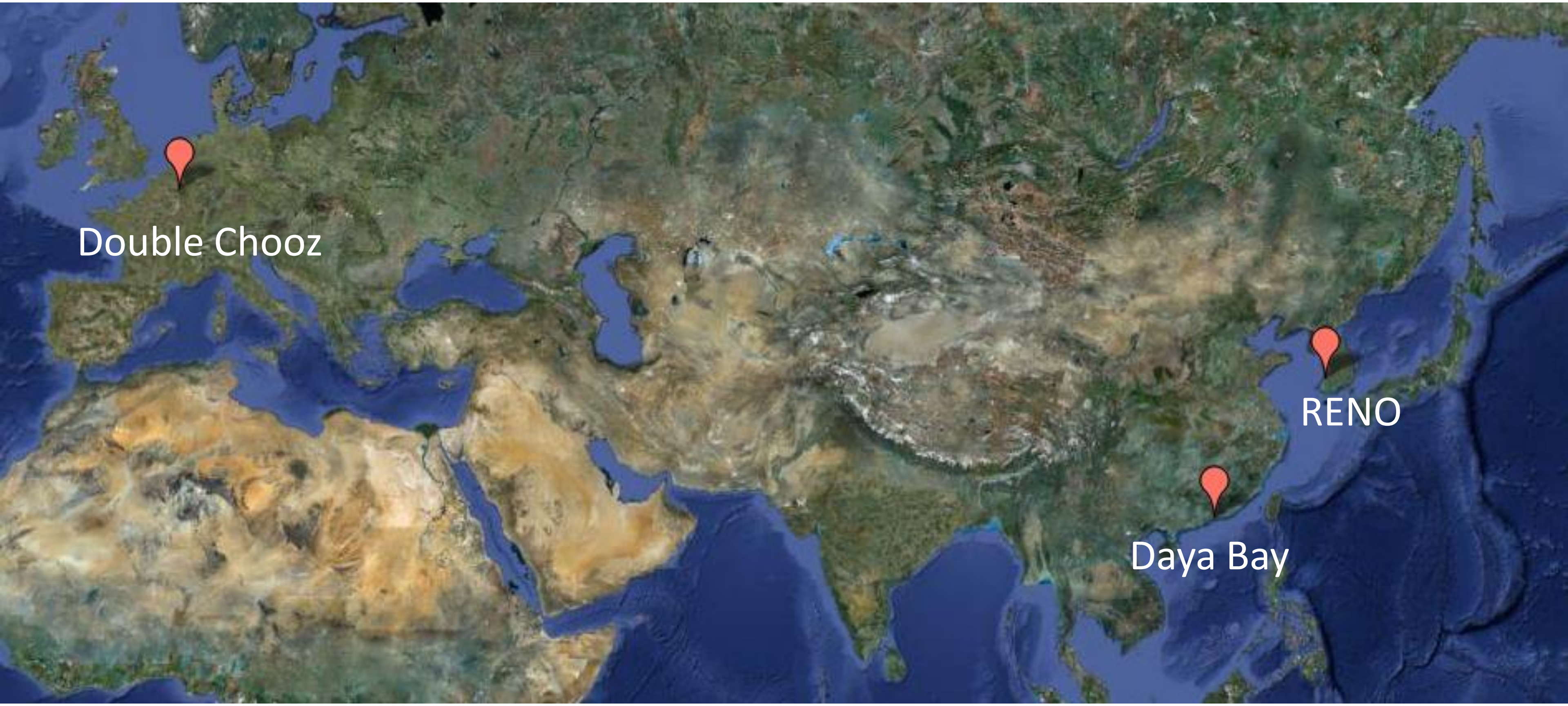
Measurement of θ_{13}



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Flavor Physics & CP Violation 2013 (FPCP 2013)

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Disclaimer

I am a member of the Daya Bay Collaboration.

Results from the Double Chooz and RENO collaborations are collected from previous publications or presentations. My apologies if I do not present their latest results or misinterpret them.

Physics Motivation

The small but finite neutrino rest mass predicts oscillation phenomena which can be utilized to measure mixing angles and mass differences. One of the mixing angles, θ_{13}, is intimately connected to leptonic CP violation which may be related to the matter-antimatter asymmetry of the universe.

Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle: Mass eigenstates ≠ Interaction (flavor) eigenstates

$$P_{\nu_e \to \nu_e}(t) = \left| \langle \nu_e(0) | \nu_e(t) \rangle \right|^2 = \left| \sum_{j=1}^{3} \langle \nu_j(0) | U_{ej}^* \sum_{i=1}^{3} e^{iE_i t} U_{ie} | \nu_i(0) \rangle \right|^2$$

Physical Parameters: (chosen by nature)

θ_{ij}: (appear in U)

3 angles between mass/flavor eigenstates set **oscillation amplitude**

Δm_{ij}^2: (appear in E_i-E_j as a function of p)

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

We want to know all θ and Δm^2

First Evidence of Oscillation:
Davis detects 1/3 expected solar neutrinos (1968)

A Decade of Progress

Many recent measurements of neutrino oscillation

$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

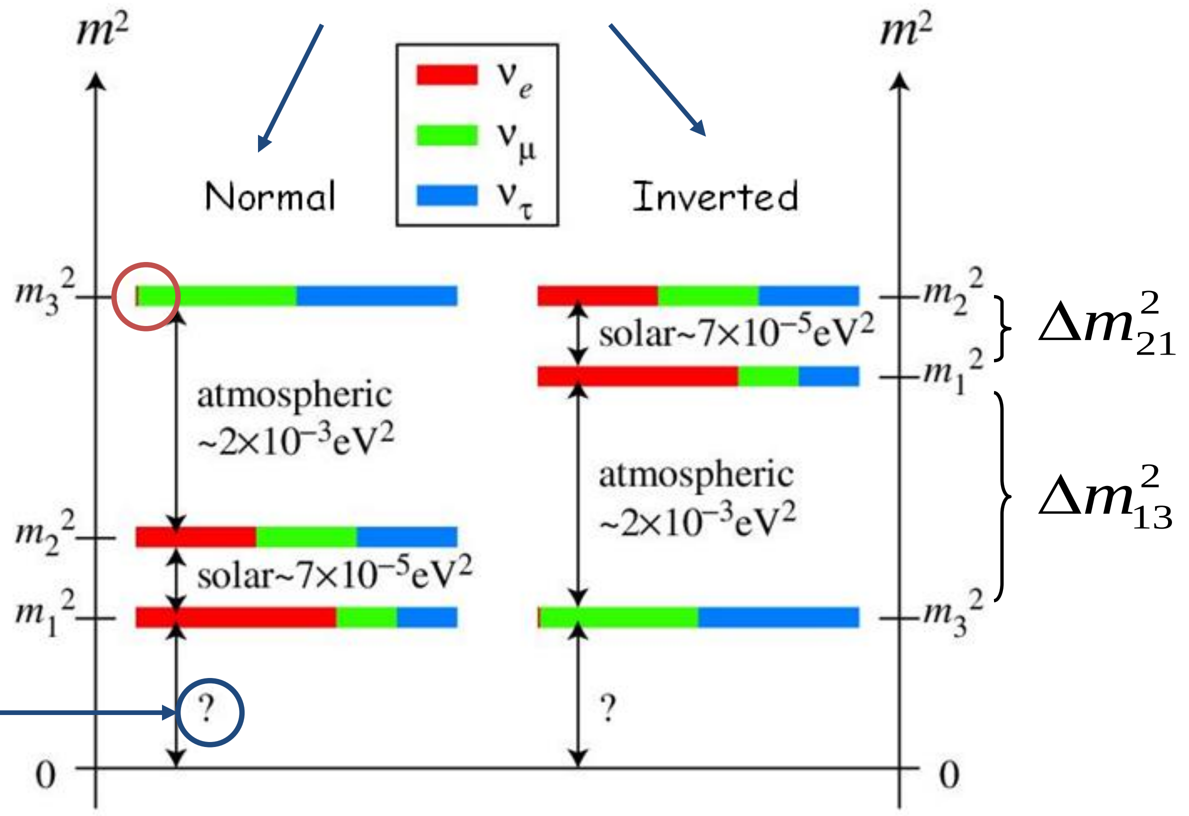
$\theta_{13} < 10^o$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 35^o$
Solar ν
Long-Baseline Reactor ν

θ_{13}: Only angle not yet firmly observed. It is the gateway to leptonic CP violation δ

❖Mass Hierarchy of Neutrinos

Which is the right mass hierarchy?



