Comparisons and Combinations of Oscillation Experiments

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- Try to make quantitative estimates of measurement capabilities for physics parameters
  - Input Assumptions
  - Determination of θ_{13}
  - Constraining CP Violation Parameters
  - Examples of possible measurements and comparisons

Input Assumptions for Study

- Oscillation parameters estimates

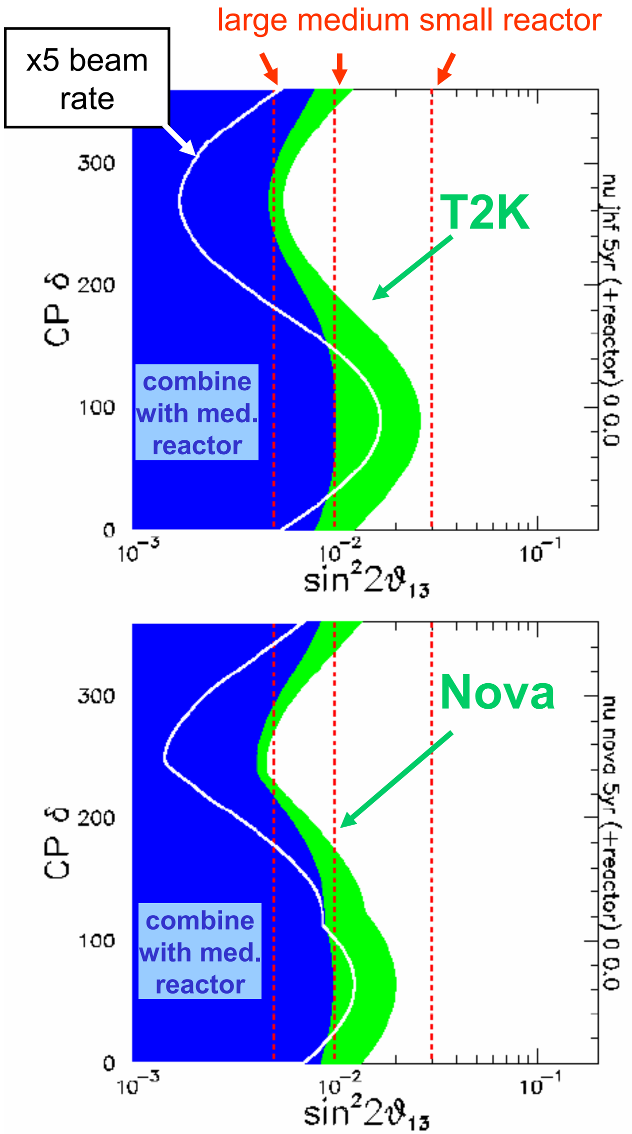
Parameter	Value	Current σ	Future σ
$\sin^2 2\theta_{23}$	1.0	0.06 (SuperK)	0.01 (T2K)
$\Delta m^2_{23}(\mathrm{eV}^2)$	2.5×10^{-3}	0.33×10^{-3} (SuperK)	0.05×10^{-3} (T2K)
$\theta_{12}(\mathrm{deg})$	30	–	–
$\Delta m^2_{12}(\mathrm{eV}^2)$	7.1×10^{-5}	–	–

- Estimates of uncertainties for future θ_{13} reactor and long-baseline exps.

