Daya Bay Scientific Goals and Run Plan

Executive Summary

Based on 139 days of 6-AD operation Daya Bay has established $\sin^2 2\theta_{13}$=0.089±0.010±0.005. This is one of most important measurements in the field of particle physics. Our discovery of a large value for θ_{13} (PRL **108**:171803) has led us to refine our goals and run plan.

During the summer of 2012 we installed the final two ADs and completed an extensive special calibration program. The calibrations allow us to complete a shape-based θ_{13} analysis of the 6-AD data set. The calibrations also allow us to measure Δm_{ee}^2 at a level comparable to the MINOS measurement of $\Delta m_{\mu\mu}^2$. Moreover, the calibrations provide a measurement of our absolute single detector efficiency enabling a precise measurement of the reactor flux and spectrum.

Our statistical error in $\sin^2 2\theta_{13}$ would reach the systematic error of 0.005 by fall 2013. We have estimated improvements in the systematic error based on the new calibrations and increased precision that is statistical in nature. We estimate that the total error on $\sin^2 2\theta_{13}$ can be reduced to 0.006 after a year and 0.003 after 3–4 years. Daya Bay will have the best measurement of θ_{13} in the disappearance mode: a fundamental measurement that is unlikely to be repeated in the future.

Daya Bay primary scientific goals:

- Precise measurement of θ_{13} without ambiguities
  - Important measurement of a fundamental parameter.
  - Improve the measurement of other mixing parameters by accelerator experiments.
  - Overconstrain the νSM interpretation of oscillations with accelerator measurements.
  - Improve the ultimate precision on J_{CP}^{ν} and unitarity of the PMNS matrix.
- Measure Δm_{ee}^2
  - Measurement of new ν mixing parameter
  - Complementary to and with similar precision as accelerator-based measurements
  - Constrains 3-ν model

Further scientific goals:

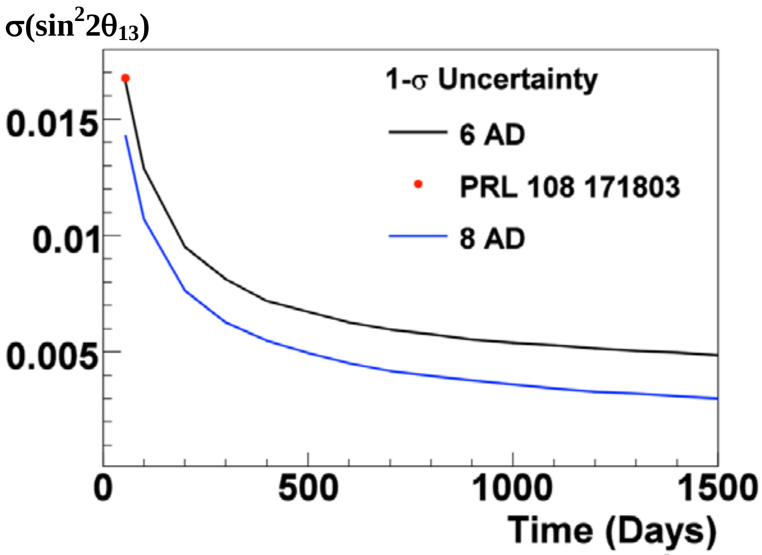
- Daya Bay collects reactor antineutrino data at a tremendous rate, enabling a precision measurement of the reactor antineutrino spectrum. A detailed comparison of the predicted and observed spectra will validate and improve reactor flux calculations and possibly resolve ambiguities in reactor antineutrino predictions.
- Make a multi-year measurement of the absolute reactor flux throughout the Daya Bay reactor fuel cycles, providing a rigorous test of reactor models.
- Measure the production of neutrons and other spallation products over a wide range of muon energies at different modest depths.
- Search for signatures of new antineutrino interactions in the observed reactor flux and spectra.
- Look for supernovae neutrinos.

Technical goals:

- Demonstrate multi-year operation of "functionally identical" antineutrino detectors in a near-far configuration, tracking detector performance over time.
- Verify and monitor long-term stability of Gd-LS for antineutrino detection.

