Comments on Sensitivities for Reactor Experiments and Combinations with Offaxis Measurements

M. Shaevitz

Feb. 8, 2003

- Investigate the sensitivity of various experimental setups
  - Use fitting program to the energy spectrum in multiple detectors
  - Determine $\sin^2 2\theta_{13}$ sensitivities
- Study generic multi-detector, multi-reactor setups
- Study actual setups from various proposed groups
- Investigations Δm^2 measurement capability
- Early results on reactor / off-axis combined sensitivities

Fitting Program

- Form χ^2 between "observed" and "predicted" event spectrum in energy bins. (100 0.1 MeV bins)

- Systematic uncertainties included through extra fit parameters that are constrained by assumed systematic error:
  - d^{xsec} = 2% xsec error
  - $d_k^{Reactor}$ = 2% reactor k power uncertainty
  - d^{Bkgnd} = 3.5 (14) % background uncertainty
  - d_j^{Near} = 0.23 (0.8) % relative error for near detector j
  - d_j^{Far} = 0.23 (0.8) % relative error for far detector j

$$\chi^2 = \sum_{i,j,k} \frac{(N_{i,j,k}^{ObsFar} - N_{i,j,k}^{Far}(1 - P_{i,j,k}^{OscFar})(1 + d^{xsec}) - N_{i,j}^{FarBkgnd}(1 - d^{Bkgnd}))^2}{N_{i,j,k}^{Far} + N_{i,j}^{FarBkgnd}}$$
$$+ \sum_{i,j,k} \frac{(N_{i,j,k}^{ObsNear} - N_{i,j,k}^{Near}(1 - P_{i,j,k}^{OscNear})(1 + d^{xsec}) - N_{i,j}^{NearBkgnd}(1 - d^{Bkgnd}))^2}{N_{i,j,k}^{Near} + N_{i,j}^{NearBkgnd}}$$
$$+ \left(\frac{d^{xsec}}{\delta_{xsec}}\right)^2 + \left(\frac{d^{Bkgnd}}{\delta_{Bkgnd}}\right)^2 + \sum_j \left(\frac{d_j^{Near}}{\delta_{eff}}\right)^2 + \sum_j \left(\frac{d_j^{Far}}{\delta_{eff}}\right)^2 + \sum_k \left(\frac{d_k^{Reactor}}{\delta_{power}}\right)^2$$

Common Parameters for Generic Studies

- Scenarios assume:
  - 3 years of data at 75% efficiency
  - Background rates are assumed to be the same in the near and far detector
    - May not be true but probably not a big effect
- Major Systematic errors
  - Relative near to far detector efficiency
    - 0.80% for identical detectors
    - 0.23% for identical detectors with capability to move far detector to near site for cross calibration
  - Syst. error on the background
    - Assume 3.5% for typical setup

Common Parameters for Runs

Reactor 1	$x = -150$ m $y = 0$ m 3.5 GW
Reactor 2	$x = 150$ m $y = 0$ m 3.5 GW
Near Det.	$x = 0$ m $y = 200$ m $z = -100$ m 50 tons 2,555,400 evnts
Data Event Eff. Far Det.'s	900 days 0.75 $z = -100$ m
Bkgnd Rate	0.2 evts/ton/day 9030 /50 tons / 900 days
Syst. xsec Syst. Power	0.02 0.02

Questions about scenarios

- What is the optimal baseline?
- How much does a moveable detector scenario help?
- Does a near and two far locations have better sensitivity?
- How well can Δm^2 be determined?

Results for Generic Studies

Far Det. 1 (50 tons)	Far Det. 2 (50 tons)	sys_bkgnd	sys_eff	No. of events N_{Far1}	N_{Far2}	$\sin^2 2\theta$ (90% CL) for Δm^2 (eV^2) 1×10^{-3}	2×10^{-3}	3×10^{-3}
1200 m	—	0.14	0.008	134,400	—	0.146	0.047	0.031
		0.035	0.008			0.110	0.038	0.027
		0.035	0.0023			0.054	0.017	0.011
(100 tons)		0.035	0.0023			0.036	0.012	0.008
1200 m	1800 m	0.14	0.008	134,400	65,440	0.090	0.033	0.025
		0.14	0.0023			0.061	0.021	0.014
		0.035	0.008			0.060	0.025	0.022
		0.035	0.0023			0.034	0.013	0.010
1200 m	2400 m	0.035	0.008	134,400	40,900	0.049	0.025	0.022
		0.035	0.0023			0.031	0.014	0.011
1200 m	3600 m	0.035	0.008	134,400	23,240	0.043	0.030	0.026
		0.035	0.0023			0.032	0.016	0.011
1500 m	—	0.035	0.008	89,907	—	0.081	0.032	0.027
		0.035	0.0023			0.044	0.016	0.012
(100 tons)		0.035	0.0023			0.029	0.011	0.009
1500 m	2000 m	0.035	0.008	89,907	54,807	0.052	0.024	0.021
		0.035	0.0023			0.031	0.012	0.010
1500 m	3000 m	0.035	0.008	89,907	29,465	0.043	0.025	0.025
		0.035	0.0023			0.029	0.014	0.012
1800 m	—	0.035	0.008	65,440		0.066	0.030	0.027
		0.035	0.0023			0.039	0.016	0.013
(100 tons)		0.035	0.0023			0.026	0.011	0.009
1800 m	2700 m	0.035	0.008	65,440	34,240	0.043	0.024	0.023
		0.035	0.0023			0.028	0.013	0.013

How well can Δm^2 be determined?

