New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay


(Daya Bay Collaboration)

1Institute of Modern Physics, East China University of Science and Technology, Shanghai
2University of Wisconsin, Madison, Wisconsin, USA
3Department of Physics, Yale University, New Haven, Connecticut, USA
4Brookhaven National Laboratory, Upton, New York, USA
5Department of Physics, National Taiwan University, Taipei
6National United University, Miaoli
7Joint Institute for Nuclear Research, Dubna, Moscow Region
8Institute of High Energy Physics, Beijing
9Chinese University of Hong Kong, Hong Kong
10Institute of Physics, National Chiao-Tung University, Hsinchu
11Shandong University, Jinan
12Department of Engineering Physics, Tsinghua University, Beijing
13North China Electric Power University, Beijing
14Shenzhen University, Shenzhen
15Siena College, Loudonville, New York, USA
16Department of Physics, Illinois Institute of Technology, Chicago, Illinois, USA
17Lawrence Berkeley National Laboratory, Berkeley, California, USA
18Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
19Shanghai Jiao Tong University, Shanghai
20Beijing Normal University, Beijing
21Department of Physics, University of Houston, Houston, Texas, USA
22Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia, USA
23China Institute of Atomic Energy, Beijing


0031-9007/15/111802(8) © 2015 American Physical Society
We report a new measurement of electron antineutrino disappearance using the fully constructed Daya Bay Reactor Neutrino Experiment. The final two of eight antineutrino detectors were installed in the summer of 2012. Including the 404 days of data collected from October 2012 to November 2013 resulted in a total exposure of $6.9 \times 10^5$ GWth ton days, a 3.6 times increase over our previous results. Improvements in energy calibration limited variations between detectors to 0.2%. Removal of six $^{241}\text{Am-\text{C}}$ radioactive calibration sources reduced the background by a factor of 2 for the detectors in the experimental hall furthest from the reactors. Direct prediction of the antineutrino signal in the far detectors based on the measurements in the near detectors explicitly minimized the dependence of the measurement on models of reactor antineutrino emission. The uncertainties in our estimates of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ were halved as a result of these improvements. An analysis of the relative antineutrino rates and energy spectra between detectors gave $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV$^2$ in the three-neutrino framework.

DOI: 10.1103/PhysRevLett.115.111802  PACS numbers: 14.60.Pq, 13.15.+g, 28.50.Hw, 29.40.Mc

Neutrino flavor oscillation due to the mixing angle $\theta_{13}$ has been observed using reactor antineutrinos [1–3] and accelerator neutrinos [4,5]. The Daya Bay experiment previously reported the discovery of a nonzero value of $\sin^2 2\theta_{13}$ by observing the disappearance of reactor antineutrinos over kilometer distances [1,6,7], and the first measurement of the effective mass splitting $|\Delta m^2_{ee}|$ [8] via the distortion of the $\bar{\nu}_e$ energy spectrum [9]. Here, we present new results with significant improvements in energy calibration and background reduction. Installation of the final two detectors and a tripling of operation time provided a total exposure of $6.9 \times 10^5$ GWth ton days, 3.6 times more than reported in our previous publication [9]. With these improvements the precision of $\sin^2 2\theta_{13}$ was enhanced by a factor of 2 compared to the world’s previous best estimate. The precision of $|\Delta m^2_{ee}|$ was equally enhanced, and is now competitive with the precision of $|\Delta m^2_{ee}|$ measured via the accelerator neutrino disappearance [10,11].

