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Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam

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(Received 16 April 2018; published 22 May 2018)

The OPERA experiment was designed to study $\nu_\mu \to \nu_\tau$ oscillations in the appearance mode in the CERN to Gran Sasso Neutrino beam (CNGS). In this Letter, we report the final analysis of the full data sample collected between 2008 and 2012, corresponding to 17.97×10^{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. $|\Delta m^2_{32}|$ has been measured, in appearance mode, with an accuracy of 20%. The measurement of the ν_τ charged-current cross section, for the first time with a negligible contamination from $\bar{\nu}_\tau$, and the first direct evidence for the ν_τ lepton number are also reported.

DOI: 10.1103/PhysRevLett.120.211801

Introduction.—The OPERA experiment was designed to conclusively prove $\nu_\mu \to \nu_\tau$ oscillations in appearance mode. The challenge of the experiment to detect the short-lived τ lepton ($c\tau = 87\ \mu$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 CERN to Gran Sasso Neutrino beam (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 $O(10^{-7})$.

The detector was a hybrid apparatus made of an emulsion and lead target with a total mass of about 1.25 kt, complemented by electronic detectors. The general structure consisted of two identical supermodules (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 ten 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 one prong (electron, muon, or hadron) or in three 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) reinteractions 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 (POT) has been collected from 2008 to 2012 and resulted in 19 505 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 $\nu_\mu \to \nu_\tau$ oscillations was assessed with a significance of 5.1σ [6].

This Letter reports an improved analysis of the full data sample, which is 3.6% higher with respect to [6]. The number of fully analyzed events is shown in Table I for each year of data taking. Events are classified as 1μ if a

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

	2008	2009	2010	2011	2012	Total
POT (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

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.

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 categorized into four channels ($\tau \to 1h$, $\tau \to 3h$, $\tau \to \mu$, $\tau \to e$) 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 the signal from the background and to evaluate a single-variable discriminant for the hypothesis test and parameter 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]. Current criteria correspond to the minimal requirements to identify the topologies showing two vertices. The Monte Carlo simulation has been validated in the whole region of the exploited parameter space, by comparing its results with the measured ν_μ CC interactions when producing hadron reinteractions [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].

TABLE II. Selection cuts.

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
$z_{\rm dec}$ (mm)	<2.6	<2.6	<2.6	<2.6
$\theta_{\rm kink}$ (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	[1, 15]	>1
p^T_{2ry} (GeV/c)	>0.15		>0.1	>0.1
Charge$_{2ry}$			Negative or unknown	

Decay topologies are identified by the following minimal requirements: the average 3D angle between the parent and its daughters ($\theta_{\rm kink}$) 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 ($z_{\rm dec}$) has to be shorter than 2600 μm. The latter cut extends the analysis of the single-prong hadronic and muonic decay modes also to the events where the decay vertex occurs in the same lead plate as the primary neutrino interaction. 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, thus minimizing the effect of multiple Coulomb scattering, with an upper limit of 15 GeV/c only for the $\tau \to \mu$ channel, in order to reduce the charmed hadron background. Moreover, for one-prong decays, the cut on the daughter transverse momentum with respect to the parent direction (p^T_{2ry}) was tuned to reduce the hadron reinteraction and LAS backgrounds. Last, for the $\tau \to \mu$ 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 with nuclear fragments emitted at the secondary vertex, a signature of the hadronic reinteraction background.

After candidate selection, a multivariate analysis is applied, based on a boosted decision tree (BDT) algorithm implemented using the Toolkit for Multivariate Data Analysis [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 ($p^T_{\rm miss}$), 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 $\tau \to \mu$ 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], normalized to the number of observed ν_μ CC interactions as explained in [9], assuming a maximal mixing $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{23} = 2.50 \times 10^{-3}$ eV^2 [20] and the ν_τ cross section as in

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

	Expected background					
Channel	Charm	Hadron reinteraction	Large μ scattering	Total	ν_τ expected	Observed
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38		1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03		0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002		0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	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 ± 1.4	10

the default implementation provided by GENIE v2.6 [21,22]. The expected number of signal and background events is 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]. The hadron reinteraction 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%.

The total expected signal is $N^{\exp\,S} = (6.8 \pm 1.4)$ events, whereas the total background expectation is $N^{\exp\,B} = (2.0 \pm 0.4)$ events.

