Braidwood Sensitivity Estimates

Abstract

Estimates of the Braidwood sensitivity to neutrino oscillations have been obtained including statistical and correlated systematic uncertainties. From these studies, the Braidwood experiment with three years of data can measure an oscillation signal at the the 3 to 5 σ level if $\sin^2 2\theta_{13} > 0.02$ for all of the currently allowed Δm^2 region or place a 90% CL limit at the $\sin^2 2\theta_{13} < 0.007$ level if the signal is small or non-existent. It is also shown that Braidwood has good sensitivity to see an oscillation signal separately in both a rate and energy spectrum comparison giving additional information to establish a convincing oscillations observation.

1 Experimental Setup and Uncertainty Assumptions

Estimates of the sensitivity for the Braidwood experiment have been obtained using the experimental setup and uncertainties given in the tables below. The method for obtaining the results is given in the Appendix and involves multi-parameter fits including correlated systematic uncertainties. Also, for the results presented here, except where indicated, Δm^2_{13} has been constrained with an uncertainty corresponding to the expected Minos sensitivity of $\delta(\Delta m^2) = 0.13 \times 10^{-3}$ eV^2.

The assumed uncertainties are given in the Table 1 with some explanation of the value indicated in the "Comment" column. (Further details on these uncertainty estimates can be found in the Braidwood project description and associated memos.) The specific uncertainty of 0.3% associated with the relative efficiency and volume between the four detectors is broken out in Table 2 which shows how the various components combine to reach this level of uncertainty. Many cross checks are available to address these uncertainties but, at this point, we have chosen not to reduce the uncertainties using these additional measurements.

The sensitivity estimates assume an experimental setup corresponding to the Braidwood site as given in Table 3. The calculations are for a three year run with two near and two far detectors

Table 1: Assumed systematic uncertainties used in the various fits.

Quantity	Uncertainty	Comment
IBD σ	2%	Overestimate; tied to neutron lifetime
Reactor Power	2%	From Chooz/Palo Verde publication
Relative Detector Eff.	0.3%	Detector mass, solid angle, neutron energy scale, optical model
^{9}Li/^{8}He	20% / 100%	Estimate from fitting observed events
Flat/Exponential Bkgnd	16% /27%	From energy fits outside of signal region
Energy Scale	0.5%	From fits to Gd capture peak, ^{12}B
Energy Offset	20 keV	From fits to Michel electrons
Energy Resolution	$\pm 1\%\sqrt{E}$	Assuming $\Delta E = 12\%\sqrt{E(MeV)}$

Table 2: Systematic Uncertainties on Relative Acceptance between Near and Far Detector

Quantity	Uncertainty (%)	Comment	Cross checks: Near site cross calibration*	Cross checks: ^{12}B production
Solid angle (baseline)	0.1	From survey: $\Delta L_{near} = \pm 10cm$		
Detector mass	0.2	volume measurement	$\surd$	$\surd$
Neutron capture E cut	0.1	E scale from n-Gd capture peak	$\surd$	
Positron E cut	<0.1	Escale from n capture peaks, ^{12}B	$\surd$	$\surd$
Optical model	0.2	Optical, source calibration	$\surd$	
Timing cuts	<0.1		$\surd$	
Total	0.3		$\sigma_{check} \sim 0.3\%$	$\sigma_{check} \sim 0.5\%$

* Note that the near site cross calibration measures the combination of the checked effects at the time of the cross calibration. Some uncertainties, such as energy scale, will have additional time dependent effects.

located under 450 mwe of rock shielding.

2 Results

Using the method described in the Appendix, three types of fits have been performed corresponding to 1) a rate or counting measurement, 2) a shape of the observed E_ν spectrum only, and 3) a combined rate and shape measurement. The rate measurement uses a comparison of the total number of observed events between neutrino energy values of 1.9 to 7.0 MeV as compared to prediction to constrain the parameters. The spectral shape measurement uses a fit to the observed energy distribution. This fit allows each detector's total rate to vary unconstrained and limits the fit parameters by comparing the observed and predicted energy distribution. In the combined fit, the rate and shape of the observed and predicted events is compared in order to constrain the fit parameters.

With the setup shown in Table 3, the statistical error of each far detector for a three year run is 0.3% which is comparable to the expected systematic error given in Table 2. Thus, a comparison of the two far detectors can be used to cross check the assumed systematic uncertainties. The near detectors have even higher statistics so will give even higher precision cross check of systematic differences.

