# Precise Measurement of Electron Antineutrino Disappearance at Daya Bay and Beyond

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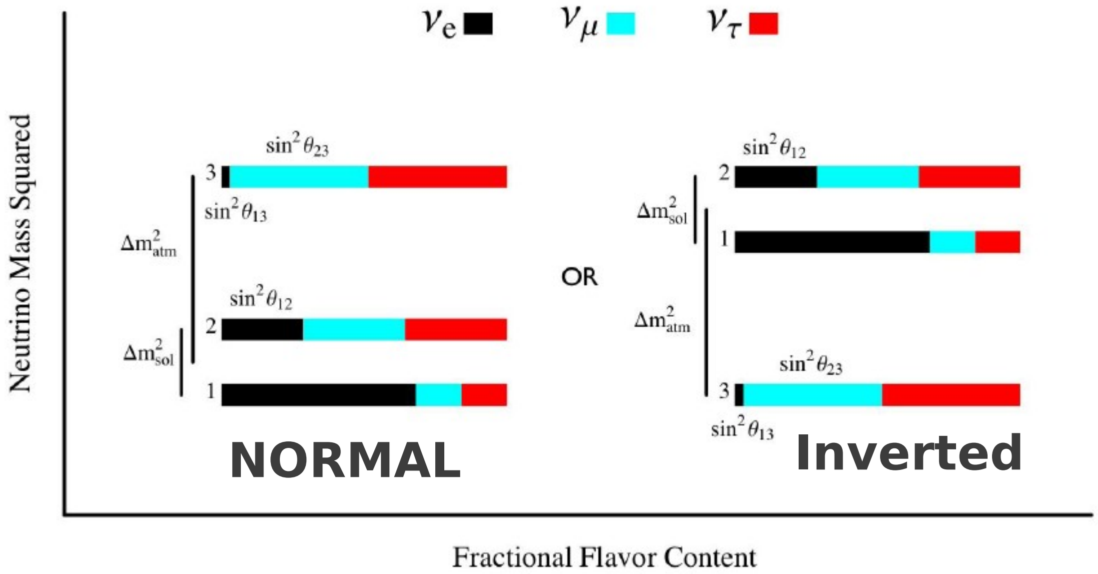
*BNL Forum 2013*

# Neutrino Mixing




## PMNS Mixing Matrix

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

$$= \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$= \begin{bmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

**atmospheric** **reactor/Accelerator** **solar** **Majorana CPV**

**atmospheric**: $\theta_{23} > 38.5°$, $|\Delta m^2_{32}| = 0.00232^{+0.00012}_{-0.00008}$ eV$^2$

**reactor/Accelerator**: $\theta_{13} = 9.1 \pm 0.6°$

**solar**: $\theta_{12} = 34° \pm 1°$, $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV$^2$

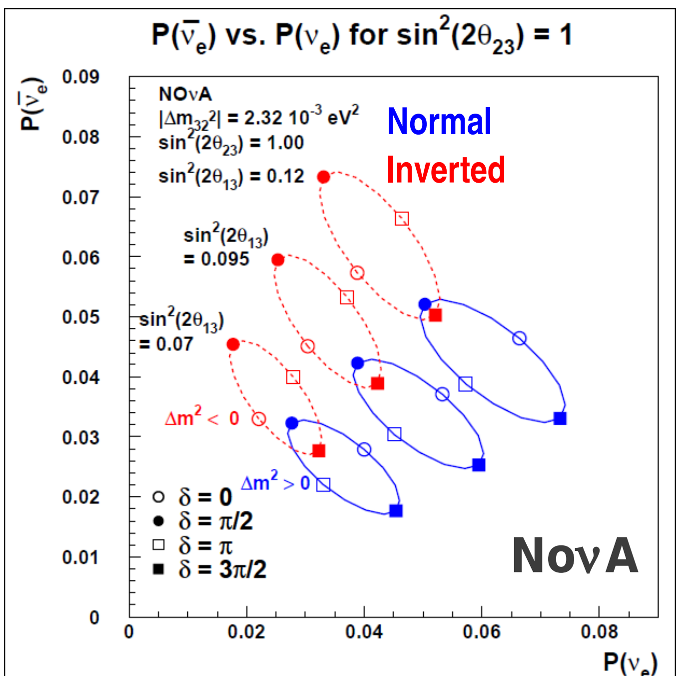
# Key Role of $\theta_{13}$

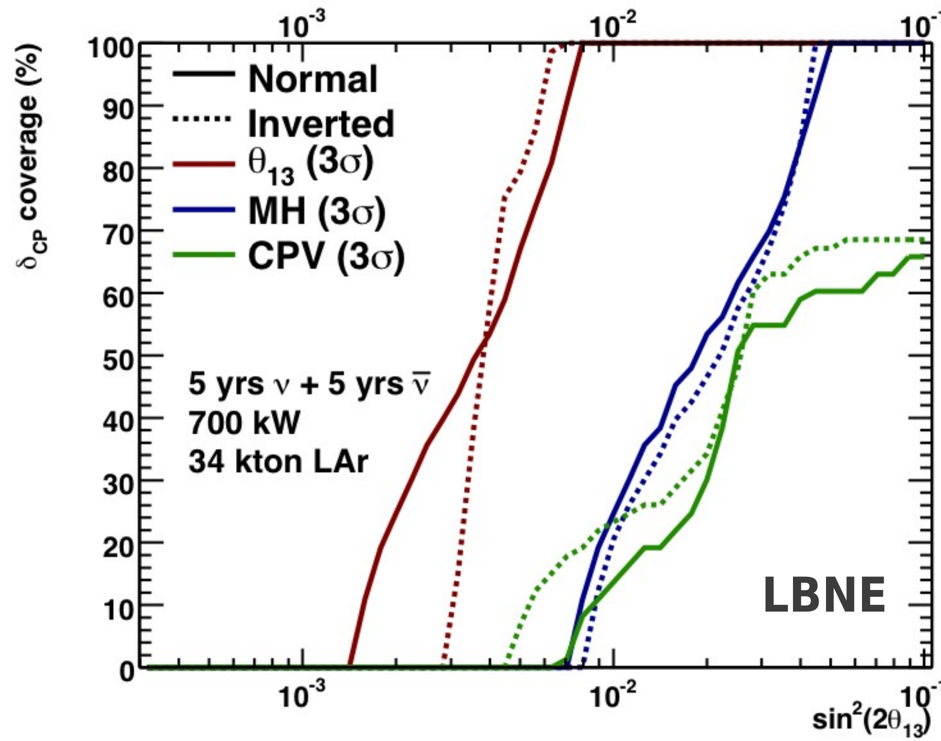
'Large' value of $\theta_{13}$ is directly connected with:

- **Neutrino mass hierarchy**
- **Octant of $\theta_{23}$**
- **Leptonic CP vialation**

**All the terms cannot be 0 in order to measure $\delta_{CP}$!**

$$J_{CP} = \Im(U_{e3}^* U_{\mu 3} U_{e2} U_{\mu 2}^*) = \frac{1}{8} \cos\theta_{13} \boxed{\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}} \boxed{\sin\delta_{CP}}$$