The Daya Bay experiment started collecting data on 24 December 2011 with six antineutrino detectors (ADs) located in three underground experimental halls (EHs). Three ADs were positioned in two near halls at short distances from six nuclear reactor cores, two ADs in EH1 and one in EH2, and three ADs were positioned in the far hall, EH3. Data taking was paused on 28 July 2012 while two new ADs were installed, one in EH2 and the other in EH3. During the installation, a broad set of calibration sources were deployed into the two ADs of EH1 using automated calibration units [12] and a manual calibration system [13]. Operation of the full experiment with all eight ADs started on 19 October 2012. This Letter presents results based on 404 days of data acquired in the 8-AD period combined with all 217 days of data acquired in the 6-AD period. A blind analysis strategy was implemented by concealing the baselines and target masses of the two new ADs, as well as the operational data of all reactor cores for the new data period.
Each of the three Daya Bay experimental halls hosts functionally identical ADs inside a muon detector system. The latter consists of a two-zone pure water Cherenkov detector, referred to as the inner and outer water shields, covered on top by an array of resistive plate chambers. Each AD consists of three nested cylindrical vessels. The inner vessel is filled with 0.1% gadolinium-doped liquid scintillator (Gd-LS), which constitutes the primary antineutrino target. The vessel surrounding the target is filled with mineral oil. A total of 192 20-cm photomultiplier tubes (PMTs) are radially positioned in the mineral-oil region of each AD. Further details on the experimental setup are contained in Refs. [14–17]. Reactor antineutrinos are detected via the inverse $\beta$-decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The gamma rays (totalling $\sim$8 MeV) generated from the neutron capture on Gd with a mean capture time of $\sim$30 $\mu$s form a delayed signal and enable powerful background suppression. The light from the $e^+$ gives an estimate of the incident $\bar{\nu}_e$ energy, $E_{\bar{\nu}_e} \approx E_p + \bar{E}_n + 0.78$ MeV, where $E_p$ is the prompt energy including the positron kinetic and annihilation energy, and $\bar{E}_n$ is the average neutron recoil energy ($\sim$10 keV).

Differences in energy responses between detectors directly impacted the estimation of $|\Delta m^2_{\text{ee}}|$. PMT gains were calibrated continuously using uncorrelated single electrons emitted by the photocathode. The signals of 0.3% of the PMTs were discarded due to abnormal hit rates or charge distributions. The detector energy scale was calibrated using Am-C neutron sources [18] deployed at the detector center, with the $\sim$8 MeV peaks from neutrons captured on Gd aligned across all eight detectors. The time variation and the position dependence of the energy scale was corrected using the 2.506 MeV gamma-ray peak from $^{60}$Co calibration sources. The reconstructed energies of various calibration reference points in different ADs are compared in Fig. 1. The spatial distribution of each calibration reference varies, incorporating deviations in spatial response between detectors. Figure 1 presents measurements of $^{68}$Ge, $^{60}$Co, and Am-C calibration sources when placed at the center of each detector. Neutrons from IBD and muon spallation that were captured on gadolinium, were distributed nearly uniformly throughout the Gd-LS region. Those neutrons that were captured on $^3$H, intrinsic $\alpha$ particles from polonium and radon decays, and gammas from $^{40}$K and $^{208}$Tl decays, were distributed inside and outside of the target volume. All of these events were selected within the Gd-LS region based on their reconstructed vertices. The uncorrelated relative uncertainty of the energy scale is thus determined to be 0.2%. This reduction of 43% compared to the previous publication [9] was enabled by improvements in the correction of position and time dependence, and enhanced the precision of $|\Delta m^2_{\text{ee}}|$ by 9%. The reduction was confirmed by an alternative method which used the $n$-Gd capture of muon-induced spallation neutrons to calibrate the scale, time dependence, and spatial dependence of the detector energy response.

Nonlinearity in the energy response of an AD originated from two dominant sources: particle-dependent nonlinear light yield of the scintillator and charge-dependent nonlinearity in the PMT readout electronics. Each effect was at the level of 10%. We constructed a semiempirical model that predicted the reconstructed energy for a particle assuming a specific energy deposited in the scintillator. The model contained four parameters: Birks’ constant, the relative contribution to the total light yield from Cherenkov radiation, and the amplitude and scale of an exponential correction describing the nonlinear electronics response. This exponential form of the electronics response was motivated by MC and confirmed with an independent FADC measurement.