Sensitivity estimates have been performed using the above fitting technique. For this study, the 90% CL limit for an underlying true distribution with no oscillations is given by multiplying the fitted $\sin^2 2\theta_{13}$ error by 1.28. The sensitivity of the Braidwood experiment is mainly dependent on size of the data sample as shown in Figure 1. With the nominal three year data sample, the rate measurement is just starting to be systematics limited but the shape measurement is completely dominated by statistical errors. A three year run will give sensitivity at or below the $\sin^2 2\theta_{13} = 0.01$ level for both the rate and shape measurement allowing a definitive indication of neutrino oscillations with two different signatures and give a combined sensitivity below 0.007.

The Braidwood sensitivity as a function of Δm^2 for the rate and shape fits is displayed in Figure 2. As seen from the figure, both fit techniques have good coverage for the expected Δm^2 region between 1.5 and 3.5×10^{-3} eV^2 with sensitivity at or below the $\sin^2 2\theta_{13} = 0.01$ level. The combination of the two types of fits can be used to substantiate an oscillation signal by observing

Table 3: Braidwood experimental setup used in the sensitivity estimates.

Component	Parameter	Value
Reactors	Power	3.59 GW
	Number	2
	Up Time	92%
Running Time		3 years
Near Detectors	Mass	65 tons
	Number	2
	Distance	270 m
	Shielding	450 mwe
	Events/Detector	3,800,000
Far Detectors	Mass	65 tons
	Number	2
	Distanace	1510 m
	Shielding	450 mwe
	Events/Detector	123,000
Detector Eff.		75%
Background Rates	^{9}Li	1045 evts/det.
	^{8}He	131 evts/det.
	Flat	785 evts/det.
	Exponential	212 evts/det.

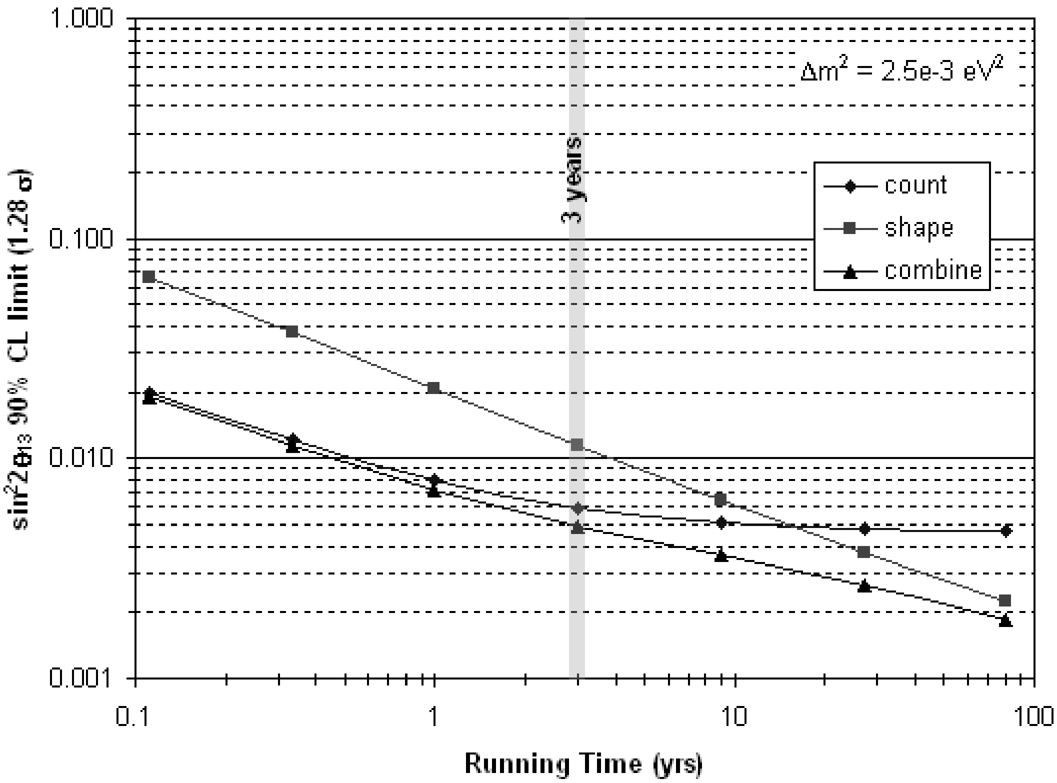

Figure 1: The 90% CL sensitivity of the Braidwood experiment versus running time. The nominal data taking period is expected to be three years. The different types of fits are indicated by the markers on the line. (The Braidwood setup includes two near and two far detectors, each with 65 tons of fiducial mass, positioned at 270 m and 1510 m from two 3.59 GW reactors. With this setup, three years of running corresponds to a luminosity exposure of 2,800 GW-ton-years in the far detectors.)