Projections of Daya Bay Sensitivity

The blue curve in Fig. 1a is a projection of Daya Bay sensitivity with 8 ADs and systematic errors improved as a result of the 2012 calibration campaign:



Time	$\sigma(\sin^2 2\theta_{13})$		$\sigma(\theta_{13})$
	6 AD curr.sys.	8 AD impr.sys.	
100 days	0.0129	0.0107	6.0%
200 days	0.0095	0.0076	4.3%
300 days	0.0081	0.0063	3.5%
1 year	0.0075	0.0057	3.2%
2 year	0.0059	0.0042	2.4%
3 year	0.0053	0.0035	2.0%
4 year	0.0049	0.0030	1.7%

Figure 1: a) Uncertainty on the Daya Bay measurement of $\sin^2 2\theta_{13}$ over time under different assumptions. b) The table provides numerical values from the figure (along with relative errors on the angle θ_{13}).

The sensitivity projections are based on rate only; we expect further improvement with the addition of spectral shape information.

Measurement of θ_{13}

– **Important measurement of fundamental parameter**

- GUT and other models predict quantitative relationships between θ_{13} and the Cabibbo angle θ_C. Since θ_C is measured to 0.3%, constraints on the ratio of these quantities will be dominated by the measurement of θ_{13} (currently 6%) and improvements in θ_{13} will further constrain these models.
- Daya Bay will stand as the best measurement of this important quantity until LBNE Phase#2 runs. We do not want to lose this opportunity to make the best measurement in a cost effective way with the Daya Bay infrastructure.

– **Will aid the extraction of information from accelerator-based experiments.**

- Improving the error on θ_{13} from the current 6% to ~1.5% (with 3–4 years running) will improve the δ_{CP} reach of NOvA+T2K over the next decade and LBNE+NOvA+T2K over the following decade. Sensitivity calculations using LBNE GLoBES for running 6 years of NOvA (14 kTon of liquid scintillator), 5 years of T2K (22.5 kTon of water) and 10 years of LBNE Phase#1 (10 kTon liquid argon) are shown in Fig. 2. The improvement shown in the left graph corresponds to an increase in exposure of 20 kTon-years (a 20% or 3-kTon mass increase) for NOvA. The improvement shown in the right graph corresponds to an increase in exposure of 75 kTon-years (a 75% or 7.5-kTon mass increase) for LBNE phase#1. The peak sensitivity to δ_{CP} increases from 3.5σ to 4.5σ.
- A precise Daya Bay measurement of $\sin^2 2\theta_{13}$ will aid in resolving the θ_{23} octant degeneracy as discussed in arXiv:1209:3023 and arXiv:1209.1870.