The nominal parameter values were obtained from an unconstrained $\chi^2$ fit to various AD calibration data sets, comprising twelve gamma lines from both deployed and naturally occurring sources as well as the continuous $\beta$-decay spectrum of $^{12}$B produced by muon spallation inside the Gd-LS volumes. The nominal positron response derived from the best fit parameters is shown in Fig. 2. The depicted uncertainty band represents other response functions consistent with the fitted calibration data within a
efficiently removed using the techniques of Ref. [6].

Emission in the voltage divider, called required

0 if their delayed signal occurred (i) within a (ii)

between the prompt and delayed signals. In order to

suppress cosmogenic products, candidates were rejected

if their delayed signal occurred (i) within a (ii)

water shield trigger with a PMT multiplicity

0.7 to 100 MeV in the 200 µs following cosmogenic

signals only detected by the outer water shield or resistive

plate chambers. The energy spectrum of these veto-tagged

signals was consistent with the spectrum of IBD-like
candidate signals above 12 MeV, and was used to estimate
the rate and energy spectrum for the fast-neutron back-
ground from 0.7 to 12 MeV. The systematic uncertainty
was estimated from the difference between this new
analysis and the extrapolation method previously
employed, and was determined to be half of the estimate
reported in Ref. [6].

The methods used in Refs. [1,6] to estimate the back-
grounds from the uncorrelated prompt-delayed pairs (i.e.,
accidentals), the correlated β − n decays from cosmogenic
4Li and 4He, and the 13C(a, n)16O reaction, were extended
to the current 6 + 8 AD data sample. The decrease in the
single-neutron rate from the Am-C sources reduced the
average rate of accidentals in the far hall by a factor of 2.7.
As a result, the total backgrounds amount to about 3% (2%)
of the IBD candidate sample in the far (near) hall(s). The
systematic uncertainties in the 13C(a, n)16O cross section
and in the transportation of the α particles were reassessed
through a comparison of experimental results and simu-
lation packages, respectively [19]. The estimation of
4Li/8He now dominated the background uncertainty in
both the near and far halls. The estimated signal and
background rates, as well as the efficiencies of the muon
veto, εµ, and multiplicity selection, εm, are summarized in
Table I.

A detailed treatment of the absolute and relative
efficiencies using the first six ADs was reported in
Refs. [6,14]. The uncertainties of the absolute efficiencies

68.3% C.L. This χ2-based approach to obtain the energy
response resulted in <1% uncertainties of the absolute
energy scale above 2 MeV. The uncertainties of the positron
response were validated using the 53-MeV cutoff in the
Michel electron spectrum gave a similar result (blue dashed line), albeit
with larger systematic uncertainties.

Estimates for the five major sources of background for
the new data sample are improved with respect to Ref. [9].
The background produced by the three Am-C neutron
sources inside the automated calibration units contributed
significantly to the total systematic uncertainty of the
correlated backgrounds in the 6-AD period. Because of
this, two of the three Am-C sources in each AD in EH3
were removed during the 2012 summer installation period.
As a result, the average correlated Am-C background rate
in the far hall decreased by a factor of 4 in the 8-AD period.
As in previous publications [1,9], this rate was determined
by monitoring the single-neutron production rate from the
Am-C sources. Removal of these Am-C sources had
negligible consequences for our calibration.

Energetic, or fast, neutrons of cosmogenic origin
produced a correlated background for this study. Relaxing
the prompt-energy selection to (0.7–100) MeV revealed
the fast-neutron background spectrum above 12 MeV.
Previously we deduced the rate and spectrum of this
background using a linear extrapolation into the IBD
prompt signal region. Here we used a background-
enhanced data set to improve the estimate. We found
6043 fast-neutron candidates with prompt energy from
0.7 to 100 MeV in the 200 µs following cosmogenic
signals detected by the outer water shield or resistive
plate chambers. The energy spectrum of these veto-tagged
signals was consistent with the spectrum of IBD-like
candidate signals above 12 MeV, and was used to estimate
the rate and energy spectrum for the fast-neutron back-
ground from 0.7 to 12 MeV. The systematic uncertainty
was estimated from the difference between this new
analysis and the extrapolation method previously
employed, and was determined to be half of the estimate
reported in Ref. [6].