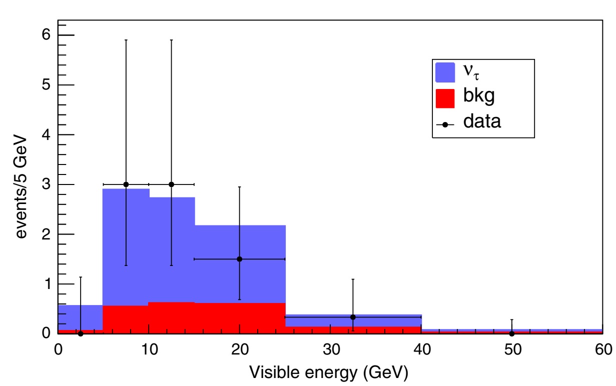

FIG. 1. Stacked plot of visible energy: data are compared with the expectation. Monte Carlo simulation is normalized to the expected number of events reported in Table III.

Observed events: Ten events ($N^{\rm obs}$) 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 gammas, is shown in Fig. 1, compared to Monte Carlo simulation. Among the ten selected ν_τ 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 one-prong decay and two a three-prong decay. Their kinematical variables are summarized 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 $\mathcal{P}$, and a Gaussian term $\mathcal{G}$ for the systematics of the expected yield:

$$\mathcal{L}(\mu, \beta_c) = \prod_{c=1}^{4} \left(\mathcal{P}(n_c | \mu s_c + \beta_c) \prod_{i=1}^{n_c} f_c(x_{ci}) \right) \times \prod_{c=1}^{4} \mathcal{G}(b_c | \beta_c, \sigma_{b_c}), \tag{1}$$

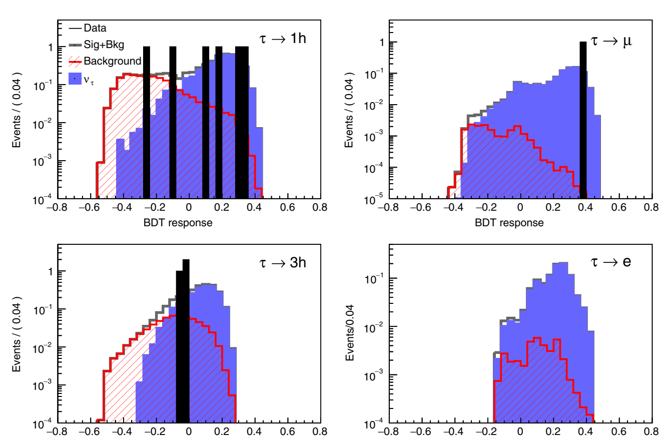

FIG. 2. BDT response for each channel.

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

Brick ID	72 693	29 570	23 543	92 217	130 577	77 152	27 972	26 670	136 759	4838
Channel	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 3h$	$\tau \to 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	−648	407
p^T_{miss} (GeV/c)	0.52	0.31		0.55	0.30	0.88	1.29	0.46	0.60	> 0.50
ϕ_{lH} (deg)	173	168		166	151	152	140	143	82	47
p^T_{2ry} (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

where

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

and c runs over the four channels, i over the n_c observed events in the cth channel, s_c is the expected signal, b_c and σ_{b_c} are the expected background in the cth 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 $\mathrm{PDF}_c^{\mathrm{bkg}}$ ($\mathrm{PDF}_c^{\mathrm{sig}}$) the distribution of x_{ci} for the background (signal) component in the cth 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 ~20% for each channel) has been proved to be negligible for all the following results.

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 $\lambda(\mu) = \mathcal{L}[\mu, \hat{\hat{\beta}}_c(\mu)]/\mathcal{L}(\hat{\mu}, \hat{\beta}_c)$ is used [24], where $\mathcal{L}(\hat{\mu}, \hat{\beta}_c)$ is the value of the likelihood at its maximum and $\hat{\hat{\beta}}_c(\mu)$ 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 6.1σ significance, corresponding to a background fluctuation probability of 4×10^{-10}. The best-fit signal strength is $\mu = 1.1^{+0.5}_{-0.4}$, which is consistent with the ν_τ appearance expected from neutrino oscillation.

First measurement of $|\Delta m^2_{32}|$ 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 $|\Delta m^2_{32}|$ can be derived using the Feldman-Cousins method [27]:

$$|\Delta m^2_{32}| = (2.7^{+0.7}_{-0.6}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{at } 68\%\ \text{C.L.} \qquad (2)$$

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 $|\Delta m^2_{32}|$, one may fix $|\Delta m^2_{32}|$ at the world average value (2.50×10^{-3} 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]:

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

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

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

$$\langle\sigma\rangle_{\mathrm{meas}} = \frac{(N^{\mathrm{obs}} - N^{\mathrm{exp}\,B})/(\epsilon N_T)}{\int \Phi_{\nu_\mu}(E)\mathcal{P}_{\nu_\mu\to\nu_\tau}(E)dE}, \qquad (4)$$

where N_T is the number of lead nuclei in the fiducial volume of the target and $\epsilon = 0.12$ is the overall efficiency of τ event reconstruction, averaged over the expected distribution of ν_τ flux [30]. The result is

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

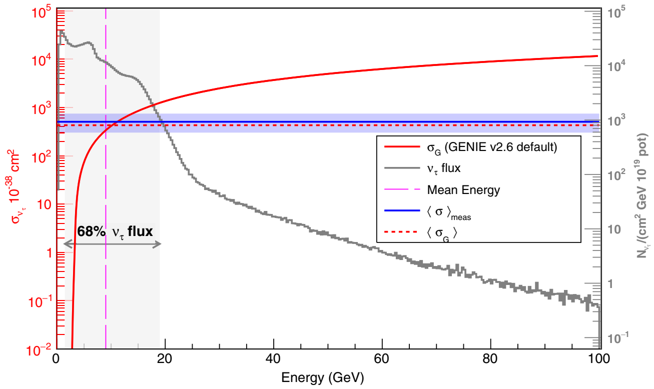

FIG. 3. Flux-averaged measurement of the CC σ_{ν_τ} on a lead target. The horizontal band includes the central 68% of the flux.

with the error dominated by the statistical uncertainty. This result has to be compared with the expected value, as provided by the default configuration of GENIE v2.6 [21,22]: $\langle\sigma_G\rangle = (4.29 \pm 0.04) \times 10^{-36}$ cm^2. The error associated with $\langle\sigma_G\rangle$ is the propagation of the flux uncertainty due to the oscillation parameter errors. Therefore, the result can be expressed as $\langle\sigma\rangle_{\mathrm{meas}} = (1.2^{+0.6}_{-0.5})\langle\sigma_G\rangle$. Figure 3 shows the measured value of the ν_τ cross section (blue line) and the value obtained by averaging the cross section implemented in GENIE, σ_G, over the ν_τ spectrum (red dashed line). This figure shows also σ_G as a function of the neutrino energy (red solid line) and the oscillated ν_τ spectrum (gray solid line) with its 68% central interval (gray band) and the mean neutrino energy (pink dashed line).

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

The hypothesis that a $\tau^- \to \mu^-$ has been observed is tested by specifying Eq. (1) to the $\tau \to \mu$ 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 in the 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 lepton number conservation in the neutrino CC interaction [32], can be considered to be the first direct evidence for the ν_τ lepton number.

Conclusions.—This Letter reports OPERA's final results on $\nu_\mu \to \nu_\tau$ 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 $\nu_\mu \to \nu_\tau$ oscillations in the appearance mode is confirmed with an improved significance of 6.1σ.

Assuming $\sin^2 2\theta_{23} = 1$, the first measurement of $|\Delta m^2_{32}|$ in appearance mode gives $(2.7^{+0.7}_{-0.6}) \times 10^{-3}$ eV^2, while the ν_τ CC cross section on the lead OPERA target is measured to be $(5.1^{+2.4}_{-2.0}) \times 10^{-36}$ cm^2, when $|\Delta m^2_{32}| = 2.50 \times 10^{-3}$ eV^2.

Furthermore, a dedicated BDT analysis in the $\tau \to \mu$ channel constitutes the first direct evidence for the ν_τ lepton number with a significance of 3.7σ [32].

We warmly thank CERN for the successful operation of the CNGS facility and INFN for the continuous support given by hosting the experiment in its LNGS laboratory. Funding is gratefully acknowledged from national agencies and institutions supporting us, namely, Fonds de la Recherche Scientifique–FNRS and Institut Interuniversitaire des Sciences Nucleaires for Belgium; Ministry of Science Education and Sport (MoSES) for Croatia; CNRS and Institut national de physique nucléaire et de physique des particules (IN2P3) for France; BMBF for Germany; INFN for Italy; JSPS, MEXT, the QFPU-Global COE program of Nagoya University, and Promotion and Mutual Aid Corporation for Private Schools of Japan for Japan; SNF, the University of Bern and ETH Zurich for Switzerland; the Russian Foundation for Basic Research (Grant No. 12-02-12142 ofim), the Programs of the Presidium of the Russian Academy of Sciences (Neutrino Physics and Experimental and Theoretical Researches of Fundamental Interactions), and the Ministry of Education and Science of the Russian Federation for Russia, the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (Grant No. NRF-2018R1A2B2007757) for Korea; and TUBITAK, the Scientific and Technological Research Council of Turkey for Turkey (Grant No. 108T324).

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