A Study of Systematic Uncertainties in the Daya Bay Neutrino Experiment using the GLoBES® Software

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ABSTRACT

The Daya Bay reactor neutrino experiment is designed to set a precision upper limit on, if not pin-point, the value of the θ_{13} neutrino oscillation parameter. As shown in the parameterized Pontecorvo-Maki-Nakagawa-Sakata matrix, accurate measurement of θ_{13} may enable the study of CP violation in the lepton sector, in addition to supporting our understanding of neutrino oscillation arising from the mixing of mass eigenstates. The Daya Bay experiment seeks higher precision than its predecessors by means of its ideal location and precise control of systematical uncertainties, the dominant limiting factor in neutrino experiments. This paper examines the Daya Bay experiment from a systematics perspective, producing a comparison with the similar Double Chooz experiment in France. Using the General Long Baseline Experiment Simulation (GLoBES) software, we calculate a simulated precision level for measurements of θ_{13} as a function of run-time and mass scale (Δm^2_{13}) for two active detector combinations, finding in each case that Daya Bay significantly exceeds the sensitivity of Double Chooz and is capable of reaching the desired level of $\sin^2 2\theta_{13} \leq 0.01$. This preliminary work will serve as a starting point for a more thorough and meticulous simulated analysis of Daya Bay's sensitivity limit.

I. INTRODUCTION

Since first proposed by Wolfgang Pauli in 1930, neutrinos have both answered and generated a variety of problems in and beyond the Standard Model of particle physics. These obscure particles eluded detection until 1956, when Cowan and Reines reported the first confirmed observation[1]. Neutrino experiments have since proved a fruitful means of investigating many of the fundamental questions and issues in nuclear and particle physics, including the distinctly quantum mechanical effect of neutrino oscillation, which has been the focus of intense observational and theoretical effort in the past several decades. These efforts have increased our understanding of the mixing of mass and flavor eigenstates, a phenomenon directly related to leptonic CP violation, a mechanism which may explain the asymmetry of matter and anti-matter in the universe.

The fundamental importance of this field has given rise to a variety of neutrino experiments designed to measure the mixing parameters defined in the Pontecorvo-Maki - Nakagawa-Sakata matrix. Considerable progress in this undertaking has left one unknown mixing angle, θ_{13}, which describes oscillation between the electron and tau flavor eigenstates. Beyond furthering our knowledge of the neutrino oscillation parameters, measuring the magnitude of this angle will directly determine whether or not

CP violation in the lepton sector can be detected with this generation of accelerator and beam experiments. The best measurement to date, performed at the Chooz experiment in France, has set an upper bound at $\sin^2 2\theta_{13} \leq 0.17$, a limit which Daya Bay will surpass.

In order to successfully reach the desired sensitivity of 1%, Daya Bay will make use of its advantageous natural terrain, as well as employ careful means of lowering systematic uncertainty, including the use of interchangeable detectors and multiple detector sites. In this paper, the sensitivity of Daya Bay as a function of experiment run-time and mass scale (Δm^2_{13}) for two detector configurations is probed. The General Long Baseline Experiment Simulator[2] (GLoBES) software is used to perform this analysis, where user-defined experiment files and χ^2 functions are employed. These simulations are then compared against the Double Chooz experiment, where Daya Bay's greater sensitivity is clearly visible.

This paper is organized in the following manner. First, a discussion of neutrino oscillation formalism is presented, in which all relevant physical and mathematical quantities are defined. Then, an overview of the Daya Bay project and the corresponding systematical considerations are presented. Finally, the results of the GLoBES simulations are introduced and discussed in Section IV, which is followed by concluding remarks.

II. NEUTRINO OSCILLATION FORMALISM

The mathematical formalism behind neutrino oscillation was put forth in 1967 by Bruno Pontecorvo, a decade after he first proposed the idea qualitatively[3, 4]. Since this time, our understanding of neutrinos and neutrino oscillation has grown exponentially through theoretical and experimental investigation. Within the last several years, it has become widely accepted that neutrinos are not mass-less, contrary to the predictions of the Standard Model. This observation allows for the three flavor (weak) eigenstates to be represented as a linear superposition of neutrino mass eigenstates:

$$\left|\nu_\alpha\right\rangle = \sum_{i=1}^{3} U_{i\alpha}\left|\nu_i\right\rangle$$

Equation 1

where α represents the three flavors (electron, muon, and tau) and i represents the three mass states. Since the weak eigenstates are not equivalent to the different mass eigenstates, each component mass eigenstate will propagate at a different frequency as the neutrino moves through space. Accordingly, quantum mechanics dictates that the probability of measuring a neutrino as a specific lepton flavor will oscillate with time. Experimentally, this implies that there is a finite probability that as a neutrino with initial flavor α propagates through space, it will oscillate into a flavor state β with $\alpha \neq \beta$. Thus, mixing of the mass eigenstates and the corresponding interference of the wavefunctions provides the mechanism through which neutrino oscillation takes place.

