Braidwood Sensitivity Estimates

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1 Overview of Method and Setup/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 uses a χ^2 with pull terms to parameterize the nuisance parameters associated with correlated systematic uncertainties. The χ^2 function 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 were used. Given a set of observed $n_{observed}\,(E_i)$, the program will fit for the values of Δm^2, $\sin^2 2\theta_{13}$, and the δ_i's.

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

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

An additional term associated with Δm^2 information from other sources can also be included to constrain Δm^2. For the fits given below, 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).

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 the 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.

The sensitivity estimates assume an experimental setup corresponding the Braidwood site as given in Table 3. The calculations are for a three year run with two near and two far detectors located under 450 mwe of rock shielding.

2 Results

Using the method described above, three types of fits have been performed corresponding to 1) a rate or counting measurement, 2) a shape only measurement, and 3) a combined rate and shape measurement. The

Table 1: Assumed systematice 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	$8\% \times 12\% = 1\%$	Assuming $\Delta E = 12\%\sqrt{E(GeV)}$

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

Quantity	Uncertainty (%)	Comment	Cross checks	
			Near site cross calibration*	^{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.

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.

ipar	name	value	error	constraint
1	dm2	0.2500E-02	0.1300E-03	0.1300E-03
2	sin2th	-0.1245E-11	0.4663E-02	none
3	dxsec	1.000	0.1162E-01	0.2000E-01
4	flat	1.000	0.1600	0.1600
5	li9	1.000	0.2000	0.2000
6	exp	1.000	0.2700	0.2700
7	he8	1.000	1.0000	1.000
8	dnear	1.000	0.1534E-02	0.2100E-02
9	dnear	1.000	0.1534E-02	0.2100E-02
10	dfar	1.000	0.1915E-02	0.2100E-02
11	dfar	1.000	0.1915E-02	0.2100E-02
12	dreactor	1.000	0.1820E-01	0.2000E-01
13	dreactor	1.000	0.1820E-01	0.2000E-01
14	escale_nea	0.4494E-14	0.5000E-02	0.5000E-02
15	escale_nea	0.4494E-14	0.5000E-02	0.5000E-02
16	escale_far	0.4597E-14	0.5000E-02	0.5000E-02
17	escale_far	0.4597E-14	0.5000E-02	0.5000E-02
18	esmear_err	0.6367E-10	0.9994	1.000
19	offse_near	0.1370E-13	0.2000E-01	0.2000E-01
20	offse_near	0.1370E-13	0.2000E-01	0.2000E-01
21	offset_far	0.1360E-13	0.2000E-01	0.2000E-01
22	offset_far	0.1360E-13	0.2000E-01	0.2000E-01

Rate Only Fit

Figure 1: Results from a "Rate Only" fit to the data from a three year data run.

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 shape measurement allows each detectors 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. Example results are given in Figures 1, 2, and 3 where the final error and external constrain is given in the third and fourth column respectively.

Sensitivity estimates are 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 4. With the nominal three year running 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 signal of neutrino oscillations.

The Braidwood sensitivity as a function of Δm^2 is shown in Figures 5, 6, and 7. As seen from the figures, the Braidwood experiment has good coverage for all of the expected Δm^2 region between 1.5 and 3.5×10^{-3} eV^2 with sensitivity at or below $\sin^2 2\theta_{13} = 0.01$.

The above fits have all used an observed event distribution corresponding to a null underlying oscillation scenario. In contrast, Figure 8 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