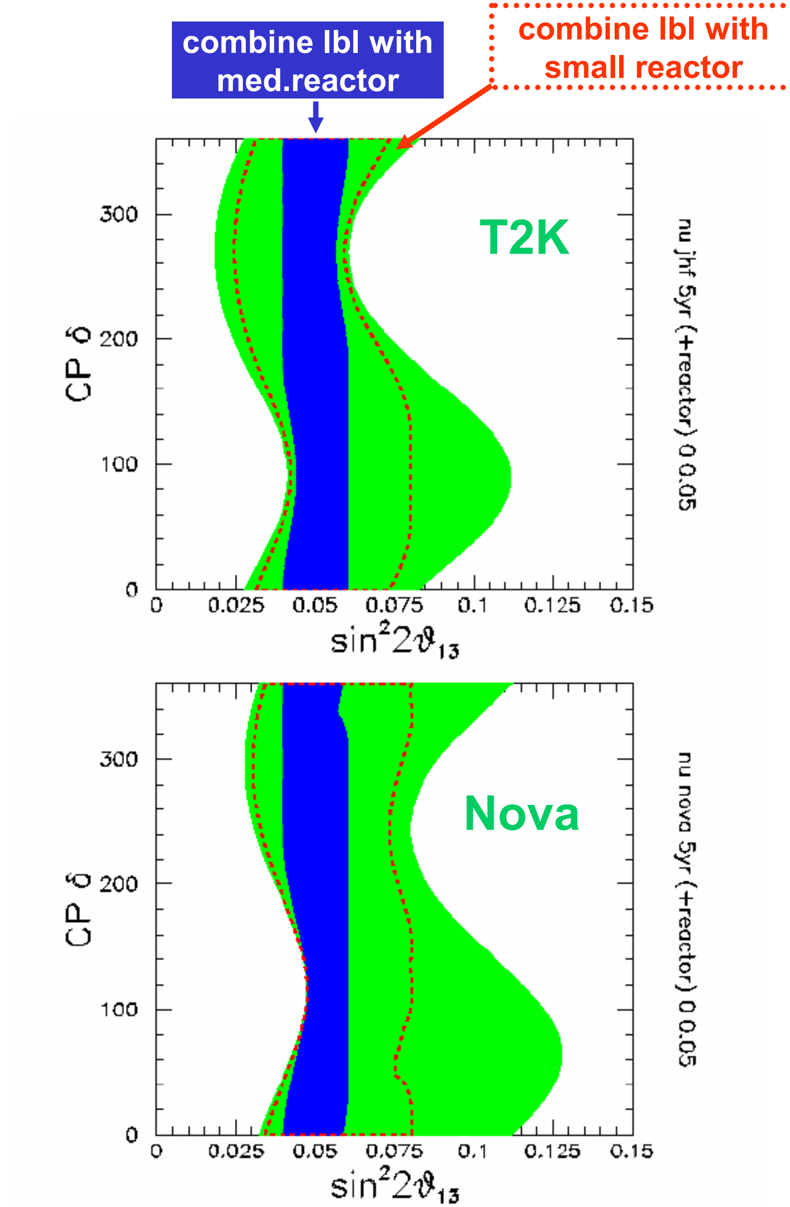
Experiment		Basis of Estimate	Osc. Prob. and σ for $\sin^2 2\theta_{13} =$ 0.02	0.05	0.10
Reactor ($E_\nu = 3.6$ MeV)		$\sin^2 2\theta_{13}^{Limit}$			
	$\langle L \rangle$	@ $\Delta m^2_{23} = 2.5 \times 10^{-3}\mathrm{eV}^2$			
Small	1.05 km	$0.03@90\%CL$	0.013 ± 0.018	0.032 ± 0.018	0.064 ± 0.018
Medium	1.8 km	$0.01@90\%CL$	0.020 ± 0.006	0.050 ± 0.006	0.100 ± 0.006
Large	1.8 km	$0.005@90\%CL$	0.020 ± 0.003	0.050 ± 0.003	0.100 ± 0.003
T2K ($E_\nu = 600$ MeV)		N^{5yrs}_{events}: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$			
$\langle L \rangle = 295$ km		@ $\Delta m^2_{23} = 2.5 \times 10^{-3}\mathrm{eV}^2$			
ν		102 signal / 24.9 bkgnd	0.011 ± 0.003	0.026 ± 0.004	0.051 ± 0.005
$\overline{\nu}$		38.5 signal / 14.4 bkgnd	0.009 ± 0.006	0.022 ± 0.007	0.044 ± 0.009
Nova ($E_\nu = 2.3$ GeV)		N^{5yrs}_{events}: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$			
$\langle L \rangle = 810$ km		@ $\Delta m^2_{23} = 2.5 \times 10^{-3}\mathrm{eV}^2$			
ν		175.2 signal / 38.1 bkgnd	0.011 ± 0.002	0.025 ± 0.003	0.048 ± 0.003
$\overline{\nu}$		66 signal / 22 bkgnd	0.008 ± 0.003	0.018 ± 0.004	0.034 ± 0.005

Determination of θ_{13}

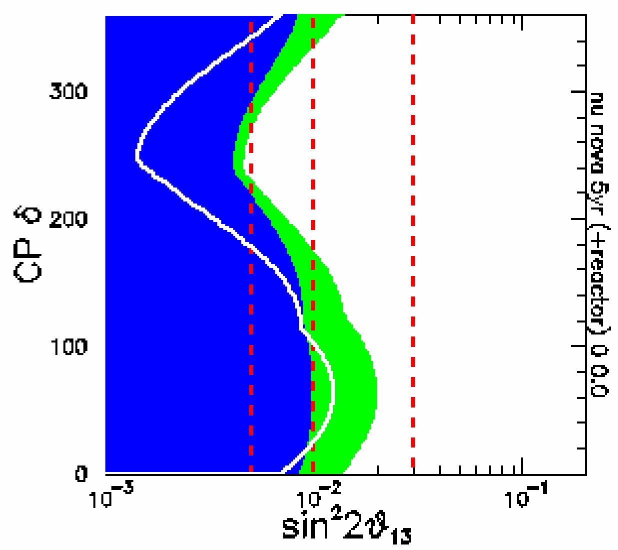
- 90% CL upper limits for underlying $\sin^2 2\theta_{13} = 0.0$



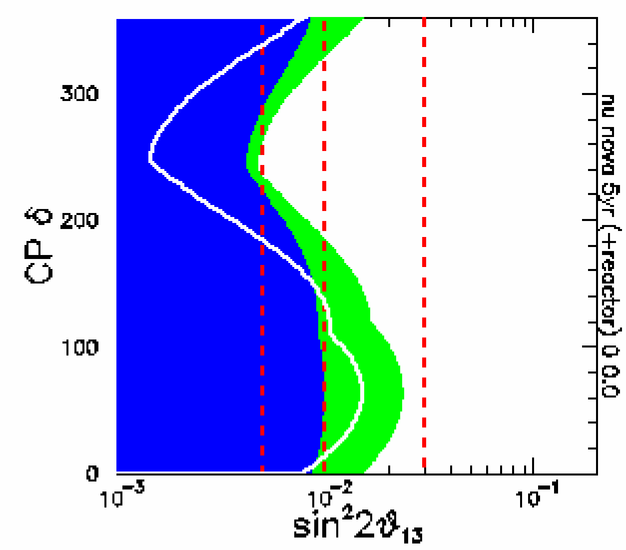
- 90%CL regions for $\sin^2 2\theta_{13} = 0.05$, $\delta_{CP} = 0$ and $\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2