The degree of interference amongst the component mass eigenstates is specified by the coefficients of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix $U_{i\alpha}$. The PMNS matrix can be parameterized using three oscillation angles (θ_{12}, θ_{13}, θ_{23}), two mass scales (Δm^2_{12}, Δm^2_{13}) and a CP violating phase factor (δ) [5]. Each oscillation angle corresponds to mixing between two neutrino flavors where the label one corresponds to the electron flavor, two corresponds to the muon flavor, and three corresponds to the tau flavor. Subsequently,

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Equation 2

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Equation 3

the angle of interest in this paper, θ_{13}, describes oscillation between the electron and tau flavor eigenstates. Experiments to date have found numerical values for several of these parameters[6]:

$$\tan^2\theta_{12} = 0.40^{+0.10}_{-0.07}$$

$$\tan^2\theta_{23} = 1^{+0.35}_{-0.26}$$

$$\sin^2\theta_{13} = ???$$

$$\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\Delta m^2_{13} = 2.2^{+0.6}_{-0.4} \times 10^{-3}\, eV^2$$

The PMNS matrix reveals that the CP violating phase factor, δ, is directly proportional to the square of the sine of the oscillation angle θ_{13}; if θ_{13} proves to be very small or zero, this term will subsequently vanish, adding to the motivation for measuring θ_{13} as its magnitude will determine whether or not CP violation in the lepton sector is observable.

From the parameterized form of the PMNS matrix, it is possible to derive an analytic expression for the probability of an electron anti-neutrino remaining in that weak eigenstate as it propagates along a baseline of length (L)[7]. This expression, P_{ee}, is shown in Equation 3 and is plotted in Figure 1 after integrating over the neutrino energy E_ν. In the figure, the green curve corresponds to the first term in the expression of P_{ee}, whereas the blue curve corresponds to the second term in the probability equation. At a baseline of

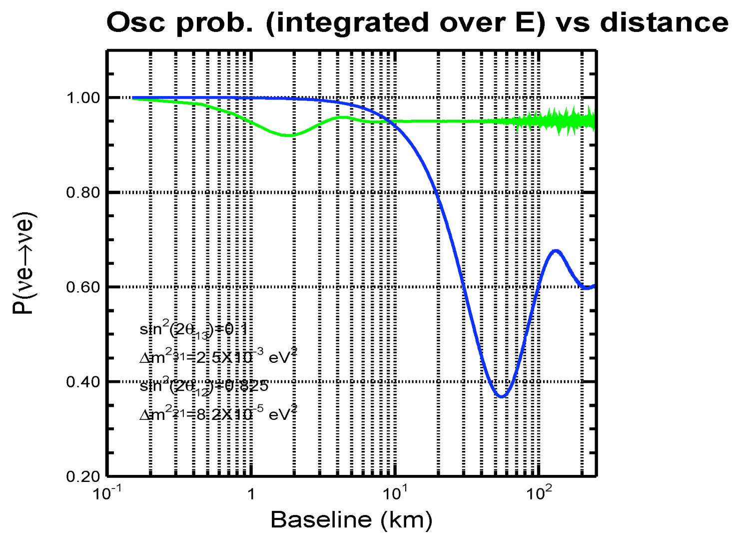

Figure 1

approximately 1.5km to 2.0km, an ideal distance for a reactor neutrino experiment, the term in P_{ee} proportional to $\sin^2 2\theta_{12}$ is negligible due to the small value of the mass parameter Δm^2_{12}. This is fortuitous as the survival probability expression simplifies to:

$$P'_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)$$

Equation 4

In this equation, the term dependant on θ_{12} and Δm^2_{12} has vanished, leaving an expression which can be used to obtain an unambiguous value of θ_{13}. Since the term proportional to $\sin^2 2\theta_{13}$ in P'_{ee} represents the probability of an electron anti-neutrino oscillating into another weak eigenstate, the difference between the normalized neutrino flux at a source (N_0) and at a distance L away (N_m) can be written:

$$N_0 - N_m = N_0 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)$$

Equation 5

$$\sin^2 2\theta_{13} = \frac{N_o - N_m}{N_0 \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right)}$$

Equation 6

This can then be solved for an explicit expression for $\sin^2 2\theta_{13}$, shown in Equation 6, which provides the desired link between the theoretical oscillation parameter and experimentally obtainable data.

III. DAYA BAY EXPERIMENTAL SETUP

Daya Bay, located approximately 55km north of Hong Kong, is an ideal location for a reactor neutrino experiment, harboring a high power nuclear power plant within one kilometer of a mountain range. Currently, two reactor plants are active, producing 5.8GW of power per plant; however, in 2010, a third plant will become active, increasing the total power output to 17.4GW, making Daya Bay one of the most powerful plants in the world.

Reaching the precision goal of 1% will require large numbers of statistics as well as meticulous control of systematical uncertainties. The current site lay-out for the Daya Bay experiment is carefully designed to accomplish this, calling for four detector locations: one near site in close proximity to the Daya Bay plant, one near site evenly spaced between the Ling Ao I and Ling Ao II reactors, one mid site, and one far site (see Figure 2). Since this experiment measures the difference in neutrino flux, precise knowledge of the initial flux is essential as a deficit could arise from either an oscillation phenomenon or inaccurate knowledge of the initial flux. Thus, the systematic uncertainty in the flux is a dominant form of error in these experiments and must be minimized for a 1% measurement to be feasible. This error suppression is achieved via the two near sites which cancel the uncertainty in the