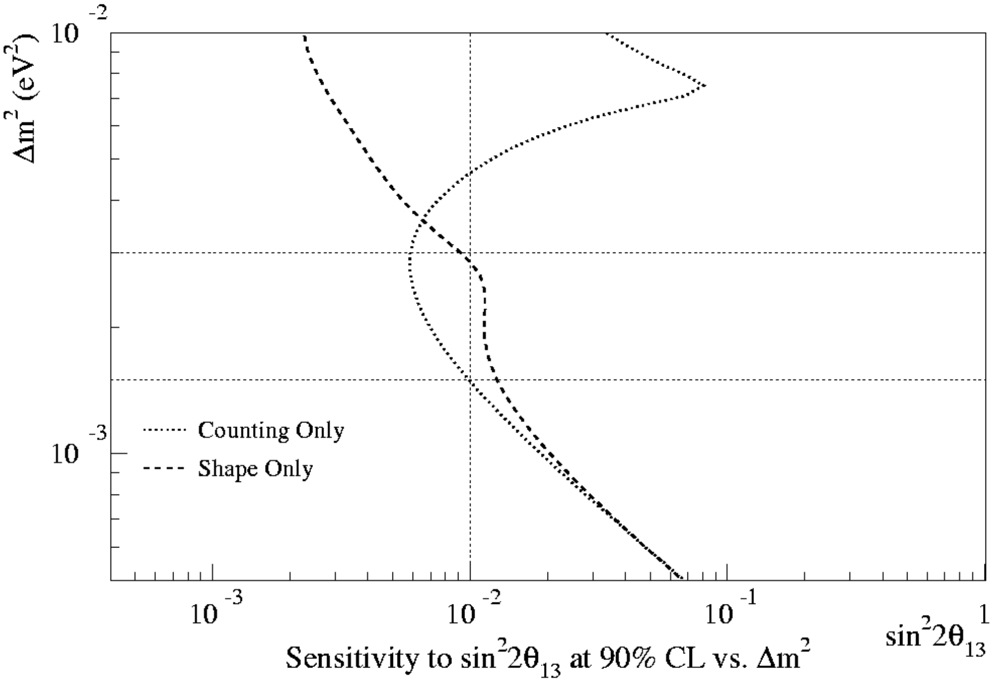

Figure 2: The 90% CL $\sin^2 2\theta_{13}$ sensitivity for a "Rate Only" or "Shape Only" measurement using a three year data sample with the Braidwood experimental setup. The horizontal lines indicate the current 2σ limit on Δm^2 and vertical line marks the sensitivity goal of $\sin^2 2\theta_{13} = 0.01$.

an anomaly in both relative near to far rate and energy distribution.

The combination of the rate and shape fits give improved sensitivity as shown in Figure 3 where 90%, 3σ, and 5σ sensitivity curves are displayed as a function of Δm^2. The figure shows that the Braidwood experiment can observe a definitive signal at the 3 to 5σ level for $\sin^2 2\theta_{13} > 0.02$ in the expected Δm^2region and set a limit of $\sin^2 2\theta_{13} < 0.007$ level if no signal is observed.

The above fits have all used an observed event distribution corresponding to a null underlying oscillation scenario. In contrast, Figure 4 shows the allowed regions for combined rate/shape fits to data with an underlying oscillation signal with $\sin^2 2\theta_{13} = 0.02$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2. The top figure gives results where the both measured variables, $\sin^2 2\theta_{13}$ and Δm^2 are unconstrained by outside measurements. In the bottom figure, Δm^2 is constrained with a uncertainty corresponding the Minos expectation after two years of data, $\delta(\Delta m^2) = 0.13 \times 10^{-3}$ eV^2. As seen in the bottom figure, the Braidwood reactor experiment will mainly give new information on the value of $\sin^2 2\theta_{13}$. With $\sin^2 2\theta_{13} = 0.02$, Braidwood will see an oscillation signal at the 5 σ level giving definitive indications of oscillations in both the rate and shape measurements. In addition, $\sin^2 2\theta_{13}$ will be measure with an accuracy 20%.