Shape Only Fit

ipar	name	value	error	constraint
1	dm2	0.2500E-02	0.1300E-03	0.1300E-03
2	sin2th	-0.4707E-11	0.8839E-02	none
3	dxsec	1.000	0.000	constant
4	flat	1.000	0.1623	0.1600
5	li9	1.000	0.1646	0.2000
6	exp	1.0000	0.2675	0.2700
7	he8	1.0000	0.9967	1.000
8	dnear	1.000	0.6974E-03	none
9	dnear	1.000	0.6974E-03	none
10	dfar	1.000	0.7736E-02	none
11	dfar	1.000	0.7736E-02	none
12	dreactor	1.000	0.000	constant
13	dreactor	1.000	0.000	constant
14	escale_nea	-0.4613E-11	0.4953E-02	0.5000E-02
15	escale_nea	-0.4613E-11	0.4953E-02	0.5000E-02
16	escale_far	-0.3348E-11	0.4998E-02	0.5000E-02
17	escale_far	-0.3348E-11	0.4998E-02	0.5000E-02
18	esmear_err	0.4216E-09	0.4927E-01	1.000
19	offse_near	-0.5930E-10	0.1617E-01	0.2000E-01
20	offse_near	-0.5930E-10	0.1617E-01	0.2000E-01
21	offset_far	-0.7712E-10	0.1982E-01	0.2000E-01
22	offset_far	-0.7712E-10	0.1982E-01	0.2000E-01

Figure 2: Results from a "Shape Only" fit to the data from a three year data run.

Combined Rate/Shape Fit

ipar	name	value	error	constraint
1	dm2	0.2500E-02	0.1300E-03	0.1300E-03
2	sin2th	-0.4707E-11	0.3869E-02	none
3	dxsec	1.000	0.1160E-01	0.2000E-01
4	flat	1.000	0.1603	0.1600
5	li9	1.000	0.1587	0.2000
6	exp	1.0000	0.2659	0.2700
7	he8	1.0000	0.9779	1.000
8	dnear	1.000	0.1503E-02	0.2100E-02
9	dnear	1.000	0.1503E-02	0.2100E-02
10	dfar	1.000	0.1887E-02	0.2100E-02
11	dfar	1.000	0.1887E-02	0.2100E-02
12	dreactor	1.000	0.1820E-01	0.2000E-01
13	dreactor	1.000	0.1820E-01	0.2000E-01
14	escale_nea	-0.4613E-11	0.4949E-02	0.5000E-02
15	escale_nea	-0.4613E-11	0.4949E-02	0.5000E-02
16	escale_far	-0.3348E-11	0.4998E-02	0.5000E-02
17	escale_far	-0.3348E-11	0.4998E-02	0.5000E-02
18	esmear_err	0.4216E-09	0.4916E-01	1.000
19	offse_near	-0.5930E-10	0.1572E-01	0.2000E-01
20	offse_near	-0.5930E-10	0.1572E-01	0.2000E-01
21	offset_far	-0.7712E-10	0.1982E-01	0.2000E-01
22	offset_far	-0.7712E-10	0.1982E-01	0.2000E-01

Figure 3: Results from a "Rate + Shape" fit to the data from a three year data run.