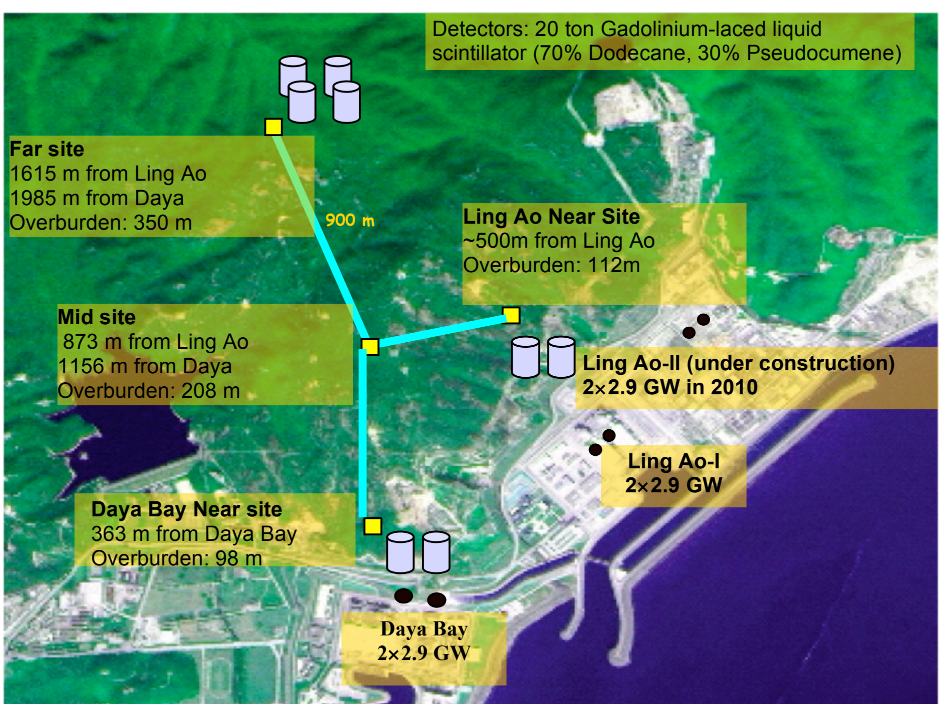

Figure 2 [8]

neutrino flux by precisely measuring the flux close to the reactor, before the probability for oscillation becomes significant. The near detectors also drastically reduce additional correlated sources of error including uncertainty in the neutrino energy spectrum, scintillator properties, interaction cross-section, and the spill in/out effects[9]. Reaching 1% precision also requires the background to be accounted for and minimized. Fortunately, the nearby mountains provide a minimum of 100m of overburden at each site, shielding the detectors from the cosmic ray background and reducing the error to an acceptable level.

The detection method used at each of the sites relies on the inverse beta decay process and employs a delayed correlation technique to reduce systematic errors. Inverse beta decay occurs when an incident electron anti-neutrino interacts with a proton in the detector, producing a single positron and neutron:

$$\bar{\nu}_e + p = n + e^+$$

Equation 7

The positron quickly annihilates with a nearby electron, releasing radiation which is detected by photo-multiplier tubes. This is called the prompt signal and is the first trigger for an event. After a random walk with an average distance of 5cm and a time delay of approximately 30μs, the neutron is captured in the target, releasing additional photons which form the second trigger, called the delay signal. Expecting two signals with known energies, time separation, and spatial separation allows for clean event definition which significantly decreases false positives and false negatives in the data collection.

To further control systematical errors, great care is taken in detector-design. Located at each of the four sites will be two 20ton, multilayered liquid scintillator detectors. The modules will be constructed as uniformly as possible and will be filled from a single batch of liquid scintillator to reduce detector related uncertainties.

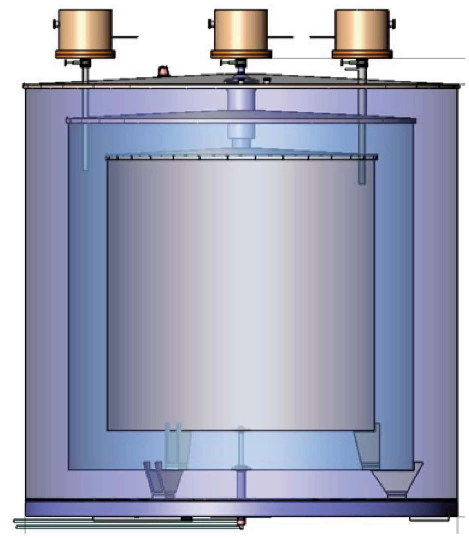

Figure 3 [8]

The target is the inner module, consisting of gadolinium laced liquid scintillator (.1% gadolinium by volume). This concentration of gadolinium decreases the capture time for neutrons in the scintillator as well as provides a larger energy release than occurs with a hydrogen reaction. Additionally, the gamma rays released in the neutron capture with gadolinium are more localized than photons released with hydrogen. The increased spatial localization and signal energy, and decreased capture-time further sharpen the event definition previously discussed. The second detector layer consists of un-doped liquid scintillator which captures photons from the inner target. This gamma-catcher reduces errors from events occurring at the boundary of the target including those associated with the spill in and spill out effects. Finally, the outer layer is a thin mineral oil buffer which protects the target from external radiation generated by the photo-multiplier tubes and the rock walls of the cavern. The entire detector is then placed in a large water tank which serves as a muon veto system, identifying cosmic ray muon events through Cerenkov radiation.

Care has also been taken to ensure that each of the large detector modules is as mobile as possible as it is currently proposed that the modules will be interchanged during the experiment run-time. This has the effect of reducing errors arising from variations amongst the eight proposed detectors and allows for detector and environmental backgrounds at the different sites to be easily determined[6]. Using this information, systematical uncertainties arising from detector efficiencies can essentially be eliminated.

IV. SIMULATION RESULTS AND SYSTEMATICS ANALYSIS

To determine whether or not Daya Bay has the potential to reach a sensitivity of 1% in measuring $\sin^2 2\theta_{13}$, the General Long Baseline Experimental Simulation (GLoBES) software was used[11, 12] GLoBES is a C++ based package which provides a framework for systematic analysis of a variety of neutrino experiments. The flexibility of its Abstract Experiment Definition Language (AEDL) and its incorporation of user-defined χ^2 functions lends itself to application in the Daya Bay experiment which requires unique analysis due to the novelty of its configuration.