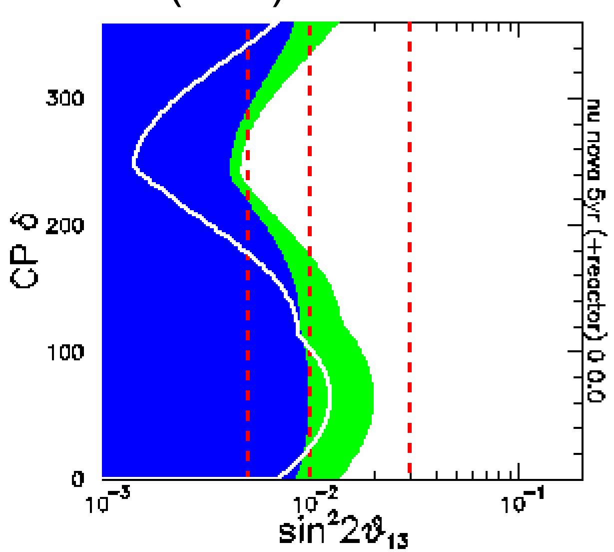
$\delta(\sin^2 2\theta_{23}) = 0.01$
$\delta(\Delta m^2) = 0.0$



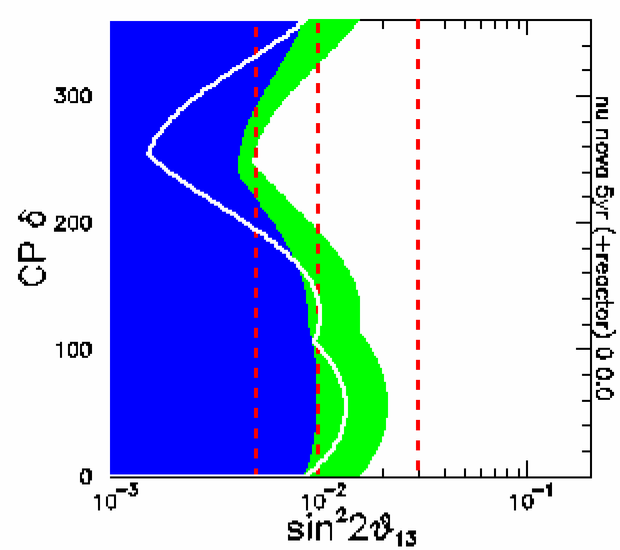
$\delta(\sin^2 2\theta_{23}) = 0.06$
$\delta(\Delta m^2) = 0.0$



$\delta(\sin^2 2\theta_{23}) = 0.01$
$\delta(\Delta m^2) = 0.5 \times 10^{-4}\ eV^2$



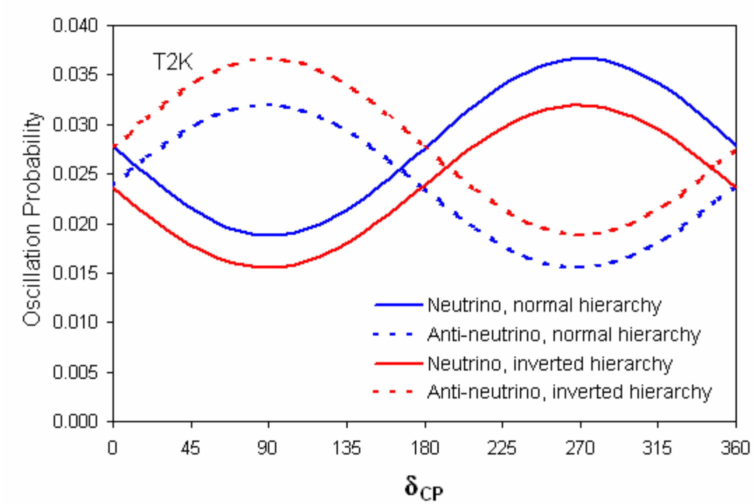
$\delta(\sin^2 2\theta_{23}) = 0.01$
$\delta(\Delta m^2) = 3.3 \times 10^{-4}\ eV^2$