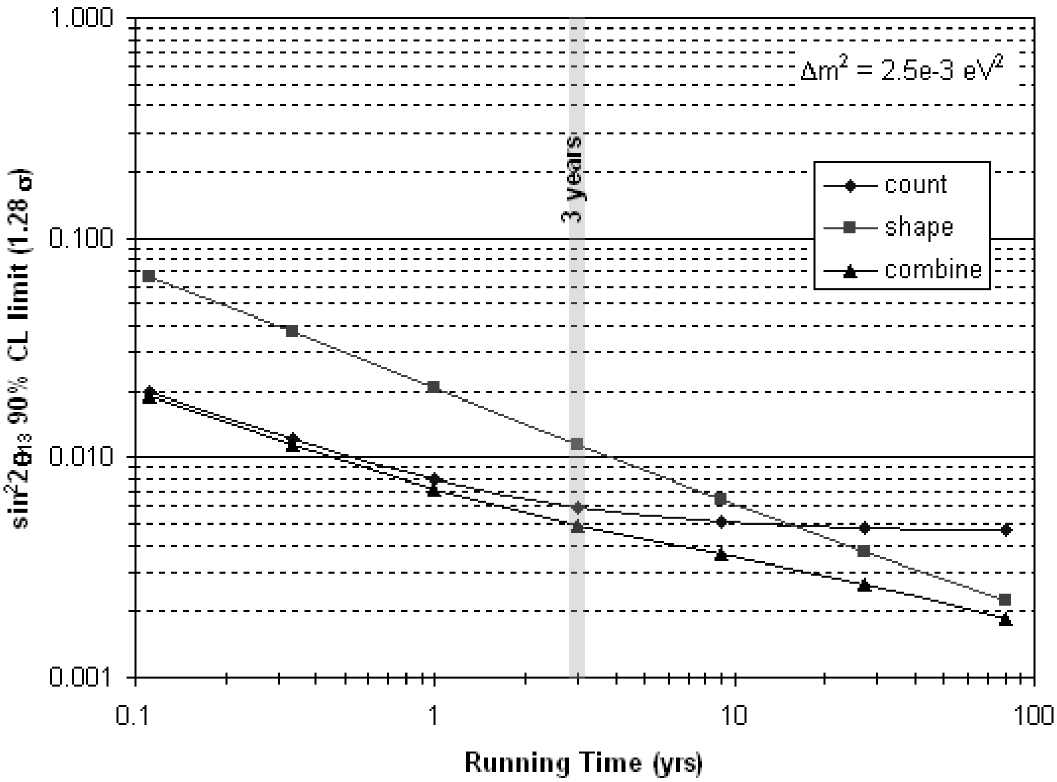

Figure 4: The 90% CL sensitivity of the Braidwood experiment versus the running time. The nominal data taking period is expected to be three years. The different types of fits are indicated by the markers on the line.

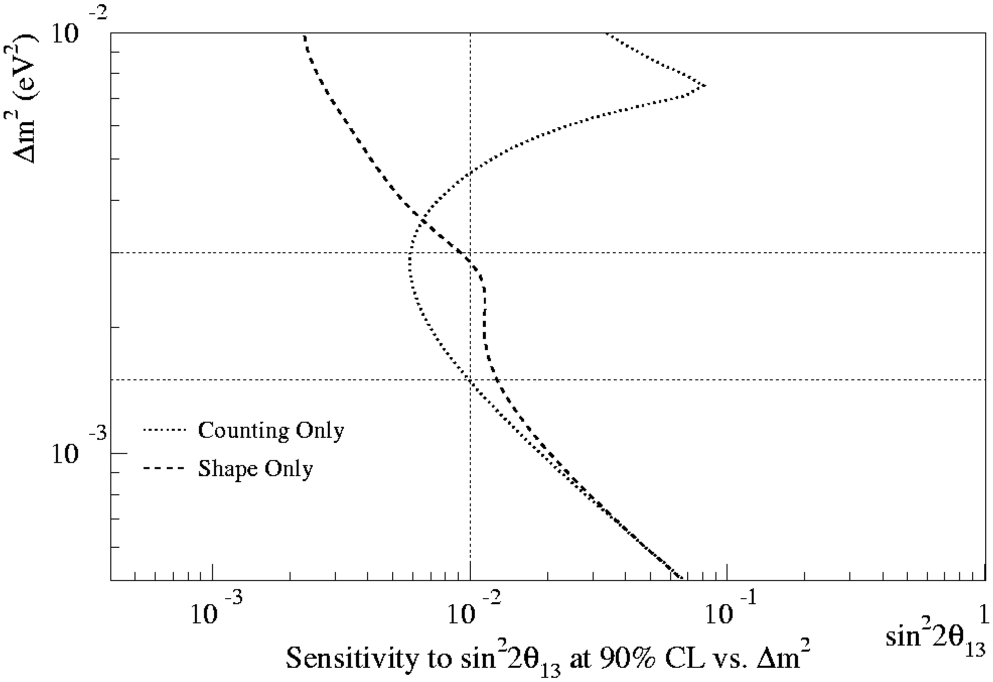

Figure 5: The 90% CL sensitivity for a "Rate Only" or "Shape Only" measurement using a three year data sample with the Braidwood experimental setup. The horizontal lines indicate the current 2σ limit on Δm^2 and vertical line marks the sensitivity goal of $\sin^2 2\theta_{13} = 0.01$.

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%.

