

Constraint on the solar Δm^2 using 4000 days of short baseline reactor neutrino data

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(Received 16 August 2019; published 20 December 2019)

There is a well-known 2σ tension in the measurements of the solar Δm^2 between KamLAND and SNO/Super-KamioKANDE. Precise determination of the solar Δm^2 is especially important in connection with current and future long baseline CP violation measurements. Seo and Parke [*Phys. Rev. D* **99**, 033012 (2019)] points out that currently running short baseline reactor neutrino experiments, Daya Bay and RENO, can also constrain solar Δm^2 value as demonstrated by a GLOBES simulation with a limited systematic uncertainty consideration. In this work, the publicly available data, from Daya Bay (1958 days) and RENO (2200 days) are used to constrain the solar Δm^2 . Verification of our method through Δm_{ee}^2 and $\sin^2\theta_{13}$ measurements is discussed in Appendix A. Using this verified method, reasonable constraints on the solar Δm^2 are obtained using above Daya Bay and RENO data, both individually and combined. We find that the combined data of Daya Bay and RENO set an upper limit on the solar Δm^2 of $18 \times 10^{-5} \text{ eV}^2$ at the 95% C.L., including both systematic and statistical uncertainties. This constraint is slightly more than twice the KamLAND value. As this combined result is still statistics limited, even though driven by Daya Bay data, the constraint will improve with the additional running of this experiment.

DOI: [10.1103/PhysRevD.100.113008](https://doi.org/10.1103/PhysRevD.100.113008)

I. INTRODUCTION

Evidence that neutrinos are massive and mix is well established by a significant number of experiments. In this paper, we are interested in the mass squared difference, Δm_{21}^2 ; the mass squared difference of the two mass eigenstates that have the greatest fraction of electron neutrino, ν_1 and ν_2 . This mass splitting is responsible for the neutrino flavor transformations that occur inside the Sun (hence the name the solar mass squared difference), and for the antineutrino oscillations observed at an $L/E \sim 15 \text{ km/MeV}$.

In this paper, we use publicly available data to follow up a recent paper [1], that Daya Bay [2] and RENO [3], the short baseline ($\sim 1.5 \text{ km}$) reactor antineutrino experiments currently running, have enough data already collected to constrain Δm_{21}^2 .

The combined constraint by Daya Bay and RENO, gives an important consistency check of the standard three neutrino paradigm as well as adding addition information to the size of Δm_{21}^2 . The $\sim 2\sigma$ tension between the combined Super-Kamiokande (SK) [4] & Sudbury Neutrino Observatory (SNO) [5] solar neutrino measurements and KamLAND [6] reactor experiment ($L/E \sim 50 \text{ km/MeV}$) is not directly addressed by this constraint. However such a combined Daya Bay plus RENO constraint is at a different L/E range ($\sim 0.5 \text{ km/MeV}$) than the above mentioned measurements as well as JUNO [7]. Moreover, the ratio of Δm_{21}^2 to Δm_{31}^2 , at an $L/E \sim 0.5 \text{ km/MeV}$, is required for the precision measurement of leptonic CP violation parameter, by NOvA [8], T2K [9] and future Long Baseline (LBL) experiments.

Currently there are two measurements of the solar mass squared difference, Δm_{21}^2 . One measurement comes from a

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combined measurement by SNO and SK using the observation of a day-night asymmetry by SK and the nonobservation of the low energy up turn of the ^8B neutrino survival probability by SNO and SK. This combined result is

$$\Delta m_{21}^2 = 5.1_{-1.0}^{+1.3} \times 10^{-5} \text{ eV}^2, \quad (1)$$

from SNO and SK. Similar results are obtained by Nu-Fit [10]. The other measurement is from KamLAND, the long baseline reactor antineutrino experiment, see [6], at

$$\Delta m_{21}^2 = 7.50_{-0.20}^{+0.20} \times 10^{-5} \text{ eV}^2, \quad (2)$$

If *CPT* invariance is a good symmetry of nature then the Δm_{21}^2 measured from solar neutrinos and reactor antineutrinos is required to give the same value. Currently this important parameter for neutrino physics suffers from a 2σ level tension. This tension could come from new physics, some error in the analysis of one or more of the experiments or a statistical fluctuation.

Moreover, the ratio of Δm_{21}^2 to Δm_{31}^2 is required for the determination of the *CP* phase, δ , in the long baseline neutrino¹ oscillation experiments (NOvA, DUNE [11], T2K, T2HK [12], T2HKK [13]) as the size of the *CP* violation is proportional to Δm_{21}^2 to Δm_{31}^2 , as well as the Jarlskog invariant. At $L/E \sim 500 \text{ km/GeV} = 0.5 \text{ km/MeV}$, the first oscillation peak in vacuum, for $\nu_\mu \rightarrow \nu_e$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \approx \pi J \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right) \quad (3)$$

where the Jarlskog invariant, J , is $J = \sin 2\theta_{12} \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin \delta \approx 0.3 \sin \delta$.