Far Det. 1 (50 tons)	Far Det. 2 (50 tons)	sys_eff	For $\Delta m^2 = 0.002$ eV^2 and $\sin^2 2\theta = 0.04$ $\delta(\Delta m^2)$ eV^2	$\delta(\sin^2 2\theta)$
1200 m	—	0.008	0.0014	0.034
(100 tons)		0.0023	0.0009	0.024
1200 m	1800 m	0.008	0.0005	0.012
		0.0023	0.0004	0.010
1200 m	2400 m	0.008	0.0003	0.011
1500 m	—	0.008	0.0008	0.017
(100 tons)		0.0023	0.0005	0.012
1500 m	2000 m	0.008	0.0004	0.011
1500 m	3000 m	0.008	0.0003	0.011
1800 m	—	0.008	0.0005	0.014
(100 tons)		0.0023	0.0004	0.008
1800 m	2400 m	0.008	0.0003	0.011
1800 m	3000 m	0.008	0.0003	0.011

- Current measurements are $\Delta m^2 = 0.002 \pm 0.0005$
- NuMI measurement expected to be:
  $\Delta m^2 = 0.002 \pm 0.0002$ for 7.4×10^{20} pot

Results for Proposed Sites

Reactors	Experiment (L_{Far} m)	Detectors	sys_eff (%)	No. of Events Near	Far (each)	Bkgnd	$\sin^2 2\theta$ (90% CL) for Δm^2 (eV^2) 1×10^{-3}	2×10^{-3}	3×10^{-3}
2× 3.6GW	**Braidwood (L_{near} = 200 m)**			(each)					
	(1800 m)	3 @ 25 ton	0.23	1.8M	34K	4.5K	0.031	0.013	0.011
	(1800 m)	5 @ 25 ton	0.23	1.8M	34K	4.5K	0.025	0.010	0.009
	(1800 m)	5 @ 25 ton	0.8	1.8M	34K	4.5K	0.037	0.016	0.015
	(1500 m)	5 @ 25 ton	0.23	1.8M	46K	4.5K	0.028	0.010	0.008
1× 3.6GW	**Wolf Creek (L_{near} = 250 m)**								
	(1500 m)	3 @ 25 ton	0.23	660K	25K	4.5K	0.051	0.019	0.014
	(1500 m)	5 @ 25 ton	0.23	660K	25K	4.5K	0.041	0.015	0.011
	(1500 m)	2 @ 100 ton	0.8	2.64M	100K	18K	0.054	0.022	0.017
2× 3.1GW	**Diablo Can. (L_{near} = 400 m)**								
	(1800 m)	3 @ 25 ton	0.8	507K	30K	4.5K	0.040	0.019	0.017
	(1800 m)	5 @ 25 ton	0.8	507K	30K	4.5K	0.036	0.018	0.015
2× 4.2GW	**CHOOZ II (L_{near} = 200 m)**								
	(1050 m)	2 @ 8.5 ton	0.8	750K	34K	352	0.124	0.038	0.025
7× 3.5GW	**Kashiwazaki (L_{near} = 325 m)**								
	(1300 m)	3 @ 8.5 ton	0.8	386K	49K	1.4K	0.056	0.022	0.018
	(1500 m)	2 @ 100 ton	0.8	2.64M	100K	18K	0.054	0.022	0.017
4× 2.9GW	**Daya Bay (L_{near} = 300 m)**								
	(1800 m)	6 @ 8.5 ton	0.8	285K	22K	1.5K	0.044	0.021	0.018
	(1800 m)	6 @ 8.5 ton	0.23	285K	22K	1.5K	0.032	0.014	0.012
	(1800 m)	12 @ 8.5 ton	0.8	285K	22K	1.5K	0.032	0.015	0.013
	(1800 m)	12 @ 8.5 ton	0.23	285K	22K	1.5K	0.024	0.010	0.009
1× 4.1GW	**Brazil (L_{near} = 325 m)**								
	(1350 m)	2 @ 50 ton	0.8	1M	68K	1K	0.065	0.024	0.019

Conclusions on Scenario Comparisons

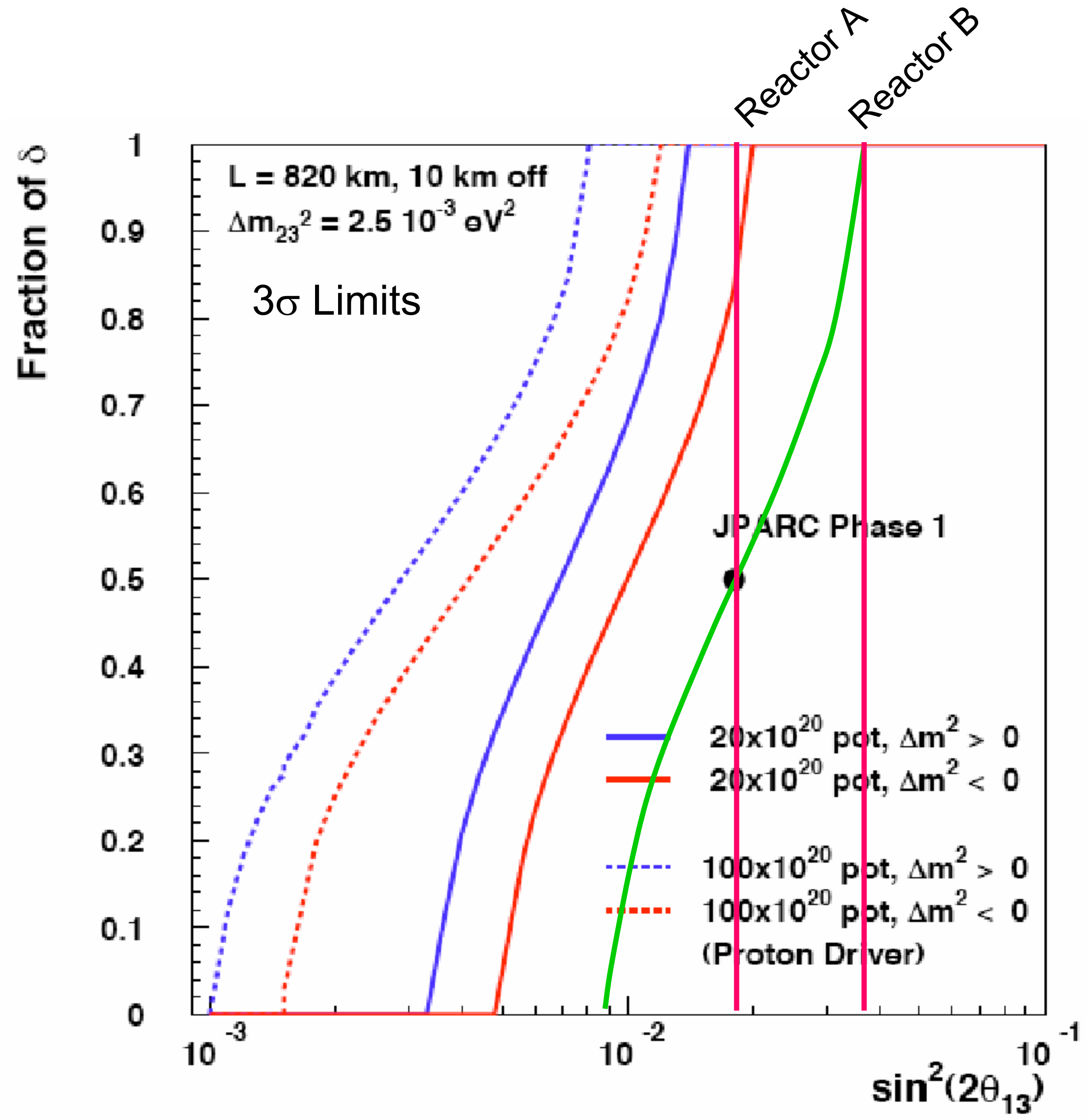
- Moveable detector gives about x2 better sensitivity
- For seeing oscillatory behavior (measuring Δm^2) , the multiple far location scenarios have only a slight advantage
  - Probably not competitive with NuMI and JHF-SK
  - But good confirmation to see oscillatory behavior
- Bottom line:

  Best sensitivity associated with one far location and multiple detectors that can be moved to the near site for cross calibration
- For next studies:
  - Reactor A ⇒ 90% CL sensitivity $\sin^2 2\theta_{13}$ = 0.01
  - Reactor B ⇒ 90% CL sensitivity $\sin^2 2\theta_{13}$ = 0.02

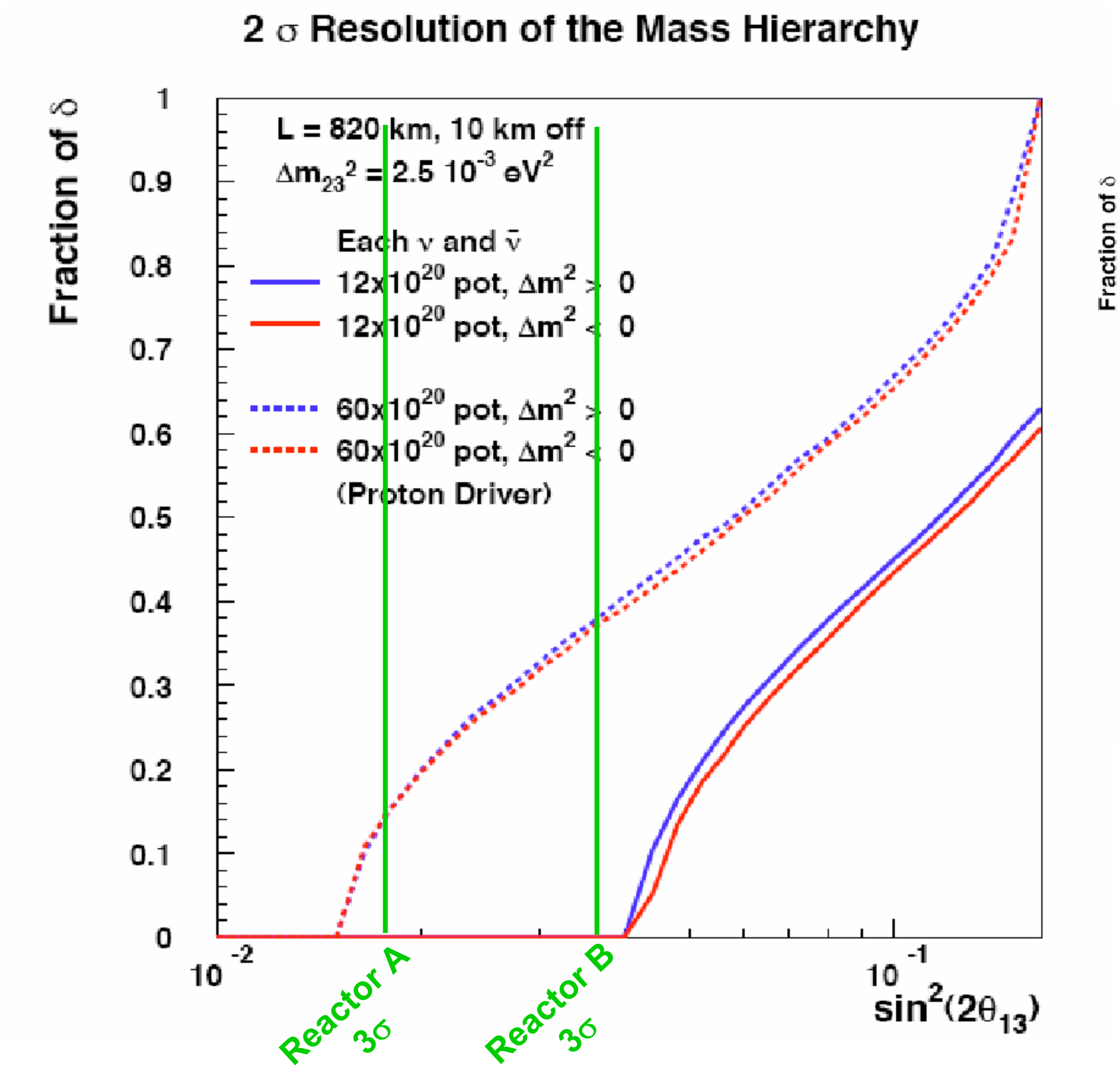
Studies for Comparing and Combining Reactor and Offaxis Measurements