The methods used in Refs. [1,6] to estimate the back-
grounds from the uncorrelated prompt-delayed pairs (i.e.,
accidentals), the correlated β − n decays from cosmogenic
4Li and 4He, and the 13C(a, n)16O reaction, were extended
to the current 6 + 8 AD data sample. The decrease in the
single-neutron rate from the Am-C sources reduced the
average rate of accidentals in the far hall by a factor of 2.7.
As a result, the total backgrounds amount to about 3% (2%)
of the IBD candidate sample in the far (near) hall(s). The
systematic uncertainties in the 13C(a, n)16O cross section
and in the transportation of the α particles were reassessed
through a comparison of experimental results and simu-
lation packages, respectively [19]. The estimation of
4Li/8He now dominated the background uncertainty in
both the near and far halls. The estimated signal and
background rates, as well as the efficiencies of the muon
veto, εµ, and multiplicity selection, εm, are summarized in
Table I.

A detailed treatment of the absolute and relative
efficiencies using the first six ADs was reported in
Refs. [6,14]. The uncertainties of the absolute efficiencies
TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\epsilon_\mu \cdot \epsilon_m$.

The measured ratio of the IBD rates in AD1 and AD2 (AD3 and AD8 in the 8-AD period) was $0.981 \pm 0.004 (1.019 \pm 0.004)$ while the expected ratio was $0.982 (1.012)$.

<table>
<thead>
<tr>
<th></th>
<th>EH1</th>
<th>EH2</th>
<th>EH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD1</td>
<td>304,459</td>
<td>309,354</td>
<td>287,098</td>
</tr>
<tr>
<td>AD2</td>
<td>309,354</td>
<td>304,459</td>
<td>289,599</td>
</tr>
<tr>
<td>AD3</td>
<td>287,098</td>
<td>289,599</td>
<td>266,370</td>
</tr>
<tr>
<td>AD4</td>
<td>190,406</td>
<td>191,207</td>
<td>168,370</td>
</tr>
<tr>
<td>AD5</td>
<td>40,956</td>
<td>40,956</td>
<td>37,840</td>
</tr>
<tr>
<td>AD6</td>
<td>41,203</td>
<td>41,203</td>
<td>38,103</td>
</tr>
<tr>
<td>AD7</td>
<td>24,077</td>
<td>24,077</td>
<td>21,953</td>
</tr>
<tr>
<td>DAQ live time</td>
<td>565,436</td>
<td>565,436</td>
<td>569,037</td>
</tr>
<tr>
<td>(days)</td>
<td>569,037</td>
<td>569,037</td>
<td>568,037</td>
</tr>
<tr>
<td>$\epsilon_\mu$</td>
<td>0.8248</td>
<td>0.8218</td>
<td>0.8575</td>
</tr>
<tr>
<td>$\epsilon_m$</td>
<td>0.9744</td>
<td>0.9744</td>
<td>0.9756</td>
</tr>
<tr>
<td>Accidental</td>
<td>8.92 ± 0.09</td>
<td>8.89 ± 0.09</td>
<td>6.76 ± 0.07</td>
</tr>
<tr>
<td>(per day)</td>
<td>6.76 ± 0.07</td>
<td>6.86 ± 0.07</td>
<td>1.70 ± 0.02</td>
</tr>
<tr>
<td>Fast neutron</td>
<td>0.78 ± 0.12</td>
<td>0.54 ± 0.19</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>(per AD per day)</td>
<td>0.78 ± 0.12</td>
<td>0.54 ± 0.19</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
<td>2.8 ± 1.5</td>
<td>2.8 ± 1.5</td>
<td>2.8 ± 1.5</td>
</tr>
<tr>
<td>(per AD per day)</td>
<td>2.8 ± 1.5</td>
<td>2.8 ± 1.5</td>
<td>2.8 ± 1.5</td>
</tr>
<tr>
<td>Am-C correlated</td>
<td>0.27 ± 0.12</td>
<td>0.27 ± 0.12</td>
<td>0.22 ± 0.10</td>
</tr>
<tr>
<td>6-AD (per day)</td>
<td>0.27 ± 0.12</td>
<td>0.27 ± 0.12</td>
<td>0.22 ± 0.10</td>
</tr>
<tr>
<td>Am-C correlated</td>
<td>0.20 ± 0.09</td>
<td>0.20 ± 0.09</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>8-AD (per day)</td>
<td>0.20 ± 0.09</td>
<td>0.20 ± 0.09</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>$^{13}$C($\alpha,n$)$^{16}$O</td>
<td>0.08 ± 0.04</td>
<td>0.08 ± 0.04</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>(per day)</td>
<td>0.08 ± 0.04</td>
<td>0.08 ± 0.04</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>IBD rate</td>
<td>657.18 ± 1.94</td>
<td>670.14 ± 1.95</td>
<td>594.78 ± 1.46</td>
</tr>
<tr>
<td>(per day)</td>
<td>590.81 ± 1.66</td>
<td>739.00 ± 0.41</td>
<td>749.49 ± 0.41</td>
</tr>
</tbody>
</table>

