A reactor experiment to measure θ_{13}

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- APS neutrino study
- Importance of θ_{13}
- Unique role of reactor experiments
- Conclusion

APS ν Study: Identify key questions of neutrino physics and evaluate most promising experimental approaches to answering them.

→ written report in summer 2004

Working groups formed to explore particular experimental approaches:
Solar/atmospheric, accelerators, reactors, neutrino factories,
$0\nu\beta\beta$ decay, cosmology/astrophysics

Reactor working group: explore possibilities for neutrino physics with nuclear reactors

Broad participation from community:

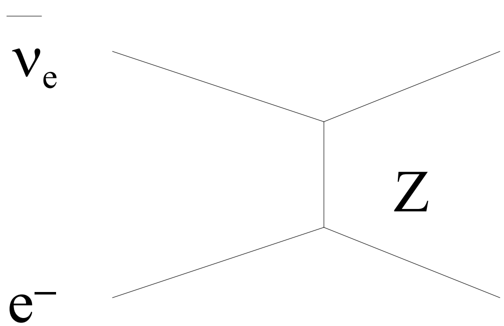
Erin Abouzaid, Kelby Anderson, Gabriela Barenboim, Andrew Bazarko, Eugene Beier, Ed Blucher, Tim Bolton, Janet Conrad, Joe Formaggio, Stuart Freedman, Dave Finley, Peter Fisher, Moshe Gai, Maury Goodman, Andre de Gouvea, Nick Hadley, Dick Hahn, Karsten Heeger, Boris Kayser, Josh Klein, John Learned, Manfred Lindner, Jon Link, Bob McKeown, Irina Mocioiu, Rabi Mohapatra, Donna Naples, Jen-chieh Peng, Serguey Petcov, Jim Pilcher, Petros Rapidis, David Reyna, Byron Roe, Mike Shaevitz, Robert Shrock, Noel Stanton, Ray Stefanski (+ Thierry Lasserre, Hervé de Kerret)

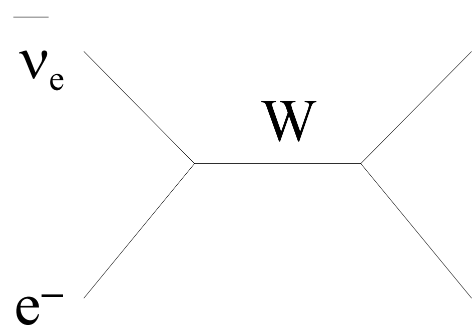
Neutrino physics at nuclear reactors

θ_{13} + several additional possibilities: $\sin^2\theta_W$, solar Δm^2, neutrino magnetic moment, SN physics, CPT tests

E.g., early studies indicate that a measurement of $\sin^2\theta_W$ with precision comparable to NuTeV could be performed using $\bar{\nu}_e - e^-$ scattering.

(Conrad, Link, Shaevitz, hep-ex/0403048)





$$\frac{d\sigma}{dT} = \frac{G^2 m}{2\pi} \left\{ (C_V + C_A)^2 + (C_V - C_A)^2 \left(1 - \frac{T}{E}\right)^2 + (C_A^2 - C_V^2)\, m \frac{T}{E^2} \right\}$$

$C_V = \frac{1}{2} + 2 \sin^2 \theta_W$

$C_A = \frac{1}{2}$

T = electron KE energy
E = neutrino energy
m= mass of electron
This assumes $\mu_\nu = 0$

APS reactor study builds on work presented in series of international workshops, and written up in whitepaper.

International Workshops:
Alabama, June 2003
Munich, Germany October 2003
Niigata, Japan, March 2004
Paris, France, June 2004

APS reactor group meetings:
Argonne, December 2003
Chicago, February 2004
May 2004

Neutrino Oscillations

- During last few years, oscillations among different flavors of neutrinos have been established; physics beyond the S.M.
- Mass eigenstates and flavor eigenstates are not the same (similar to quarks):

flavor eigenstates — MNSP matrix — mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Raises many interesting questions including possibility of CP violation in neutrino oscillations.
- CP violation in neutrino sector could be responsible for the matter-antimatter asymmetry.

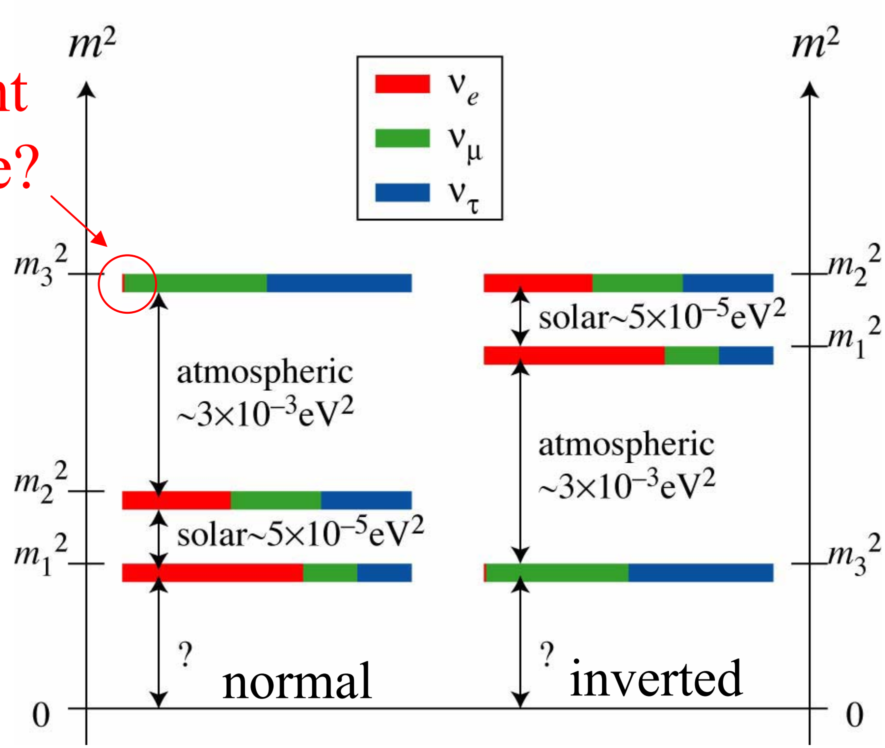
What do we know?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\theta_{12} \sim 30°$ $\quad$ $\sin^2 2\theta_{13} < 0.2$ at 90% CL $\quad$ $\theta_{23} \sim 45°$

What is ν_e component of ν_3 mass eigenstate?