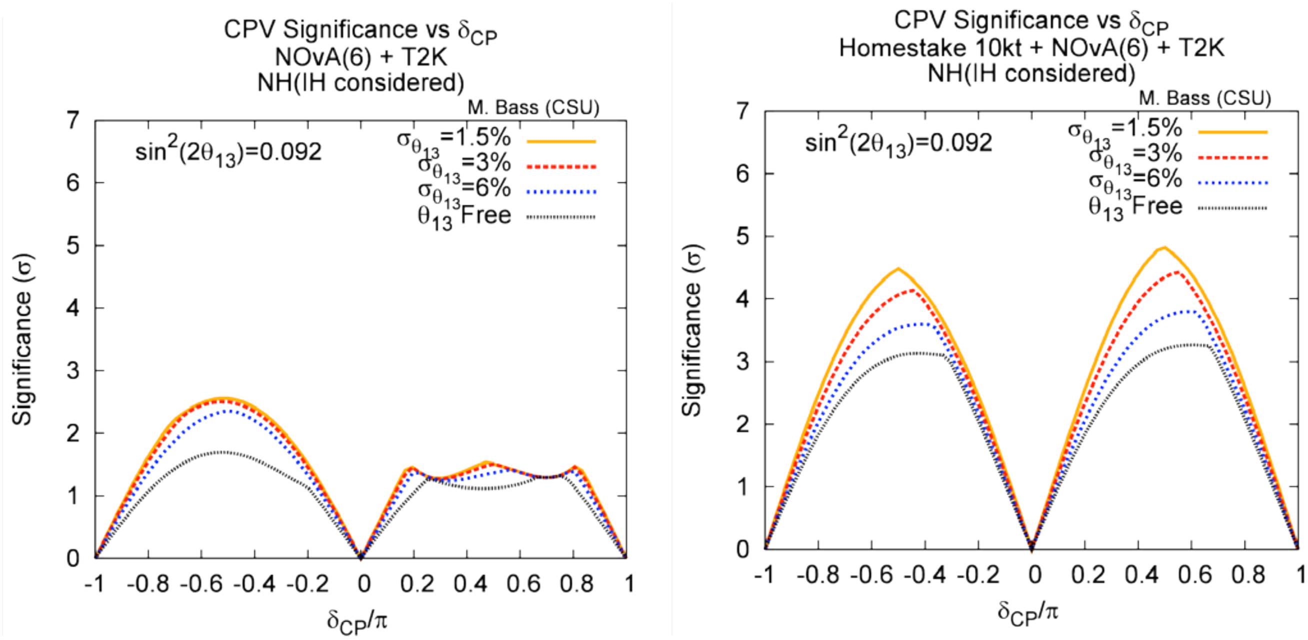


Figure 2: Significance with which CP violation can be observed, by NOvA+T2K (left) and NOvA+T2K+LBNE (right), as a function of the true value of δ_{CP}. Observation of CP violation is equivalent to the measurement $\delta_{CP}\neq 0,\pi$. The significance is calculated by minimizing over both the normal and inverted hierarchies, as the mass hierarchy is not assumed to be known. The effects of external constraints on θ_{13} from Daya Bay are shown.

- **Precise measurement from Daya Bay will eventually allow overconstraints of the νSM interpretation of oscillations in combination with accelerator measurements.**
  - The LBNE Phase#1 measurement of θ_{13} is expected to have an uncertainty of 5% (10% on $\sin^2 2\theta_{13}$), with some dependence on δ_{CP} (Fig. 3). The current uncertainty from Daya Bay is 6%, with an ultimate uncertainty (after 4 years) of ~1.5%.
  - Daya Bay will set the standard for precision comparison.
  - Comparison of θ_{13} measured via disappearance at reactors versus appearance at accelerators will constrain sterile or non-standard interactions.

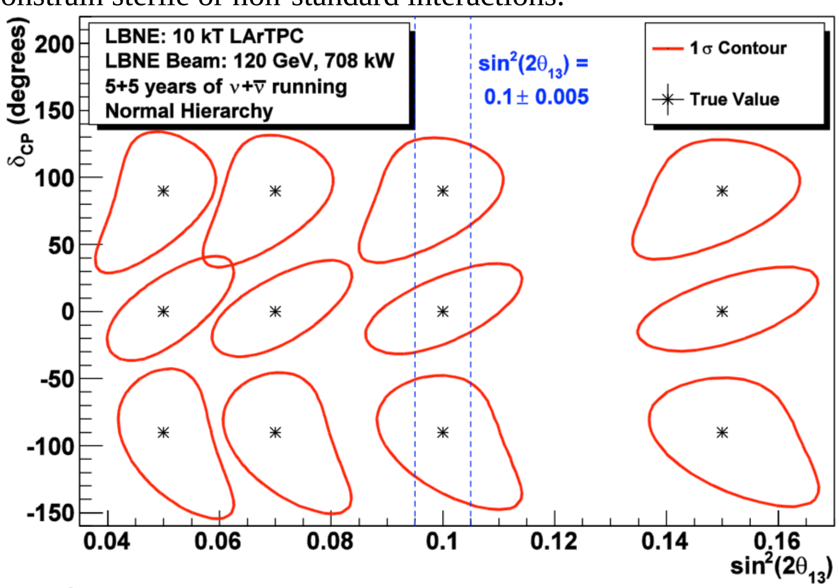


Figure 3: Sensitivity to $\sin^2 2\theta_{13}$ for LBNE Phase#1 after 10 years running (red 1σ contours). The Daya Bay sensitivity after 1 year of running is also shown (vertical dotted lines, a central value of 0.1 is shown).