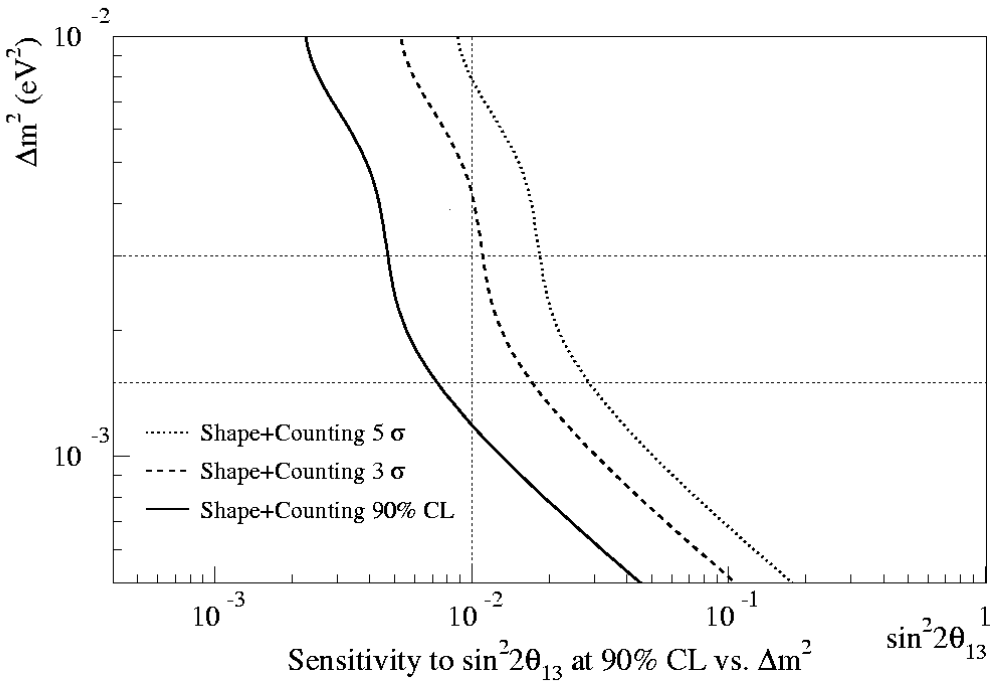

Figure 3: The 90% CL, 3σ, and 5σ $\sin^2 2\theta_{13}$ limits for a "Rate Plus Shape" measurement using a three year data sample with the Braidwood experimental setup. The horizontal lines indicate the current 2σ limit on Δm^2 and vertical line marks the sensitivity goal of $\sin^2 2\theta_{13} = 0.01$.