Key questions

- What is value of θ_{13}?

- What is mass hierarchy?

- Do neutrino oscillations violate CP symmetry?

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

- Why are quark and neutrino mixing matrices so different?

$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

Value of θ_{13} central to these questions; it sets the scale for experiments needed to resolve mass hierarchy and search for CP violation.

Methods to measure $\sin^2 2\theta_{13}$

- Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{not small terms } (\delta_{CP},\ sign(\Delta m_{13}^2))$$

Use fairly pure, accelerator produced ν_μ beam with a detector a long distance from the source and look for the appearance of ν_e events

T2K: $\langle E_\nu \rangle = 0.7$ GeV, L = 295 km
NOνA: $\langle E_\nu \rangle = 2.3$ GeV, L = 810 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)

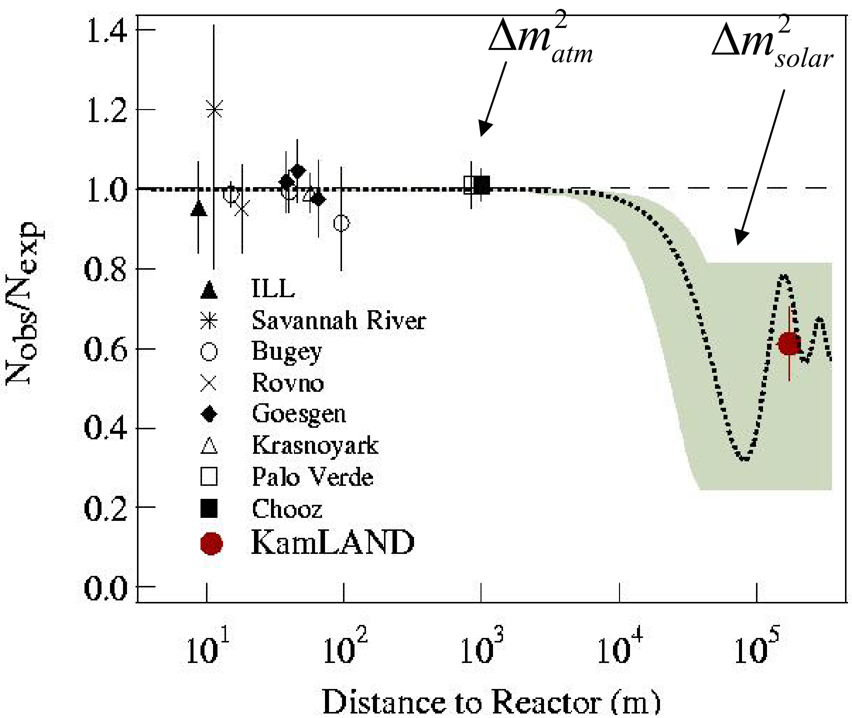
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{ very small terms}$$

Use reactors as a source of ν_e ($\langle E_\nu \rangle \sim 3.5$ MeV) with a detector 1-2 kms away and look for non-$1/r^2$ behavior of the ν_e rate

⇒ Reactor experiments provide the only clean measurement of $\sin^2 2\theta_{13}$:
no matter effects, no CP violation, almost no correlation with other parameters.

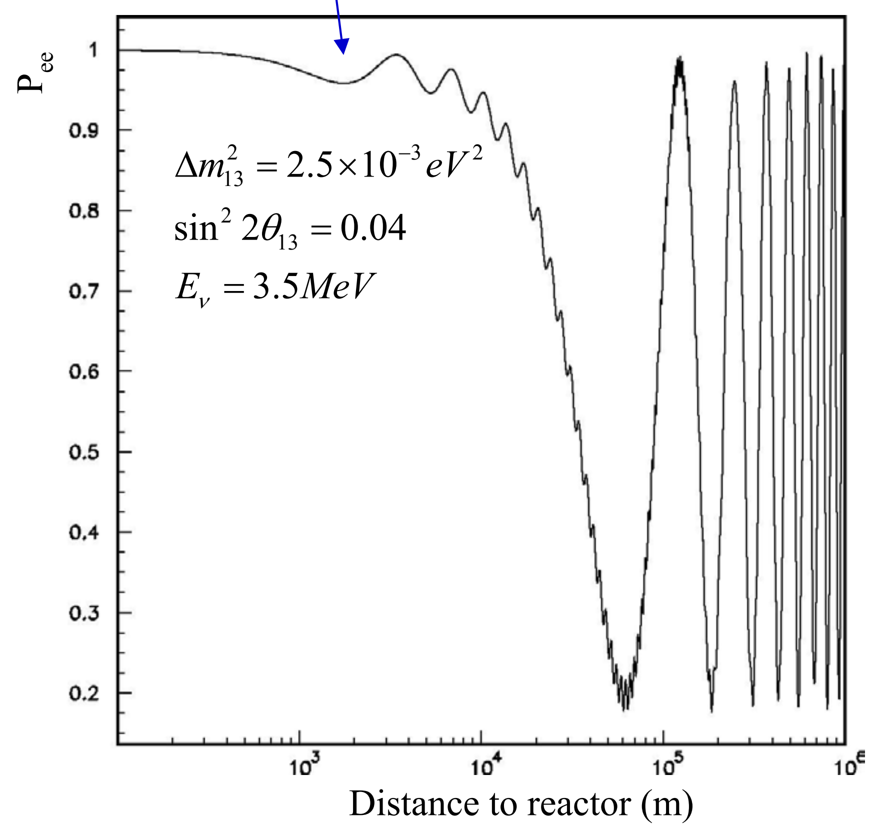
Reactor Measurements of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

Past measurements:



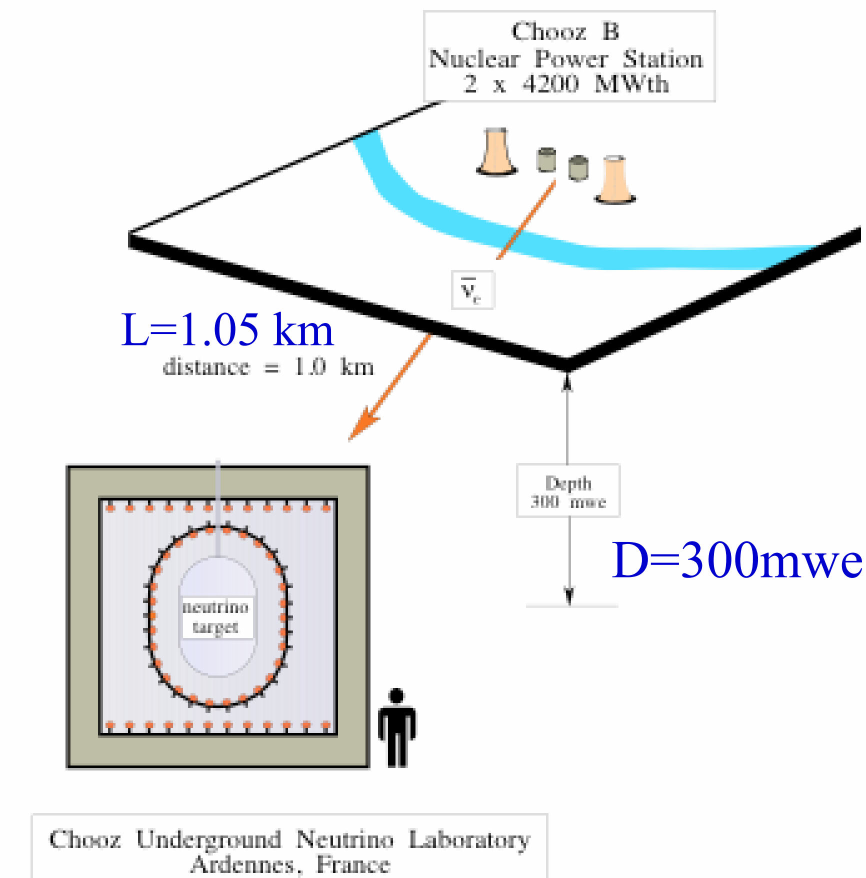
θ_{13}: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



Chooz: Current Best θ_{13} Experiment

P=8.4 GW_{th}

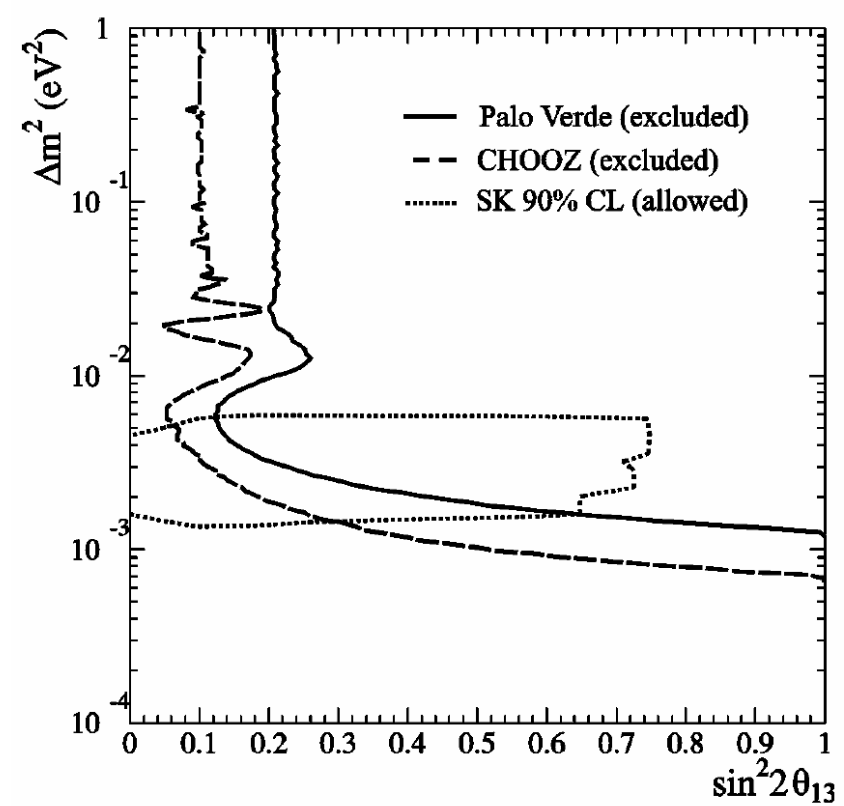


m = 5 tons, Gd-loaded liquid scintillator

Neutrino detection by $\overline{\nu}_e + p \rightarrow e^+ + n$,

$n + Gd \rightarrow 8 MeV$ of γs; $\tau \sim 30 \mu$sec

CHOOZ Systematic errors	
Reactor ν flux	2%
Detect. Acceptance	1.5%
Total	2.7%

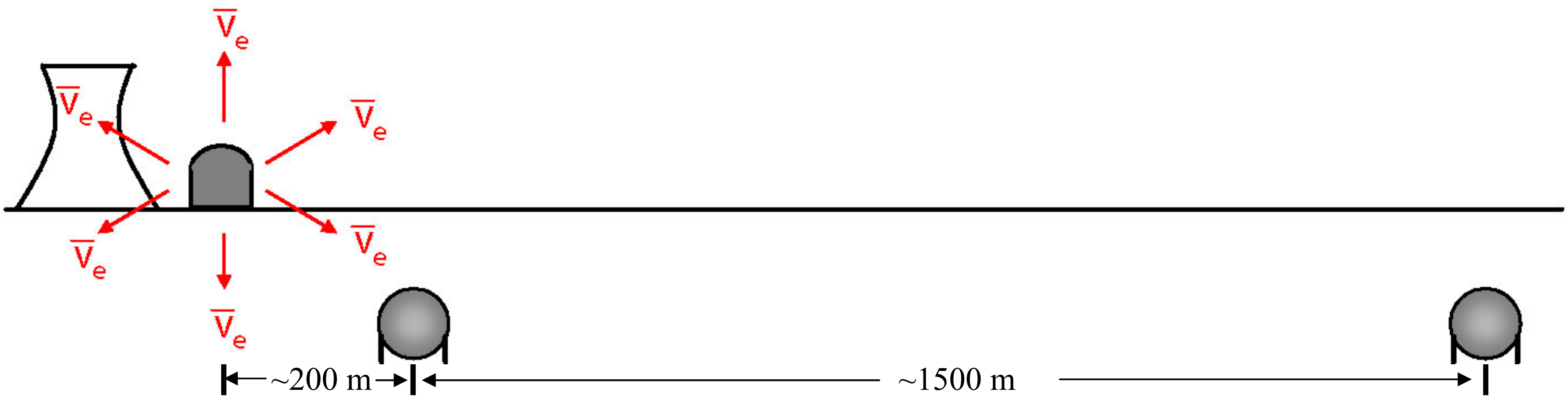


$\sin^2 2\theta_{13} < 0.2$ for $\Delta m^2 = 2\times10^{-3}$ eV^2

How can Chooz measurement be improved?