Measurement of Δm^2_{ee}

In addition to the neutrino mixing angles and Dirac CP-violating phase, the mass-squared differences are crucial for understanding the nature of neutrinos. Daya Bay will provide a precise measurement of Δm^2_{ee}, better than 5% as shown in Fig. 4, that is complementary to $\Delta m^2_{\mu\mu}$ determined by accelerator-based experiments. Independent determination of the three mass-squared differences will validate the sum rule of neutrino mixing, $\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$. Any deviation from this sum rule could signal the existence of neutrinos beyond three generations.

– **Measurement of Δm^2_{ee}**
  - Measurement of new ν mixing parameter
  - Complementary and with similar precision to accelerator-based measurements
  - Constrains 3-ν model

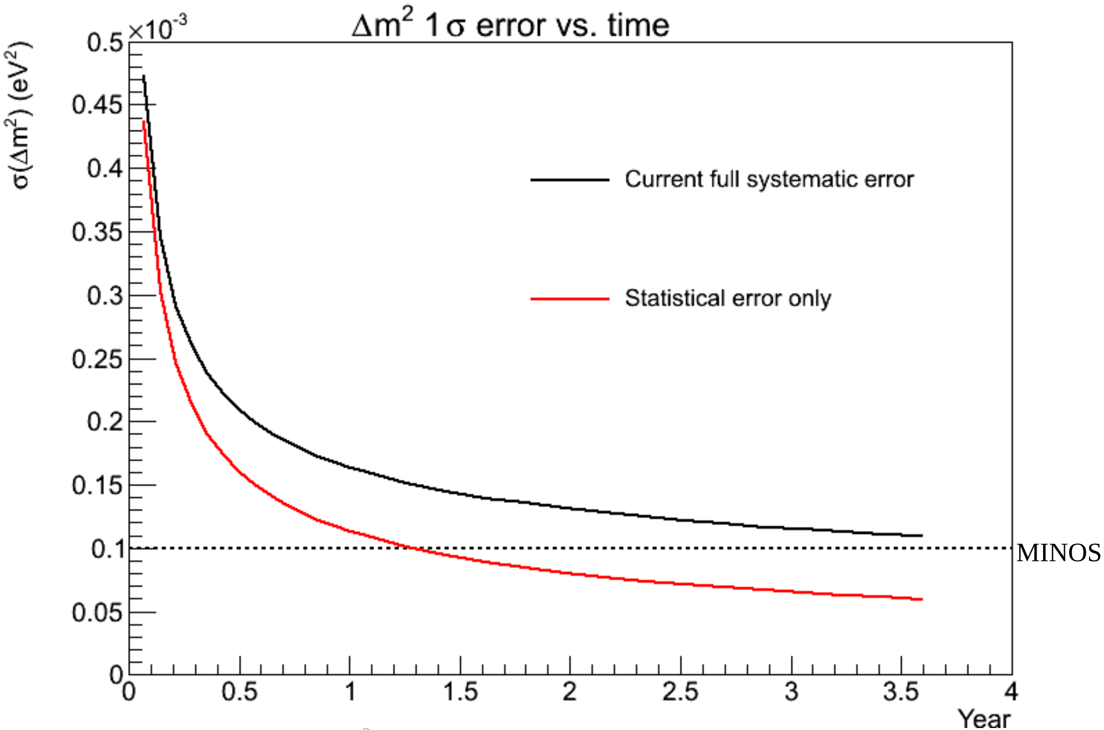


Figure 4: Expected Daya Bay uncertainty on Δm^2_{ee} from statistics alone or with existing systematic errors. We expect the result will lie between the two curves.

Based on statistics alone Daya Bay should reach an uncertainty of 1×10^{-4} eV^2 after 1 year and 0.6×10^{-4} eV^2 after 3 years. With the current estimated systematic uncertainty included Daya Bay should reach 1.6×10^{-4} eV^2 after one year and 1.2×10^{-4} eV^2 after 3 years.

Further scientific goals

Measurement of the Reactor Flux and Spectrum at Daya Bay

Daya Bay collects reactor antineutrino data at an unprecedented rate which enables a precision measurement of the reactor antineutrino spectra in the near site detectors. The Daya Bay experimental configuration allows spectral and flux measurements as close as 360m from the reactor cores at the Daya Bay site and 480m at the Ling Ao site. At these detector locations the measured reactor antineutrino flux from the nearest reactor cores remains largely non-oscillated in the standard 3-neutrino oscillation framework.[1] With this detector configuration Daya Bay will be able to report the following measurements and physics analyses:

1. **Highest-precision measurement of the reactor antineutrino spectrum** in a reactor antineutrino experiment. An O(1%) statistical uncertainty is achievable in a 2-year run over a large range of energies at the near sites as shown in Fig. 5.