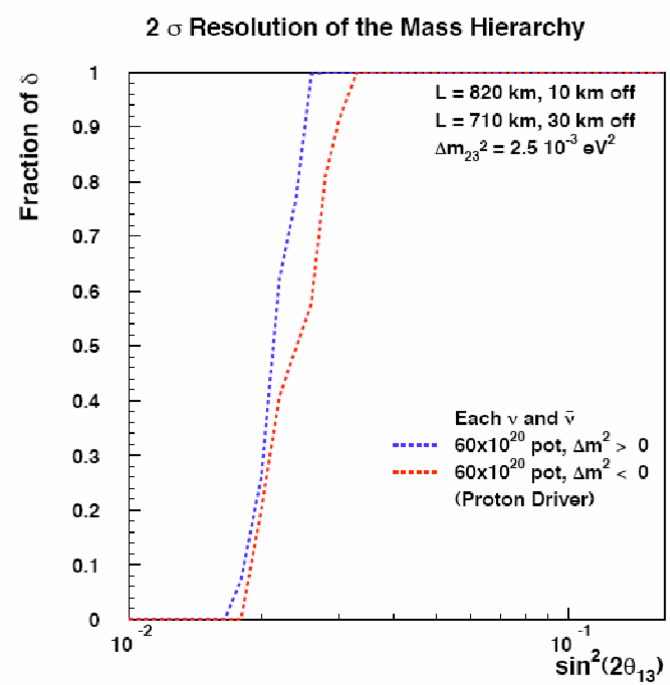
- Early stages of work
- Plan: Determine sensitivities to various physics parameters
  - Try combinations of various Offaxis data:
    - JHF Phase I (3yr ν and 3yr $\bar{\nu}$)
    - NuMI Phase 1 (3yr ν and 3yr $\bar{\nu}$)
    - Reactor measurement with
      - 90%CL = 0.01 $\Rightarrow \delta(\sin^2 2\theta_{13}) = 0.006$ ***(Reactor A)***
      - 90%CL = 0.02 $\Rightarrow \delta(\sin^2 2\theta_{13}) = 0.012$ ***(Reactor B)***
  - Include systematic physics uncertainties
    - $\sin^2 2\theta_{23}$ ambiguity
    - matter effect ambiguity
    - CP violation δ parameter variations
  - Include experimental setups and measurement errors
    - Try to use realistic estimates from the various proposals
    - Include 20% nu contamination in offaxis nubar running
  - Using oscillation code from Stephan Park

Question 1: What is $\sin^2 2\theta_{13}$?



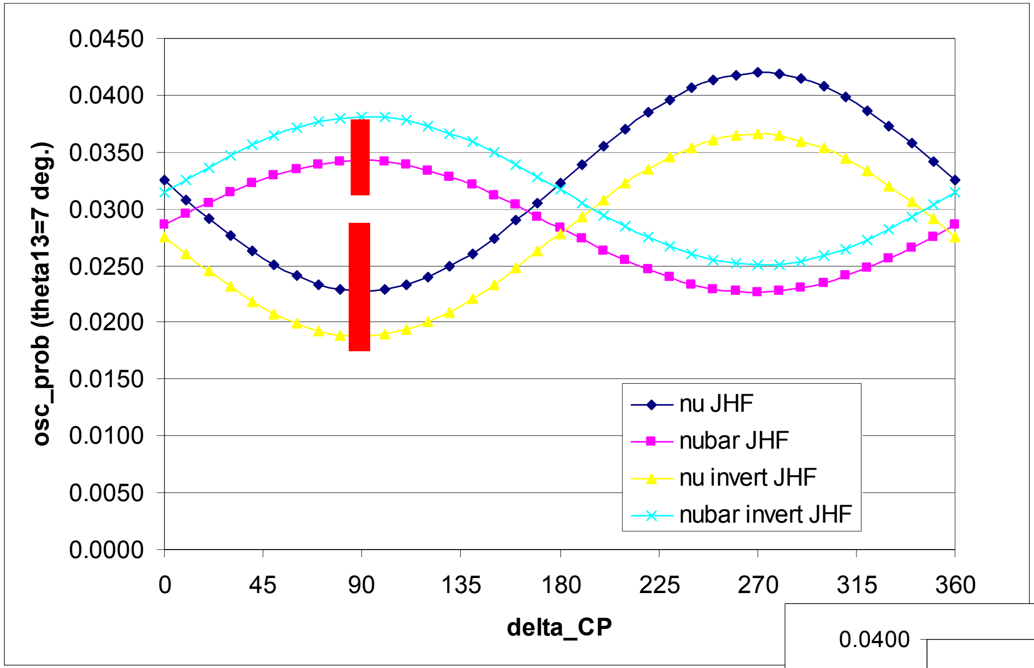
Question 2: What is the mass hierarchy?