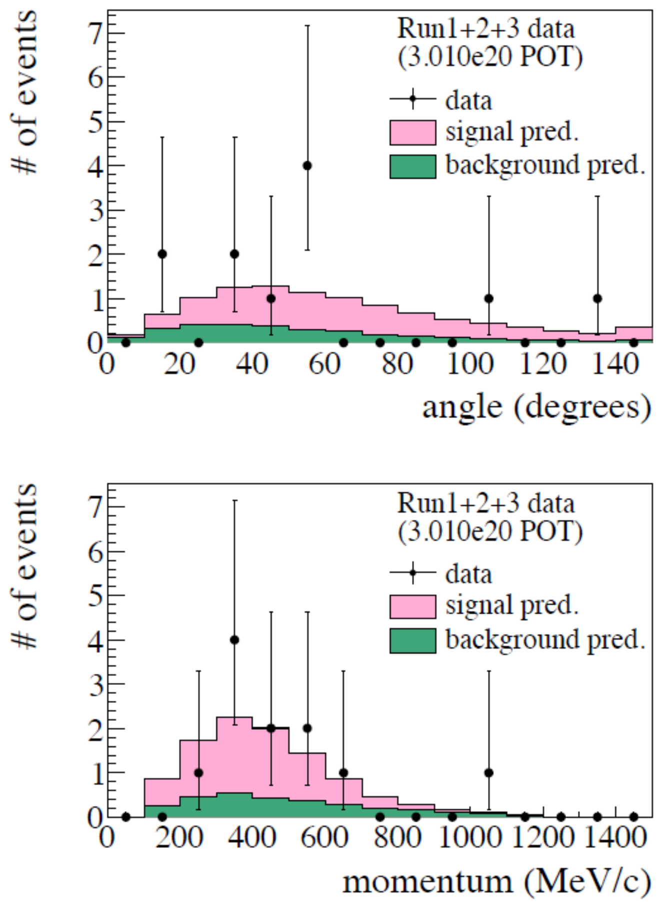


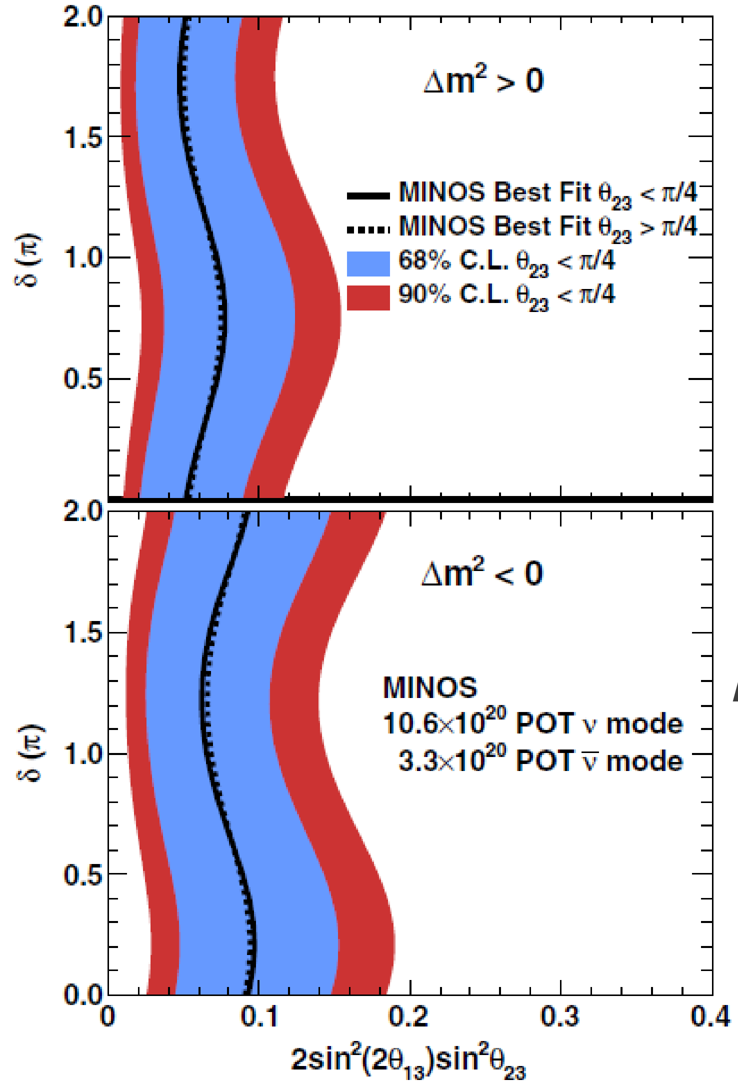



# Accelerator Approach

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{1.267\,\Delta m^2_{31}\,L}{E}\right) + \cdots$$

Plus potentially large modifications (CPV, matter effects.)



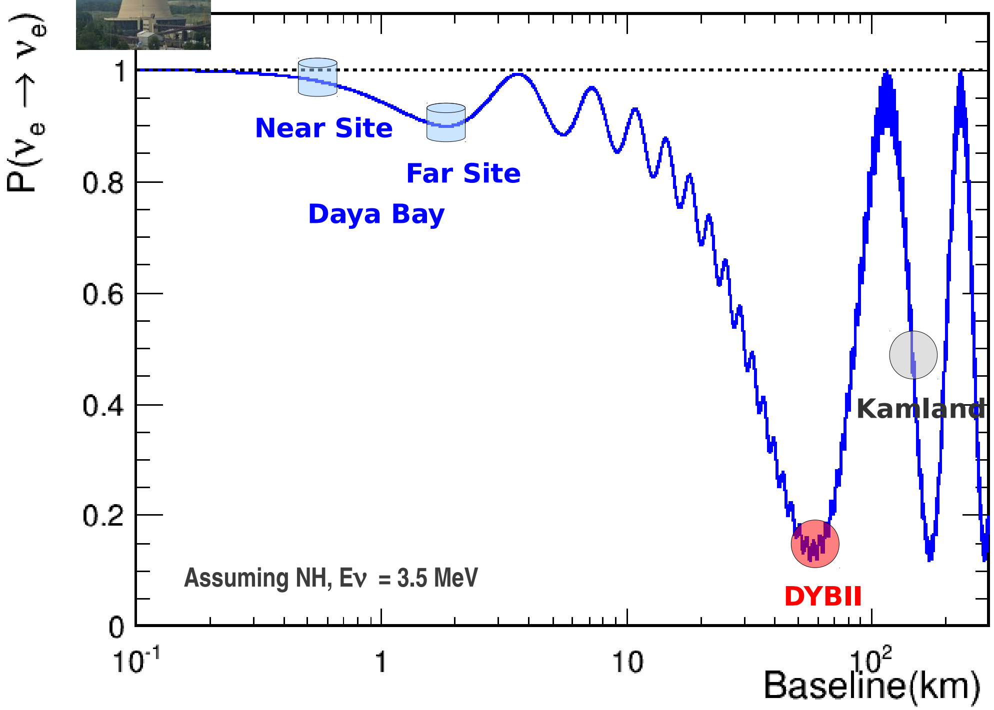

**MINOS: Combined fit with $\nu_\mu$ and $\overline{\nu}_\mu$ data**

***[prl 110,171801]***

**T2K: 11 $\nu_e$ candidates with 3.3±0.4 backgrounds (3.1σ)** ***[arXiv:1304.0841]***

# Reactor Approach

**$\theta_{13}$ revealed by a deficit of reactor antineutrinos at ~2km**




- Pure $\bar{\nu}_e$ source
- Clean detection signal
- No CP violation
- Negligible matter effect
- Dominant $\theta_{12}$ oscillation
- Sub-dominant $\theta_{13}$ oscillation

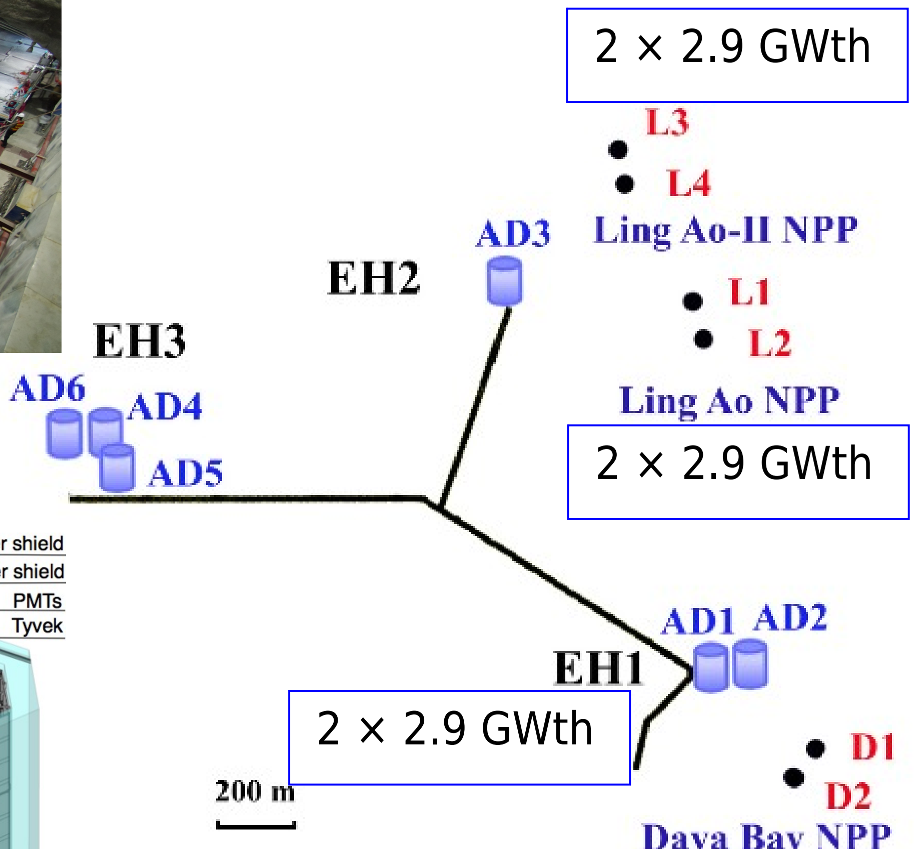
**Relative Measurement**

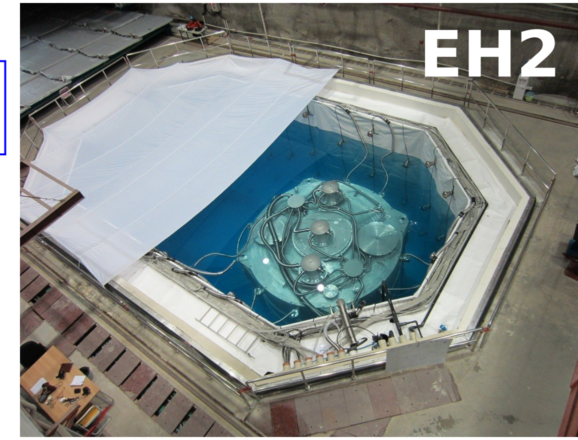
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