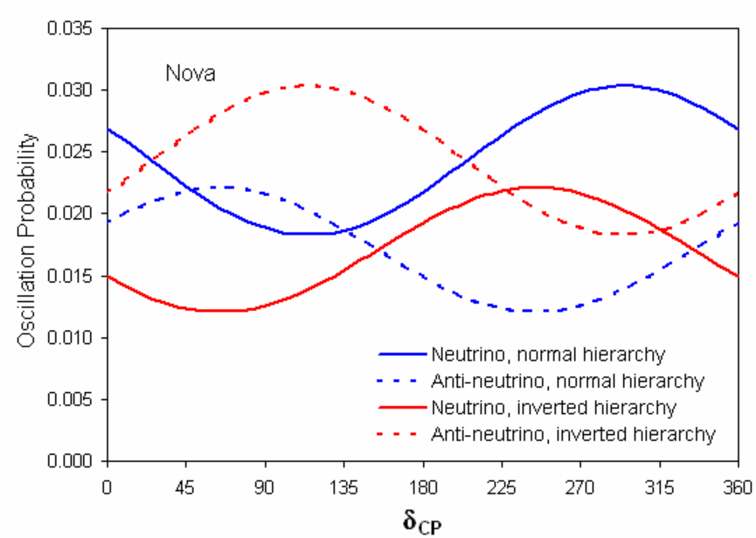


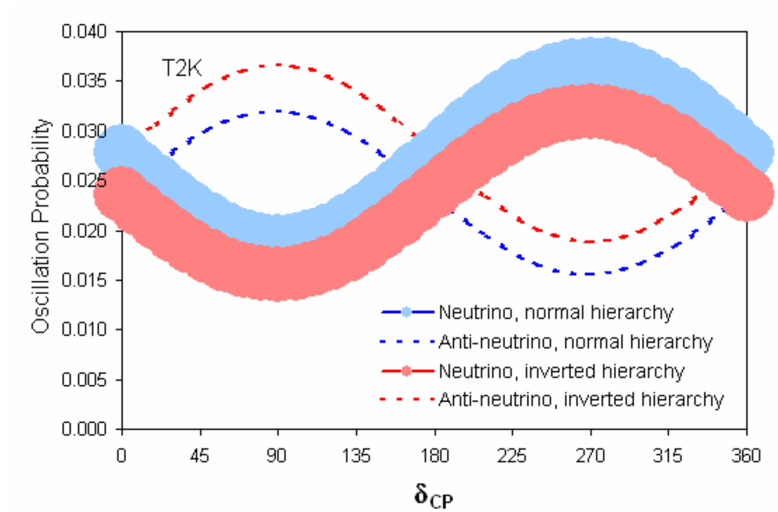
Contraining CP Violation Parameter, δ_{CP}

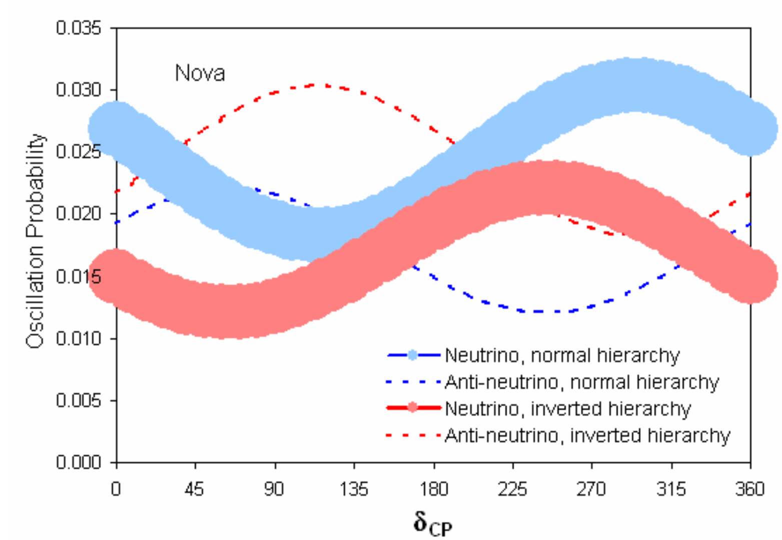
- Oscillation probability vs δ_{CP} ($\Delta m^2 = 2.5\mathrm{x}10^{-3}$ eV^2 , $\sin^2 2\theta_{13} = 0.05$)

- Use Medium Reactor to predict the neutrino prob.
  - $\Rightarrow$ Sensitivity to δ_{CP} and mass hierarchy
  - $\Rightarrow$ Not very good for this small $\sin^2 2\theta_{13} = 0.05$