As a measure of the value of the Daya Bay experiment, our sensitivity analysis, as a function of run-time and mass scale (Δm^2_{13}), was also performed for Double Chooz, a comparable experiment currently under construction in France which will utilize two detector sites, one near and one far, to reach an estimated sensitivity of 2% in measuring $\sin^2 2\theta_{13}$. Double Chooz will begin taking data in the near future (2008-2009) and will likely lead the field for the first couple of years after its inception[10]. Our simulations show, however, that Daya Bay will reach a notably higher sensitivity than that of Double Chooz.

The first half of our simulations examined the evolution of the sensitivity of $\sin^2 2\theta_{13}$ measurements as a function of experiment run-time. Within this analysis, a variety of systematic and statistical uncertainties are considered. When basic systematical uncertainty is calculated, errors in flux normalization, energy resolution, and fiducial mass are included in the equation for χ^2. The best case scenario was calculated assuming no systematical contribution, deriving all error from statistics alone. Following this calculation, layers of systematics were incorporated, including basic systematics, spectral error, and two different levels of $\sigma_{\text{bin-to-bin}}$, an open-ended parameter which accounts for any type of systematical uncertainty not explicitly included in the calculation. This parameter was set to 0.5%, and 2.0% in these simulations; however, these choices are slightly pessimistic as the value of $\sigma_{\text{bin-to-bin}}$ will likely be less than 0.1% once all factors are accounted for[13].

The first detector configuration examined for Daya Bay is the most basic setup, using only the Daya Bay near detector and the mid detector. The sensitivity of this arrangement was examined with only the Daya Bay power plant active, ignoring the contribution from the Ling Ao plants. The result of this analysis, and the same analysis performed for Double Chooz, appears in Figure 4 on the following page. From the plots, it is clear that without spectral and bin-to-bin considerations, the Daya Bay experiment is significantly more sensitive than Double Chooz; however, as more layers of systematic analysis are included, this advantage lessens notably. Thus, this minimal version of Daya Bay is slightly

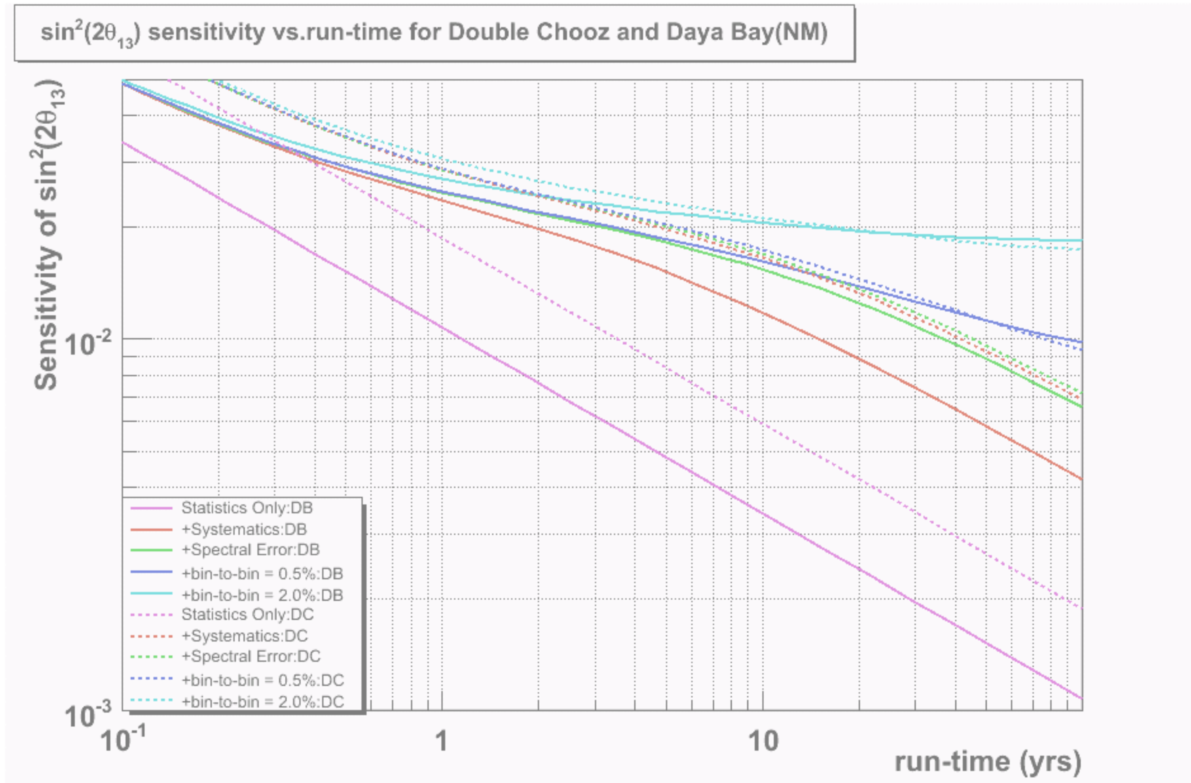

Figure 4

This plot of Daya Bay and Double Chooz illustrates that the minimal configuration at Daya Bay, with only two detectors active, is comparable to the Double Chooz experiment. For Daya Bay to reach its sensitivity goal within a reasonable amount of time, a more effective detector set up is necessary. (NM stands for near and mid detectors)