In the biveient plane for T2K, see Fig 44 of [14],

$$N(\nu_\mu \rightarrow \nu_e) = 37 \quad \text{and} \quad N(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4$$

is outside the allowed region (by about 1σ). This can be well accommodated by a Δm_{21}^2 value, approximately twice the KamLAND value. Again, this is probably a statistical fluctuation but with only the KamLAND precision measurement of Δm_{21}^2 , other possibilities are still viable.

The future medium baseline, $L/E \sim 15 \text{ km/MeV}$, reactor experiment JUNO will measure to better than 1% precision Δm_{21}^2 and $\sin^2\theta_{12}$, see [7]. JUNO experiment is currently under construction and their precision measurements of Δm_{21}^2 and $\sin^2\theta_{12}$ will not be available until approximately 5 years from now. Later next decade, the proposed experiments Hyper-K & DUNE will also give us

¹In the rest of this paper, when referring to neutrinos, we mean both neutrinos and/or antineutrinos.

precision measurements of Δm_{21}^2 using ^8B solar neutrinos, see [15,16] respectively.

In Sec. II, we briefly discuss in detail the effects of increasing Δm_{21}^2 on the $\bar{\nu}_e$ survival probability. Then in Sec. III Daya Bay and RENO data sets used in this work are discussed followed by Secs. IV, V, and VI for methods and systematic uncertainties, results, and conclusion, respectively.

II. SURVIVAL PROBABILITY

In vacuum, the electron antineutrino survival probability is

$$\begin{aligned} P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &= 1 - P_{12} - P_{13} \quad \text{with} \\ P_{12} &= \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}, \\ P_{13} &= \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}), \end{aligned} \quad (4)$$

where the kinematic phases are given by $\Delta_{jk} \equiv \Delta m_{jk}^2 L / (4E)$ and $\theta_{13} \approx 8^\circ$ and $\theta_{12} \approx 33^\circ$ are the reactor and solar mixing angles respectively. The P_{12} term is associated with the solar oscillation scale of 15 km/MeV and the P_{13} term is associated with the atmospheric oscillation scale of 0.5 km/MeV . To excellent fractional precision,² the P_{13} term can be approximated by

$$P_{13} \approx \sin^2 2\theta_{13} \sin^2 \Delta_{ee} \quad (5)$$

where $\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$ [17,18], interpreted as the ν_e average of Δm_{31}^2 and Δm_{32}^2 .

Using the fit values given in [10], and an L/E range around the first oscillation minimum ($L/E \sim 0.5 \text{ km/MeV}$), P_{12} and P_{13} is well approximated by:

$$P_{12} \approx 0.002 \left(\frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left(\frac{\Delta m_{21}^2}{7.5 \times 10^{-5} \text{ eV}^2} \right)^2 \quad (6)$$

$$P_{13} \approx 0.08 \sin^2 \left(\frac{\pi}{2} \left(\frac{L/E}{0.5 \text{ km/MeV}} \right) \right). \quad (7)$$

The P_{12} term is almost negligible for all $L/E < 1 \text{ km/MeV}$, if $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2$. For Daya Bay and RENO this covers the full L/E range.

Suppose that Δm_{21}^2 is 3 times larger than KamLAND value, i.e., $22.5 \times 10^{-5} \text{ eV}^2$, then

²The fractional precision is better than 0.05% for $L/E < 1 \text{ km/MeV}$. Also, in this L/E range, the exact P_{13} is very insensitive to mass ordering provided the value of $|\Delta m_{ee}^2|$ is the same for both mass orderings.

TABLE I. Live days (not operational days), effective baseline distance (L_{eff}), observed IBD and background events for Daya Bay and RENO used in this work. For Daya Bay there are two near detectors in different sites.

	Daya Bay: Near	Daya Bay: Far	RENO: Near	RENO: Far
Live days	(1,637.12, 1,647.64)	1,692.69	1,807.88	2,193.04
L_{eff} (m)	(562.2, 594.2)	1637	430.4	1445.4
Total # of IBD events	(1,763,939, 1,651,088)	486,873	833,433	98,292
Total # of background events	(19,056, 13,634)	2,230	17,229	4,912

$$P_{12} \approx 0.02 \left(\frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left(\frac{\Delta m_{21}^2}{22.5 \times 10^{-5} \text{ eV}^2} \right)^2. \quad (8)$$

Now P_{12} is now no longer tiny compared to P_{13} at $L/E = 0.5$ km/MeV, oscillation minimum, and as L/E gets larger than 0.5 km/MeV, P_{12} gets bigger, whereas P_{13} is getting smaller. At an $L/E = 1$ km/MeV, P_{12} would be approximately equal to $\sin^2 2\theta_{13}$ (0.08) for this value of Δm_{21}^2 . It is this quadratic rise in P_{12} as Δm_{21}^2 increases that we exploit to place an upper limit on Δm_{21}^2 . For further details on the survival probability as Δm_{21}^2 increases see [1].