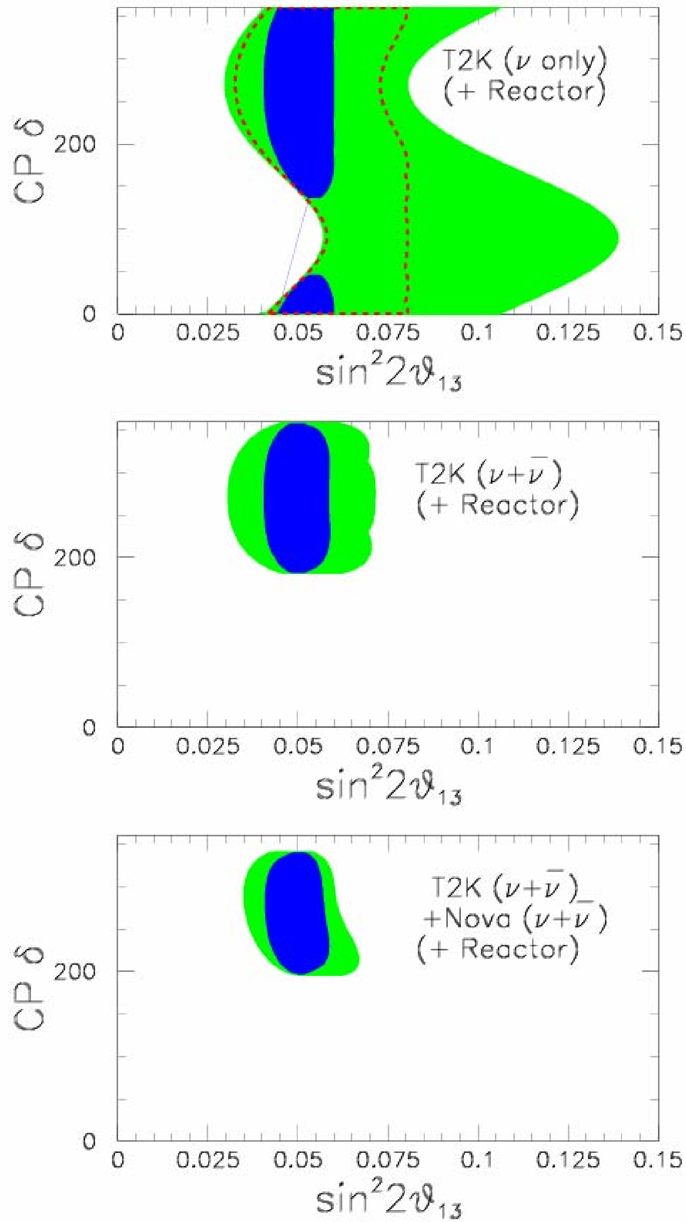








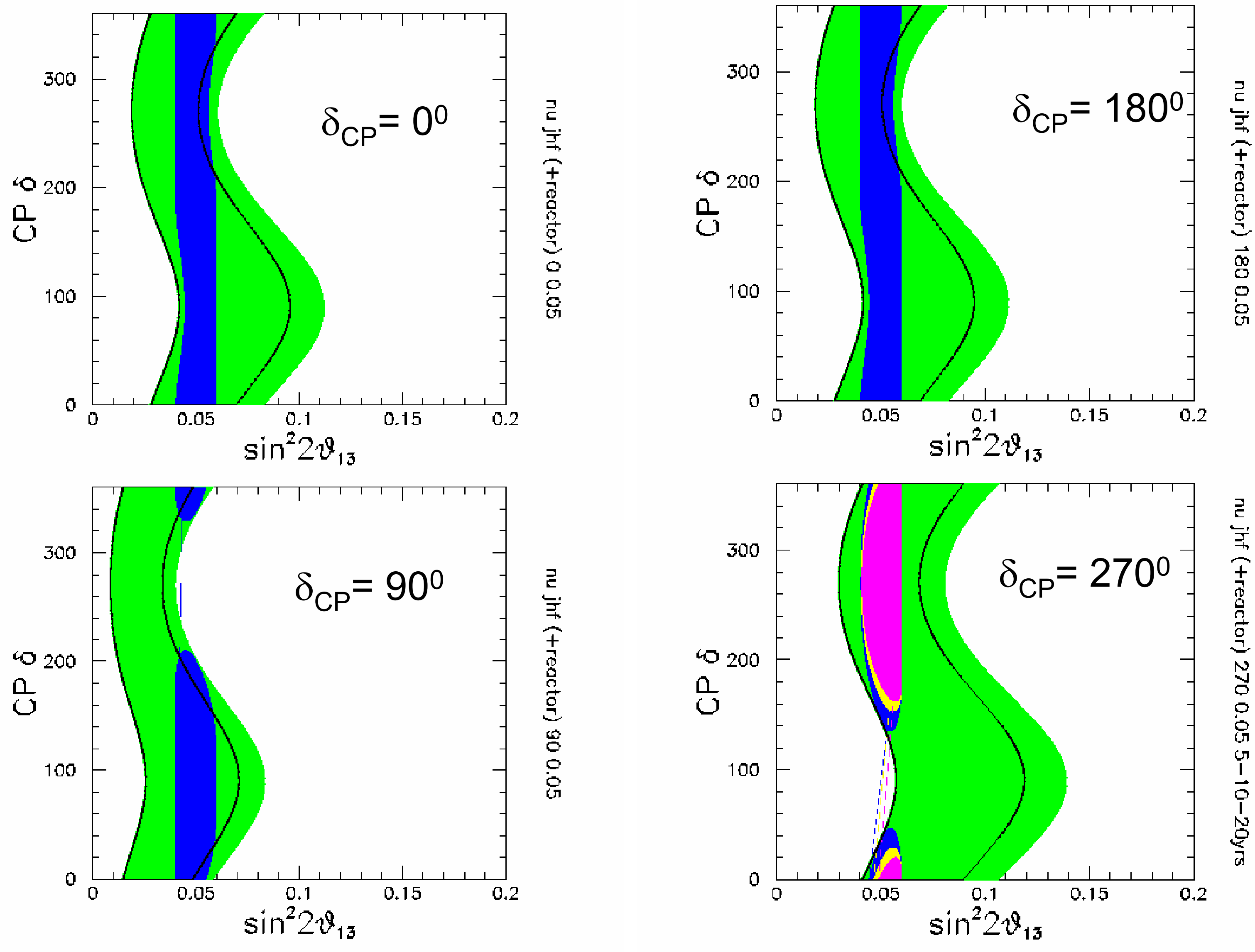
Combined Fits for $\delta_{CP} = 270^0$



90% CL Regions
$\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2
$\sin^2 2\theta_{13} = 0.05$
$\delta_{CP} = 270^0$
Green Region: LBL only
Blue Region: with reactor