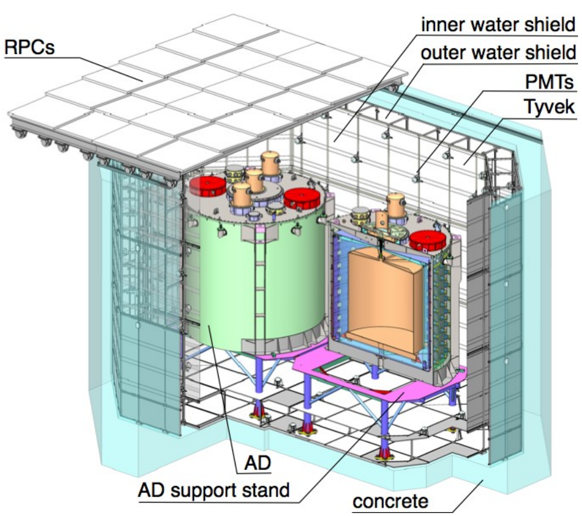
Far/Near Neutrino Ratio | Detector Target Mass | Distance from Reactor | Detector Efficiency | Survival Probability (θ13)

# Daya Bay: An Ideal Location

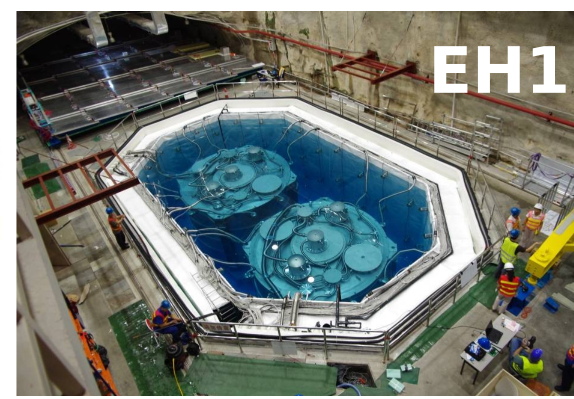
**6 Antineutrino Detectors (ADs) in 3 underground halls.**

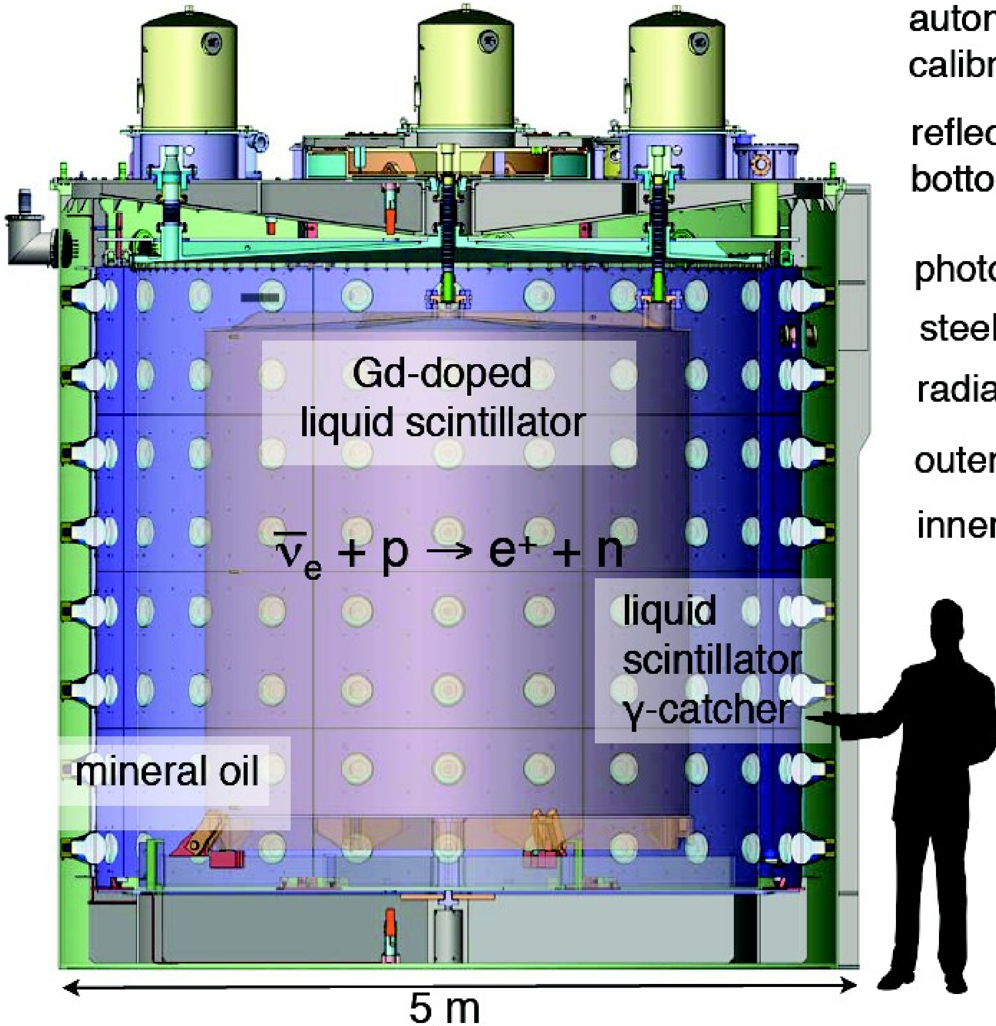



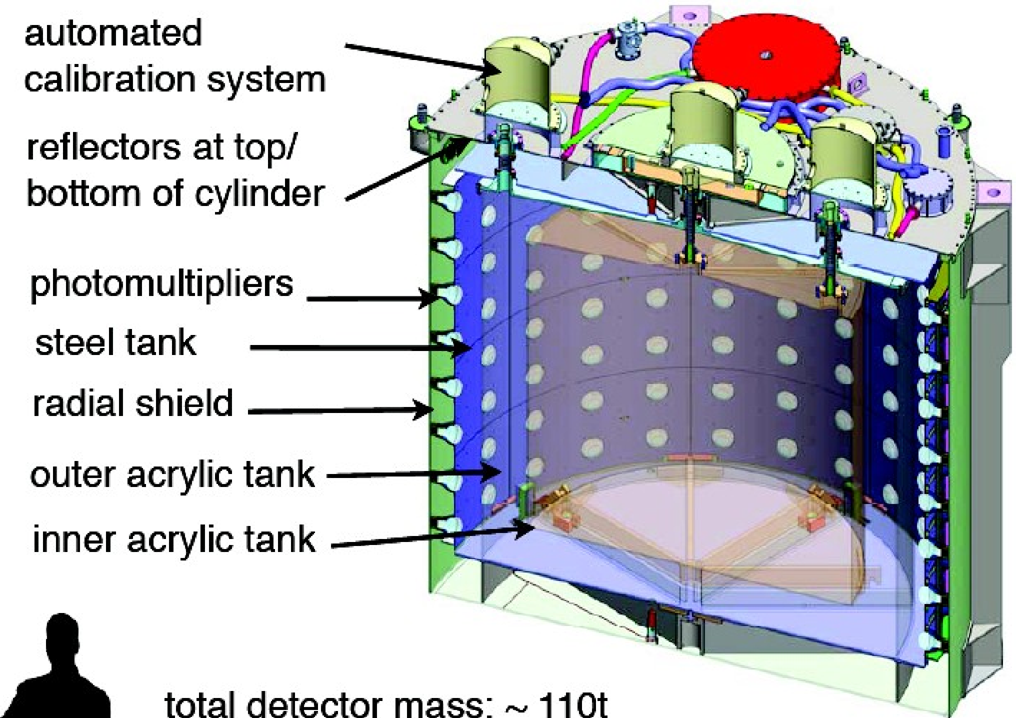




| | Overburden | $R_\mu$ | $E_\mu$ | D1,D2 | L1,L2 | L3,L4 |
|---|---|---|---|---|---|---|
| EH1 | 280 | 1.27 | 57 | 364 | 857 | 1307 |
| EH2 | 300 | 0.95 | 58 | 1348 | 480 | 528 |
| EH3 | 880 | 0.056 | 137 | 1912 | 1540 | 1548 |