Add near detector: eliminate dependence on reactor flux calculation; need to understand relative acceptance of two detectors rather than absolute acceptance of a single detector

+ optimize baseline, larger detectors, reduce backgrounds

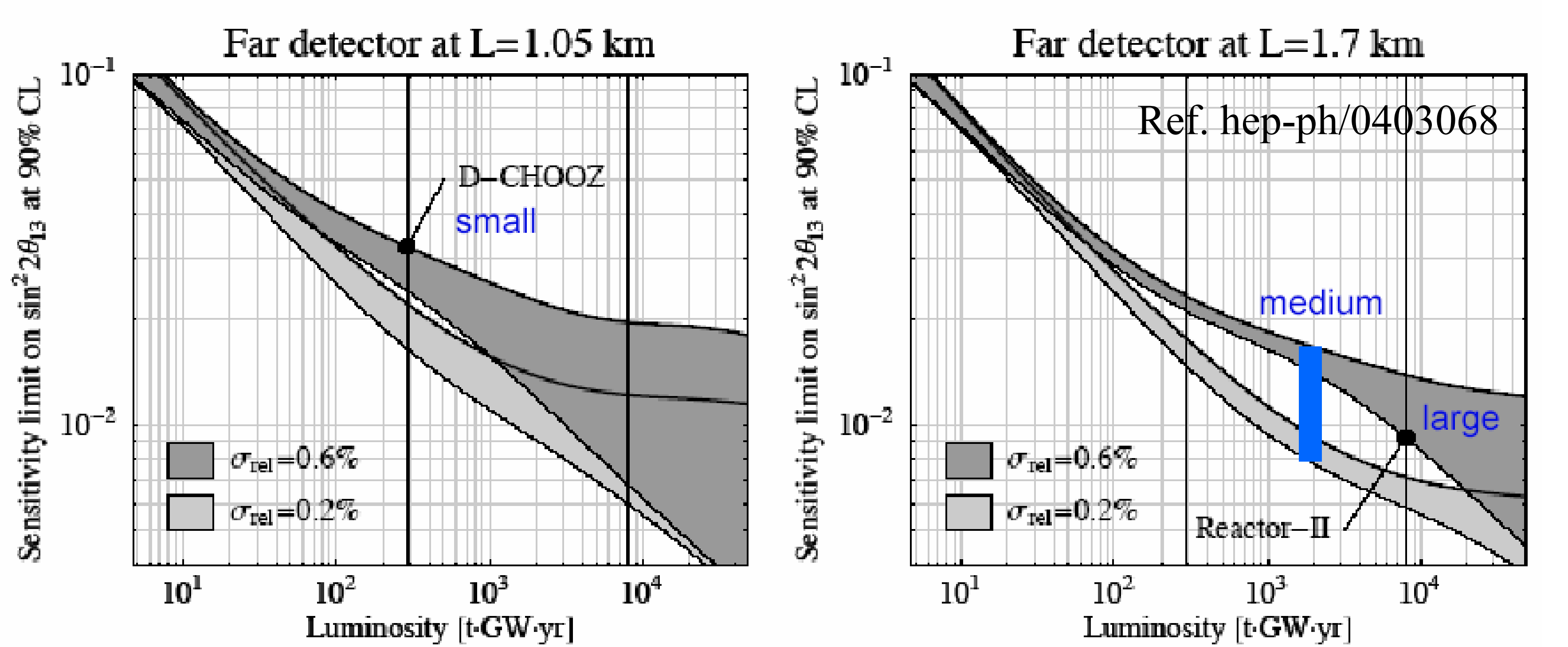


Issues affecting precision of experiment:

- Relative uncertainty on acceptance
- Relative uncertainty on energy scale and linearity
- Background (depth)
- Detector size
- Baseline
- Reactor power

Study has focused on three scales of experiments:

- **Small** $\sin^2 2\theta_{13} \sim 0.03\text{-}0.04$ (e.g., Double-Chooz)
- **Medium** $\sin^2 2\theta_{13} \sim 0.01$ (e.g., Braidwood, Diablo Canyon, Daya Bay)
- **Large** $\sin^2 2\theta_{13} < 0.01$



For each scenario, understand cost, timescale, and physics impact.

Strong consensus in working group that experiment with sensitivity of $\sin^2 2\theta_{13} \sim 0.01$ should be our goal.

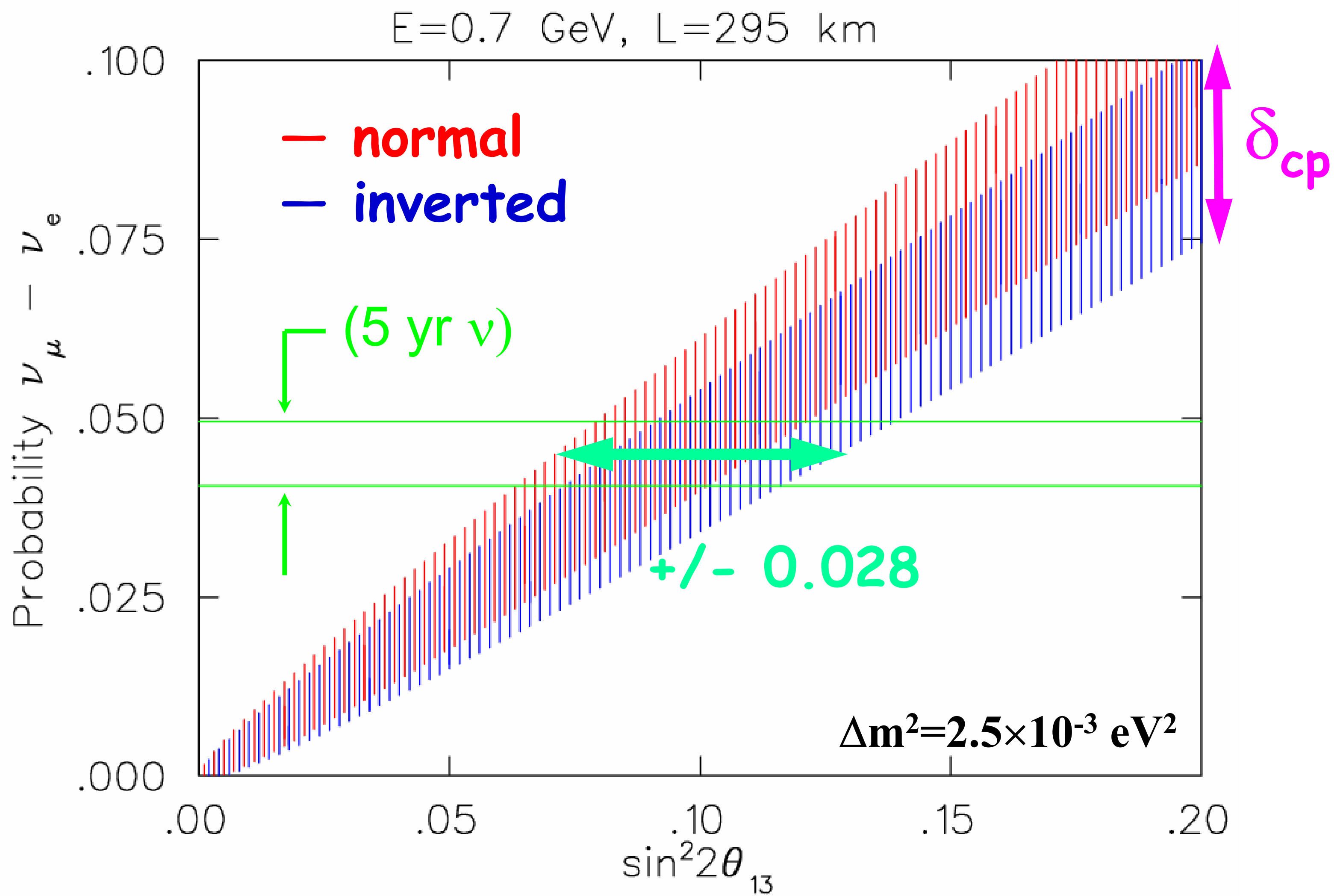
- If $\sin^2 2\theta_{13} < 0.01$, it will be difficult for long-baseline "superbeam" experiments to investigate mass hierarchy and CP violation.

