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Response to Comment on Daya Bay's definition and use of Delta(m^2_ee)

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Comment on "Comment on Daya Bay's definition and use of Δm^2_{ee}" by S. Parke and R. Zukanovich Funchal

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"Comment on Daya Bay's definition and use of Δm^2_{ee}" by S. Parke and R. Zukanovich Funchal [1] seems to have confounded two different concepts: an experimental measurement vs. the interpretation of the measurement. We clarify a few points in our response.

First, all relevant Daya Bay publications [2–5] have consistently reported two values of Δm^2_{32} in the standard three-neutrino framework under the assumption of the normal or inverted mass hierarchy. These values were always obtained through a fit with the exact full three-neutrino oscillation formula and used the best knowledge of the solar oscillation parameters at the time.

Second, in all these publications we also reported the value of Δm^2_{ee} through another fit, independent from the one mentioned above, with the formula

$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right). \quad (1)$$

Such a fit is viable since a reactor neutrino experiment at kilometer baselines is only sensitive to two effective neutrino oscillation frequencies: one leading frequency (instead of two) with an amplitude driven by θ_{13}, and one sub-leading frequency with an amplitude driven by θ_{12}. The leading frequency Δm^2_{ee}, naturally a constant as a fitting parameter, is our measurement. It enables interpretation in various theoretical models, either in the three-neutrino framework or beyond.

The main motivation for the use of Δm^2_{ee} is to report our observations in a model-independent way. In Eq. 1 at Daya Bay's baseline, the sub-leading oscillation has been well measured by KamLAND [6] and the leading oscillation is well supported by our data. Therefore, we fit Δm^2_{ee} based on existing experimental facts, largely independent of the three-neutrino framework. Our measurement Δm^2_{ee} does not depend on the choice of mass ordering. Moreover, it can be interpreted in other models and/or as new measurements come to light.

In the supplemental material of Ref. [3], we provided a discussion about the interpretation of this quantity in the three-neutrino framework. In this supplement, two interpretations were provided: one with a slight L/E dependence, which was identified as the second Daya Bay definition $\Delta m^2_{ee}(\mathrm{DB2})$ in Parke and Zukanovich Funchal's comment, and another one with a constant $\Delta m^2_{\phi} = 5.17 \times 10^{-5}$ eV^2 offset between Δm^2_{ee} and Δm^2_{32}. Both were demonstrated to be numerically equivalent to the one proposed by Nunokawa, Parke and Zukanovich Funchal in Ref. [7] across Daya Bay's L/E regime in the three-neutrino model.

It is important to note that we have never defined Δm^2_{ee} in terms of a combination of fundamental oscillation parameters. Instead, all measurements of Δm^2_{ee} reported to date by Daya Bay used the effective oscillation model of Eq. 1 as the primary definition of this parameter without exception. When we fit the data, Δm^2_{ee} is an independent parameter. It is not necessary nor advantageous to impose an additional relation with the fundamental parameters. To avoid confusion, recent Daya Bay publications have used the "≈" sign instead of the "=" in Eq. 1; however, this change has no impact on our fitting process nor on the interpretation of the parameter.

As a final comment, introducing the definition $\Delta m^2_{ee}(\mathrm{NPZ}) \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$ as argued by Parke and Zukanovich Funchal [1], 1) does not provide any new information since we have provided the fit value of Δm^2_{32}; 2) does not extend the approximate oscillation formula to the large L/E regime as all other similar interpretations, although itself is L/E independent; 3) would invalidate our publications in case new physics beyond the three-neutrino framework is found, e.g. the sterile neutrino.

Because of all these reasons, we disagree with the authors' criticism "... Daya Bay's new definition of Δm^2_{ee} does not manifestly show the simple relationship to the fundamental parameters of the neutrino sector for short baseline reactor experiments, such as Daya Bay and RENO. Nor is it useful for future medium baseline experiments like JUNO ...". Daya Bay's reported value of Δm^2_{ee} is a model-independent measurement of the leading oscillation frequency observed in our experiment. This definition is simple, intuitive, and supported by experimental observations.

In conclusion, Daya Bay will continue to extract Δm^2_{ee} as a model-independent fitting parameter and to provide it to the community alongside the fundamental parameter Δm^2_{32}, obtained independently using the exact formula in the three-neutrino oscillation framework. For experiments where the two-constant-frequency approximation does not apply, such as JUNO [8], the exact three-neutrino oscillation formula that explicitly depends on Δm^2_{31} and Δm^2_{32} should always be used.

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