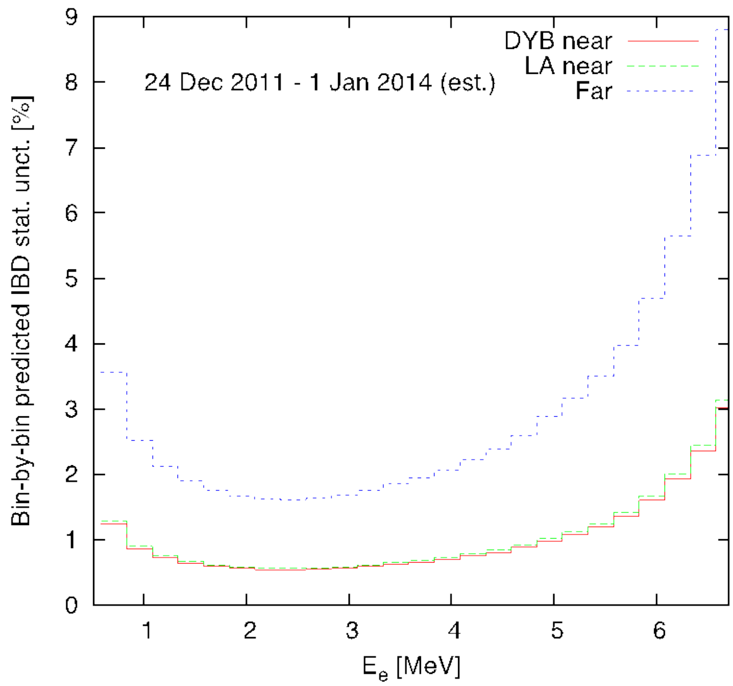


Figure 5: Projected bin-to-bin statistical uncertainty in the measurement of the reactor flux and spectrum at the Daya Bay and Ling Ao near sites.

2. **Test of the reactor antineutrino spectrum and search for new antineutrino interactions:** Using known reactor data such as thermal power output and fission fraction evolution from reactor core simulations we can predict the expected non-oscillated spectral shape of reactor antineutrinos emitted from each reactor. A precise comparison of the spectral prediction with the Daya Bay measurement will test our understanding of reactor antineutrino spectrum calculations and reveal potential shape effects (see Fig. 6). *Shape discrepancies may point to (a) missing nuclear physics in the reactor spectrum predictions or (b) new physics beyond the 3-neutrino framework including non-standard interaction (NSI) effects.* Daya Bay can search for new antineutrino interactions through comparison of the measured and expected reactor spectra.

   Understanding the shape of the measured and predicted reactor spectrum is a pre-requisite to any absolute reactor flux measurement. In particular, experts from the nuclear physics community have been skeptical of the small uncertainties quoted in flux predictions. Due to the high statistics of the Daya Bay measurement, the statistical bin-to-bin uncertainty in the 2011–2012 Daya Bay data set is already below the flux conversion uncertainty on the spectrum.

[1] The contribution from the more distant reactors at ~900m is approximately 20% (7.5%) of the total event rate at Daya Bay (Ling Ao). The oscillation effects from the far reactor can be corrected for in any spectral analysis assuming a 3-neutrino framework.

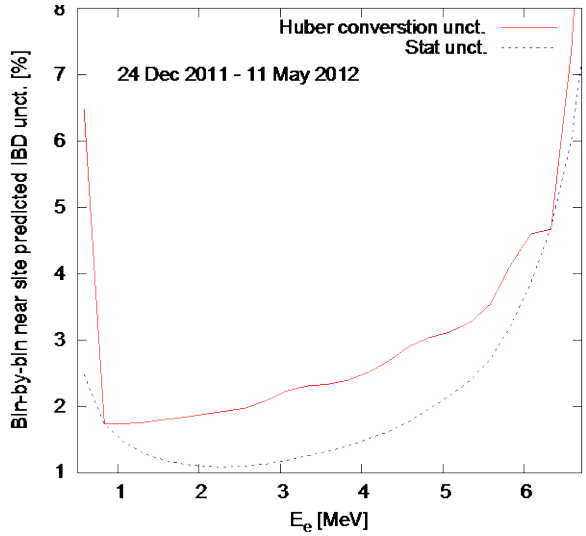


Figure 6: Projected per-bin statistical uncertainty (blue) and uncertainty from flux conversion (red) for a single AD in the Daya Bay near site over the published Daya Bay data period versus positron energy, E_e. Detection efficiency is ignored.