III. DAYA BAY AND RENO DATA SETS

In this work, 1958 days of Daya Bay data [19] and 2200 days of RENO data [20] are used, where Daya Bay has about five times more inverse beta decay (IBD) events than RENO in their far detectors. Daya Bay data including background estimation, energy response function, and systematic uncertainties are taken from the supplementary material in [19]. RENO data and background estimation are extracted from Fig. 1 in [20] and systematic uncertainties are also taken from [20]. Table I shows summary of the basic parameters, i.e., L_{eff} , IBD rate, and background rate, for near and far detectors of Daya Bay and RENO used in this analysis. Note that there are two near detectors in different sites for Daya Bay.

IV. METHODS AND SYSTEMATIC UNCERTAINTIES

Best fit values on Δm_{21}^2 and $\sin^2 2\theta_{13}$ are obtained by finding minimum χ^2 values between data and predictions for all possible combination of the two parameters. Far-to-near ratio method is employed in this χ^2 analysis to avoid the spectral shape anomaly around 5 MeV region [21] as well as to reduce systematic uncertainties.

The χ^2 formalism as written below contains a covariance matrix ($V_{\text{stat},ij}$) to include statistical uncertainty and pull parameters (ξ_α) to include systematic uncertainties.

$$\chi^2 = \sum_{i,j}^{N_{\text{bins}}} (D_i^{F/N} - P_i^{F/N}) V_{\text{stat},ij}^{-1} (D_j^{F/N} - P_j^{F/N}) + \sum_{\alpha}^{N_{\text{pull}}} \frac{(\xi_\alpha - 1)^2}{\sigma_\alpha^2},$$

where, $D_i^{F/N} \equiv \frac{O_i^F - B_i^F}{O_i^N - B_i^N}$, $P_i^{F/N} \equiv \frac{X_i^F}{X_i^N}$, and $F(N)$ and i (j) represent the Far (Near) detector and i th (j)th prompt energy bin, respectively. Being O the observed number of IBD candidate events, B the estimated background number of events and X the expected number of events for a given Δm_{21}^2 and $\sin^2 2\theta_{13}$ pair. A total of 26 energy bins (N_{bins}) is used for RENO from 1.2 to 8.4 MeV. The same number of energy bins are used for Daya Bay from 0.7 to 12 MeV but two near detectors are taken into account in the χ^2 formalism by replacing N_{bins} to $2N_{\text{bins}}$ where for $1 \leq i \leq N_{\text{bins}}$, $F = \text{EH3}$ and $N = \text{EH1}$, and for $N_{\text{bins}} + 1 \leq i \leq 2N_{\text{bins}}$, $F = \text{EH3}$ and $N = \text{EH2}$.

For both Daya Bay and RENO, systematic uncertainties on the relative detection efficiency, relative energy scale and the main background contributions are taken into account as summarized in Table II.

Besides the systematic uncertainties, additional systematic paddings (adjustment factors) are added in our work to match Daya Bay and RENO results on θ_{13} and Δm_{ee}^2 measurements. For Daya Bay a 1.3 adjustment factor to the relative energy scale and Li-He background uncertainties is added. Whereas in RENO a 1.4 adjustment factor is added to the relative detection efficiency uncertainty. More details on the validation of our method and expected event description can be found in Appendixes A and B. The RENO predictions are computed using the Daya Bay detector response function and the relative far-to-near normalization is computed comparing our total number of expected events with the total number of expected events in the RENO Far detector. In order to match the best fit values of θ_{13} and Δm_{ee}^2 a 0.984 adjustment factor is added to this normalization of a total event rate for RENO.

TABLE II. Relative systematic uncertainties used in this work for Daya Bay and RENO, taken from [19,20] respectively.

Source	Daya Bay	RENO
	Uncertainty %	
Detection efficiency	0.13	0.21
Energy scale	0.2	0.15
Li-He background	30	5–8
Fast neutron background	13–17	...
Accidental background	1	...