- For ν-only data plus reactor, one can constrain allowed values slightly
- Combinations of ν and $\bar{\nu}$ is much more constraining
- In all cases, reactor experiments gives the best measurement of $\sin^2 2\theta_{13}$

90% CL regions for JHF ν-only(5yr) (+reactor)



In all cases, reactor determines value of $\sin^2 2\theta_{13}$

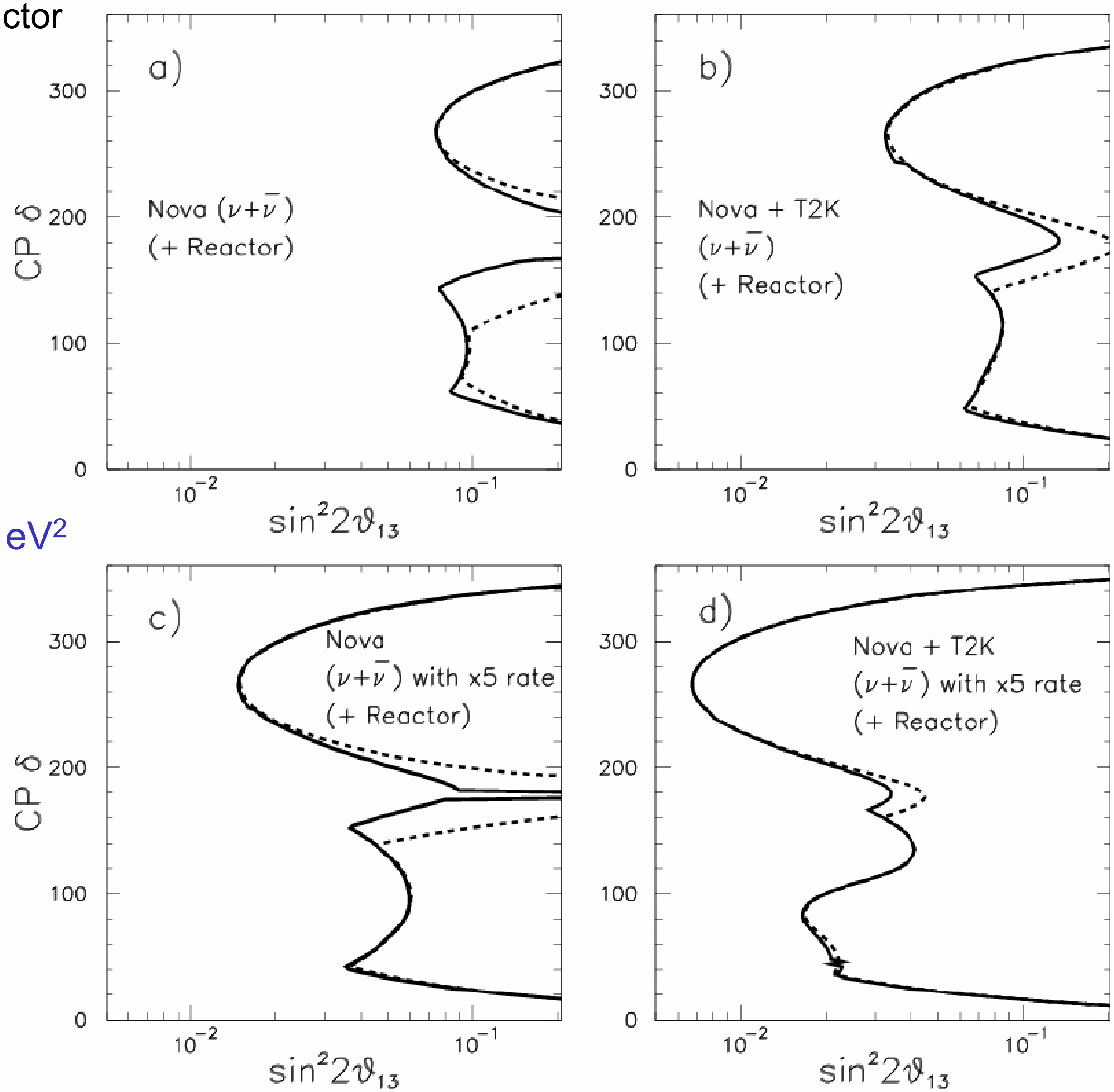
Two Sigma δ_{CP}=0 Excluded Regions

Dashed – without Reactor

Solid – with Reactor

Given a point to the right of the curves, δ_{CP}=0 is excluded by at least two sigma