3. **Absolute reactor flux measurement:** In addition to a shape analysis, an absolute flux measurement tests our understanding of reactor flux predictions and can, in principle, shed light on the apparent deficit in the measured reactor neutrino flux at short baselines, also known as the "reactor anomaly". An analysis of past measurements and reactor flux predictions has revealed a discrepancy of about 5.7%. While Daya Bay has demonstrated superb relative detector uncertainties, an absolute measurement will be systematics limited. Table 1 summarizes the current and projected absolute uncertainties. A statistical precision of 0.1% will be achievable. Improvements in the analysis may eventually reduce absolute detector uncertainties to <1%. An absolute flux measurement will be limited by our knowledge of the reactor flux normalization: this includes a theoretical uncertainty of 2.7% in the reactor flux predictions. Some nuclear theorists believe that the uncertainty may even be larger than the quoted value. We can compare Daya Bay data to previous reactor flux measurements by "anchoring" it to the absolute Bugey-4 measurement with an uncertainty of 1.4%. Daya Bay's measured flux and spectrum will provide important input to test the reactor anomaly.

Source	Item	Abs Uncertainty (%)	
		Current	Goal
Statistics		**0.2**	**0.1**
Detector	H/Gd n-Capture Ratio	0.5	0.2
	Delayed Energy	0.6	0.3
	Number of Protons	0.47	0.3
	Spill-in Effects	1.5	0.3
	Subtotal	**1.8**	**0.6**
Reactor	Thermal power uncertainty	0.5	0.5
	Fission fraction	0.6	0.6
	Spent fuel contribution	0.3	0.3
	Subtotal	**0.8**	**0.8**
Flux normalization	Theoretical prediction	2.7	
	Bugey-4 anchor		1.4
	subtotal	**2.7**	**1.4**
Reactor Anomaly		**5.7**	**5.7**

Table 1: Current and goal uncertainties for a Daya Bay absolute reactor antineutrino flux measurement compared to the reactor anomaly of 5.7%.

Study of the time-evolution of the reactor antineutrino flux: The large reactor antineutrino event rate measured at Daya Bay allows a detailed study of the time variation of the reactor antineutrino flux. This contains information on the operation of the reactors as well as the evolution and isotopic composition of the core fuel. Correlating the measured antineutrino flux with reactor operations is of interest to reactor monitoring and applied neutrino science. With six reactors and 4 near-site detectors Daya Bay will provide the largest data set on reactor flux variations as a function of time.

Measure neutron and other spallation product production

Daya Bay has detectors at multiple modest depths and with overburden that varies with muon angle. Measurement of neutron and isotope production as a function of overburden will be of general use to the underground science community. Daya Bay plans to measure neutron and isotope production as a function of mean incident muon energy and direction.

Supernovae search

Daya Bay has been approached to join SNEWS and we are evaluating our potential contribution. While the Daya Bay detector mass is relatively small, our large number of dispersed detectors may enable a much more rapid supernova identification, quasi-online, by requiring antineutrinos in multiple detectors simultaneously.

Technical goals

Measurement of functionally identical detectors

The concept of identical near and far detectors is central to neutrino oscillation experiments. Daya Bay has arguably come closest to achieving “identical” near and far detectors. The study of the identicality of the Daya Bay detectors will provide valuable input for future detector and experimental design.

Measure long-term stability of gadolinium load liquid scintillator

Metal-loaded liquid scintillator (M-LS) is an effective detection media for both antineutrinos and neutrons. Previous experience with long term operation of M-LS has been problematic so that long term evaluation of the Daya Bay M-LS will aid future detector development efforts.