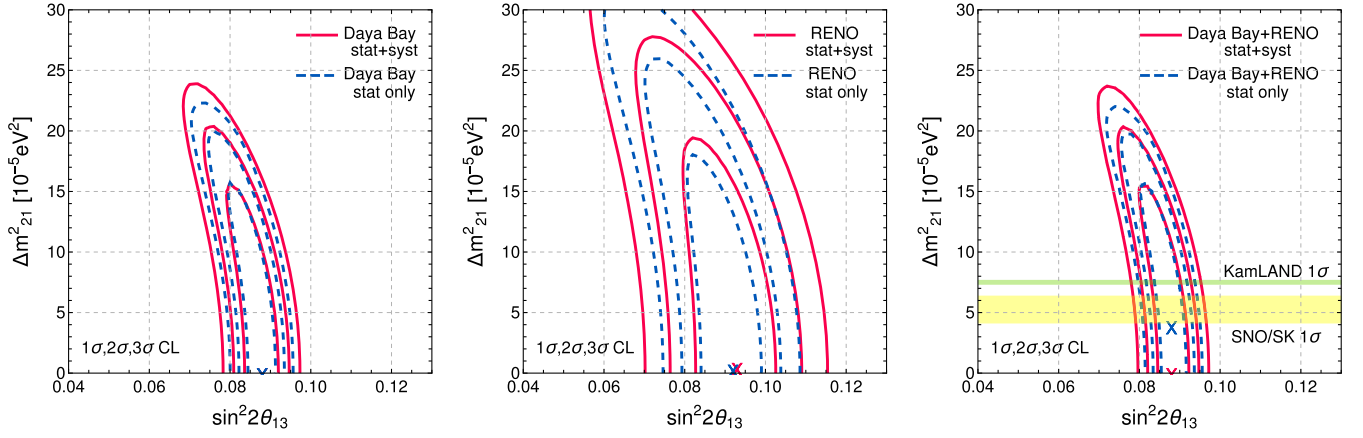


FIG. 1. The 1, 2 and 3 σ allowed regions in the Δm_{21}^2 vs $\sin^2 2\theta_{13}$ parameter space for Daya Bay (1958 days, 487 K IBD events at Far) (left panel) and RENO (2200 days, 98 K IBD events at Far) (middle panel) and the Daya Bay and RENO combined (right panel). In this fitting, the Δm_{ee}^2 value is constrained using the value from current long baseline (LBL) neutrino experiments, see Eq. (9). In the right panel the KamLAND and SNO/SK 1 σ bands are overlaid for comparison and this contour plot shows that this measurement is still statistics limited.

V. RESULTS

A 2-dimensional scan over Δm_{21}^2 and $\sin^2 2\theta_{13}$ is performed to find the best fit value pair at the minimum value of χ^2 described earlier, where in the oscillation probability, the parameter θ_{12} is fixed³ at $\sin^2 \theta_{12} = 0.310$. The Δm_{ee}^2 parameter is constrained with a pull parameter, allowing it to vary within a 2σ range of a prior Δm_{ee}^2 value with a penalizing term

$$\left(\frac{\Delta m_{ee,\text{prior}}^2 - \Delta m_{ee}^2}{\sigma} \right)^2$$

The prior Δm_{ee}^2 value and its uncertainty are taken to be

$$\Delta m_{ee}^2 = 2.45 \pm 0.15 \times 10^{-3} \text{ eV}^2 \quad (9)$$

which is inferred from the combined measurement on $\Delta m_{\mu\mu}^2$ by current long baseline neutrino experiments in [10] through $\Delta m_{ee}^2 \simeq \Delta m_{\mu\mu}^2 \pm \cos 2\theta_{12} \Delta m_{21}^2$, see [17], where the $+/-$ comes from the unknown mass ordering (NO/IO) and ignoring terms proportional to $\sin \theta_{13} \Delta m_{21}^2$. The unknown mass ordering is treated as an additional uncertainty (4%) to $\Delta m_{\mu\mu}^2$ uncertainty (4%) for the Δm_{ee}^2 uncertainty which, therefore, becomes about 6%.

The best fit, 1, 2, and 3 σ allowed regions of Δm_{21}^2 vs $\sin^2 2\theta_{13}$ are shown in Fig. 1 with (solid lines) and without (dashed lines) systematic uncertainties for Daya Bay and RENO, separately and combined. Daya Bay's result is better than RENO's due to about five time more statistics at the far detector, see Table I.

³A discussion on the effects of varying θ_{12} in this analysis can be found in [1].

Figure 2 shows the χ^2 projection over Δm_{21}^2 , obtained by minimizing over $\sin^2 2\theta_{13}$, for the Daya Bay plus RENO combined analysis. The upper bounds on Δm_{21}^2 , including systematic uncertainties, are 12.3, 18.3 and $22.3 \times 10^{-5} \text{ eV}^2$ at 1, 2 and 3 σ CL, respectively. Current upper bounds are limited by statistics.

In Fig. 3, we give the constraints on the three parameter fit, Δm_{21}^2 , Δm_{ee}^2 and $\sin^2 2\theta_{13}$, without imposing any constrain on Δm_{ee}^2 , using the combined Daya Bay and RENO data sets. Both statistical and systematic uncertainties are included in this plot. As before θ_{12} is fixed at $\sin^2 \theta_{12} = 0.310$, see [1] for discussion on allowing $\sin 2\theta_{12}$ to also vary.