# Daya Bay Antineutrino Detectors (AD)




total detector mass: ~ 110t

- inner: 20 tons Gd-doped LS (d=3m)
- mid: 20 tons LS (d=4m)
- outer: 40 tons mineral oil buffer (d=5m)

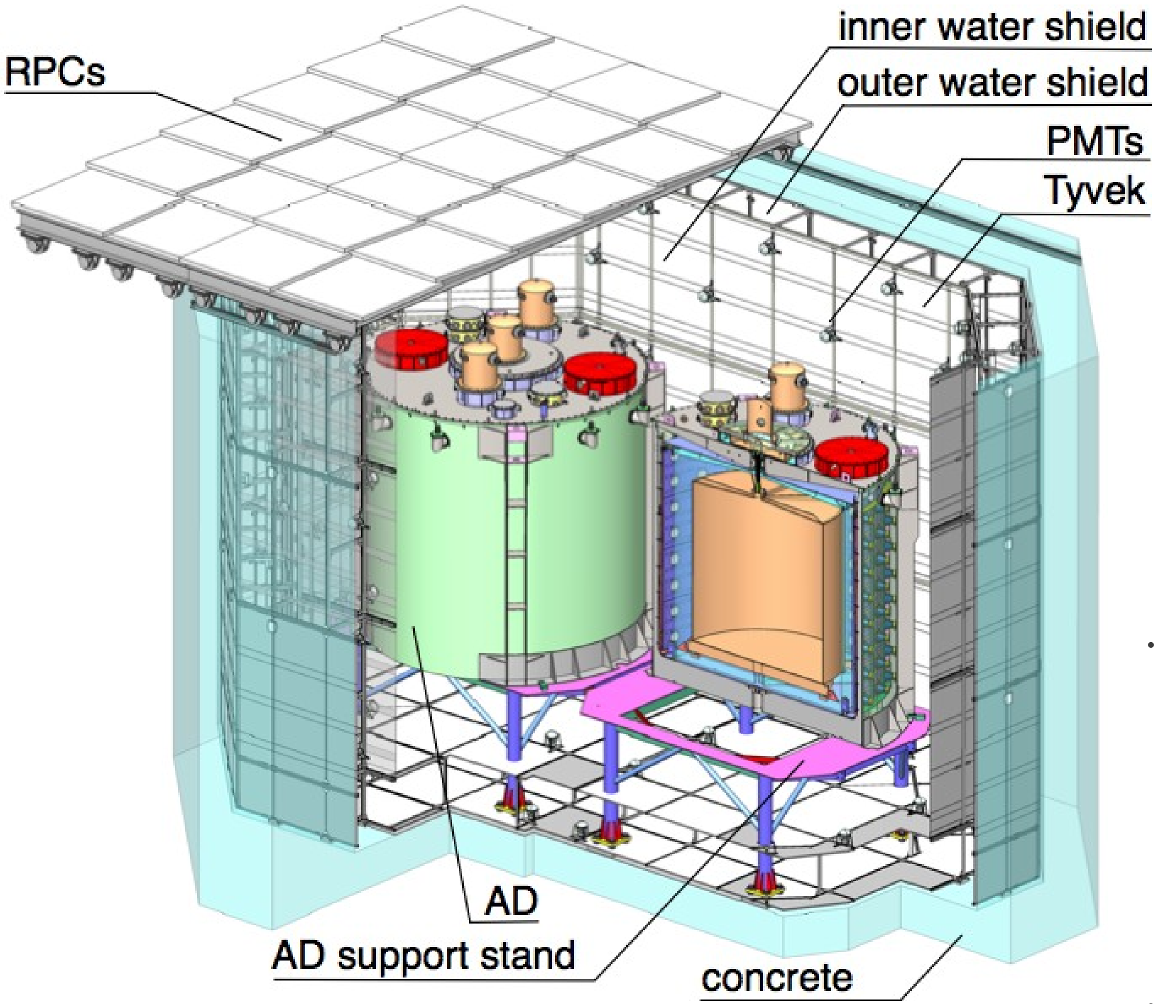
photosensors: 192 8"-PMTs

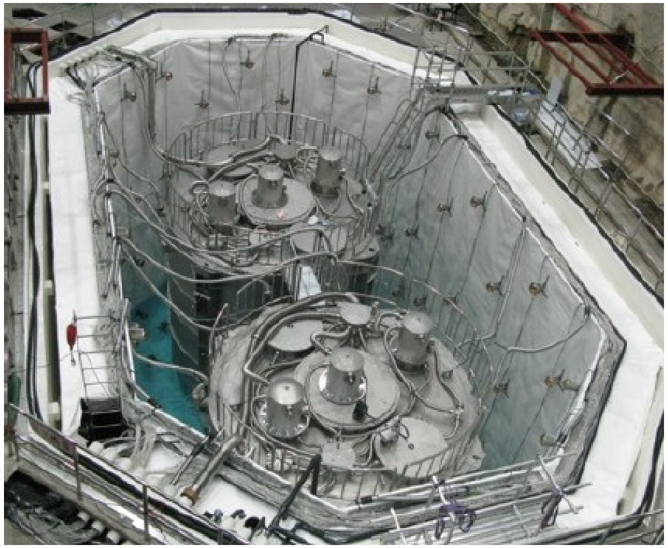
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

**6 "functionally identical", 3-zone detectors reduce systematic uncertainties**

# Muon Tagging System

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs



Two Zone ultrapure water Cherenkov detector

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall

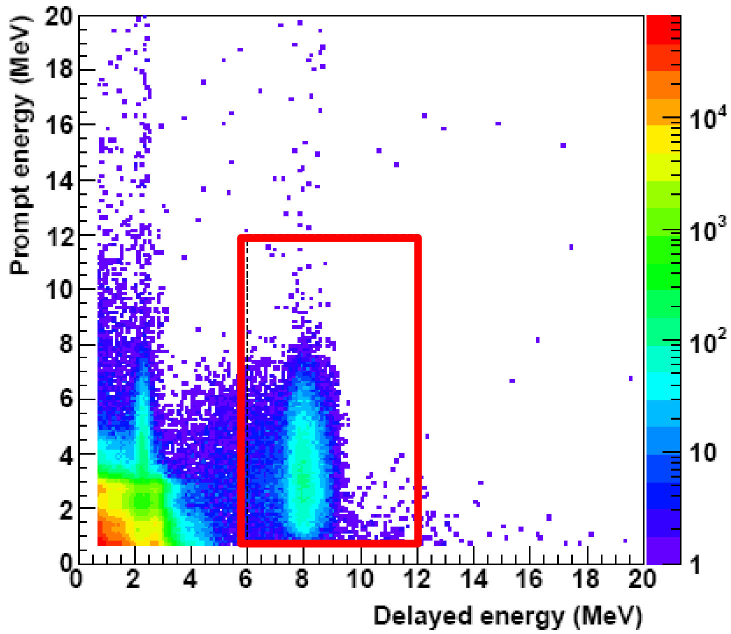
# Antineutrino Selection

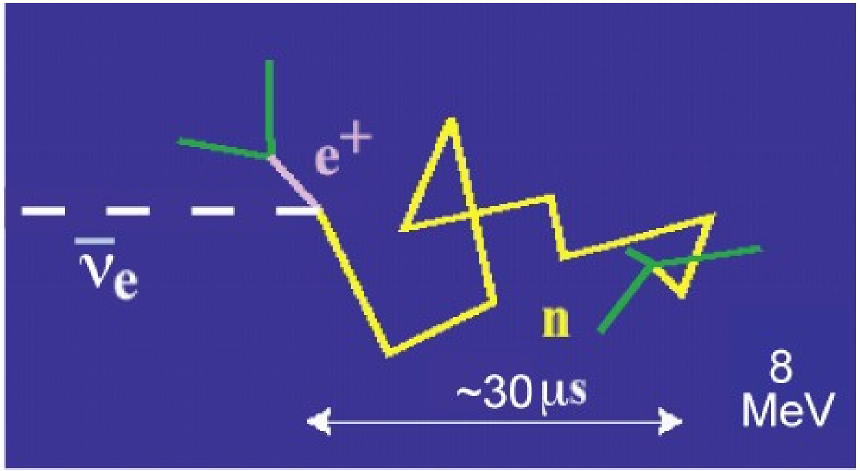
Use IBD Prompt + Delayed correlated signal to select antineutrinos