Two! 50kt detectors and Proton Driver can do a better

Question 3: Is there CP Violation? ⇒ Measure δ

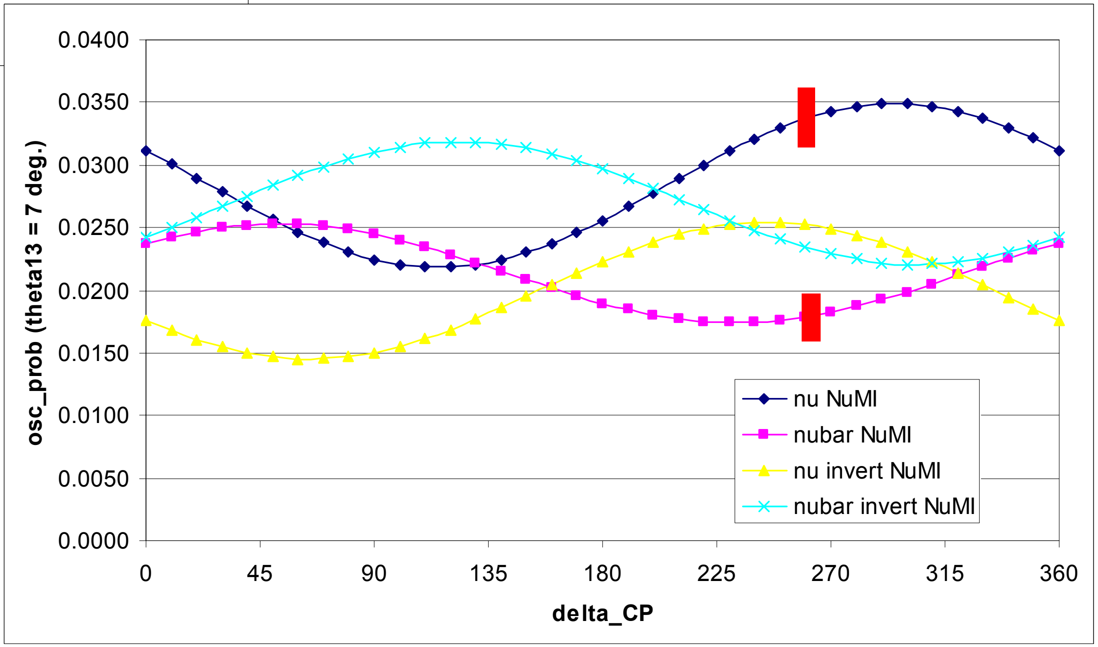


Offaxis Error Bar

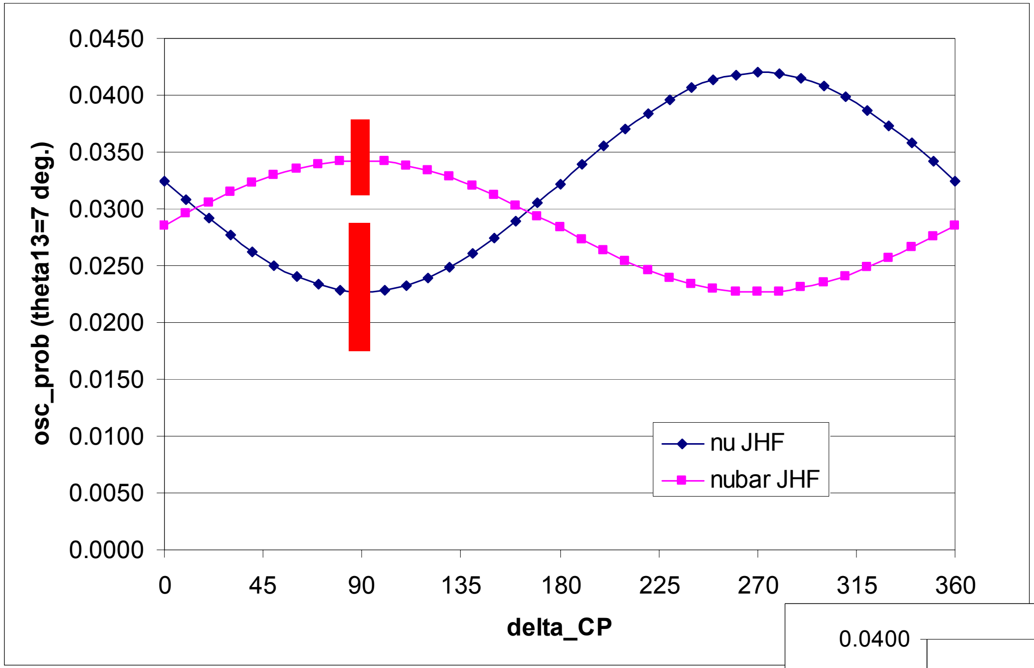
JHF
- No matter effects
- Clear CP variation

$\theta_{13} = 7°$ or $\sin^2 2\theta_{13} = 0.059$

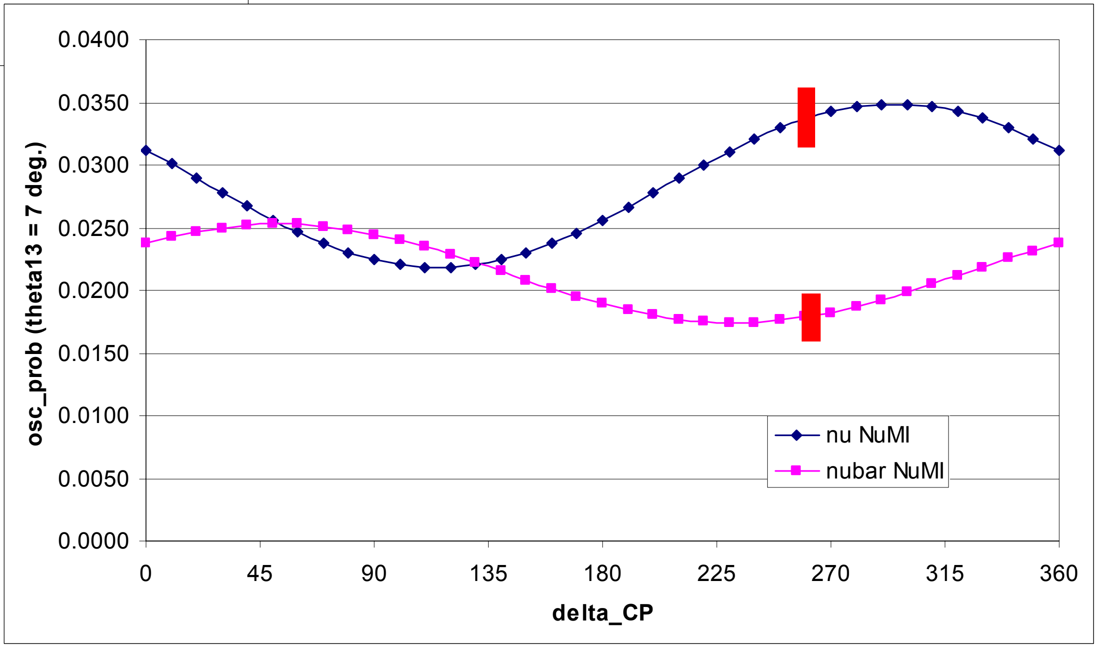
NuMI
- Large matter effects so sensitivity to mass hierarchy.
- Complications for disentangling the matter and CP