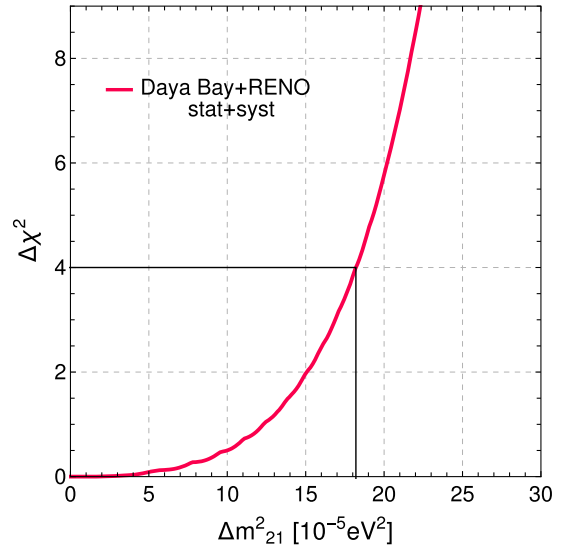


FIG. 2. The Daya Bay and RENO combined analysis for the $\Delta\chi^2$ projection of the Δm_{21}^2 measurement including systematic uncertainty, minimizing over $\sin^2 2\theta_{13}$. At the 2 σ (95%) C.L. Δm_{21}^2 is constrained to be less than $18.3(18) \times 10^{-5} \text{ eV}^2$.

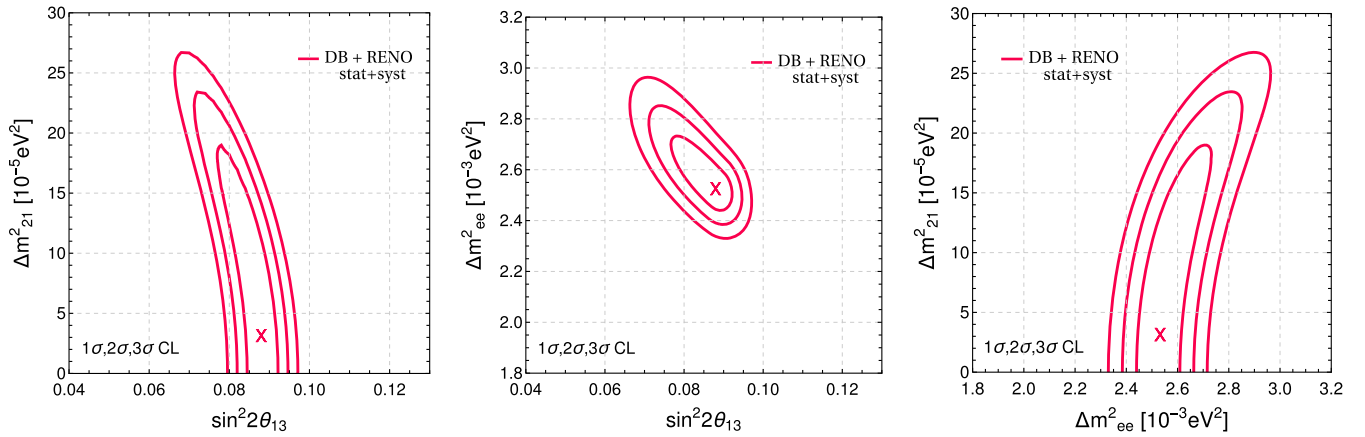


FIG. 3. Simultaneous three parameter fit for Δm_{21}^2 , Δm_{ee}^2 and $\sin^2 2\theta_{13}$ using the combined Daya Bay (1,958 days, 487 K IBD events at Far) and RENO (2,200 days, 98 K IBD events at Far) data. The best fit point is found at $\Delta m_{21}^2 = 3.3 \times 10^{-5} \text{ eV}^2$, $\Delta m_{ee}^2 = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} = 0.088$.

Results with Δm_{ee}^2 fixed or free are obtained for each experiment and for when the data from both experiments are combined. These are described and given in Appendix C. It was found that the effect of free Δm_{ee}^2 is bigger than that of systematic uncertainty, but our representing results are based on constrained Δm_{ee}^2 since it is a reasonably well measured oscillation parameter using LBL experiments.

VI. CONCLUSION

Using the currently available public data from Daya Bay (1,958 days) and RENO (2,200 days), we have provided additional information on the solar Δm^2 . A reasonable upper bound is obtained from a combined analysis of the Daya Bay and RENO data as $18 \times 10^{-5} \text{ eV}^2$ at 95% CL, where Δm_{ee}^2 was constrained using a pull parameter with input information from LBL experiments. Our combined analysis result is currently limited by statistics and, as expected, Daya Bay data drives the combined analysis results. Our analysis method was validated by reproducing the Δm_{ee}^2 and $\sin^2 \theta_{13}$ contours for each experiment as discussed in Appendix A.