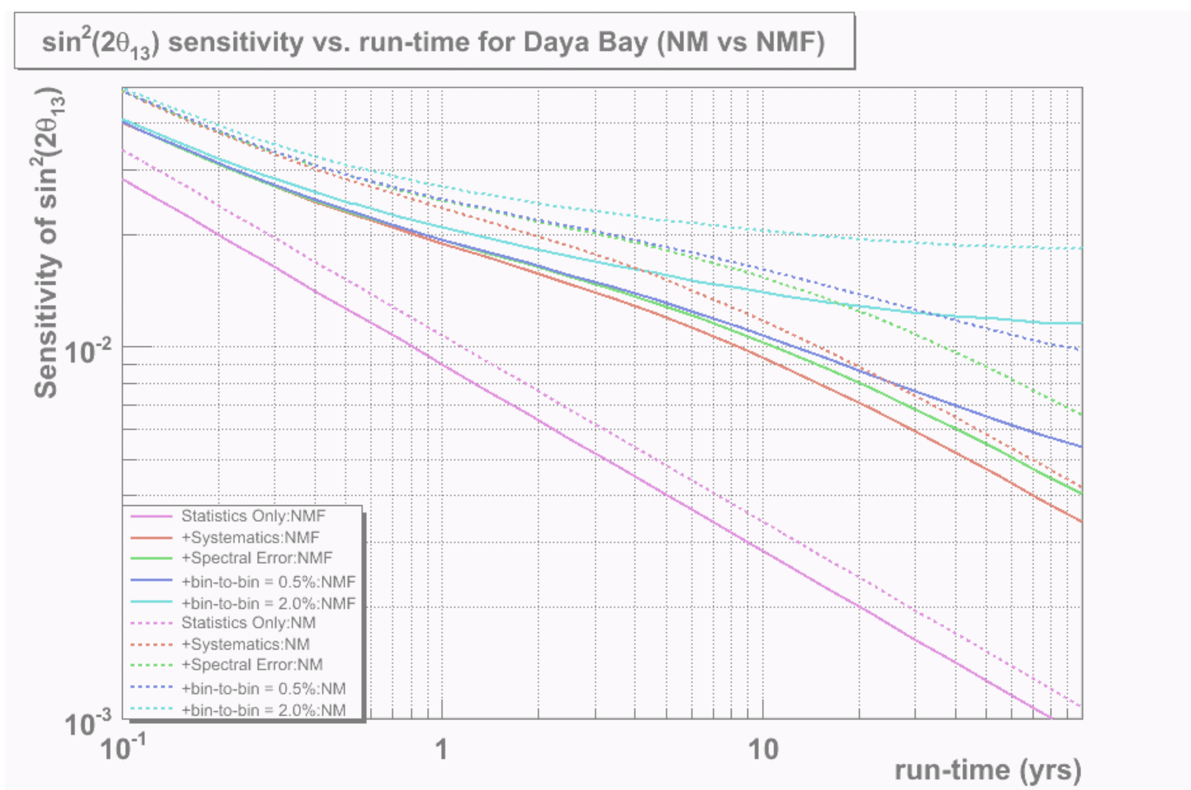

Figure 5

When the far detector (NMF) is included in the simulation, the sensitivity increases dramatically, especially when the spectral and bin-to-bin errors are included. This shows the effect of the far detector on limiting the systematics in the experiment.

more sensitive, but generally comparable to the Double Chooz experiment. This reveals that for Daya Bay to be competitive, a more complete configuration is necessary.

The second step in our analysis was to add the far detector site into the GLoBES simulation. As discussed above, this longer baseline significantly increases the sensitivity when used in conjunction with near and mid detectors, which function to decrease systematic uncertainties. The result of this simulation is plotted in Figure 5 along with the two detector case. When the far detector is implemented, the sensitivity is significantly increased for each layer of systematic analysis; however, the effect is more dominant when spectral and bin-to-bin errors are considered. This reinforces the importance of the baseline distance and the positive effect of obtaining accurate flux knowledge at multiple points along that distance.

It is important to note that these simulations are incomplete and the results obtained above are preliminary. As such, the data is best examined relatively between the configurations versus as an absolute result. Once the simulations are completed, the true sensitivity as a function of run-time can then be determined. In light of this, Figure 6, below, shows both detector setups for Daya Bay and Double Chooz on the same plot. It is clear that the three detector setup at Daya Bay is the most sensitive amongst the configurations under examination. The solid curves represent a realistic best case scenario and the dashed curves provide a worst case estimate. The plot shows that the three detector setup will reach a sensitivity of 1% after approximately 8 years of run-time. This large time requirement is due to the preliminary nature of the simulation; as the additional reactors and

