux: the observed modulation has a phase of $(176 \pm 4)$ days, with an effective coefficient in good agreement with expectations.

Results about the on-going analyses reported in these proceedings will appear in forthcoming papers.

REFERENCES