

Final results of the OPERA experiment on ν_τ appearance in the CNGS beam

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The OPERA experiment was designed to study $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in the CNGS neutrino beam. In this letter we report the final analysis of the full data sample collected between 2008 and 2012, corresponding to $17.97 \cdot 10^{19}$ protons on target. Selection criteria looser than in previous analyses have produced ten ν_τ candidate events, thus reducing the statistical uncertainty in the measurement of the oscillation parameters and of ν_τ properties. A multivariate approach for event identification has been applied to the candidate events and the discovery of ν_τ appearance is confirmed with an improved significance level of 6.1σ . Δm_{23}^2 has been measured, in appearance mode, with an accuracy of 20%. The measurement of ν_τ CC cross-section, for the first time with a negligible contamination from $\bar{\nu}_\tau$, and the first direct observation of the ν_τ lepton number are also reported.

INTRODUCTION

The OPERA experiment was designed to conclusively prove $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode. The challenge of the experiment to detect the short-lived τ lepton ($c\tau = 87 \mu\text{m}$), produced in the charged-current (CC) ν_τ interactions, was accomplished with the nuclear emulsion technique, that provides sub-micrometric spatial resolution.

The detector [1] was located in the underground Gran Sasso Laboratory (LNGS), 730 km away from the neutrino source and exposed to the CNGS muon neutrino beam [2, 3]. The average neutrino energy was about 17 GeV, the $\bar{\nu}_\mu$ fraction was 2.1% in terms of expected CC interactions, the sum of ν_e and $\bar{\nu}_e$ was below 1%, while the prompt ν_τ contamination was negligible $\mathcal{O}(10^{-7})$.

The detector was an hybrid apparatus made of an emulsion/lead target with a total mass of about 1.25 kt, complemented by electronic detectors. The general structure consisted of two identical Super Modules (SM). Each SM was made of a target section, composed of 31 target walls, and a muon spectrometer. Each target wall was an assembly of horizontal trays loaded with target units, hereafter called *bricks*. Each brick consisted of 57 emulsion films, 300 μm thick, interleaved with 56 lead plates, 1 mm thick, with a (12.7×10.2) cm^2 cross-section, a thickness of 7.5 cm corresponding to about 10 radiation lengths and a mass of 8.3 kg. Downstream of each target wall, two orthogonal planes of scintillator strips (Target Tracker detector) recorded the position and the energy deposition of charged particles [4]. Finally, a magnetic spectrometer instrumented with Resistive Plate Chambers and high-resolution Drift Tubes was used to identify muons and measure their charge and momentum [1]. Neutrino interactions and decay topologies were detected in the bricks with micrometric accuracy. A pair of emulsion films was attached to the downstream face of each brick, acting as an interface between the brick and the electronic detectors [5]. Their measurements allowed confirming the presence of tracks recorded in the electronic detectors before unpacking and developing the entire brick. A detailed description of the OPERA detector can be found in [1].

Event selection and analysis The appearance of the τ lepton is identified by the detection of its characteristic decay topologies, either in 1-prong (electron, muon or hadron) or in 3 hadron prongs. Kinematical selection criteria are applied to reduce the background coming from the processes that mimic the τ decay topologies, which are: i) the decays of charmed particles produced in ν_μ CC interactions; ii) re-interactions of hadrons from ν_μ events in lead; iii) the large-angle scattering (LAS) of muons produced in ν_μ CC interactions. Processes i) and ν_μ CC in ii) represent a background source when the μ^- at the primary vertex is not identified.

A sample corresponding to 17.97×10^{19} protons on target (p.o.t.) has been collected from 2008 to 2012 and resulted in 19505 neutrino interactions in the target fiducial volume.

In 2015, five ν_τ candidates were observed following a selection performed by cuts on specific kinematical and topological parameters. The discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations was assessed with a significance of 5.1σ [6].

This paper reports an improved analysis of the full data sample, which is 3.6% higher with respect to [6]. The number of fully analysed events is shown in Tab. I for each year of data taking. Events are classified as 1μ if a track is tagged as a muon by the electronic detectors [7], as 0μ otherwise. The analysis described below is performed on all 0μ events and on 1μ events with a muon momentum below 15 GeV/c.

	2008	2009	2010	2011	2012	Total
p.o.t. (10^{19})	1.74	3.53	4.09	4.75	3.86	17.97
0μ events	150	255	278	291	223	1197
1μ events ($p_\mu < 15$ GeV/c)	543	1024	1001	1031	807	4406
Total events	693	1279	1279	1322	1030	5603

TABLE I. Number of events used in this analysis, grouped into 0μ and 1μ .