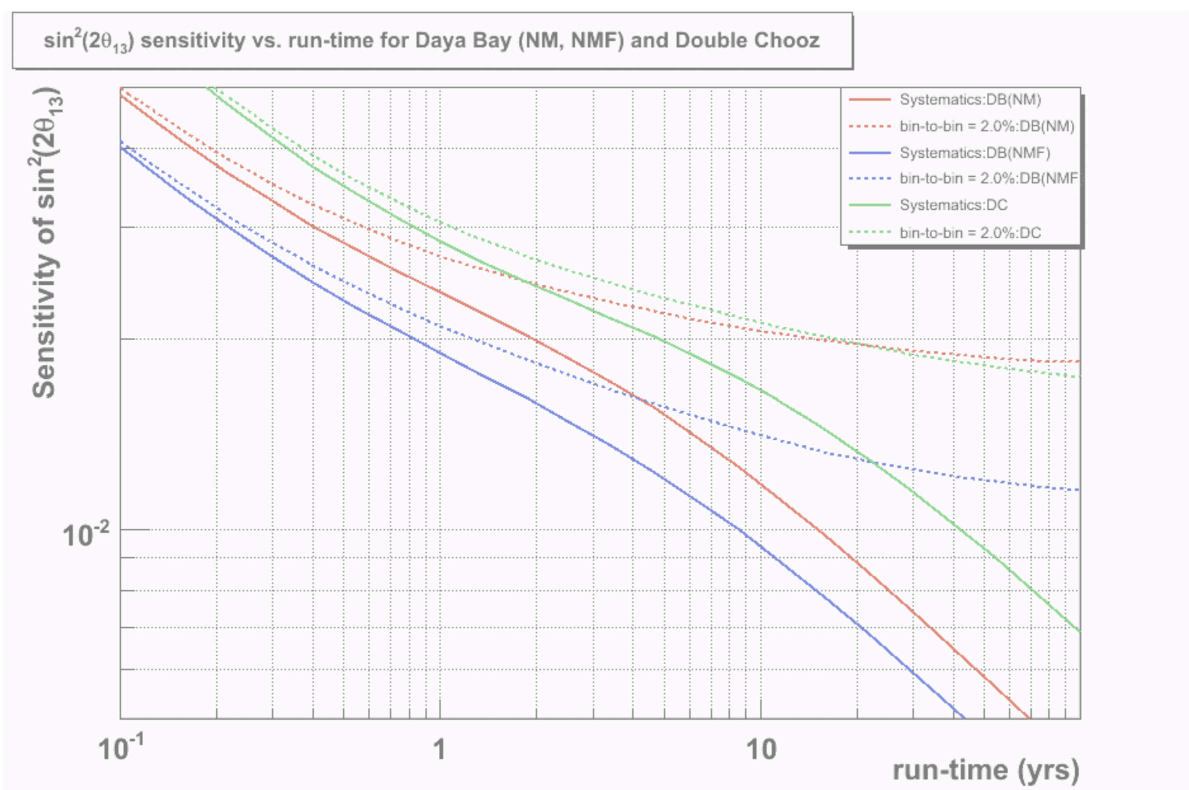

Figure 6

This plot of Day Bay with both detector configurations and Double Chooz further illustrates that the three detector Daya Bay setup is the most expedient means of reaching the 1% sensitivity mark.

fourth detector are included, and the error parameters are fine-tuned, this will get increasingly accurate and the time necessary to reach 1% will significantly decrease.

The second half of the simulation analysis focused on determining the sensitivity of the Daya Bay experiment as a function of the mass parameter Δm^2_{13}. Since this value is known to within roughly 20%, a sizeable parameter space exists within which the sensitivity to measurements of $\sin^2 2\theta_{13}$ could easily vary. The same statistical and systematic calculations were performed with identical error types and values to those discussed above. The value of Δm^2_{13} was varied from $2.0\times10^{-3}\text{eV}^2$ to $6\times10^{-3}\text{eV}^2$ while the remaining oscillation parameters were set to the following values:

$\Delta m_{12}^2 = 7.9 \times 10^{-5}\ \text{ev}^2$
$\delta_{cp} = \pi/2$
$\theta_{12} = 33.2^\circ$
$\theta_{13} = 0.0^\circ$
$\theta_{23} = 45^\circ$

The analysis for Daya Bay with only near and mid detectors active and Double Chooz, with a run-time of 5 years, is plotted in Figure 7 below. From the plot, it is evident that throughout the parameter space examined, the Daya Bay setup, even in its simplest configuration, is more sensitive than Double Chooz. Figure 8 shows that when the far detector is added to the simulation, the sensitivity is further improved. Again, we see that the effects of the far detector are more dramatic when