Inverse beta decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$




**Prompt positron:**

- Carries antineutrino energy

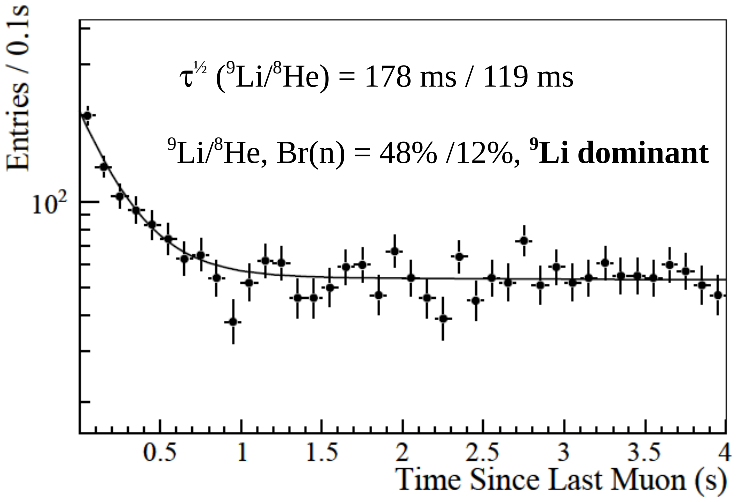
$E_{prompt} \cong E_{\nu}$ - 0.8 MeV

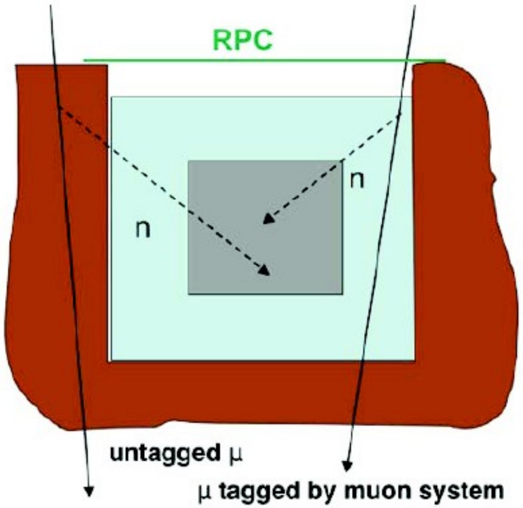
**Delayed neutron capture:**

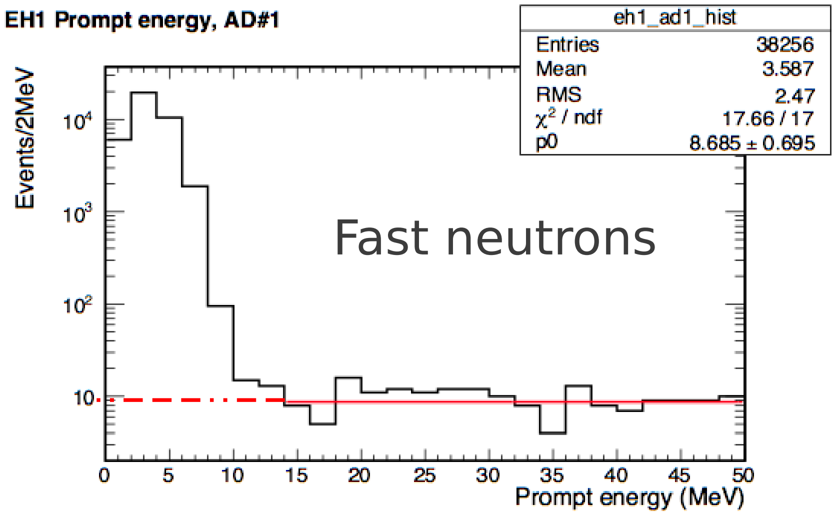
- Above radioactive background
- Efficiently tags antineutrino signal

# Backgrounds

- **Uncorrelated**
  - *Accidentals: two uncorrelated events "accidentally" passing the cuts and mimic IBD events.*
- **Correlated**
  - *Muon spallation:*
    - *$\beta$-n decay: $^{9}Li$ / $^{8}He$*
    - *Fast neutrons*
  - *Correlated signals from $^{241}Am^{13}C$ neutron source*
  - *$^{13}C(\alpha,n)^{16}O$*