The new analysis is based on a multivariate approach for event identification, fully exploiting the expected features of ν_τ events, rather than on the sheer selection of candidate events by independent cuts on topological or kinematical parameters as in previous analyses. It is performed on candidate events preselected with looser

cuts than those applied in the previous cut-based approach [6, 8–11]. Looser cuts increase the number of ν_τ candidates, thus leading to a measurement of the oscillation parameters and of the ν_τ cross-section with a reduced statistical uncertainty. Given the higher discrimination power of the multivariate analysis that fully exploits the features of each event the significance of the ν_τ appearance is increased.

ANALYSIS STRATEGY

The first stage of the analysis is to select events showing a decay topology. These events are categorised into 4 channels ($\tau \rightarrow 1h$, $\tau \rightarrow 3h$, $\tau \rightarrow \mu$, $\tau \rightarrow e$) according to the identification of daughter particles. Then, kinematical cuts are applied to refine the selection and to reject background events in each channel. Finally, a multivariate approach is exploited to separate signal from background and to evaluate a single-variable discriminant for the hypothesis test and parameters estimation in the statistical analysis for the extraction of results, as described in the next section.

The rectangular cuts on the topological and kinematical variables, shown in Table II, are looser than those used in previous papers [6, 8–11]. The Monte Carlo simulation has been validated comparing its results with the measured ν_μ CC interactions when producing hadron re-interactions [12], charmed hadron decays [13] and LAS muons [14]. The momentum of hadrons has been estimated by the multiple Coulomb scattering method [15], while the muon momentum is measured by the magnetic spectrometer with a resolution of about 20% [1].

Decay topologies are identified by the following requirements: the average 3D angle between the parent and its daughters (θ_{kin}) has to be larger than 0.02 rad and the distance between the decay vertex and the downstream face of the lead plate containing the primary vertex (z_{dec}) has to be shorter than 2600 μm . To define the decay vertex position with sufficient precision, the total momentum of the visible tracks coming out of the secondary vertex (p_{2ry}) has to be at least 1 GeV/c, with an upper limit of 15 GeV/c only for the $\tau \rightarrow \mu$ channel, in order to reduce the charmed hadrons background. Moreover, for 1-prong decays, the cut on the daughter transverse momentum with respect to the parent direction (p_{2ry}^T) was tuned to reduce the hadron re-interaction and LAS backgrounds. Lastly, for the $\tau \rightarrow \mu$ channel, only events where the muon daughter has negative or unknown charge [16] are considered.

The tracks related to events passing the selection criteria of Table II have been measured within an angular acceptance up to $\tan\theta < 1$ (θ being the angle of the track with the z axis) for kinematical measurements. In addition, a specific search for large angle tracks, up to $\tan\theta < 3$, has been performed, in order to reject events

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

TABLE II. Selection cuts.

with nuclear fragments emitted at the secondary vertex, a signature of the hadronic re-interaction background.

After candidate selection, a multivariate analysis is applied, based on a Boosted Decision Tree (BDT) algorithm implemented in TMVA [17]. For each channel, the BDT was trained with Monte Carlo events selected according to the topology and the kinematical cuts of Table II. As input for the BDT analysis, additional kinematical variables have been used. As described in [9], they are: the missing transverse momentum with respect to the incoming neutrino direction (p_{miss}^T), the transverse opening angle between the τ candidate and the hadronic system (ϕ_{lH}) and the invariant mass of the parent particle (m). In addition, for the $\tau \rightarrow \mu$ channel, the charge measurement status [16] of the daughter muon (negative or unknown) is also used.

Expected Events The expected number of ν_τ events has been evaluated using the simulated CNGS flux [18, 19], normalised to the number of observed ν_μ CC interactions as explained in [9], assuming a maximal mixing $\sin^2 2\theta_{23} = 1$, $\Delta m_{23}^2 = 2.50 \cdot 10^{-3} \text{ eV}^2$ [20] and the ν_τ cross-section as in the default implementation provided by GENIE v2.6 [21, 22]. The expected number of signal and background events are reported in Table III, together with the number of observed ν_τ candidates for each channel. The background from π and K decays remain negligible.

The total systematic uncertainty on the expected signal, largely dominated from the limited knowledge of the ν_τ cross-section and the detection efficiency, is conservatively set to 20%. Since signal expectation is calculated by using data-driven estimates of location efficiencies, this value is at first order insensitive to systematic effects on efficiencies up to the primary vertex location level.

