NuFIT 5.1: Three-neutrino fit based on data available in October 2021

Ivan Esteban,[a] M. C. Gonzalez-Garcia,[b,c,d] Michele Maltoni,[e] Thomas Schwetz,[f] Albert Zhou[f]

[a] *Center for Cosmology and AstroParticle Physics (CCAPP) and Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*

[b] *Departament de Física Quàntica i Astrofísica and Institut de Ciencies del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*

[c] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, 08010 Barcelona, Spain.*

[d] *C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3840, USA*

[e] *Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13–15, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*

[f] *Institut für Astroteilchenphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

E-mail: esteban.6@osu.edu, maria.gonzalez-garcia@stonybrook.edu, michele.maltoni@csic.es, schwetz@kit.edu, albert.zhou@kit.edu

Abstract: We present updated results for our global analysis of solar, atmospheric, reactor, and accelerator neutrino data in the framework of three-neutrino oscillations. We also provide χ^2 tables for various one-, two- and three-dimensional projections of the global analysis. If you use these results, please refer to both [1] and [2]. Data sets which have been updated with respect to NuFIT 5.0 are marked by the "⇒" tag.

Solar experiments

- *External information*: Standard Solar Model [3].
- Chlorine total rate [4], 1 data point.
- Gallex & GNO total rates [5], 2 data points.
- SAGE total rate [6], 1 data point.
- SK1 full energy and zenith spectrum [7], 44 data points.
- SK2 full energy and day/night spectrum [8], 33 data points.
- SK3 full energy and day/night spectrum [9], 42 data points.
- SK4 2970-day day-night asymmetry and energy spectrum [10], 24 data points.
- SNO combined analysis [11], 7 data points.
- Borexino Phase-I 741-day low-energy data [12], 33 data points.
- Borexino Phase-I 246-day high-energy data [13], 6 data points.
- Borexino Phase-II 408-day low-energy data [14], 42 data points.

Atmospheric experiments

- *External information*: Atmospheric neutrino fluxes [15].
- IceCube/DeepCore 3-year data [16, 17], 64 data points.

⇒ SK1-4 364.8 kiloton years [10], χ^2 map [18] added to our global analysis.

Reactor experiments

- KamLAND separate DS1, DS2, DS3 spectra [19] with Daya Bay reactor ν fluxes [20], 69 data points.
- Double-Chooz FD/ND spectral ratio, with 1276-day (FD), 587-day (ND) exposures [21], 26 data points.
- Daya Bay 1958-day EH2/EH1 and EH3/EH1 spectral ratios [22], 52 data points.
- Reno 2908-day FD/ND spectral ratio [23], 45 data points.

Accelerator experiments

- MINOS 10.71×10^{20} pot ν_μ-disappearance data [24], 39 data points.
- MINOS 3.36×10^{20} pot $\bar{\nu}_\mu$-disappearance data [24], 14 data points.
- MINOS 10.6×10^{20} pot ν_e-appearance data [25], 5 data points.
- MINOS 3.3×10^{20} pot $\bar{\nu}_e$-appearance data [25], 5 data points.
- T2K 19.7×10^{20} pot ν_μ-disappearance data [26], 35 data points.
- T2K 19.7×10^{20} pot ν_e-appearance data [26], 23 data points for the CCQE and 16 data points for the CC1π samples.
- T2K 16.3×10^{20} pot $\bar{\nu}_\mu$-disappearance data [26], 35 data points.
- T2K 16.3×10^{20} pot $\bar{\nu}_e$-appearance data [26], 23 data points.
- NOvA 13.6×10^{20} pot ν_μ-disappearance data [27], 76 data points.
- NOvA 13.6×10^{20} pot ν_e-appearance data [27], 13 data points.
- NOvA 12.5×10^{20} pot $\bar{\nu}_\mu$-disappearance data [27], 76 data points.
- NOvA 12.5×10^{20} pot $\bar{\nu}_e$-appearance data [27], 13 data points.