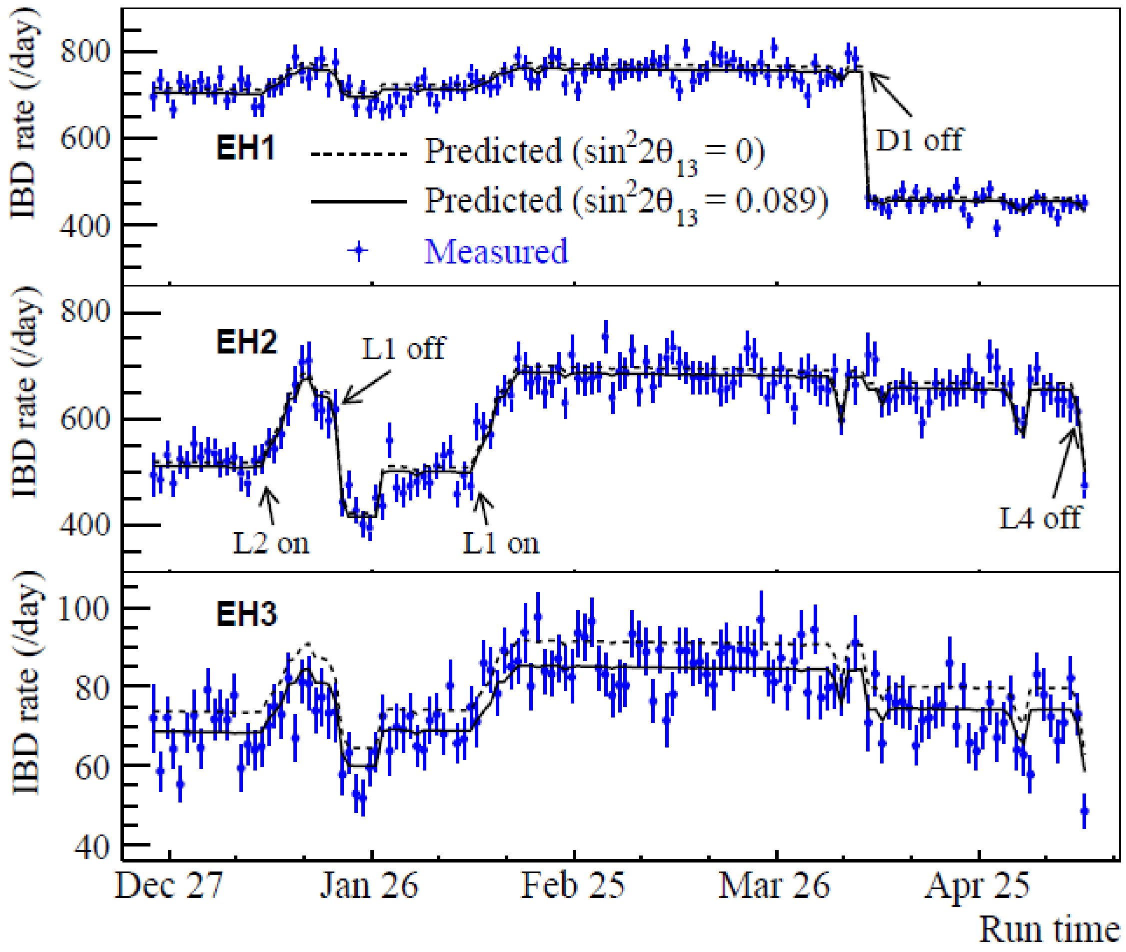




Total background are about 2% (5%) in the near (far) hall

# Antineutrino Rate .vs. Time

Dec. 24, 2011 – May 11, 2012

**Over 200K antineutrino interactions are collected.**

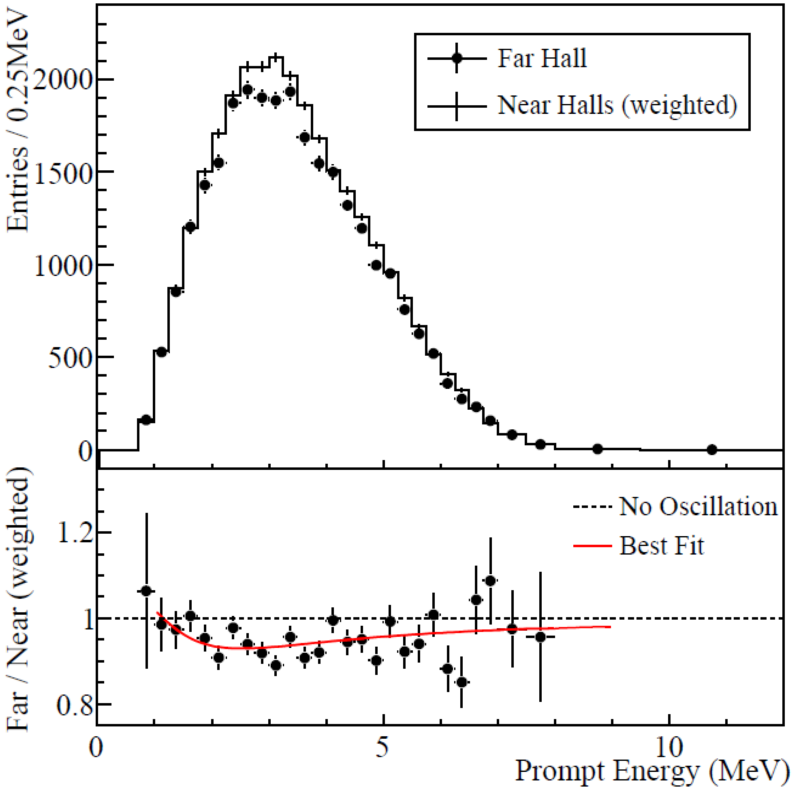


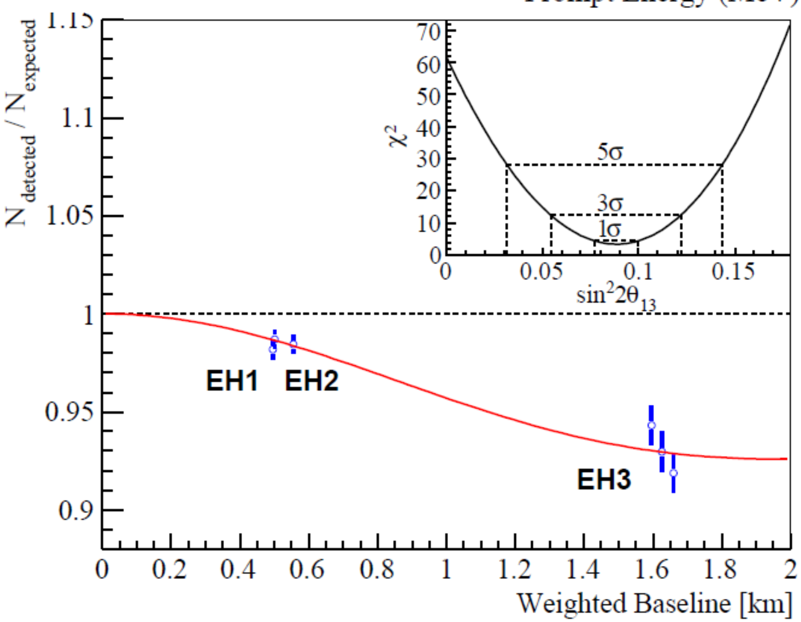

Detected rate strongly correlated with reactor flux expectations.

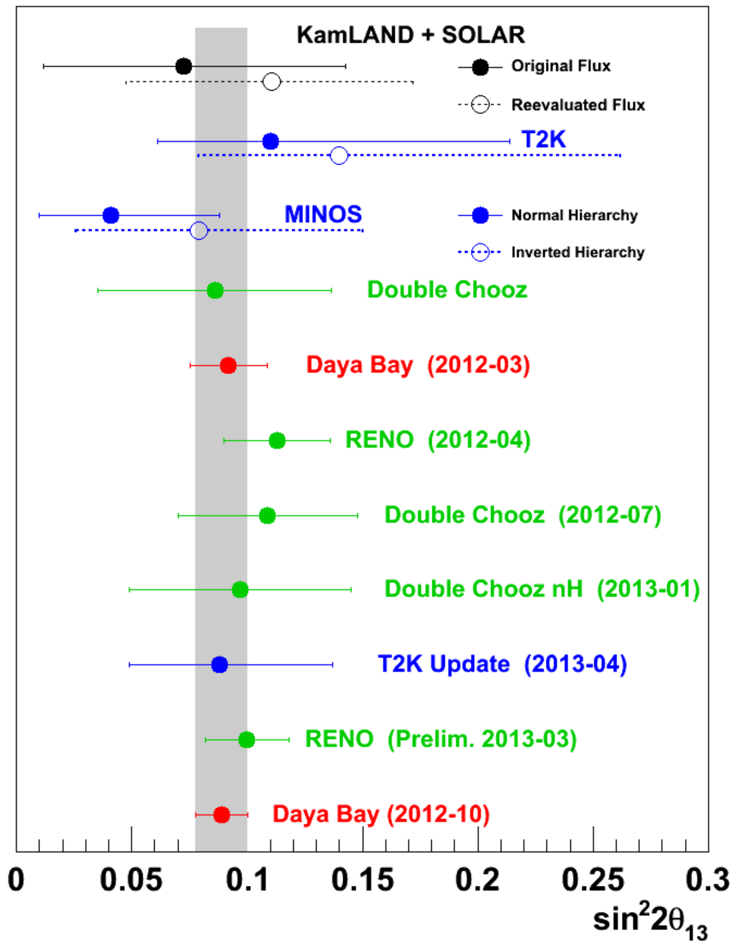
Predicted Rate: (in figure)

- Assumes no oscillation.
- Normalization is determined by fit to data.
- Absolute normalization is within a few percent of expectations.