Given that the previous measurements by KamLAND and SK/SNO of the solar Δm^2 are in a 2σ tension and the importance of solar Δm^2 for the determination of CP violation in LBL experiments, it is crucial that we understand the value of the solar Δm^2 better. It is expected by circa 2025 that the JUNO experiment will provide additional, important information on the value of the of solar Δm^2 .

ACKNOWLEDGMENTS

We are grateful to Thomas Schwetz for fruitful discussions. This work (S. H. S.) was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Ministry of Science and ICT (MSIT) (No. 2017R1A2B4012757 and IBS-R016-D1-2019-b01). This manuscript

has been authored (S. J. P.) by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This project (S. J. P.) has received funding/support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 690575 & No. 674896.

APPENDIX A: VALIDATION OF OUR ANALYSES

Using the data and the χ^2 formalism described in Secs. III and IV, our method reproduces the contours in

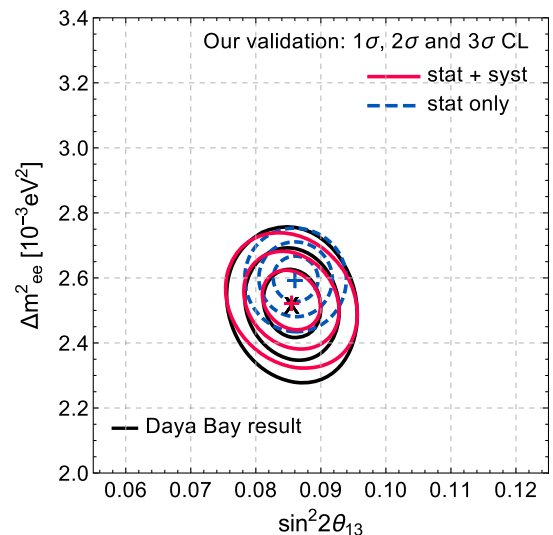


FIG. 4. Our validation on Δm_{ee}^2 vs $\sin^2 2\theta_{13}$ fit using the Daya Bay data (1958 days), including systematics and statistics uncertainties in red solid lines, and including statistics only in blue dashed lines, for 1, 2 and 3σ allowed regions. The fit of the Daya Bay collaboration with 1958 days from [19] is represented in the solid black lines. The agreement between our analysis (solid red lines) and Daya Bay's analysis (solid black lines) is excellent.

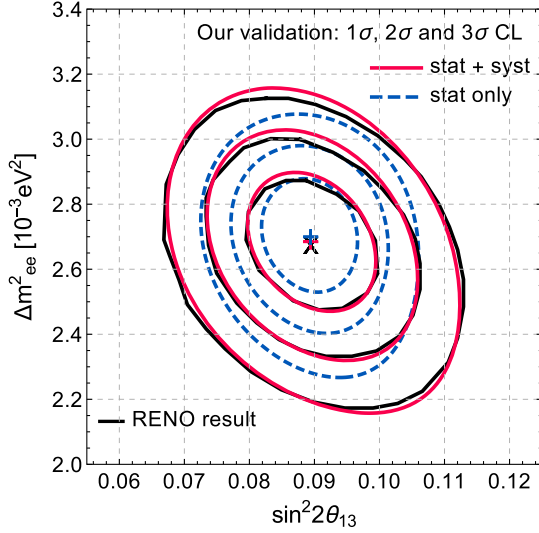


FIG. 5. Our validation on Δm_{ee}^2 vs $\sin^2 2\theta_{13}$ fit using the RENO data (2200 days), including systematics and statistics uncertainties in red solid lines, and including statistics only in blue dashed lines, for 1, 2 and 3 σ allowed regions. The fit of the RENO collaboration with 2,200 days from [20] is represented in the solid black lines. The agreement between our analysis (solid red lines) and RENO's analysis (solid black lines) is excellent.

the Δm_{ee}^2 vs $\sin^2 2\theta_{13}$ from the Daya Bay and RENO collaborations as it is shown in Figs. 4, 5. The Daya Bay and RENO collaboration contours are taken from the Supplementary Material of [19] and from Fig. 3 of [20], respectively.

The agreement between our results and Daya Bay as well as RENO for the measurements of Δm_{ee}^2 vs $\sin^2 2\theta_{13}$ is an excellent validation of the methods and numbers used in our analysis. Therefore, our constraint on Δm_{21}^2 , using the publicly available data of Daya Bay and RENO, has a firm basis.