Using the measured sample of ν_μ CC interactions with charm production, the uncertainty on the charm background has been estimated to be about 20% [13]. Hadron re-interaction background has an estimated uncertainty of 30% from measurements of test-beam pion interactions in the OPERA bricks [12]. The systematic uncertainty on LAS has been obtained by a comparison between two different estimates, one based on a data-tuned GEANT4 Monte Carlo simulation [14] and the other one on a direct extrapolation of data in the literature [23] and it is set at 50%.

Channel	Expected Background				ν_τ Exp.	Observed
	Charm	Had. re-interaction	Large μ -scat.	Total		
$\tau \rightarrow 1h$	0.15 ± 0.03	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
$\tau \rightarrow \mu$	0.008 ± 0.002	—	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

TABLE III. The expected number of signal and background events for the analysed data sample, evaluated assuming $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1$ and the default implementation for the ν_τ cross-section of GENIE v2.6.

The total expected signal is $N^{\text{expS}} = (6.8 \pm 0.75)$ events, whereas the total background expectation is $N^{\text{expB}} = (2.0 \pm 0.4)$ events.

Observed events Ten events (N^{obs}) passed all the topological and kinematical cuts. The distribution of their visible energy, i.e. the scalar sum of the momenta of charged particles and γ s, is shown in Fig. 1, compared to Monte Carlo simulation. Among the ten selected ν_τ

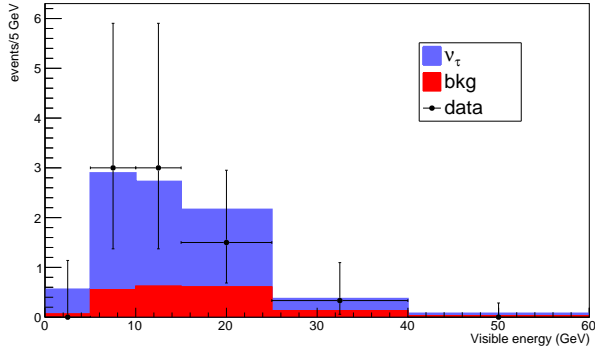


FIG. 1. Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalised to the expected number of events reported in Table III.

candidates, five ν_τ were already described in [6, 8–11]. The other five ν_τ candidates are all events without muon in the final state: three of them show a 1-prong decay and two a 3-prong decay. Their kinematical variables are summarised in Table IV, where the BDT response for each event is also reported. The resulting BDT output distributions are shown in Fig. 2.

RESULTS

The statistical analysis of the data employs a maximum-likelihood fit jointly across the four channels. For each channel, the likelihood is constructed as the product of a probability density function combining the BDT responses of signal and background, a Poissonian term and a Gaussian term for the systematics of the ex-

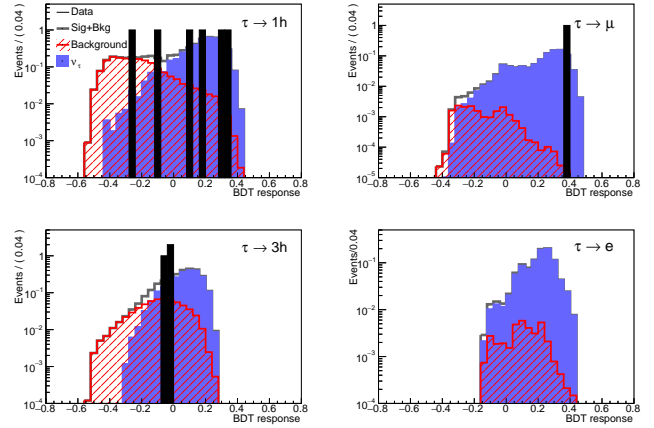


FIG. 2. BDT response for each channel.

pected yield:

$$\mathcal{L}(\mu, \beta_c) = \prod_{c=1}^4 \left(\text{Pois}(n_c | \mu s_c + \beta_c) \prod_{i=1}^{n_c} f_c(x_{ci}) \right) \cdot \prod_{c=1}^4 \text{Gauss}(b_c | \beta_c, \sigma_{b_c}), \quad (1)$$

where

$$f_c(x_{ci}) = \frac{\mu s_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{sig}} + \frac{\beta_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{bkg}},$$

and c runs over the 4 channels, i over the n_c observed events in the c^{th} channel, s_c is the expected signal, b_c and σ_{b_c} are the expected background in the c^{th} channel and its uncertainty as reported in Table III, β_c is a floating parameter which represents the true background, x_{ci} is the BDT response, and $\text{PDF}_c^{\text{bkg}}$ ($\text{PDF}_c^{\text{sig}}$) the distribution of x_{ci} for the background (signal) component in the c^{th} channel. The parameter μ is the ν_τ signal strength, i.e. a scale factor on the number of events expected by the model of neutrino interactions: $\mu = 0$ corresponds to the background-only hypothesis and $\mu = 1$ corresponds to the oscillated ν_τ signal, on top of the background, reported in Table III. The effect of uncertainties on the expected number of signal events (estimated $\sim 20\%$ for each channel) has been proved to be negligible for all the following results.