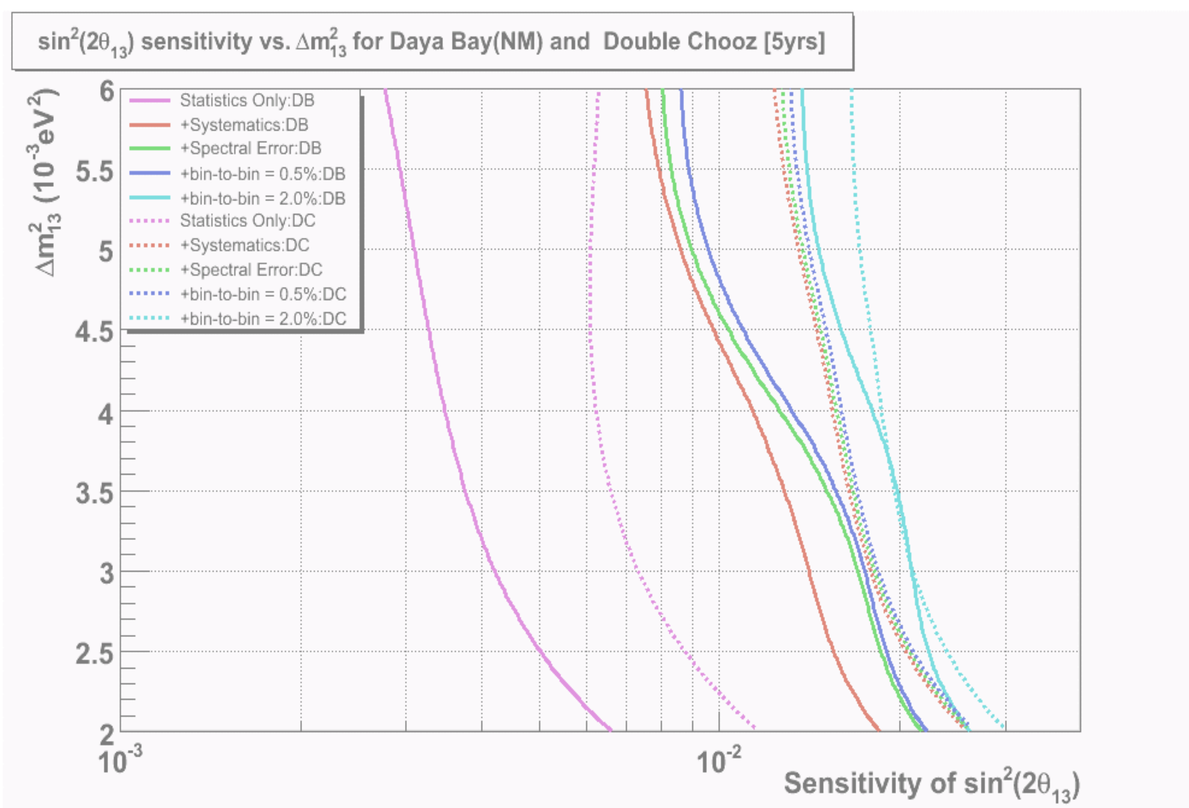

Figure 7

This plot shows that Daya Bay, even with just two active detectors is more sensitive than Double Chooz throughout the parameter space for Δm^2_{13} considered, including the experimentally probable range between 2 and 3 $\times10^{-3}$ eV^2.

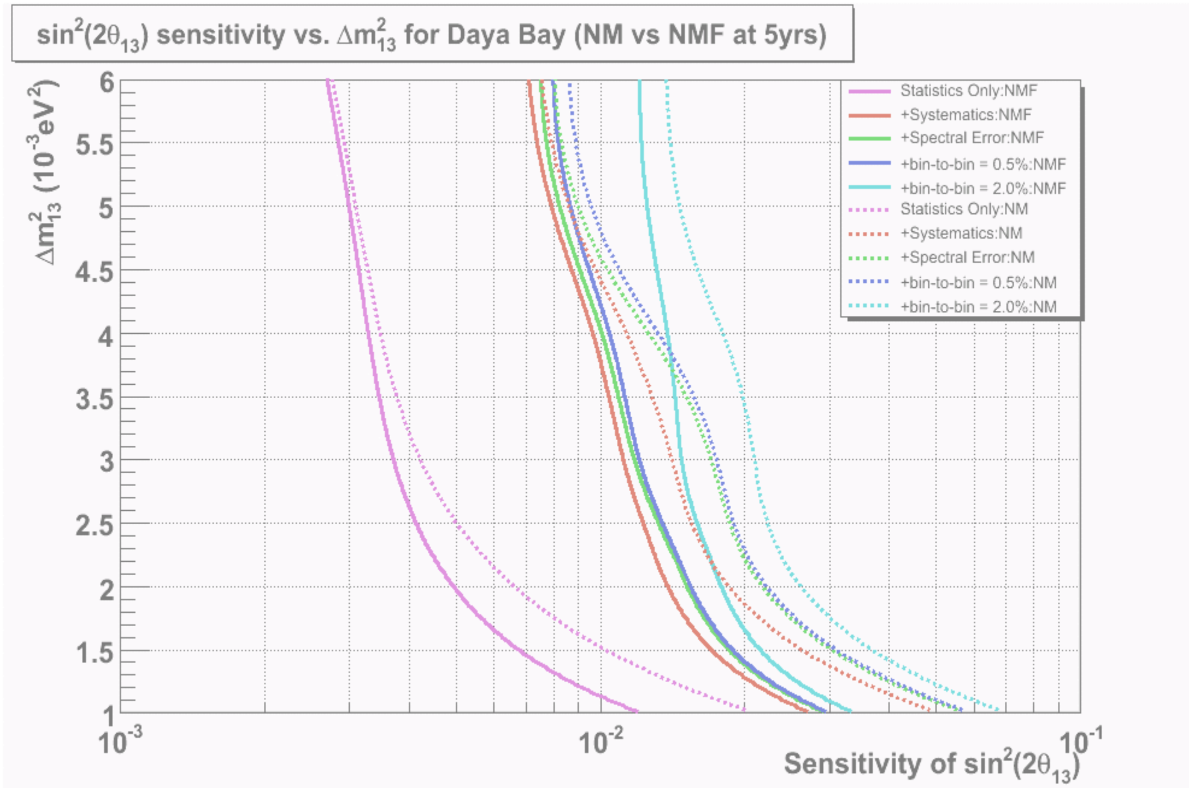

Figure 8

As with the run-time simulations, adding the far detector improves sensitivity in each calculation; however, the effect is more notable when spectral and bin-to-bin errors are included.