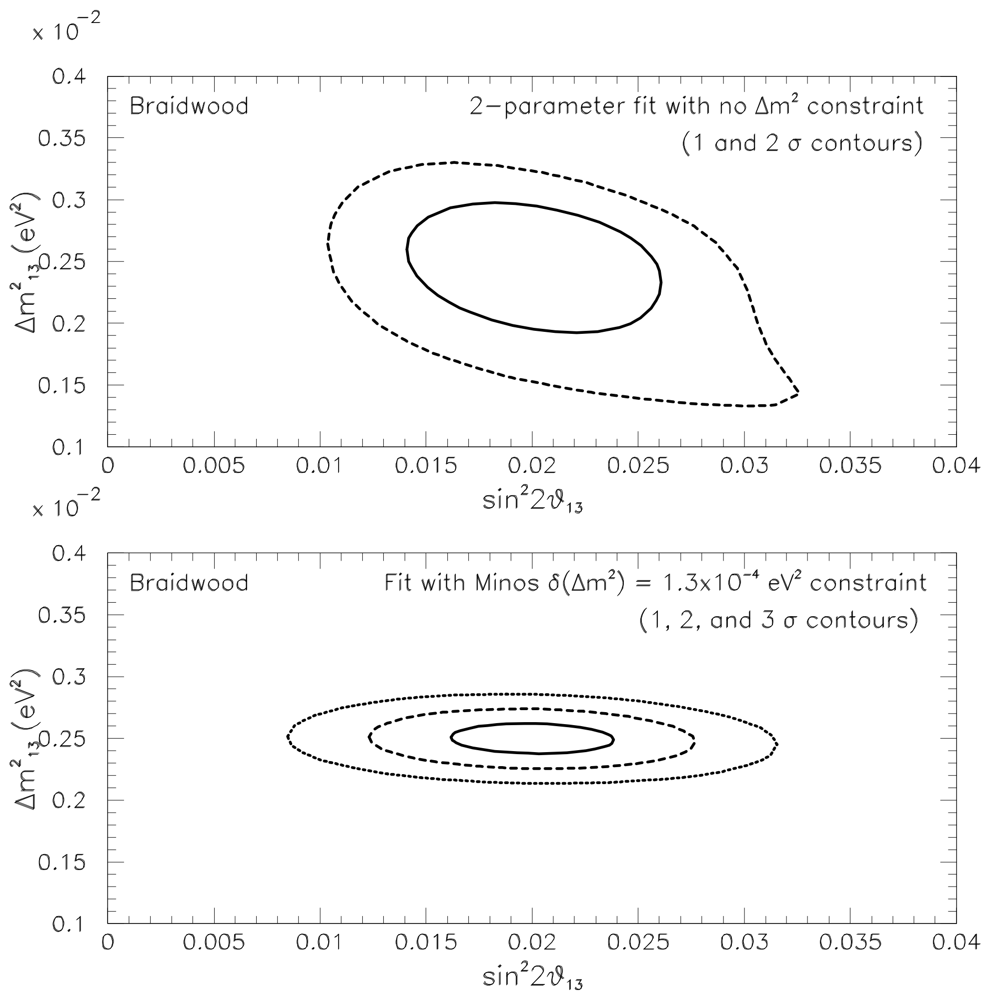

Figure 4: Combined rate and shape fit results for observed data with an oscillation signal corresponding to $\sin^2 2\theta_{13} = 0.02$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2. The top figure gives the one and two σ contours with no external constraints on Δm^2. The bottom figure shows the one, two, and three σ contours with Δm^2 constrained with an uncertainty of 0.13×10^{-3} eV^2 corresponding to the expected Minos measurement capability.

Appendix

The method for obtaining the sensitivity for a given experimental setup uses a χ^2 with pull terms to parameterize parameters associated with the correlated systematic uncertainties. The χ^2 function for each detector is given below with the systematic parameters given by the various δ variables. The n variables refer to the observed and predicted number of events in energy bins. For this study, 100 0.1 MeV energy bins were used and χ^2 contributions are included for each detector separately. Given a set of observed events, $n_{observed}(E_i)$, the program does fits for the values of Δm^2, $\sin^2 2\theta_{13}$, and the δ_i's that minimize the total χ^2 function.

$$\chi^2 = \sum_{\textit{energy bins}} \frac{(n_{observed} - n_{predicted})^2}{n_{observed}} + \frac{(\delta_{\mathrm{xsec}} - 1)^2}{\sigma^2_{\mathrm{xsec}}} + \sum_{\mathrm{bkgnds}} \frac{(\delta_{bkgnd} - 1)^2}{\sigma^2_{\mathrm{bkgnd}}} + \sum_{\mathrm{reactors}} \frac{(\delta_{\mathrm{power}} - 1)^2}{\sigma^2_{\mathrm{power}}}$$
$$+ \sum_{\mathrm{detectors}} \frac{(\delta_{\mathrm{rel\ eff}} - 1)^2}{\sigma^2_{\mathrm{rel\ eff}}} + \sum_{\mathrm{detectors}} \frac{\delta^2_{\mathrm{e\_scale}}}{\sigma^2_{\mathrm{e\_scale}}} + \sum_{\mathrm{detectors}} \frac{\delta^2_{\mathrm{e\_offset}}}{\sigma^2_{\mathrm{e\_offset}}} + \sum_{\mathrm{detectors}} \frac{\delta^2_{\mathrm{e\_smear}}}{\sigma^2_{\mathrm{e\_smear}}}$$

$$n_{predicted} = n(\Delta m^2, \sin^2 2\theta_{13}) \cdot \delta_{\mathrm{xsec}} \cdot \delta_{\mathrm{power}} \cdot \delta_{\mathrm{rel\ eff}} + \delta_{bkgnd} \cdot n_{bkgnd}$$
$$+ \delta_{\mathrm{e\_scale}} \cdot \Delta n_{\mathrm{e\_scale}} + \delta_{\mathrm{e\_offset}} \cdot \Delta n_{\mathrm{e\_offset}} + \delta_{\mathrm{e\_smear}} \cdot \Delta n_{\mathrm{e\_smear}}$$

An additional term associated with Δm^2 information from other sources can also be included to constrain Δm^2. For the results presented here, except where indicated, a value of $\delta(\Delta m^2) = 0.13 \times 10^{-3}$ eV^2 has been used. This corresponds to the expected error from Minos with a few years of running. (The current uncertainty is 0.55×10^{-3} eV^2 and T2K is expecting to reach 0.1×10^{-3} eV^2).