BRICK ID	72693	29570	23543	92217	130577	77152	27972	26670	136759	4838
<i>Channel</i>	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	-648	407
p_{miss}^T (GeV/c)	0.52	0.31	/	0.55	0.30	0.88	1.29	0.46	0.60	> 0.50
ϕ_{1H} (degrees)	173	168	/	166	151	152	140	143	82	47
p_{2ry}^T (GeV/c)	0.47	/	0.69	0.82	1.00	0.24	0.25	0.33	/	/
p_{2ry} (GeV/c)	12	8.4	2.8	6.0	11	2.7	2.6	2.2	6.7	> 6.3
θ_{kink} (mrad)	41	87	245	137	90	90	98	146	231	83
m (GeV/c ²)	/	0.80	/	1.2	> 0.94	/	/	/	1.2	> 0.94
γ at decay vtx	2	0	0	0	0	1	0	0	0	2
charge _{2ry}	/	/	-1	/	/	/	/	/	/	/
BDT Response	0.32	-0.05	0.37	0.12	0.35	0.18	-0.25	-0.10	-0.04	-0.03

TABLE IV. Kinematical variables and BDT response for all ν_τ candidates.

Significance of ν_τ appearance The significance of ν_τ appearance is expressed in terms of a hypothesis test where the background-only ($\mu = 0$) is the null hypothesis and the signal-plus-background ($\mu \neq 0$) is the alternative one. In order to test which values of the signal strength μ are consistent with data, the profile likelihood ratio $\lambda(\mu) = \mathcal{L}(\mu, \hat{\beta}_c(\mu)) / \mathcal{L}(\hat{\mu}, \hat{\beta}_c)$ is used [24], where $\mathcal{L}(\hat{\mu}, \hat{\beta}_c)$ is the value of the likelihood at its maximum and $\hat{\beta}_c(\mu)$ indicates the profiled values of the nuisance parameter β_c , maximizing \mathcal{L} for the given μ . The results presented in this letter are obtained using the asymptotic approximation [25], as implemented in the RooStats package [26].

The null hypothesis is excluded with 6.1 σ significance, corresponding to a background fluctuation probability of $4.8 \cdot 10^{-10}$. The best-fit signal strength is $\mu = 1.1_{-0.4}^{+0.5}$, which is consistent with the ν_τ appearance expected from neutrino oscillation.

First measurement of Δm_{23}^2 in appearance mode The ν_τ signal strength μ is proportional to the oscillation probability and the ν_τ cross-section. Assuming maximal mixing and ν_τ CC interaction cross section as in previous section, the following interval of Δm_{23}^2 can be derived using the Feldman-Cousins method [27]:

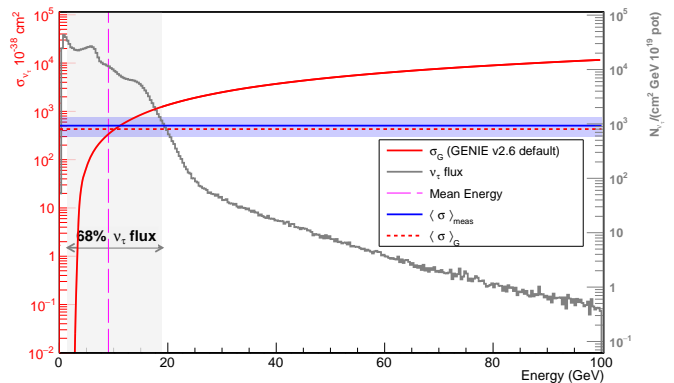
$$\Delta m_{23}^2 = (2.7_{-0.6}^{+0.7}) \cdot 10^{-3} \text{ eV}^2 \text{ at } 68\% \text{ C.L.} \quad (2)$$

This is the first result obtained in appearance mode and it is consistent with the disappearance results from different experiments, including the world average [24].