⇒ Reactor experiment with sensitivity of 0.01 will indicate scale of future experiments needed to make progress.

- If $\sin^2 2\theta_{13} > 0.01$, a precise measurement will be needed to combine with accelerator experiments.

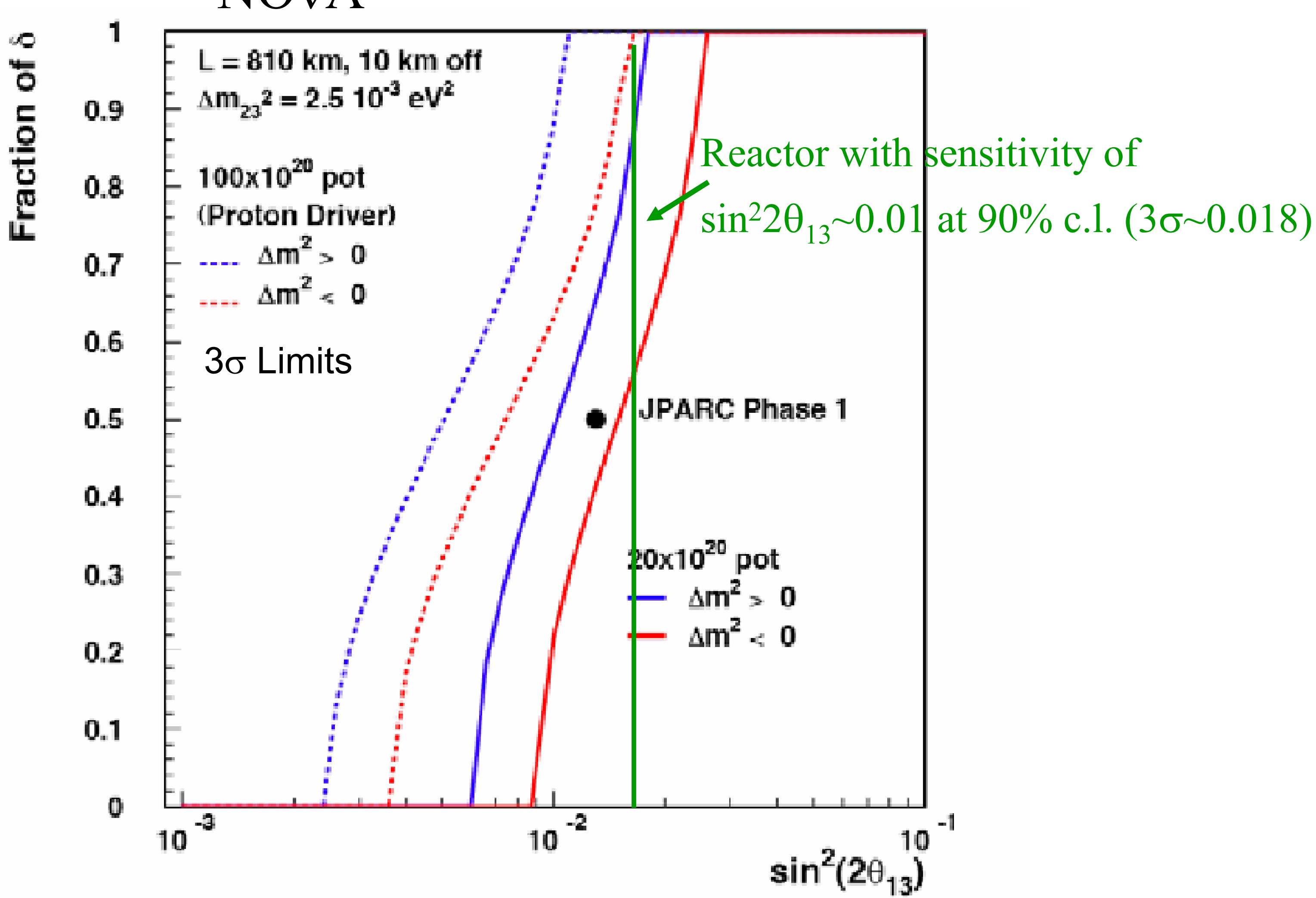
Both reactor and accelerator experiments have sensitivity to $\sin^2 2\theta_{13}$, but accelerator measurements have ambiguities

Example: T2K. $\Delta P(\nu_\mu \rightarrow \nu_e)=0.0045 \rightarrow \Delta\sin^2 2\theta_{13}=0.028$