What is the rest mass of neutrinos?

Neutrino Survival Probability

Neutrino survival probability depends on mixing angles and time (baseline)

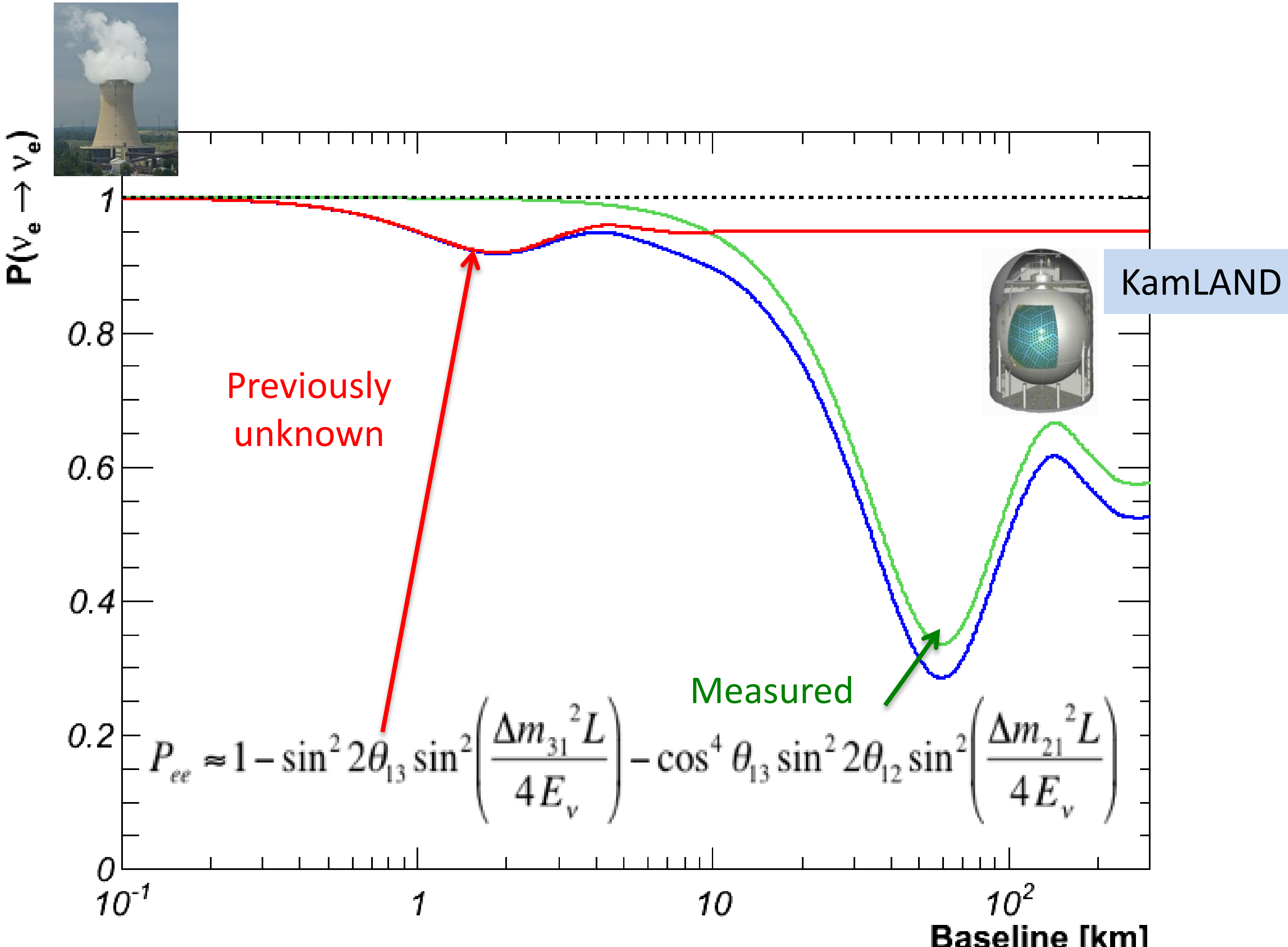
$$P_{\nu_e \to \nu_e}(t) = \left| \langle \nu_e(0) | \nu_e(t) \rangle \right|^2 = \left| \sum_{j=1}^{3} \langle \nu_j(0) | U_{ej}^{*} \sum_{i=1}^{3} e^{iE_i t} U_{ie} | \nu_i(0) \rangle \right|^2$$