If only consider normal hierarchy, much easier



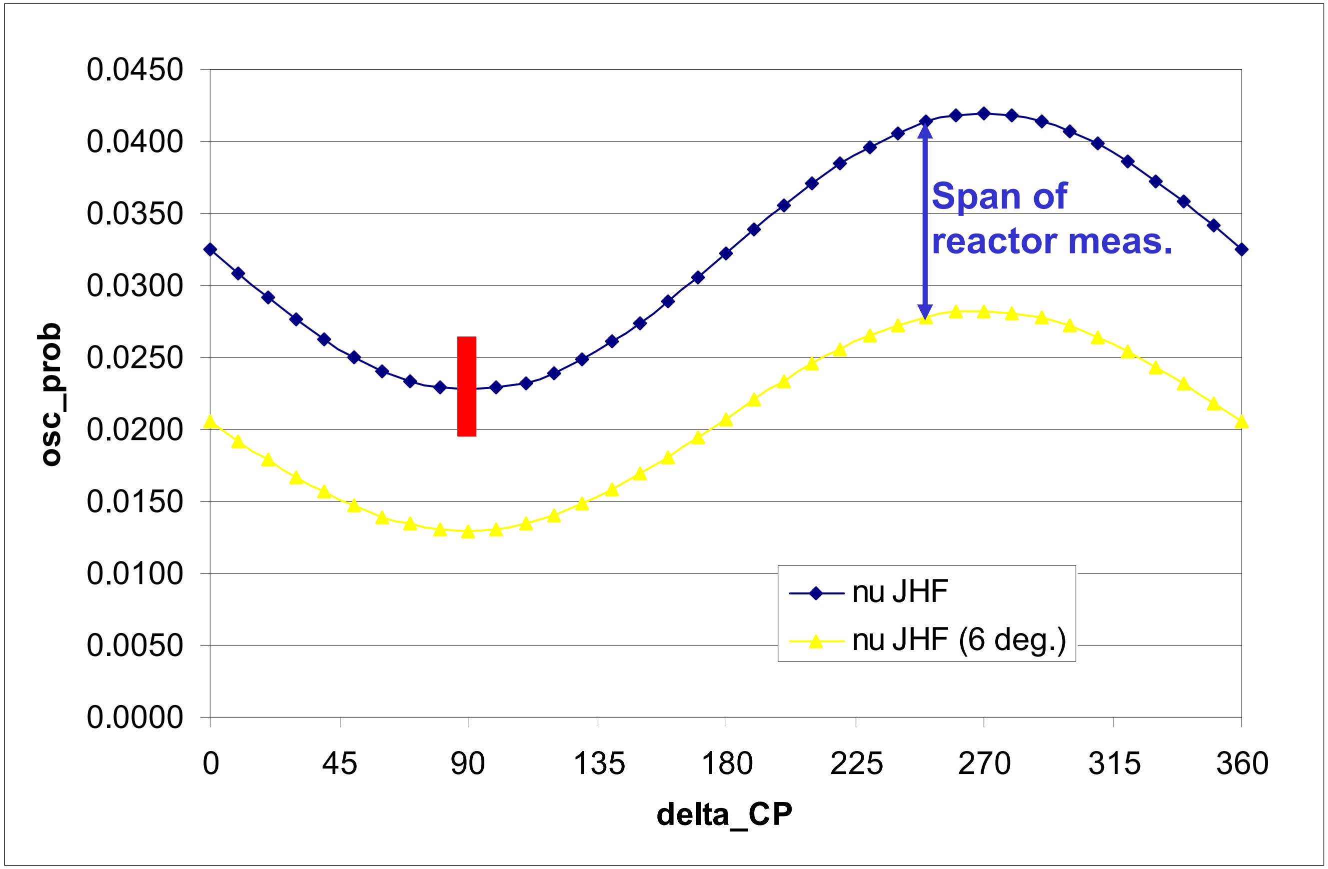
$\theta_{13} = 7°$ or $\sin^2 2\theta_{13} = 0.059$



Combining Reactor and Offaxis

-Combine JHF nu-only with

$\Rightarrow$ Reactor A $(\delta(\sin^2 2\theta_{13})_{90\%CL} = 0.006 \Rightarrow \theta_{13} = 7.0° \pm 0.5°)$



$\theta_{13} = 7.0° \pm 0.4°$ or $\sin^2 2\theta_{13} = 0.059$

Studies of Combining Offaxis and Reactor Results

- Program to do combined fits with reactor, JHF, NuMI offaxis results

- Scenarios: Compare with/without reactor measurement
  - Reactor + JHF (or NuMI offaxis) nu only
  - Reactor + JHF nu only + NuMI offaxis nu only
  - Reactor + JHF (or NuMI offaxis) nu + nubar
  - Reactor + JHF (nu + nubar) + NuMI offaxis (nu + nubar)

- Investigate the $\sin^2 2\theta_{23}$ ambiguity
  - Reactor data really helps here especially if $\sin^2 2\theta_{23} \neq 1$

Parameter Assumptions for Studies

Studies include:

- Uncertainties in $\sin^2 2\theta_{23}$
- 20% ν contamination in $\bar{\nu}$ running
- Only normal hierarchy for now

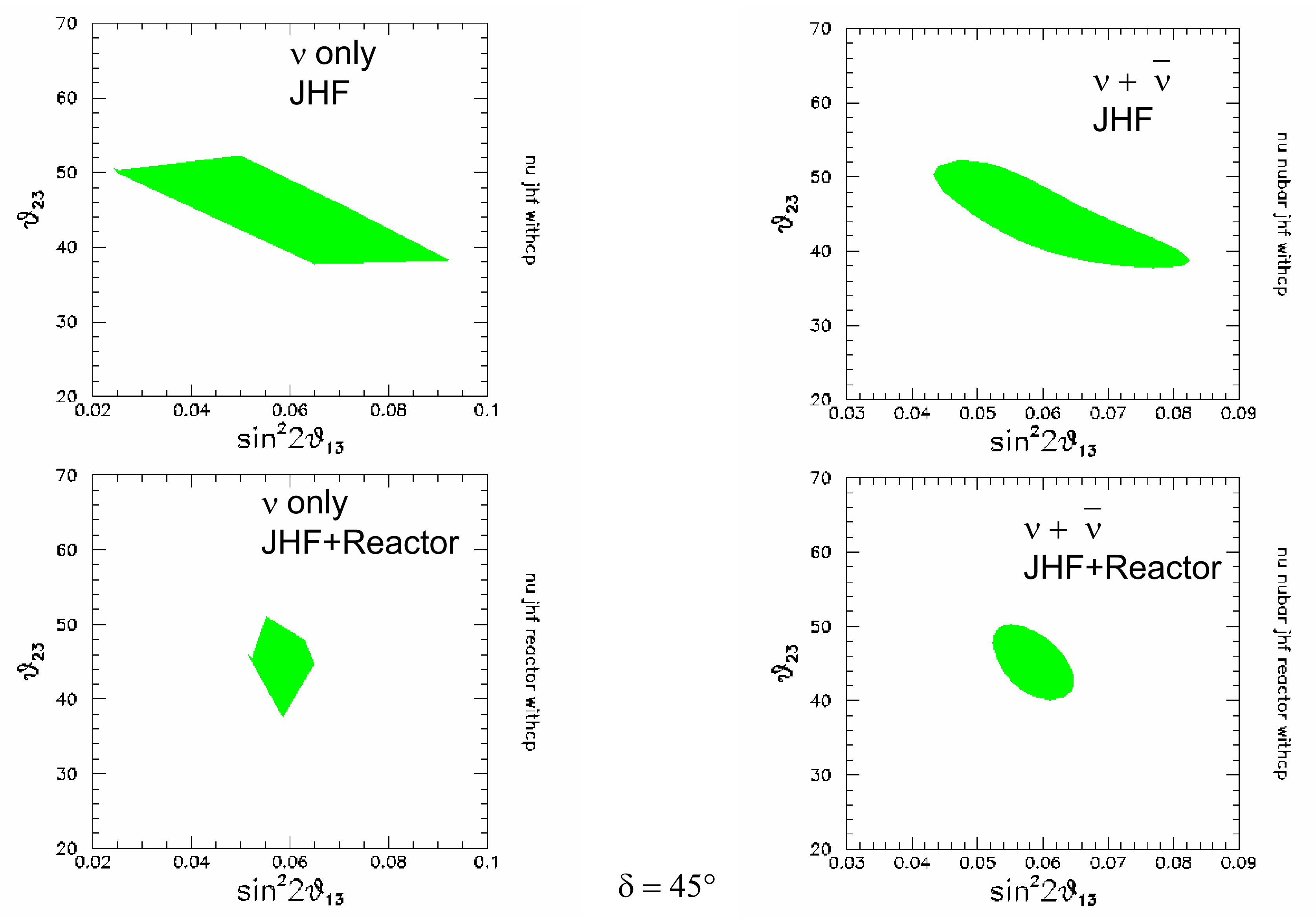
Parameter	Value
$\sin^2 2\theta_{13}$	0.058
$\sin^2 2\theta_{23}$	1 ± 0.06 ← NuMI 3yr
θ_{12}	30 deg.
δ_{CP}	45 or 270 deg.
Δm^2_{13}	2.5×10^{-3} eV^2
Δm^2_{12}	7.1×10^{-5} eV^2