Description of the χ^2 data tables

We provide four xz-compressed files, containing the χ^2 data tables for both Normal and Inverted Ordering of our global «w/o SK-atm» and «with SK-atm» analyses. Each file is divided into 22 sections, identified by a unique tag and corresponding to a particular one-, two- or three-dimensional projection. The tags and the meaning of the data columns for each section are listed below (note that $\ell = 1$ for NO and $\ell = 2$ for IO).

N°	Section tag	1st column	2nd column	3rd column	4th column
1	`# T23/DMA/DCP`	$\sin^2\theta_{23}$	$\Delta m^2_{3\ell} \,/\, [10^{-3}\ \text{eV}^2]$	$\delta_{CP} \,/\, [\text{deg}]$	$\Delta\chi^2$
2	`# T13/T12`	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	$\Delta\chi^2$	—
3	`# T13/DMS`	$\sin^2\theta_{13}$	$\log_{10}(\Delta m^2_{21} \,/\, [\text{eV}^2])$	$\Delta\chi^2$	—
4	`# T12/DMS`	$\sin^2\theta_{12}$	$\log_{10}(\Delta m^2_{21} \,/\, [\text{eV}^2])$	$\Delta\chi^2$	—

N°	Section tag	1st column	2nd column	3rd column	4th column
5	`# T13/T23`	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta\chi^2$	—
6	`# T13/DMA`	$\sin^2\theta_{13}$	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\Delta\chi^2$	—
7	`# T23/DMA`	$\sin^2\theta_{23}$	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\Delta\chi^2$	—
8	`# T13/DCP`	$\sin^2\theta_{13}$	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—
9	`# T23/DCP`	$\sin^2\theta_{23}$	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—
10	`# DMA/DCP`	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—
11	`# T12/T23`	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\Delta\chi^2$	—
12	`# T12/DCP`	$\sin^2\theta_{12}$	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—
13	`# T12/DMA`	$\sin^2\theta_{12}$	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\Delta\chi^2$	—
14	`# DMS/T23`	$\log_{10}(\Delta m^2_{21}\,/\,[\text{eV}^2])$	$\sin^2\theta_{23}$	$\Delta\chi^2$	—
15	`# DMS/DCP`	$\log_{10}(\Delta m^2_{21}\,/\,[\text{eV}^2])$	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—
16	`# DMS/DMA`	$\log_{10}(\Delta m^2_{21}\,/\,[\text{eV}^2])$	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\Delta\chi^2$	—
17	`# T13`	$\sin^2\theta_{13}$	$\Delta\chi^2$	—	—
18	`# T12`	$\sin^2\theta_{12}$	$\Delta\chi^2$	—	—
19	`# T23`	$\sin^2\theta_{23}$	$\Delta\chi^2$	—	—
20	`# DCP`	$\delta_{CP}\,/\,[\text{deg}]$	$\Delta\chi^2$	—	—
21	`# DMS`	$\log_{10}(\Delta m^2_{21}\,/\,[\text{eV}^2])$	$\Delta\chi^2$	—	—
22	`# DMA`	$\Delta m^2_{3\ell}\,/\,[10^{-3}\text{ eV}^2]$	$\Delta\chi^2$	—	—

References

[1] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou, *The fate of hints: updated global analysis of three-flavor neutrino oscillations*, *JHEP* **09** (2020) 178 [2007.14792].

[2] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou, "NuFIT 5.1 (2021)." http://www.nu-fit.org.

[3] N. Vinyoles, A. M. Serenelli, F. L. Villante, S. Basu, J. Bergström, M. C. Gonzalez-Garcia et al., *A new Generation of Standard Solar Models*, *Astrophys. J.* **835** (2017) 202 [1611.09867].

[4] B. T. Cleveland et al., *Measurement of the solar electron neutrino flux with the Homestake chlorine detector*, *Astrophys. J.* **496** (1998) 505.

[5] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, *Reanalysis of the GALLEX solar neutrino flux and source experiments*, *Phys. Lett.* **B685** (2010) 47 [1001.2731].

[6] SAGE collaboration, J. N. Abdurashitov et al., *Measurement of the solar neutrino capture rate with gallium metal. III: Results for the 2002–2007 data-taking period*, *Phys. Rev.* **C80** (2009) 015807 [0901.2200].