# Rate Analysis




**$\sin^2 2\theta_{13} = 0$ excluded at 7.7σ**

**$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) $\pm 0.005$ (syst)**

**Most precise measurement of $\sin^2 2\theta_{13}$ to date.**

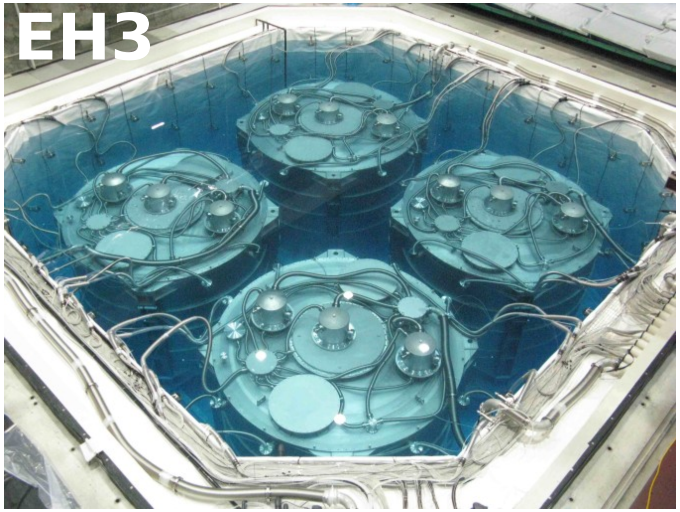
# Future Physics Goals of Daya Bay

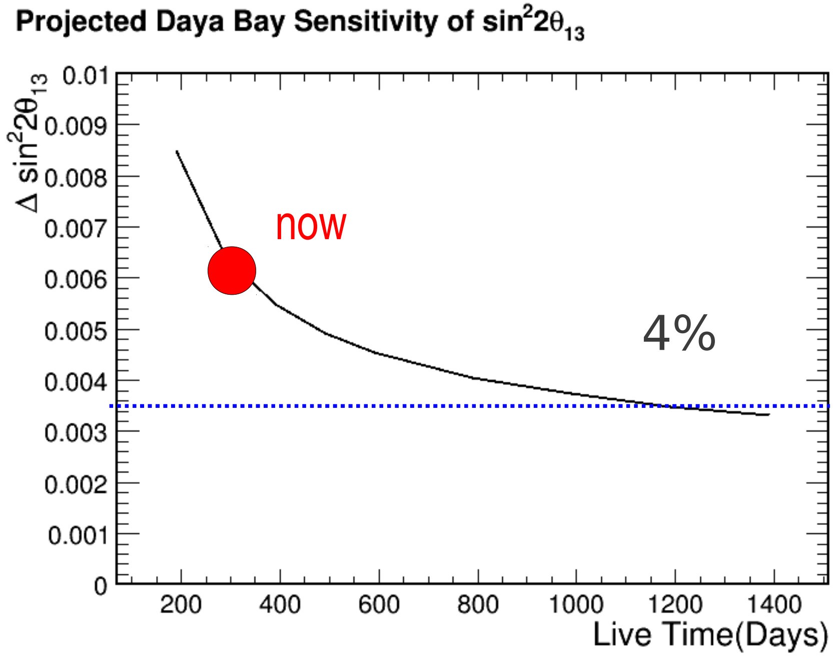
## Primary physics goals

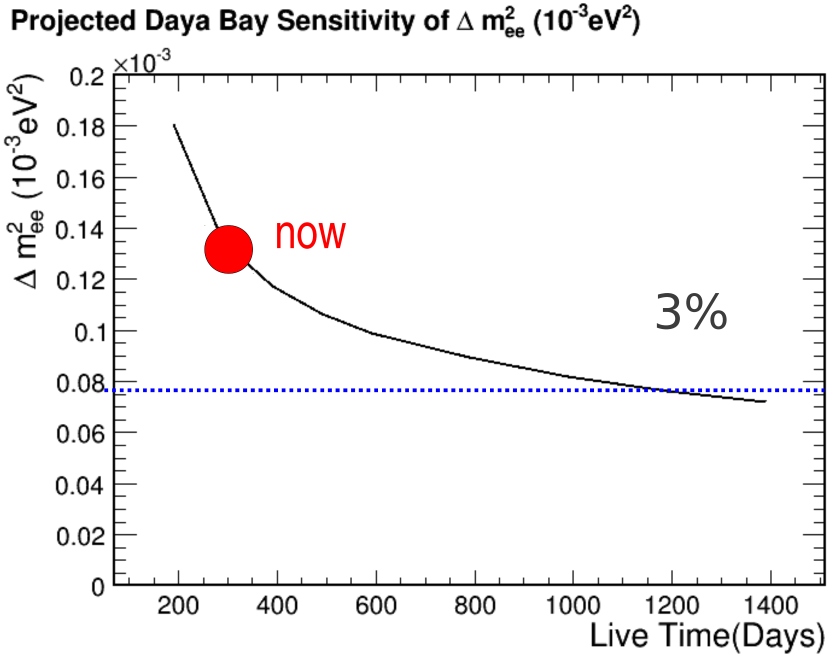
- Precision measurement of $\sin^2 2\theta_{13}$
- Measurement of $\Delta m^2_{ee}$

## Additional physics goals

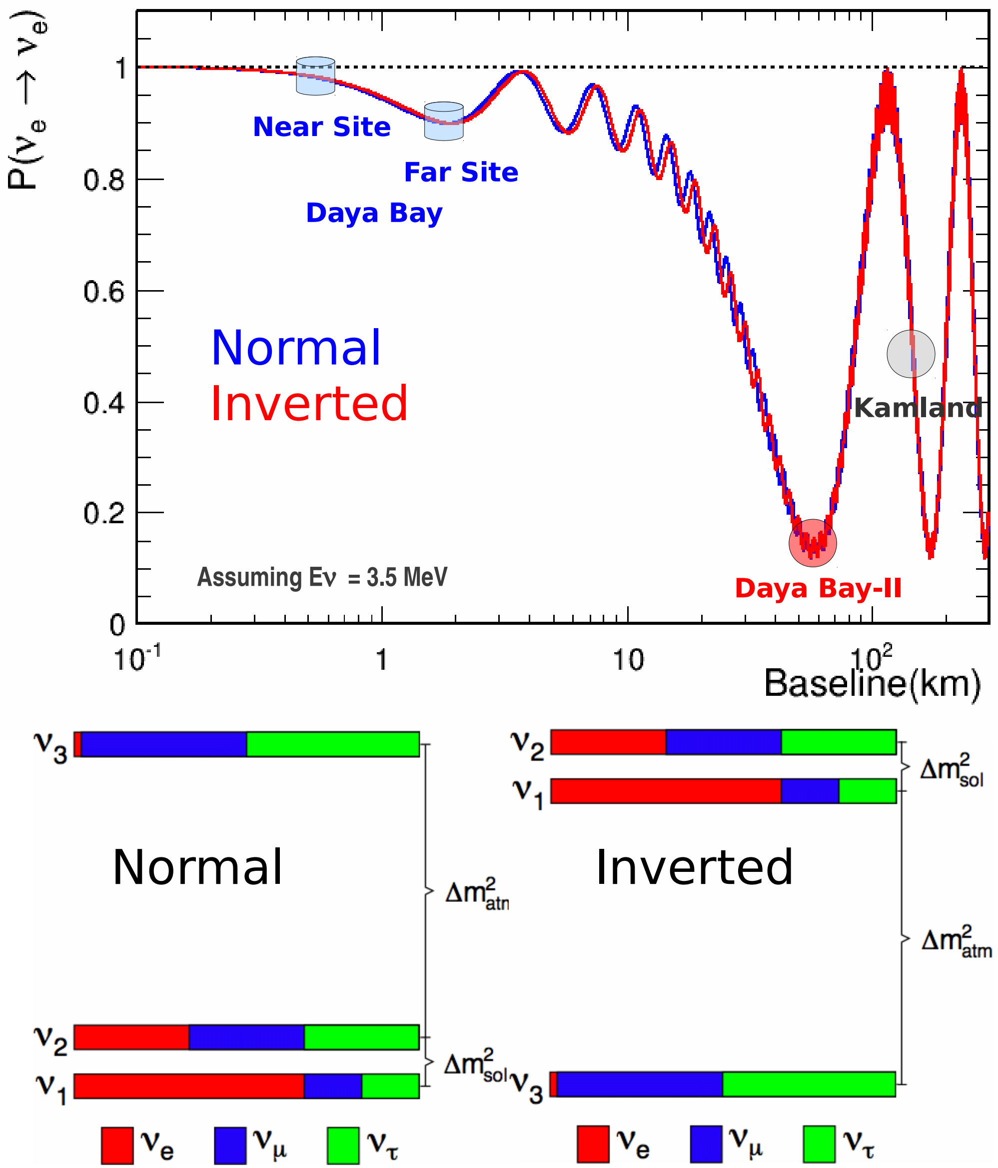
- Precise reactor flux and spectrum measurement.
- Measurement of cosmogenic neutrons & isotopes over a range of muon energies and depth.