Parameter	Value	
Reactor		Reactor A Scenario
E_ν	2.5 GeV	
L	1250 m	
δP_{osc}	0.006	
JHF-SK		JHF-SK 3yr ν 3yr $\bar{\nu}$
E_ν	0.6 GeV	
L	295 km	
δP^{ν}_{osc}	0.0033	
$\delta P^{\bar{\nu}}_{osc}$	0.0072	
NuMI-Offaxis		NuMI-Off. 3yr ν 3yr $\bar{\nu}$
E_ν	2.3 GeV	
L	820 km	
δP^{ν}_{osc}	0.0014	
$\delta P^{\bar{\nu}}_{osc}$	0.0029	

Results for Various Scenarios

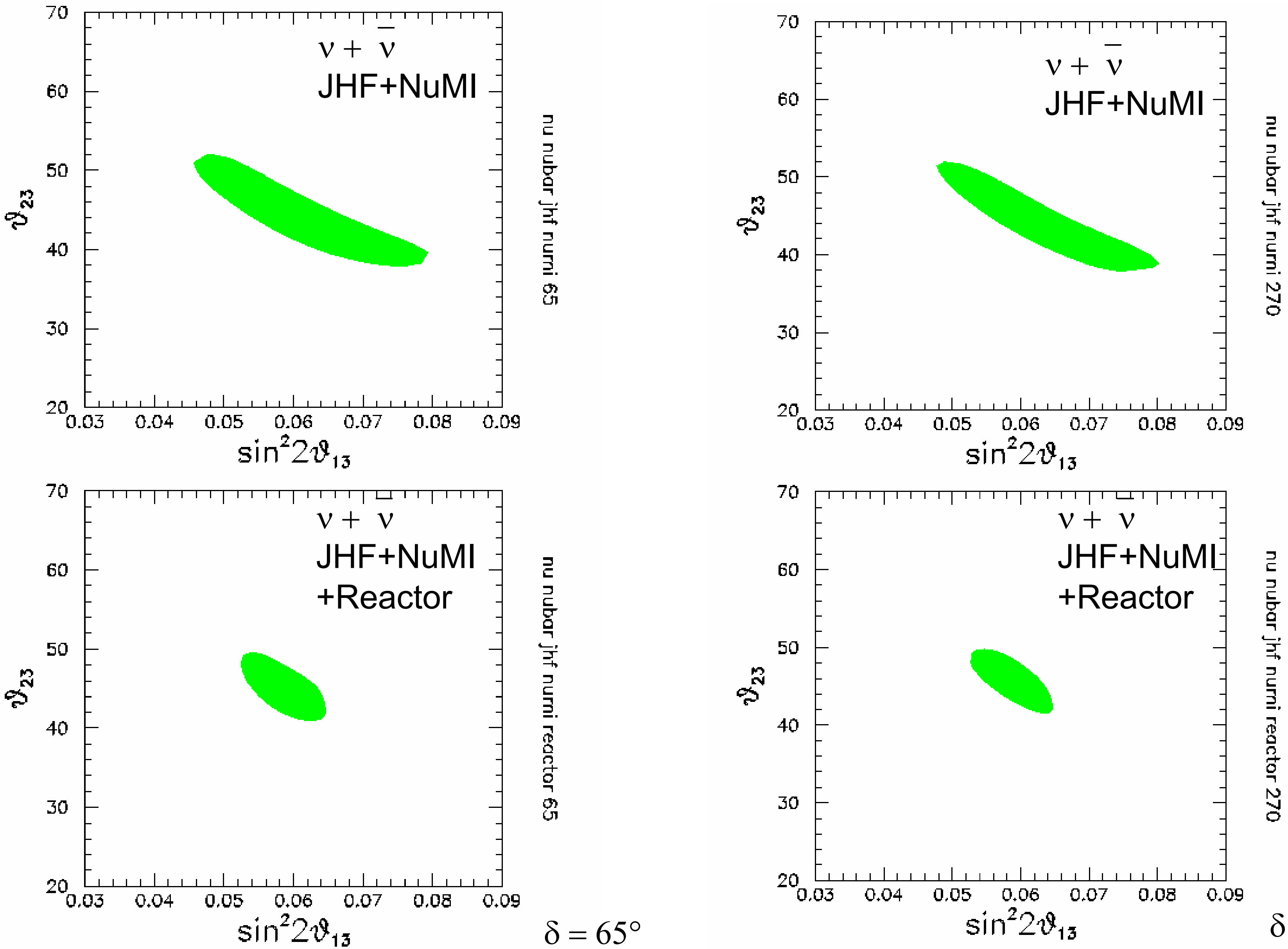
Experiments	$\delta(\theta_{23})$ deg	$\delta\left(\sin^2 2\theta_{13}\right)$	δ_{CP}(deg.)
ν_{JHF}	7	+0.023/-0.015	(*fixed*)
	7	±0.033	(*variable*)
ν_{JHF}+ Reactor A	4	±0.006	(*fixed*)
	6.5	±0.006	(*variable*)
$(\nu + \overline{\nu})_{JHF}$	7	+0.022/-0.014	(*fixed*)
No CP δ fit →	7	+0.024/-0.015	(*variable*)
$(\nu + \overline{\nu})_{JHF}$ + Reactor A	4	±0.006	(*fixed*)
	4	±0.006	45^{+125}_{-35}
ν_{NuMI} (norm. Δm^2)	7	+0.020/-0.012	(*fixed*)
	7	+0.036/-0.024	(*variable*)
$(\nu + \overline{\nu})_{JHF} + (\nu + \overline{\nu})_{NuMI}$	7	+0.019/-0.012	(*fixed*)
Problems with CP δ fit →	7	+0.050/-0.020	45^{+177}_{-50}
	7	+0.020/-0.010	270^{+40}_{-49}
$(\nu + \overline{\nu})_{JHF} + (\nu + \overline{\nu})_{NuMI}$ + Reactor A	4	±0.006	45^{+51}_{-23}
	4	±0.006	270^{+39}_{-46}