[7] Super-Kamiokande collaboration, J. Hosaka et al., *Solar neutrino measurements in Super-Kamiokande-I*, *Phys. Rev.* **D73** (2006) 112001 [hep-ex/0508053].

[8] Super-Kamiokande collaboration, J. Cravens et al., *Solar neutrino measurements in Super-Kamiokande-II*, *Phys. Rev.* **D78** (2008) 032002 [0803.4312].

[9] Super-Kamiokande collaboration, K. Abe et al., *Solar neutrino results in Super-Kamiokande-III*, *Phys. Rev.* **D83** (2011) 052010 [1010.0118].

[10] Y. Nakajima, "Recent results and future prospects from Super-Kamiokande." Talk given at the *XXIX International Conference on Neutrino Physics and Astrophysics*, Chicago, USA, June 22–July 2, 2020 (online conference).

[11] SNO collaboration, B. Aharmim et al., *Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory*, 1109.0763.

[12] Borexino collaboration, G. Bellini et al., *Precision measurement of the 7Be solar neutrino interaction rate in Borexino*, *Phys. Rev. Lett.* **107** (2011) 141302 [1104.1816].

[13] Borexino collaboration, G. Bellini et al., *Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector*, *Phys. Rev.* **D82** (2010) 033006 [0808.2868].

[14] BOREXINO collaboration, G. Bellini et al., *Neutrinos from the primary proton–proton fusion process in the Sun*, *Nature* **512** (2014) 383.

[15] M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara and S. Midorikawa, *Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model*, *Phys. Rev.* **D92** (2015) 023004 [1502.03916].

[16] IceCube collaboration, M. Aartsen et al., *Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data*, *Phys. Rev.* **D91** (2015) 072004 [1410.7227].

[17] IceCube collaboration, J. P. Yañez et al., "IceCube Oscillations: 3 years muon neutrino disappearance data." http://icecube.wisc.edu/science/data/nu_osc.

[18] SuperKamiokande collaboration, "SK Atmospheric Oscillation Analysis 2020 (preliminary) results." link to data release: https://indico-sk.icrr.u-tokyo.ac.jp/event/5517/, 2020.

[19] KamLAND collaboration, A. Gando et al., *Reactor On-Off Antineutrino Measurement with KamLAND*, *Phys. Rev.* **D88** (2013) 033001 [1303.4667].

[20] Daya Bay collaboration, F. P. An et al., *Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay*, *Chin. Phys.* **C41** (2017) 013002 [1607.05378].

[21] T. Bezerra, "New Results from the Double Chooz Experiment." Talk given at the *XXIX International Conference on Neutrino Physics and Astrophysics*, Chicago, USA, June 22–July 2, 2020 (online conference).

[22] Daya Bay collaboration, D. Adey et al., *Measurement of Electron Antineutrino Oscillation with 1958 Days of Operation at Daya Bay*, 1809.02261.

[23] J. Yoo, "RENO." Talk given at the *XXIX International Conference on Neutrino Physics and Astrophysics*, Chicago, USA, June 22–July 2, 2020 (online conference).

[24] MINOS collaboration, P. Adamson et al., *Measurement of Neutrino and Antineutrino Oscillations Using Beam and Atmospheric Data in MINOS*, *Phys. Rev. Lett.* **110** (2013) 251801 [1304.6335].

[25] MINOS collaboration, P. Adamson et al., *Electron neutrino and antineutrino appearance in the full MINOS data sample*, *Phys. Rev. Lett.* (2013) [1301.4581].

[26] P. Dunne, "Latest Neutrino Oscillation Results from T2K." Talk given at the *XXIX International Conference on Neutrino Physics and Astrophysics*, Chicago, USA, June 22–July 2, 2020 (online conference).

[27] A. Himmel, "New Oscillation Results from the NOvA Experiment." Talk given at the *XXIX International Conference on Neutrino Physics and Astrophysics*, Chicago, USA, June 22–July 2, 2020 (online conference).