# Daya Bay II Experiment

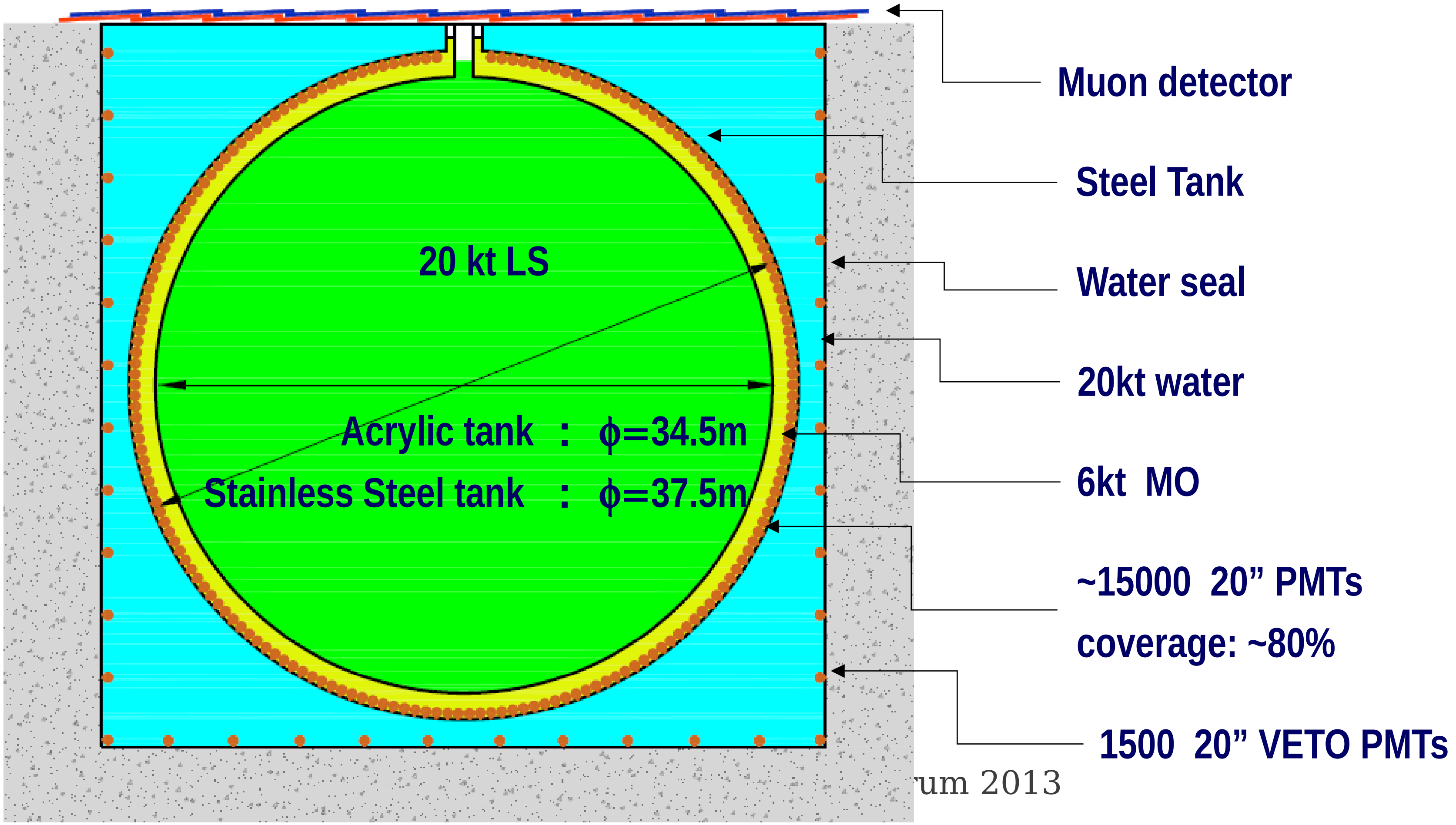



- **58 km baseline**
- **20 kton LS detector**
- **2-3 % energy resolution**
- **Sub-percent scale absolute energy nonlinearity**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 4 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Exotic searches**

# Detector Technology: a Large LS Detector

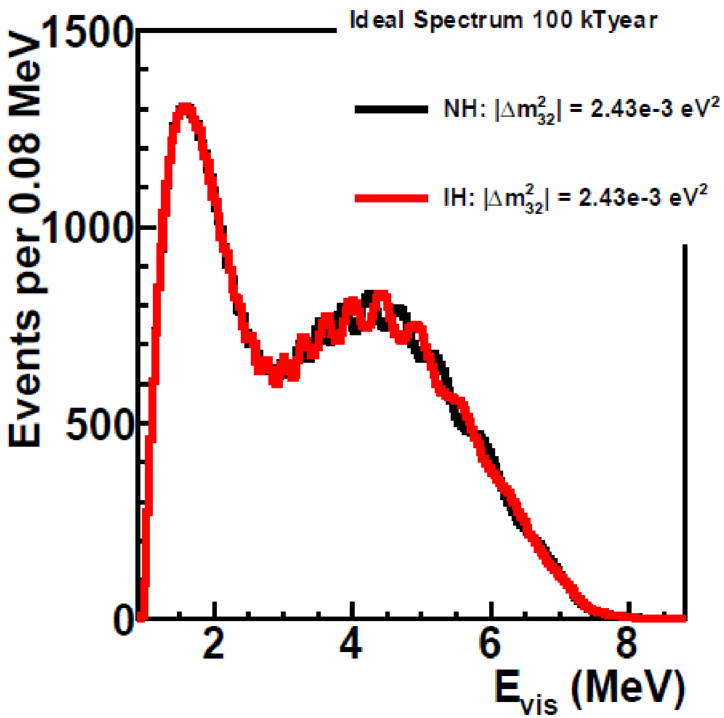
| | KamLAND | Daya Bay II |
|---|---|---|
| **LS mass** | **~1 kt** | **20 kt** |
| **Energy Resolution** | **6%/√E** | **3%/√E** |
| **Light yield** | **250 p.e./MeV** | **1200 p.e./MeV** |

**Challenging!**

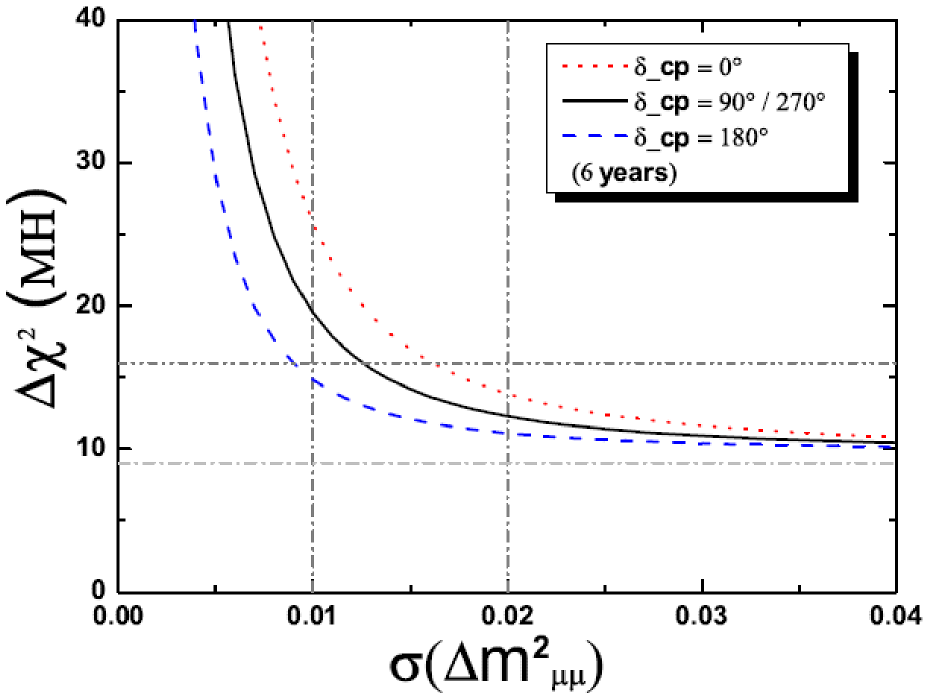


# Mass Hierarchy Sensitivity

arXiv: 1208.1551 Q.Xin et.al




arXiv: 1303.6733 Y.F.Li et.al




With 6 years of data, assuming 3% resolution, 2% energy nonlinearity assuming known energy nonlinearity curve shape and with external T2K/NoυA $\Delta m^2_{\mu\mu}$ of 1.5%, Daya Bay II can achieve $\Delta\chi^2 = 14$.

# Precise Measurement of Mixing Parameters

- **Fundamental to the standard model and beyond**
- **Probing the unitarity of UPMNS to 1% level.**
  - Uncertainties from other oscillation parameters and systematic errors, mainly energy scale, are included.

| | Current | Daya Bay II |
|---|---|---|
| $\Delta m^2_{12}$ | 3% | 0.6% |
| $\Delta m^2_{23}$ | 5% | 0.6% |
| $\sin^2\theta_{12}$ | 6% | 0.7% |
| $\sin^2\theta_{23}$ | 20% | N/A |
| $\sin^2\theta_{13}$ | 14% → 4% | ~ 15% |

# Summary

- Neutrino physics is now in the precision era.
- Daya Bay's latest result ruled out $\theta_{13} = 0$ at more than 7 standard deviations

$$\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$$

- Spectrum analysis is underway.
- Daya Bay has been now running with full 8-AD configuration since Oct 2012.
- Daya Bay II experiment is boosted by the discovery of $\theta_{13}$.

Z. Isvan: “The Future of Long-baseline Neutrino Oscillation Experiment” (May 2, Neutrino/Cosmology session)

C. Zhang: “New Water-based Liquid Scintillator for Large Physics Experiment” (May 2, Neutrino/Cosmology session)