JHF (with / without Reactor)



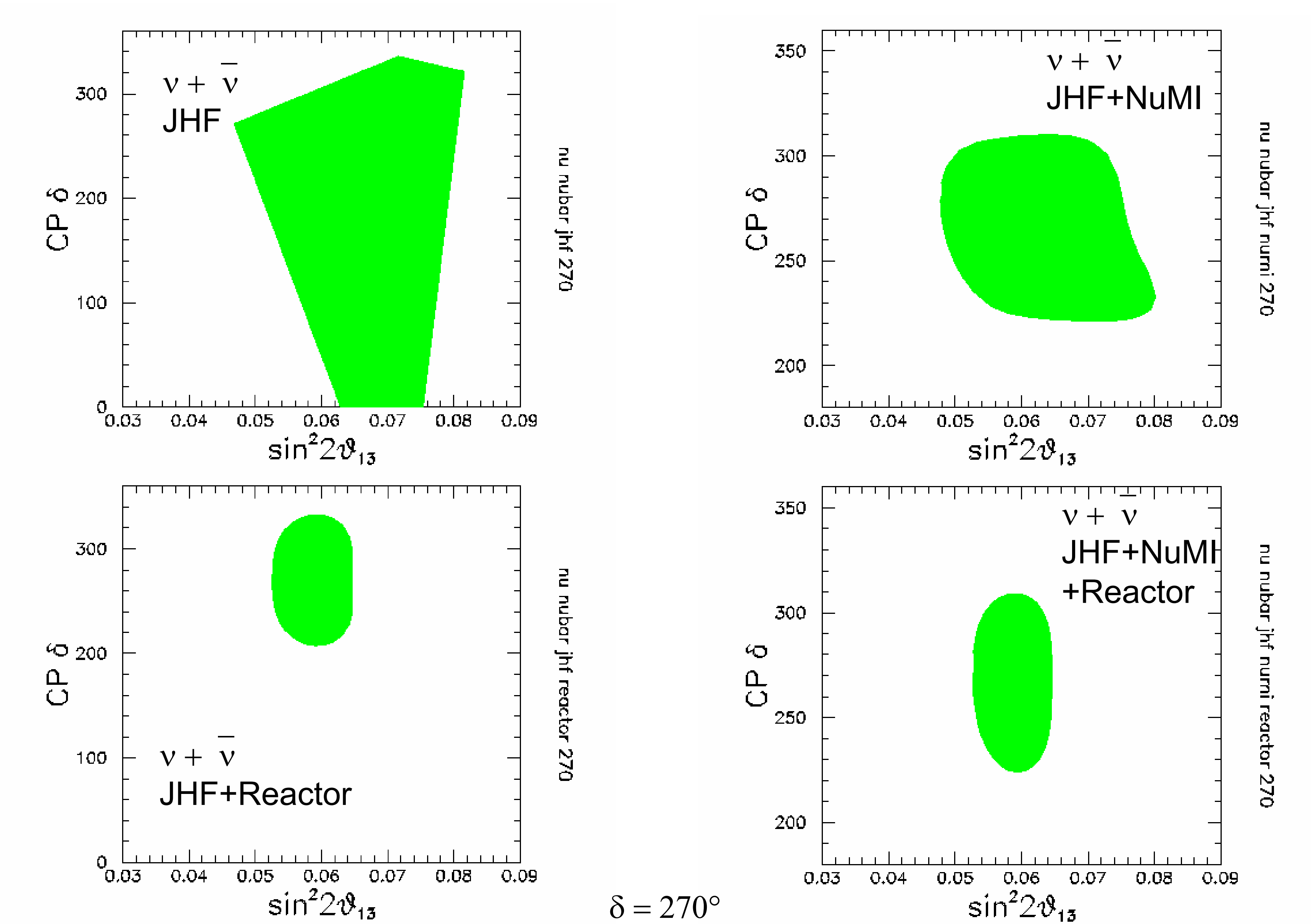
$\delta = 45°$

JHF+NuMI (with / without Reactor)



$\delta = 65°$ $\delta = 270°$

δ_{CP} Measurement (with / without Reactor)



$\delta = 270°$

Conclusions

- Reactor measurements of $\sin^2 2\theta_{13}$ sets the scale for pursuing CP violation and mass hierarchy.
  - If $\sin^2 2\theta_{13}$ is too small they will be out of reach for the offaxis experiments even with a proton driver
- Ambiguities associated with $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{23}$, mass hieracrchy, and δ make parameter measurements difficult with only offaxis measurements
  - CP violation measurements particularly difficult depending on value of δ
- Adding a reactor measurement makes a significant improvement in extracting the physics parameters
  - For some values of δ, one only has sensitivity for a combination of reactor and offaxis measurements.