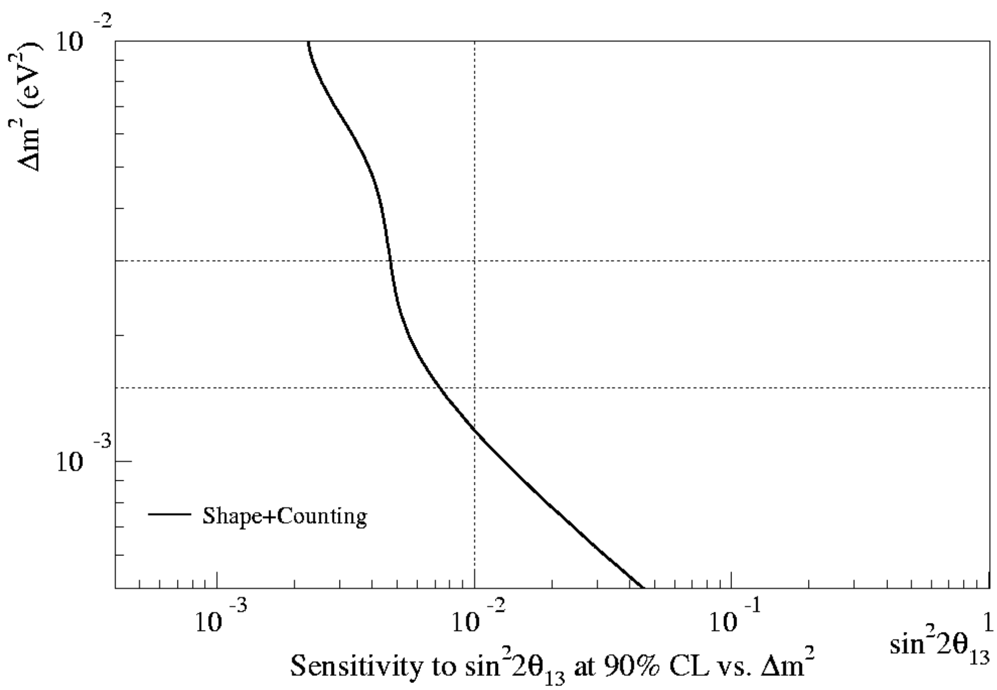

Figure 6: The 90% CL sensitivity for a "Rate Plus Shape" measurement using a three year data sample with the Braidwood experimental setup. The horizontal lines indicate the current 2σ limit on Δm^2 and vertical line marks the sensitivity goal of $\sin^2 2\theta_{13} = 0.01$.

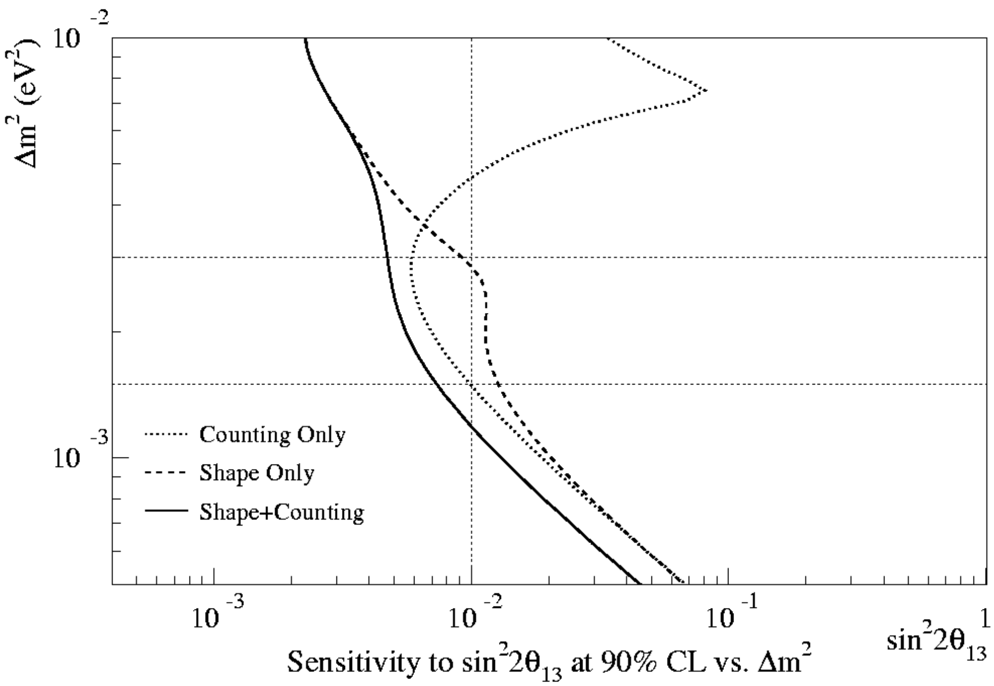

Figure 7: The 90% CL sensitivity for all three types of measurement using a three year data sample with the Braidwood experimental setup. The horizontal lines indicate the current 2σ limit on Δm^2 and vertical line marks the sensitivity goal of $\sin^2 2\theta_{13} = 0.01$.