Reactor and accelerator sensitivities to $\sin^2 2\theta_{13}$

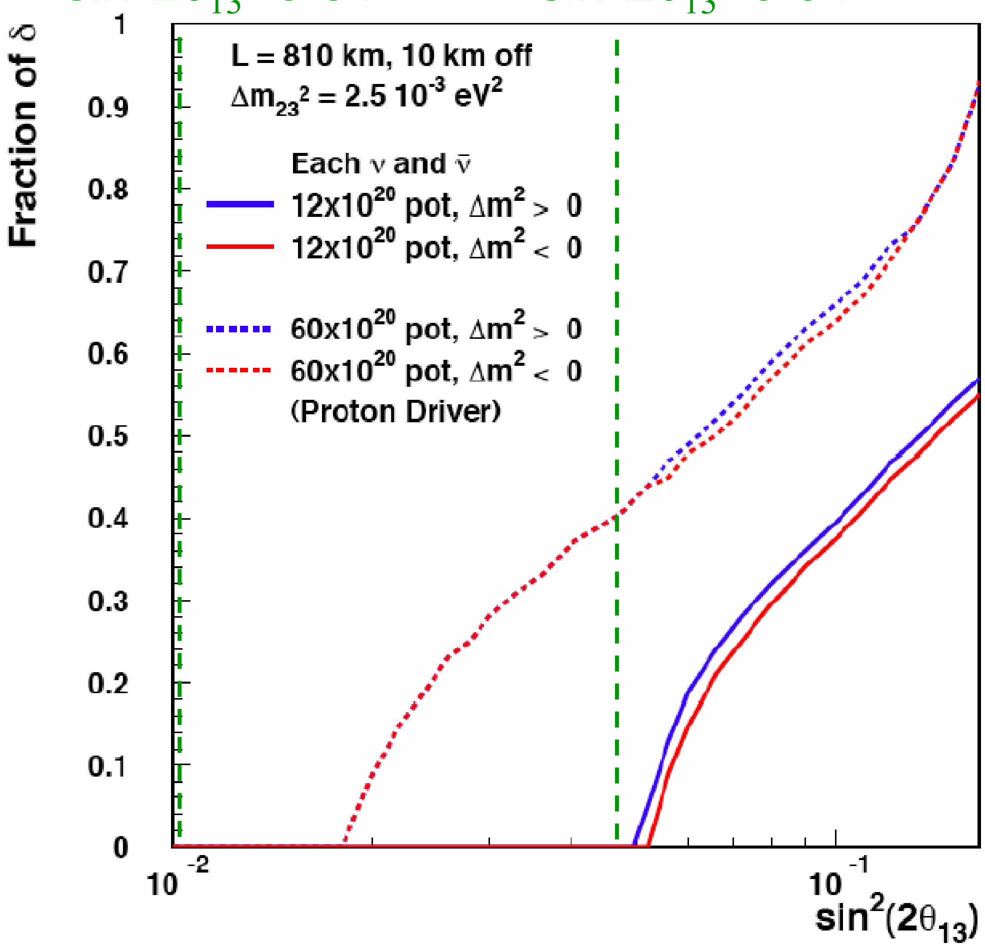
NOνA



Value of θ_{13} sets scale of experiment needed to resolve mass hierarchy and study CP violation.

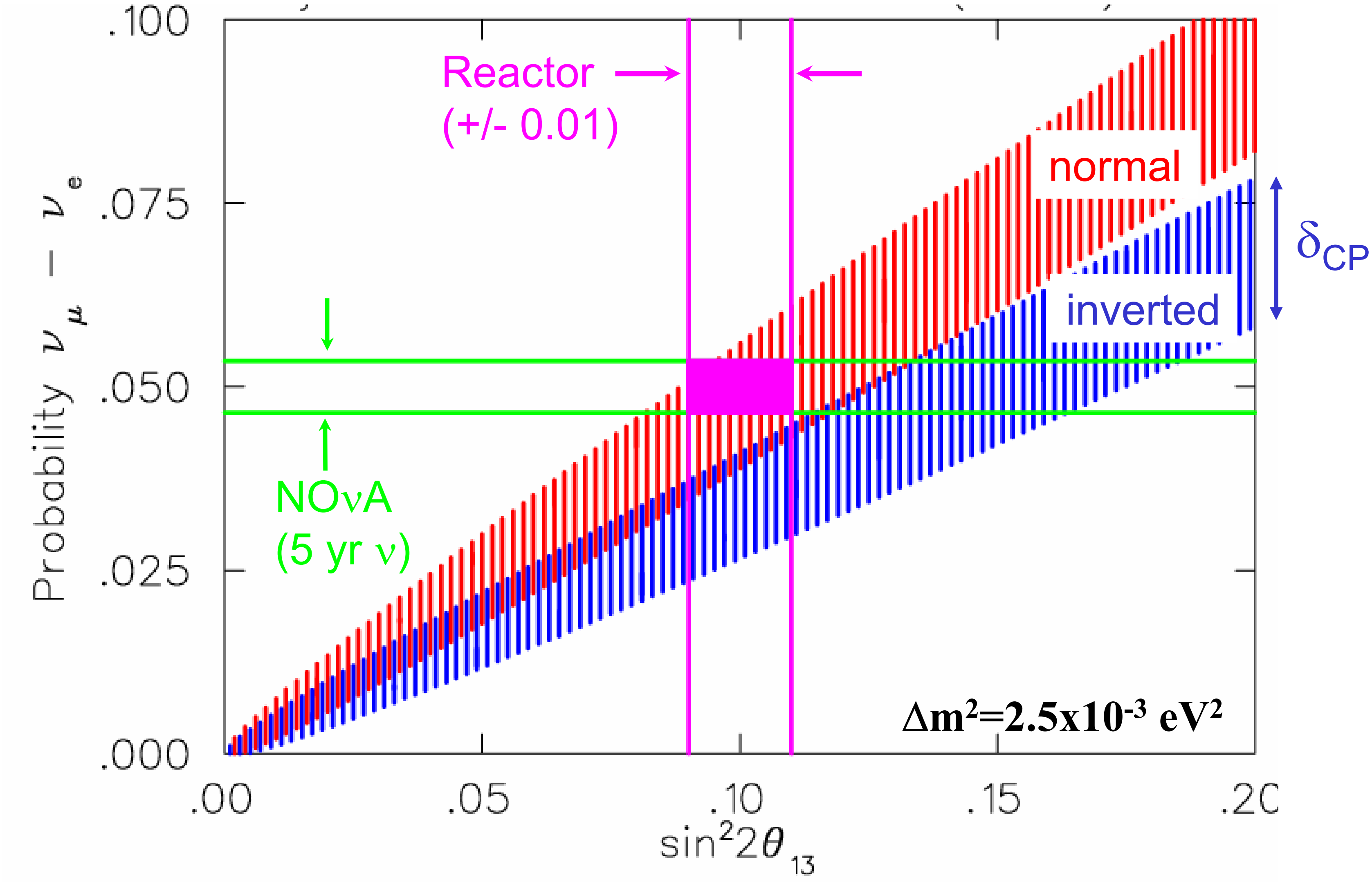
Example: FNAL Off-Axis (NOνA)