$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$

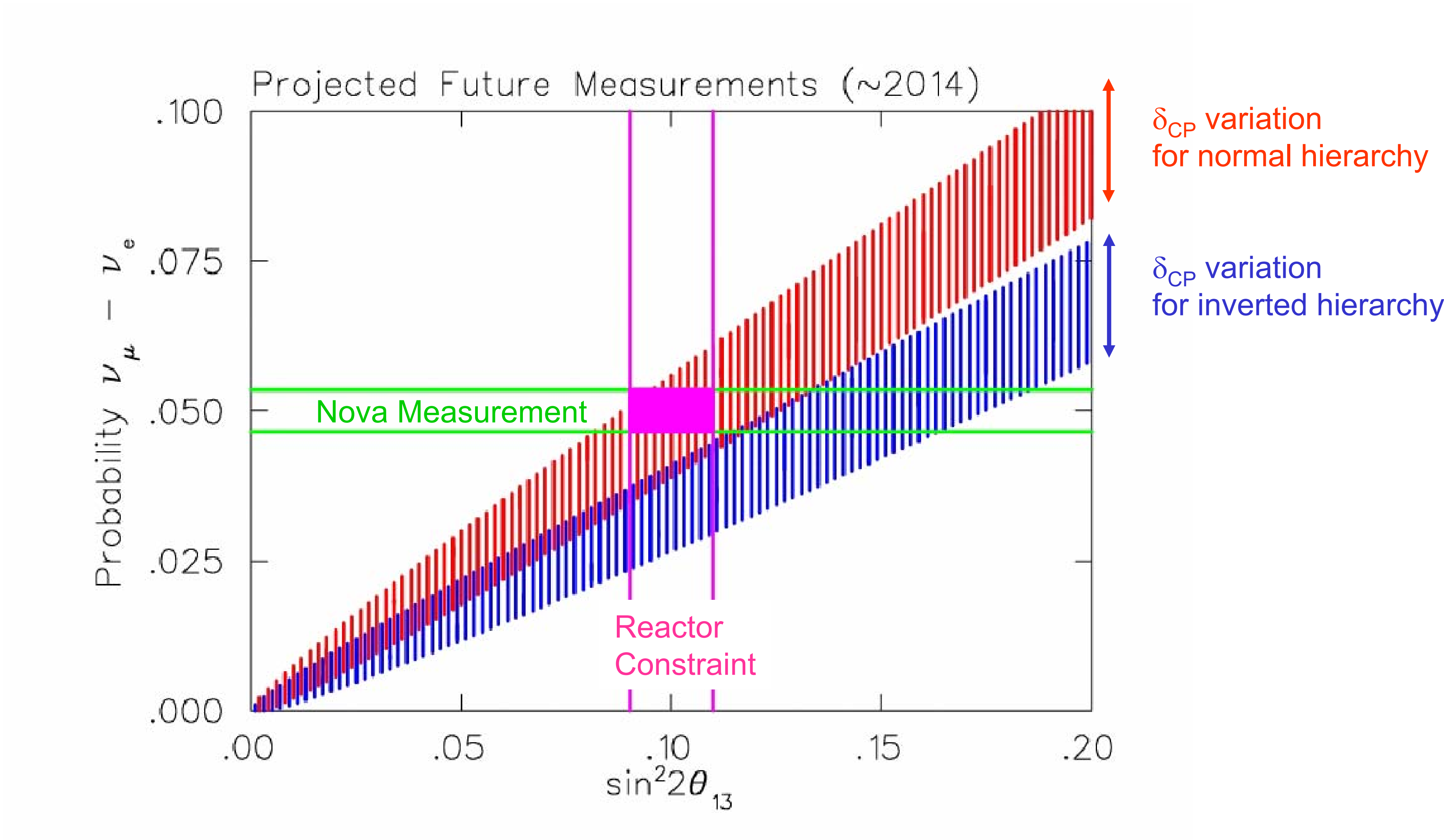


Nominal Beam Rates

x5 Nominal Beam Rates

Determination of the Mass Hierarchy

- Combining Nova ν-only plus reactor to get a first look at mass hierarchy

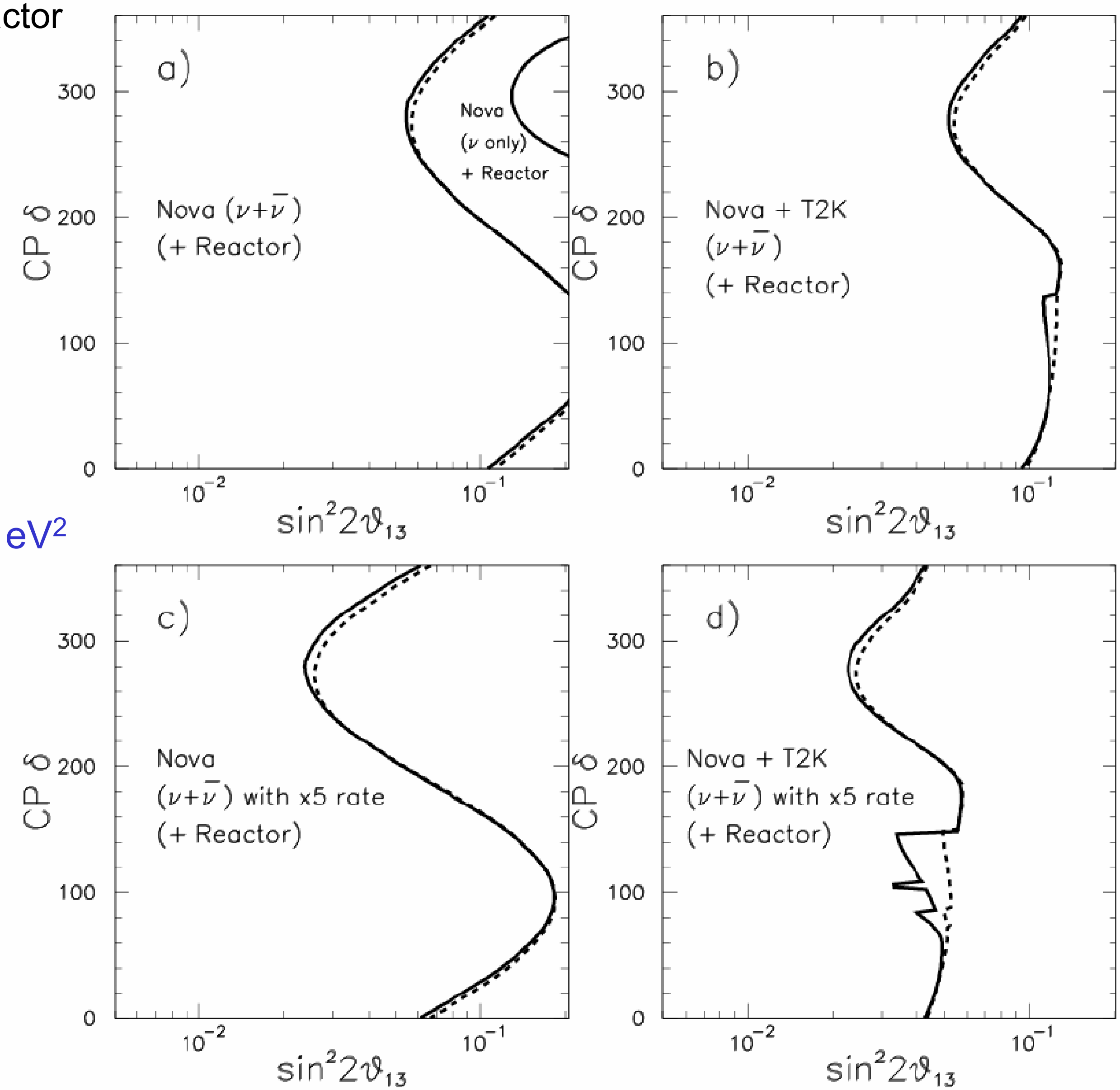


Two Sigma Regions for Mass Hierarchy Resolution

Dashed – without Reactor

Solid – with Reactor

$\Delta m^2 = 2.5x10^{-3}\ eV^2$



Given a point to the right of the curves, mass hierarchy is resolved by at least two sigma

Nominal Beam Rates

x5 Nominal Beam Rates

Conclusions

- Reactor experiment is "the" prime and only unambiguous measurement of θ_{13}
  - θ_{13} is a important physics parameter
    - Needed to constrain the models of lepton mixing matrix
    - If very small, probably indicates a new symmetry
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy
    - If $\sin^2 2\theta_{13}$ is > ~0.02, T2K and Nova make a nice program
    - If $\sin^2 2\theta_{13}$ is < ~0.01, need other techniques to access the physics (1st,2nd maxima measurements; BNL-Homestake, NuMI-Homestake,….)
- Reactor measurements may be important for sorting out the θ_{23} ambiguity (θ_{23} vs $90^0 - \theta_{23}$)
  - Again this is an important, fundamental physics parameter (like θ_{13})
  - Need more study here
- Reactor measurements do not add much to constraining CP violation and mass hierarchy with T2K and Nova type measurements
  - Is this also true for other techniques? (1st,2nd maxima i.e. BNL-Homestake)
    $\Rightarrow$ This also needs more study

Draft Conclusion Paragraphs for Discussion

The worldwide program to understand neutrino oscillations and determine the mixing parameters, CP violating effects, and mass hierarchy will require a broad combination of measurements. Progress in the past associated with solving the solar and atmospheric neutrino puzzles took a full suite of experiments to isolate and understand the phenomenology. As measurements became available, they defined the direction for future studies. One would expect a similar chain for the current goals where the program grows as information is obtained.

Reactor measurements hold the promise of constraining or measuring the θ_{13} mixing parameter. In addition to setting the scale for further studies, a reactor result when combined with long-baseline measurements may also give early indications of CP violation and the mass hierarchy. The combination of the T2K and Nova longbaseline experiments will be able to make significant measurements of these effects if $\sin^2 2\theta_{13} >$ **0.05** and with enhanced beam rates can improve their reach to the $\sin^2 2\theta_{13} > 0.02$ level. If theta13 turns out to be smaller than these values, one will need other stategies for getting to the physics. Thus, an unambiguous reactor measurement of θ_{13} is an important ingredient in planning the strategy for this program.