Measurement of the ν_τ CC cross-section Alternatively to the above measurement of Δm_{23}^2 , one may fix Δm_{23}^2 at the world average value ($2.50 \cdot 10^{-3} \text{ eV}^2$) and maximal mixing $\sin^2 2\theta_{23} = 1$ and estimate the ν_τ CC cross-section on the lead target, made of ^{204}Pb (1.4%), ^{206}Pb (24.1%), ^{207}Pb (22.1%) and ^{208}Pb (52.4%) [28]. The total flux integrated cross-section is defined as [29]:

$$\langle \sigma \rangle = \frac{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) \sigma_{\nu_\tau}(E) dE}{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) dE}, \quad (3)$$

where $\Phi_{\nu_\mu}(E)$ is the CNGS flux [19], $\mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}$ the oscillation probability, $\sigma_{\nu_\tau}(E)$ is the ν_τ cross-section and E is the neutrino energy.

FIG. 3. Flux-averaged measurement of the CC σ_{ν_τ} on a lead target. The horizontal bar includes central 68% of the flux.

An estimate of σ_{ν_τ} can be extracted from the observed data by using the following equation:

$$\langle \sigma \rangle_{meas} = \frac{(N^{obs} - N^{expB}) / (\epsilon N_T)}{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) dE}, \quad (4)$$

where N_T is the number of lead nuclei in the fiducial volume of the target and ϵ is the overall efficiency of τ event reconstruction, averaged over the expected distribution of ν_τ flux [30]. The result is:

$$\langle \sigma \rangle_{meas} = (5.1_{-2.0}^{+2.4}) \cdot 10^{-36} \text{ cm}^2, \quad (5)$$

with the error dominated by statistical uncertainty. This result has to be compared with the expected value, as provided by the default configuration of GENIE v2.6 [21, 22]: $\langle \sigma \rangle_G = (4.29 \pm 0.04) \cdot 10^{-36} \text{ cm}^2$. The error associated with $\langle \sigma \rangle_G$ is the propagation of the flux uncertainty due to the oscillation parameter errors. Therefore, the result can be expressed as: $\langle \sigma \rangle_{meas} = (1.2_{-0.5}^{+0.6}) \langle \sigma \rangle_G$.

This is the first measurement of the ν_τ CC cross-section with a negligible contamination of $\bar{\nu}_\tau$. No deviation from GENIE expectations is observed.

ν_τ lepton number The lepton number of ν_τ has never been observed. In the muonic channel, the OPERA ex-

periment can distinguish neutrinos from anti-neutrinos looking at the charge of the muon produced in τ decays, which, was measured to be negative at 5.6σ level for the $\tau \rightarrow \mu$ candidate [10, 31].

The hypothesis that a $\tau^- \rightarrow \mu^-$ has been observed is tested by specifying Eq. 1 to the $\tau \rightarrow \mu$ channel. A dedicated BDT analysis has been performed for this channel: on top of the charm and LAS background, we have considered the additional contribution from the 2% contamination in interactions of $\bar{\nu}_\tau$ resulting from $\bar{\nu}_\mu$ oscillation. Interactions of $\bar{\nu}_\tau$ are background in the muonic channel if the μ^+ charge is either misidentified or not measured: this gives a background yield of 0.0024 ± 0.0005 events. The result gives a significance of 3.7σ , which, assuming the lepton number conservation in the neutrino interaction, can be considered as the first direct observation of the ν_τ lepton number.

CONCLUSIONS

This letter reports OPERA's final results on $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode, obtained with the complete data sample, corresponding to 5603 ν interactions fully reconstructed.

Given the validation of the Monte Carlo simulation of ν_τ events, based on different control data samples, a new analysis strategy was developed, fully exploiting the features expected for ν_τ events. A multivariate approach for the identification of ν_τ events was applied to candidate events selected by means of moderately tight topological and kinematical cuts.

Ten ν_τ candidates were observed, with 2.0 ± 0.4 expected background events. The discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode is confirmed with an improved significance of 6.1σ .

Assuming $\sin^2 2\theta_{23} = 1$, the first measurement of Δm_{23}^2 in appearance mode gives $(2.7_{-0.6}^{+0.7}) \cdot 10^{-3} \text{eV}^2$, while the ν_τ CC cross-section on the lead OPERA target is measured to be $(5.1_{-2.0}^{+2.4}) \cdot 10^{-36} \text{cm}^2$, when $\Delta m_{23}^2 = 2.50 \cdot 10^{-3} \text{eV}^2$.

Furthermore, a dedicated BDT analysis in the $\tau \rightarrow \mu$ channel allows claiming for the first direct observation of the ν_τ lepton number with a significance of 3.7σ .

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