are correlated among the ADs and thus play a negligible role in the relative measurement of $\bar{\nu}_e$ disappearance. The performance of the two new ADs was found to be consistent with the other detectors. Estimates of two prominent uncorrelated uncertainties, the delayed-energy selection efficiency and the fraction of neutrons captured on Gd, were confirmed for all eight ADs using improved energy reconstruction and increased statistics.

Oscillation was measured using the $L/E$-dependent disappearance of $\bar{\nu}_e$, as given by the survival probability

$$P = 1 - \cos^2\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267\Delta m^2_{21} L}{E} - \sin^2 \theta_{13} \sin^2 \frac{1.267\Delta m^2_{ee} L}{E}. \quad (1)$$

Here $E$ is the energy in MeV of the $\bar{\nu}_e$, $L$ is the distance in meters from its production point, $\theta_{12}$ is the solar mixing angle, and $\Delta m^2_{21} = m_2^2 - m_1^2$ is the mass-squared difference of the first two neutrino mass eigenstates in eV$^2$.

Recent precise measurements of the IBD positron energy spectrum disagree with models of reactor $\bar{\nu}_e$ emission [3,20–22]. The characteristics of the signals in this energy range are consistent with reactor antineutrino emission, and disfavor background or detector response as possible origins for the discrepancy. Reference [20] presents the evidence in detail and provide the necessary data to allow detailed comparison of our measurement with existing and future models. Given these discrepancies between measurements and models, here we present a technique for predicting the signal in the far hall based on measurements obtained in the near halls, with minimal dependence on models of the reactor antineutrinos. In our previous measurements [9], model dependence was limited by allowing variation of the predicted $\bar{\nu}_e$ flux within model uncertainties, while the technique here provides an explicit demonstration of the negligible model dependence. A $\chi^2$ was defined as

$$\chi^2 = \sum_{i,j}(N^f_{ij} - w_iN^n_{ij})(V^{-1})_{ij}(N^f_i - w_iN^n_i), \quad (2)$$

where $N_i$ is the observed number of events after background subtraction in the $i$th bin of reconstructed positron energy $E_{\nu}$. The superscript $f(n)$ denotes a far (near) detector. The symbol $V$ represents a covariance matrix that includes known systematic and statistical uncertainties. The quantity $w_i$ is a weight that accounts for the differences between near and far measurements. For the case of a single reactor, the weight $w_i$ can be simply calculated from the ratios of detector mass, distance to the reactor, efficiency, and antineutrino oscillation probability, as given by the relation:

$$w^\text{SR}_i = \frac{N^f_i}{N^n_i} = \left(\frac{T_i}{T^n_i}\right)^{\epsilon_f/\epsilon^n} \left(\frac{L^n_i}{L_i}\right)^2 \left(\frac{P^n_f}{P^n_i}\right)^{\phi_f/\phi^n}. \quad (3)$$

Here $T$ is the number of target protons, $\epsilon$ is the efficiency, and $L$ is the distance to the reactor for a given detector. $P_i$ is
the oscillation probability for the $i$th reconstructed energy bin and $\phi$ the reactor antineutrino flux (which cancels from $w_i$). With $P$, calculated in reconstructed positron energy, the detector response introduces small (< 0.2% above 2 MeV) calculable deviations from Eq. (1).