APPENDIX B: NUMBER OF EXPECTED EVENTS AND PULL PARAMETERS IN χ^2

The expected numbers of signal events in a detector d in a prompt energy bin i , X_i^d , is computed as follows up to a common input (e.g., reactor power, total number of protons) which cancels when taking ratios in the χ^2 computation.

$$X_i^d = \sum_r \sum_{\text{iso}} \frac{a^d}{L_{rd}^2} \int_{E_i^{\text{rec}}}^{E_{i+1}^{\text{rec}}} dE^{\text{rec}} \int_0^\infty dE_\nu \sigma(E_\nu) f^{\text{iso}} \phi^{\text{iso}}(E_\nu) \times P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^d(E_\nu) R(E^{\text{rec}}, E_\nu) \quad (\text{B1})$$

where, the indices i , r , d , and iso refers to the i th energy bin, r th reactor, d th detector, and a fissionable isotope (^{235}U , ^{239}Pu , ^{238}U , or ^{241}Pu), respectively, and a^d is the detector efficiency. L_{rd} is the baseline between the reactor r

and the detector d . E_ν and E^{rec} are the neutrino true energy and the reconstructed energy, both related by the detector response function $R(E^{\text{rec}}, E_\nu)$. The $\sigma(E_\nu)$ is the IBD cross section computed performing the integral in $d\cos\theta$ of the differential cross section in [22] and the f^{iso} is the averaged fission fraction⁴ and the $\phi^{\text{iso}}(E_\nu)$ is the Huber-Mueller flux prediction [23,24]. $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^d(E_\nu)$ is the oscillation probability from reactor r to detector d in the three neutrino oscillation paradigm.

The pull parameters accounting for detection efficiency (ϵ^d) and relative energy scale (η^d) are included in the number of expected events as follows

$$X_i^d(\epsilon^d, \eta^d) = \epsilon^d \sum_r \sum_{\text{iso}} \frac{a^d}{L_{rd}^2} \int_{\eta^d E_i^{\text{rec}}}^{\eta^d E_{i+1}^{\text{rec}}} dE^{\text{rec}} \int_0^\infty dE_\nu \times \sigma(E_\nu) f^{\text{iso}} \phi^{\text{iso}}(E_\nu) P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^d(E_\nu) R(E^{\text{rec}}, E_\nu).$$

For RENO, the efficiency pull parameter is included in the ratio.

The background pull parameters are included in background events B_i^d used in $D_i^{F/N} \equiv \frac{O_i^F - B_i^F}{O_i^N - B_i^N}$ as follows

$$B_i^d(b_{\text{LH}}^d, b_{\text{acc}}^d, b_{\text{n}}^d) = B_i^d + (b_{\text{LH}}^d - 1)B_{\text{LH},i}^d + (b_{\text{acc}}^d - 1)B_{\text{acc},i}^d + (b_{\text{n}}^d - 1)B_{\text{n},i}^d,$$

where B_i^d ($B_{\text{LH},i}^d$, $B_{\text{acc},i}^d$ and $B_{\text{n},i}^d$) represents the number of total (Li-He, accidental and fast neutron) background events in the i th prompt energy bin in the d th detector, and the small b represents the corresponding pull parameter.

APPENDIX C: FIXED VS FREE Δm_{ee}^2

For the results in the main body of our paper we constrained Δm_{ee}^2 treating it as a pull parameter using LBL experiments input. In this section we show the impact of Δm_{ee}^2 fixed and set free. A 2-dimensional scan over Δm_{21}^2 and $\sin^2 2\theta_{13}$ is performed to find the best fit value pair at the minimum value of χ^2 described earlier, where in the oscillation probability θ_{12} is fixed as $\sin^2 \theta_{12} = 0.310$ but Δm_{ee}^2 is set free within the range of $[1.55, 3.55] \times 10^{-3} \text{ eV}^2$. Results with a fixed $\Delta m_{ee}^2 = 2.45 \times 10^{-3} \text{ eV}^2$ are also obtained and compared to those with Δm_{ee}^2 set free. Figure 6, left and middle panels, shows the results of Δm_{ee}^2 fixed and free for Daya Bay and RENO. It is observed that the effect of floating Δm_{ee}^2 is bigger than adding systematic uncertainty for both Daya Bay and RENO. For floating Δm_{ee}^2 case, the corresponding

⁴Ideally we would have the information on the fission fractions as a function of time in each reactor, but since we do not have this information we take the same averaged values for all the detectors. This means that any systematic uncertainty on the flux predictions will cancel when taking ratios of the expected events in different experimental sites.