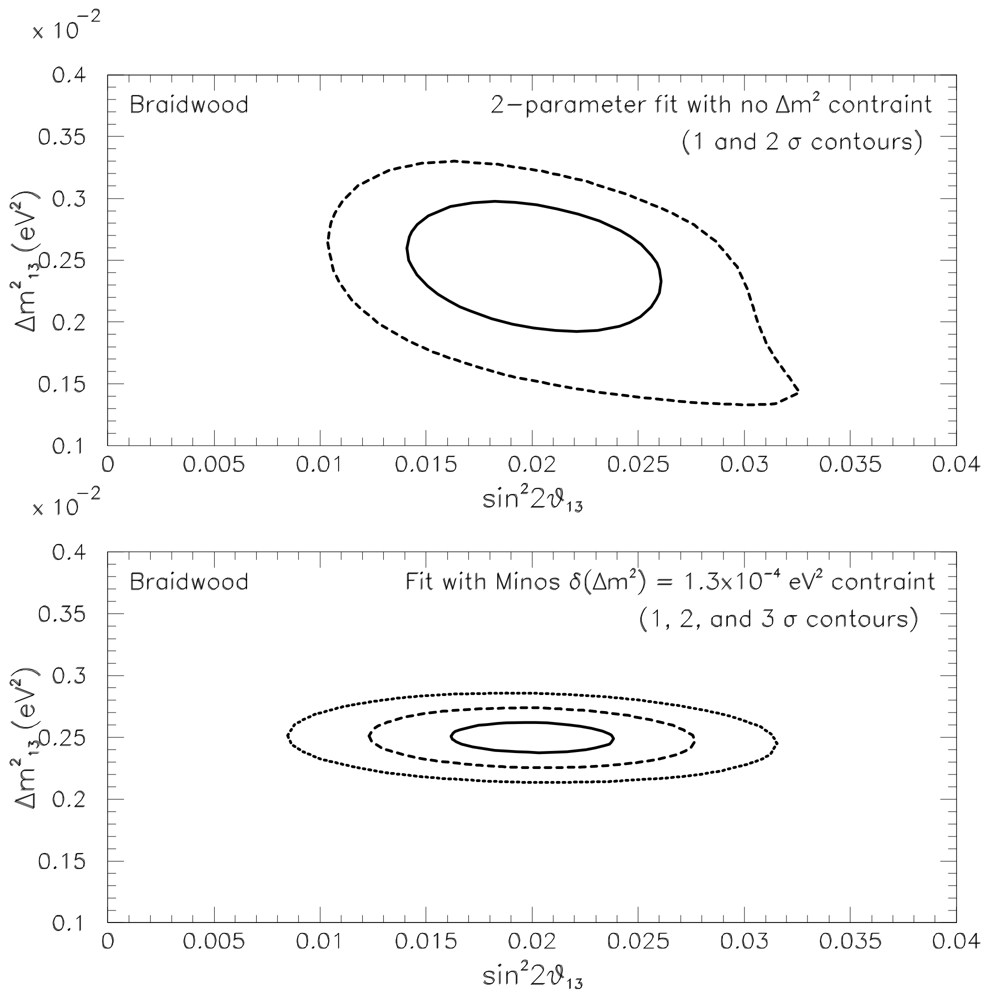

Figure 8: Combined rate and shape fit results for observed data with an oscillation signal corresponding to $\sin^2 2\theta_{13} = 0.02$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2. The top figure gives the one and two σ contours with no external constraints on Δm^2. The bottom figure shows the one, two, 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.