$\sin^2 2\theta_{13} < 0.01$ $\sin^2 2\theta_{13} < 0.04$ ← Possible reactor limits

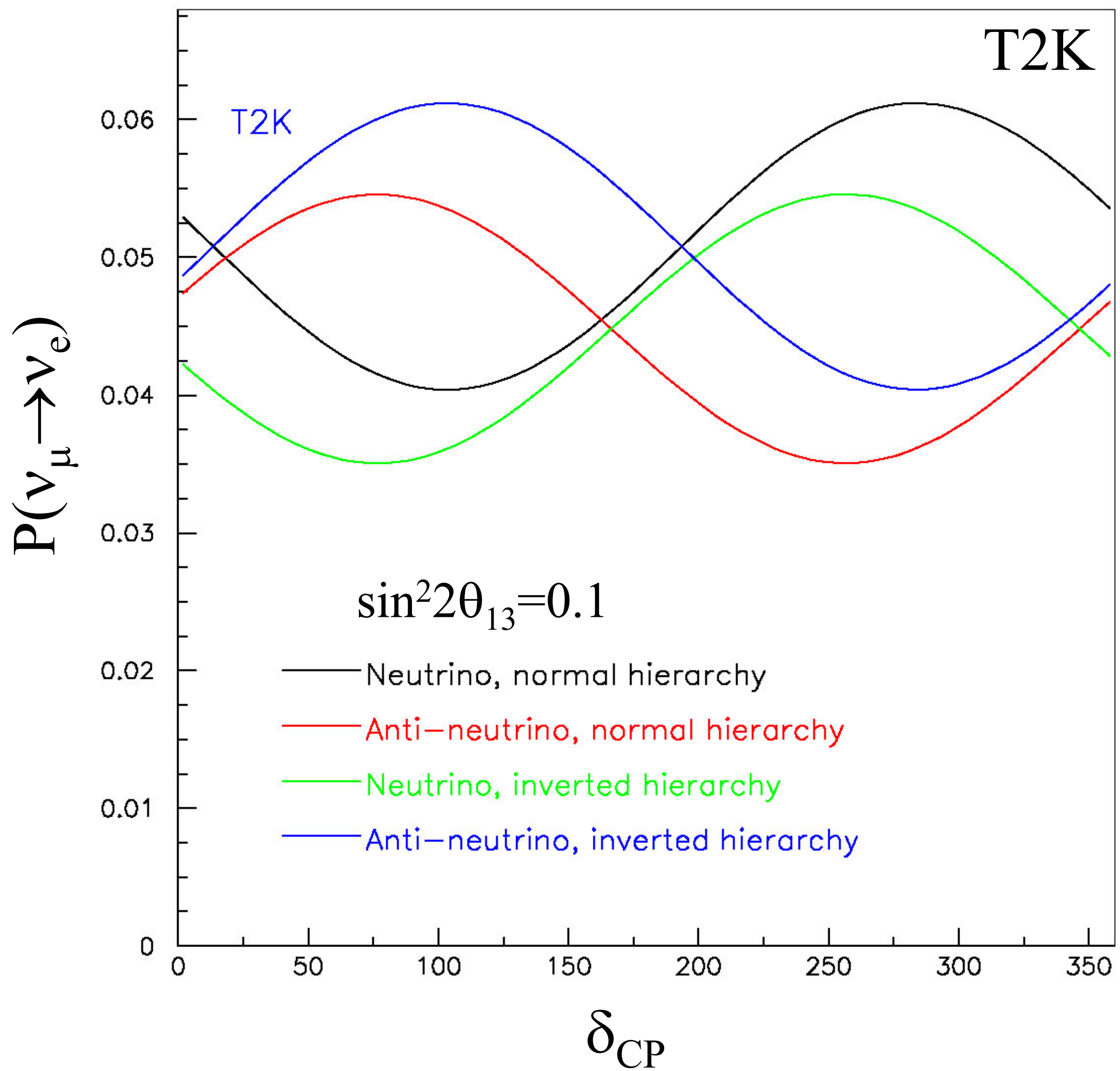


2σ limits for resolution of mass hierarchy for 3 years of ν and 3 years of $\bar{\nu}$ running