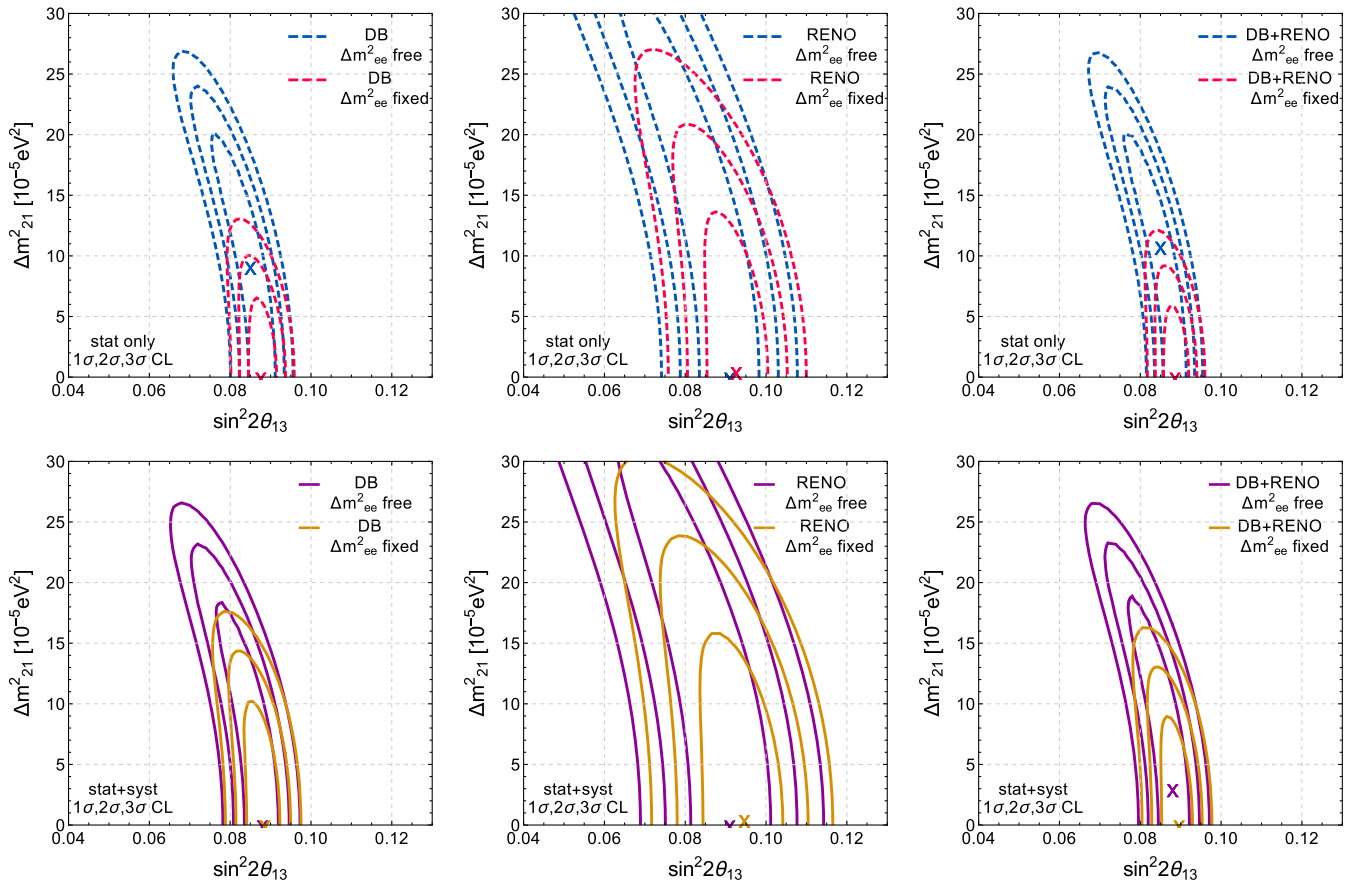


FIG. 6. Daya Bay (left panels), RENO (middle panels) and combined (right panels) 1, 2 and 3 σ allowed regions in the Δm_{21}^2 vs $\sin^2 2\theta_{13}$ parameter space, leaving Δm_{ee}^2 free or fixed at $2.45 \times 10^{-3} \text{ eV}^2$. For all panels, the dashed lines include only statistical uncertainties whereas the solid lines include both statistical and systematic uncertainties. The best fit values are shown with \times signs. This figure demonstrates the extremes of our result to variation of Δm_{ee}^2 .

Δm_{ee}^2 values for the minimum χ^2 are found to be $2.50 \times 10^{-3} \text{ eV}^2$ ($2.68 \times 10^{-3} \text{ eV}^2$) for Daya Bay (RENO) and it is within 1σ uncertainty of each of their measurements. Figure 6, right panels shows the results with combined analysis. For

floating Δm_{ee}^2 case, the corresponding Δm_{ee}^2 value for the minimum χ^2 is found to be $2.54 \times 10^{-3} \text{ eV}^2$ and it is within 1σ uncertainty of the Daya Bay best fit value, i.e., $[2.52 \pm 0.07] \times 10^{-3}$.

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