For multiple reactor cores, the weight $w_i$ was modified:

$$w_i = \frac{N_i^f}{N_i^r} = \left(\frac{T_i^f}{T_i^r}\right) \left(\frac{\epsilon_i^f}{\epsilon_i^r}\right) \sum_j P(E_j^\text{true}|E_i^\text{rec}) r_j. \quad (4)$$

The probability distribution $P(E_j^\text{true}|E_i^\text{rec})$ accounts for the energy transfer from the $\bar{\nu}_e$ to the $e^+$ and imperfections in the detector energy response (loss in nonactive elements, nonlinearity, and resolution). The extrapolation factor $r_j$ was calculated as

$$r_j = \frac{\sum_k P(E_k^\text{true}, L_k^f|E_k^\text{true}, L_k^r) \phi_{jk}/(L_k^r)^2}{\sum_k P(E_k^\text{true}, L_k^f|E_k^\text{true}, L_k^r) \phi_{jk}/(L_k^r)^2}, \quad (5)$$

where $P$ is given by Eq. (1), $L_k^f$ is the distance between a far (near) detector and core $k$, and $\phi_{jk}$ is the predicted antineutrino flux from core $k$ for the $j$th true energy bin. In the single-reactor core case, the antineutrino flux $\phi$ cancels in the expression for $r_j$ and Eq. (4) reduces to Eq. (3). Although the cancellation is not exact for multiple cores, the impact of the uncertainty in reactor antineutrino flux was found to be $\leq 0.1\%$.

The covariance matrix element $V_{ij}$ was the sum of a statistical term, calculated analytically, and a systematic term determined by Monte Carlo calculation using

$$V_{ij} = \frac{1}{N} \sum S_i^j (S_i^f - w_i S_i^p) (S_j^f - w_j S_j^p). \quad (6)$$

Here, $N$ is the number of simulated experiments generated with energy spectra $S$, including systematic variations of detector response, $\bar{\nu}_e$ flux, and background. The choice of reactor antineutrino model [22–28] in calculating the covariance had negligible (< 0.2%) impact on the determination of the oscillation parameters.

Without loss of sensitivity, we summed the IBD signal candidates of the ADs within the same hall, accounting for small differences of target mass, detection efficiency, background, and baseline. We considered the 6-AD and 8-AD periods separately in order to properly handle correlations in reactor antineutrino flux, detector exposure, and background. This means that $i$ and $j$ in the above equations ran over the 37 reconstructed energy bins for the two near versus far combinations and for the two periods considered (37 $\times$ 2 $\times$ 2 = 148). More details of this method are described in Ref. [29].

Using this method, we found $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{21}| = (2.42 \pm 0.11) \times 10^{-3}$ eV$^2$, with $\chi^2$/NDF = 134.6/146 (see the Supplemental Material [30]). While we use $\sin^2 2\theta_{13} = 0.857 \pm 0.024$ and $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV$^2$ from Ref. [31], our result was largely independent of these values. Consistent results were obtained when our previous methods [1,9] were applied to this larger data set. Under the normal (inverted) hierarchy assumption, $|\Delta m^2_{ee}|$ yields $|\Delta m^2_{23}| = (2.37 \pm 0.11) \times 10^{-3}$ eV$^2$ ($|\Delta m^2_{23}| = (-2.47 \pm 0.11) \times 10^{-3}$ eV$^2$). This result was consistent with and of comparable precision to measurements obtained from accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance [10,11]. Using only the relative rates between the detectors and $|\Delta m^2_{23}|$ from Ref. [10] we found $\sin^2 2\theta_{13} = 0.085 \pm 0.006$, with $\chi^2$/NDF = 1.37/3.