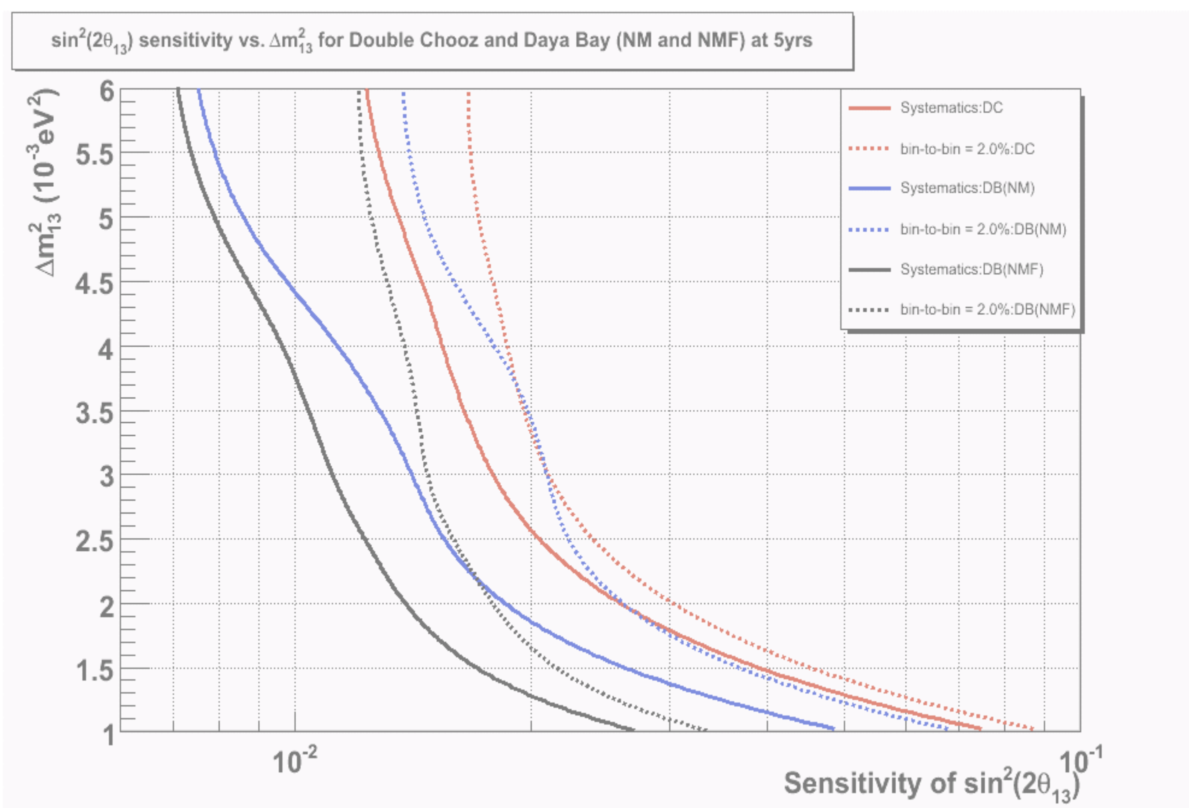

Figure 9

Effect of far detector is clear when plotted versus both the basic Daya Bay configuration and the Double Chooz data.

additional layers of systematic uncertainty are included. As a final display of the increased sensitivity of Daya Bay, Figure 9 plots the sensitivity of both Daya Bay configurations as well as Double Chooz. This graph clearly shows the relative increase in sensitivity moving from Double Chooz, to the basic Daya Bay setup, to the three detector configuration.

V. CONCLUSIONS

The simulations discussed above reveal that the Daya Bay configuration with three active detectors and one active power plant is easily capable of surpassing the sensitivity of both Double Chooz and a simpler configuration of itself when examined as a function of run-time and as a function of the oscillation parameter Δm^2_{13}. Though the absolute sensitivity can not be determined from this study, it is clear that Daya Bay has the potential to reach a sensitivity of 1% in measuring $\sin^2 2\theta_{13}$. While on route to that sensitivity, Daya Bay may pin-point the value of the θ_{13} oscillation angle which, depending on its magnitude, may provide valuable information regarding the search for leptonic CP violation. To fully understand the potential of the Daya Bay experiment, more complete simulations need to be performed. The preceding results are very preliminary and several factors still need to be addressed, including implementing the remaining two power plants and fourth detector site as well as fine tuning the values used for systematic errors and the overall normalization constant used in the simulation. Based on theoretical predictions, it is clear that the sensitivity of the experiment will only improve as the complexity and accuracy of the simulation is increased. This work will serve as the foundation for future, more detailed and meticulous simulations which will reveal absolute sensitivity of the Daya Bay experiment in measuring the θ_{13} mixing angle.

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REFERENCES

1. C. L. Cowan, F. Reines, et al. "Detection of the Free Neutrino: A Confirmation". *Science* **124** (3212), 103-104 (1956).
2. P. Huber, M. Lindner, W. Winter, Computational Physics Communications 167, 195 (2005).
3. B. Pontecorvo. J. Exp. Theor. Phys. **33**, 549(1957) [Sov. Phys. JETP **6**, 429(1958)].
4. B. Pontecorvo. J. Exp. Theor. Phys. **53**, 1717(1967) [Sov. Phys. JETP **26**, 984(1968)].
5. B. Kayser. "Neutrino Mass, Mixing, and Flavor Change". Review of Particle Physics, Phys. Lett. B592 (2004).
6. M. Honda, Y. Kao, N. Okamura, T. Takeuchi. "A Simple Parameterization of Matter Effects in Neutrino Oscillation". YITP. 05-52. (2006).
7. U.S. Collaborators of Daya Bay Experiment. "A Precision Measurement of $\sin^2 2\theta_{13}$ with

Reactor Antineutrinos at Daya Bay, China. Project Proposal. (2005).

8. J. Liu. “Daya Bay Reactor Neutrino Experiment: A Precise Measurement of θ13 in Near Future”. Power-Point Presentation. C2CR07 Conference, Lake Tahoe, Feb. 28, 2007.
9. P. Huber, J. Kopp, M. Lidner, M. Rolinec, W. Winter. “From Double Chooz to Triple Chooz: Neutrino Physics at the Chooz Reactor Complex”.
10. http://doublechooz.in2p3.fr/. Press Release: September 19th, 2006. “Launching of the Double Chooz Experiment”. Accessed August 24th, 2007.
11. H. Murayama, A. Pierce. "Energy Spectra of Reactor Neutrinos at KamLAND". Physical Review Letters D65 (2002).
12. K. Eguchi et al. "First Results from KamLand: Evidence for reactor anti-neutrino disappearance" Physical Review Letters. 90 (2003).
13. P. Huber, M. Linder, T. Schwetz, W. Winter. “Reactor Neutrino Experiments Compared to Superbeams”. Journal of Nuclear Physics. B665 Pg 487-519 (2003).