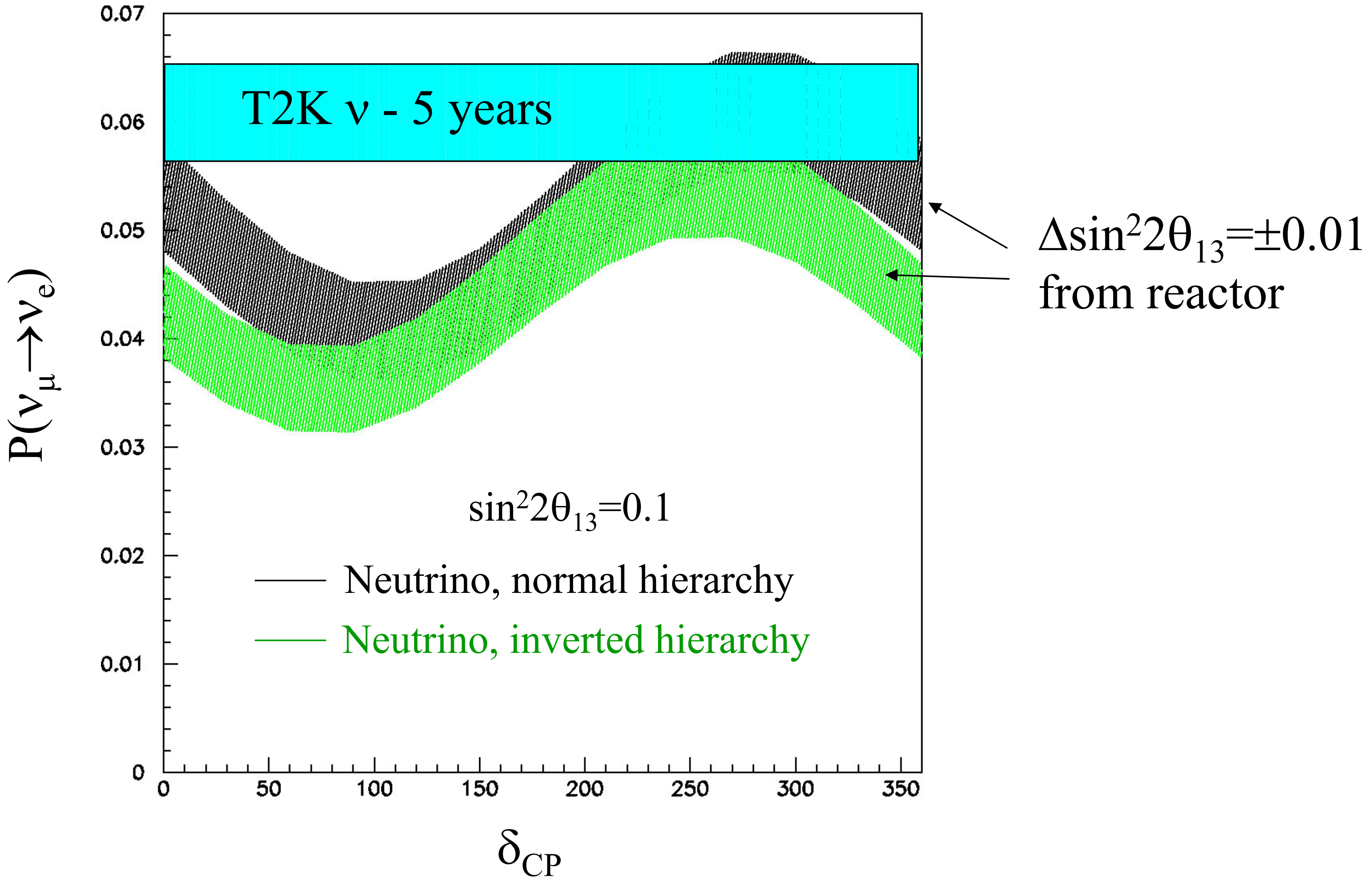
Complementarity of reactor and accelerator experiments



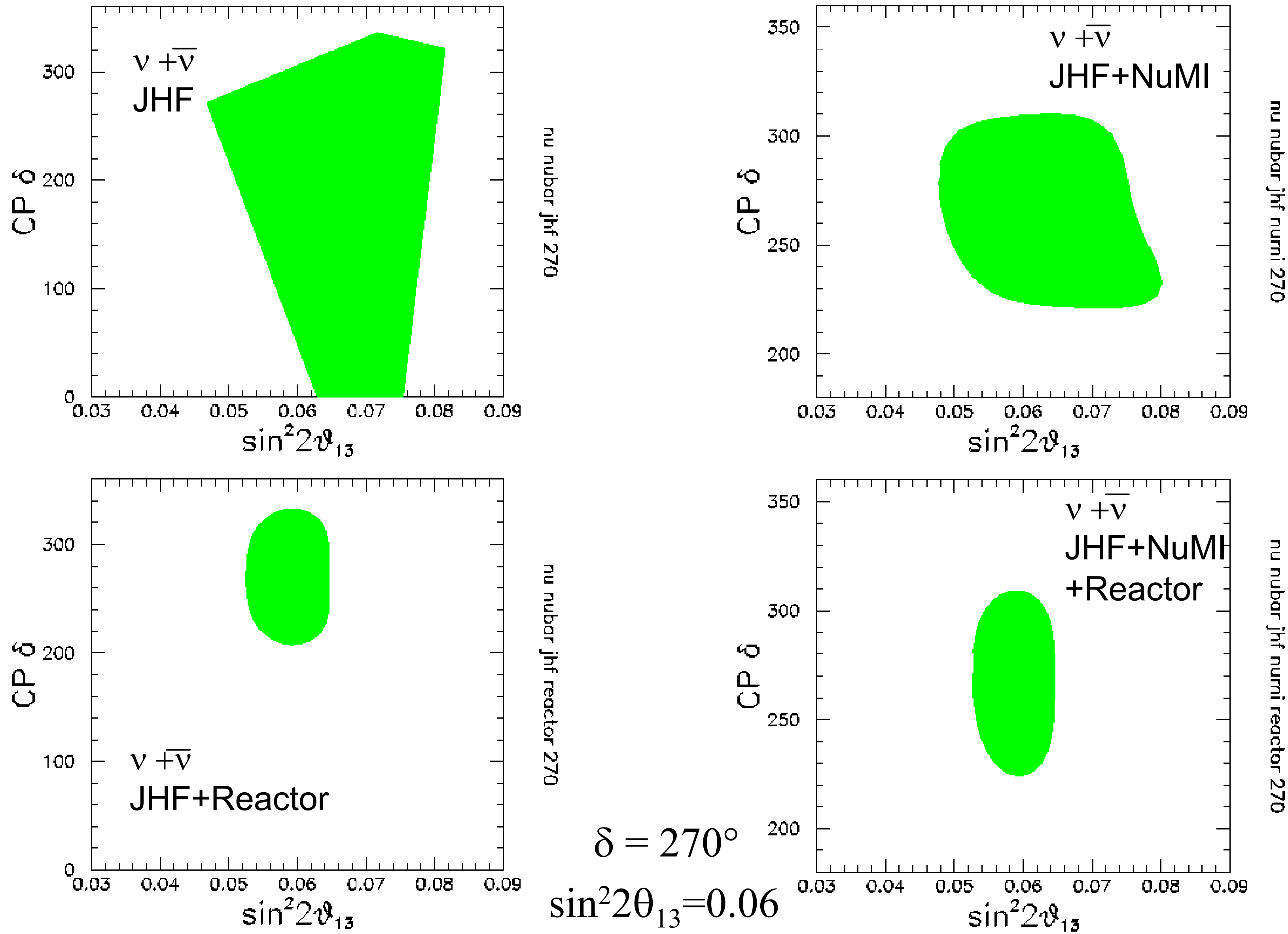
Searching for CP violation



Example: Reactor + T2K ν running



δ_{CP} Measurement (with / without Reactor)



Conclusions

- Extremely exciting time for neutrino physics!
- Value of $\sin^2 2\theta_{13}$ sets the scale for experiments needed to study mass hierarchy and CP violation
- Reactor experiment has potential to be fastest, cheapest, and cleanest way to establish value of θ_{13}
- Reactor experiment with sensitivity of $\sin^2 2\theta_{13} \sim 1\%$ will give information needed to understand future roadmap of neutrino program
- Reactor information improves sensitivity of accelerator experiments to CP violation and mass hierarchy