The reconstructed positron energy spectrum observed in the far site is compared in Fig. 3 with the expectation based on the near-site measurements. The 68.3%, 95.5%, and 99.7% C.L. allowed regions in the $|\Delta m^2_{23}|$–$\sin^2 2\theta_{13}$ plane are shown in Fig. 4. The spectral shape from all experimental halls is compared in Fig. 5 to the electron antineutrino survival probability assuming our best estimates of the oscillation parameters. The total uncertainties of both $\sin^2 2\theta_{13}$ and $|\Delta m^2_{23}|$ are dominated by statistics. The most significant systematic uncertainties for $\sin^2 2\theta_{13}$ are due to the relative detector efficiency, reactor power, relative energy scale, and $^9\text{Li}/^9\text{He}$ background. The

![FIG. 3 (color online). Upper: Background-subtracted reconstructed positron energy spectrum observed in the far site (black points), as well as the expectation derived from the near sites excluding (blue line) or including (red line) our best estimate of oscillation. The spectra were efficiency corrected and normalized to one day of live time. Lower: Ratio of the spectra to the no-oscillation case. The error bars show the statistical uncertainty of the near site data. The shaded area includes the systematic and statistical uncertainties from the near-site measurements.](image-url)
systematic uncertainty in $|\Delta m_{ee}^2|$ is dominated by uncertainty in the relative energy scale.

In summary, enhanced measurements of $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ have been obtained by studying the energy-dependent disappearance of the electron antineutrino interactions recorded in a $6.9 \times 10^8$ GW$_{th}$ ton days exposure. Improvements in calibration, background estimation, as well as increased statistics allow this study to provide the most precise estimates to date of the neutrino mass and mixing parameters $|\Delta m_{ee}^2|$ and $\sin^2 2\theta_{13}$.

Daya Bay is supported in part by the Ministry of Science and Technology of China, the U.S. Department of Energy, the Chinese Academy of Sciences, the CAS Center for Excellence in Particle Physics, the National Natural Science Foundation of China, the Guangdong provincial government, the Shenzhen municipal government, the China General Nuclear Power Group, Key Laboratory of Particle and Radiation Imaging (Tsinghua University), the Ministry of Education, Key Laboratory of Particle Physics and Particle Irradiation (Shandong University), the Ministry of Education, Shanghai Laboratory for Particle Physics and Cosmology, the Research Grants Council of the Hong Kong Special Administrative Region of China, the University Development Fund of The University of Hong Kong, the MOE program for Research of Excellence at National Taiwan University, National Chiao-Tung University, and NSC fund support from Taiwan, the U.S. National Science Foundation, the Alfred P. Sloan Foundation, the Ministry of Education, Youth, and Sports of the Czech Republic, the Joint Institute of Nuclear Research in Dubna, Russia, the NSFC-RFBR joint research program, the National Commission of Scientific and Technological Research of Chile, and the Tsinghua University Initiative Scientific Research Program. We acknowledge Yellow River River Engineering Consulting Co., Ltd., and China Railway 15th Bureau Group Co., Ltd., for building the underground laboratory. We are grateful for the ongoing cooperation from the China General Nuclear Power Group and China Light and Power Company.

[8] $\Delta m_{ee}^2$ is an effective mass splitting that can be obtained by replacing $\cos^2 \theta_{13} \sin^2 \Delta_{31} + \sin^2 \theta_{13} \sin^2 \Delta_{32}$ with $\sin^2 \Delta_{ee}$, where $\Delta = 1.267 m_{ee}^2 (eV^2)[L/(m)/E(MeV)]$, and $m_{ee}^2$ is the difference between the mass-squares of the mass eigenstates $\nu_e$ and $\nu_\mu$. To estimate the values of $\Delta_{ee}$ and $\Delta_{ee}$ from the measured value of $\Delta_{ee}$, See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.115.111802.