$$P_{\nu_e \to \nu_e} = (c_{13}c_{12})^2 (c_{13}c_{12})^2 + (c_{13}s_{12})^2 (c_{13}s_{12})^2 (c_{13}s_{12})^2 + (s_{13})^2 (s_{13})^2$$
$$+ (c_{13}s_{12})^2 (c_{13}c_{12})^2 2\cos\left(\frac{\Delta m_{21}^2 t}{2p}\right) + (s_{13})^2 (c_{13}c_{12})^2 2\cos\left(\frac{\Delta m_{31}^2 t}{2p}\right)$$
$$+ (s_{13})^2 (c_{13}s_{12})^2 2\cos\left(\frac{\Delta m_{32}^2 t}{2p}\right)$$

$$P_{\nu_e \to \nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Reactor Neutrino Oscillation

θ_{13} revealed by a deficit of reactor antineutrinos at ~ 2 km.



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

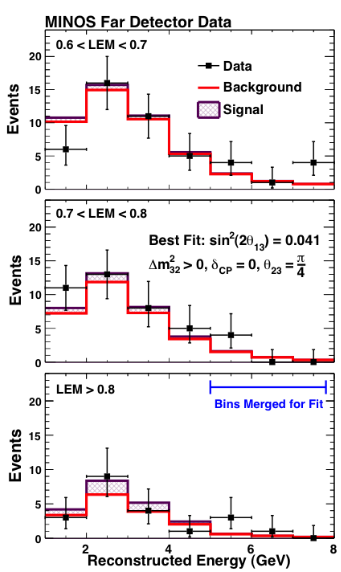
Early Hints of non-zero θ_{13}

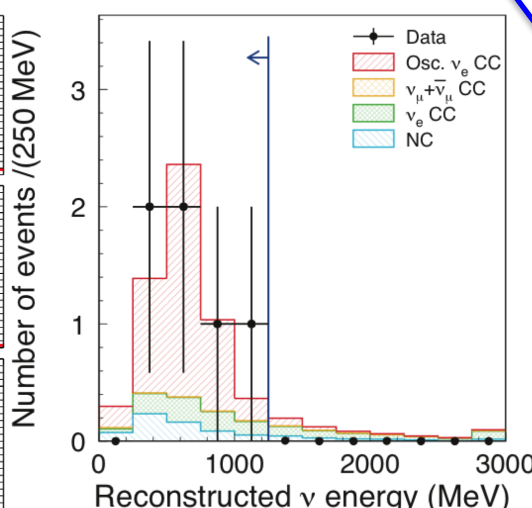
2011 has given many hints:

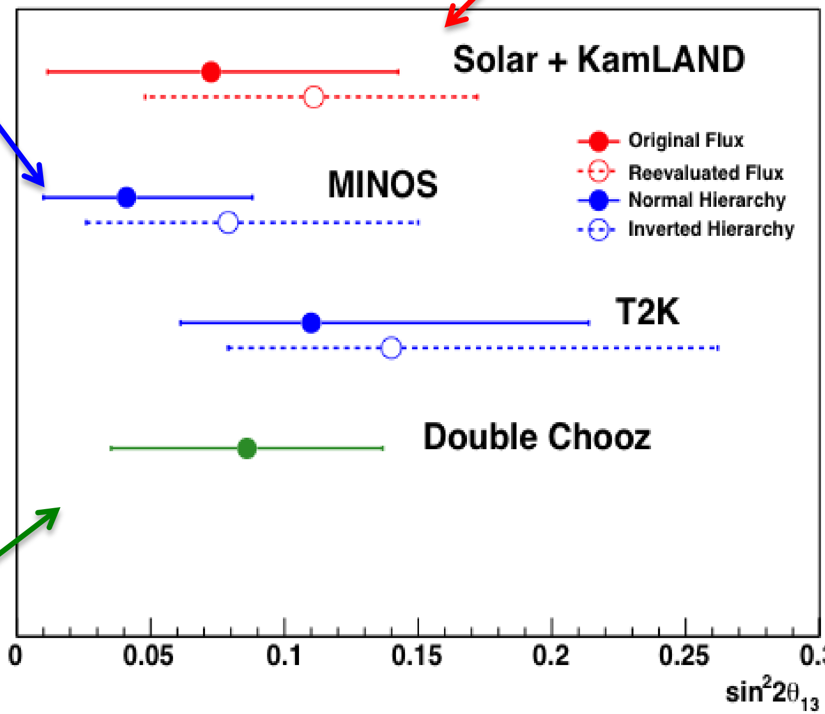
Solar + KamLAND: G.L.Fogli *et al.*, Phys. Rev. D 84, 053007 (2011)
MINOS: P. Adamson *et al.*, Phys. Rev. Lett. 107, 181802 (2011)
T2K: K. Abe *et al.*, Phys. Rev. Lett. 107 041801 (2011)
Double CHOOZ: Y. Abe *et al.*, arXiv:1112.6353

Summary of θ_{13} measurements before Daya Bay

Appearance of ν_e in ν_μ accelerator beam







Double Chooz reported improved single detector measurement.

No result >2.5σ from θ_{13} = 0 as of March 7, 2012

Design principles of Reactor-based experiments

In order to measure the potentially small θ_{13} to levels of 0.01 for $\sin^2 2\theta_{13}$, the experiments were designed to measure relative quantities with multiple functionally identical detectors, paying detailed attention to background rejection and control.

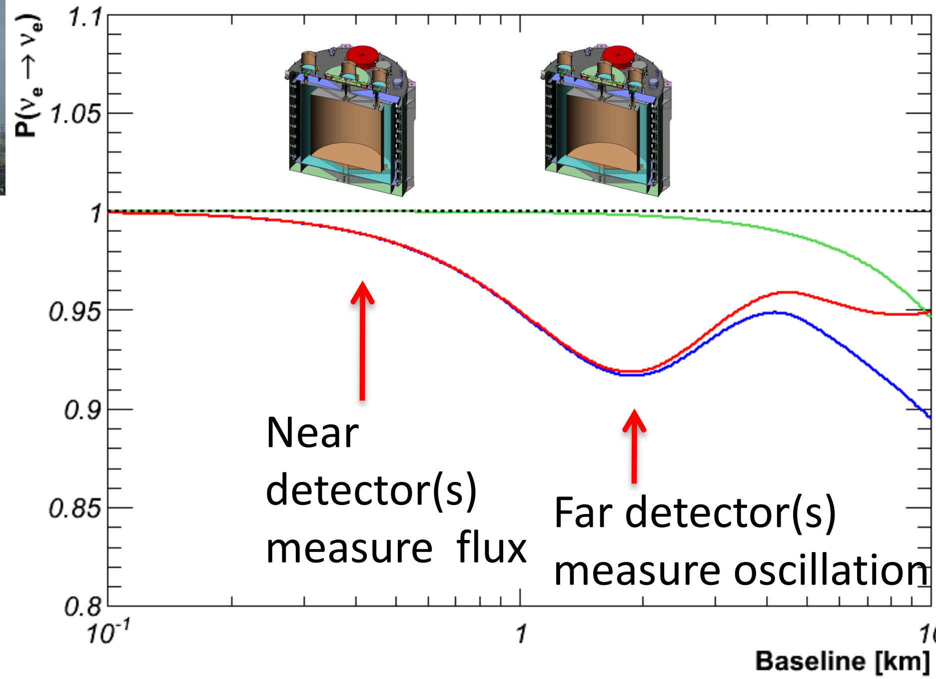
Relative Measurement

Absolute Reactor Flux:

Largest uncertainty in previous measurements (~ 3%)

Relative Measurement:

Removes absolute uncertainties!



Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

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

Detector Target Mass

Detector efficiency

Detection Method

Inverse β-decay (IBD):

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

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

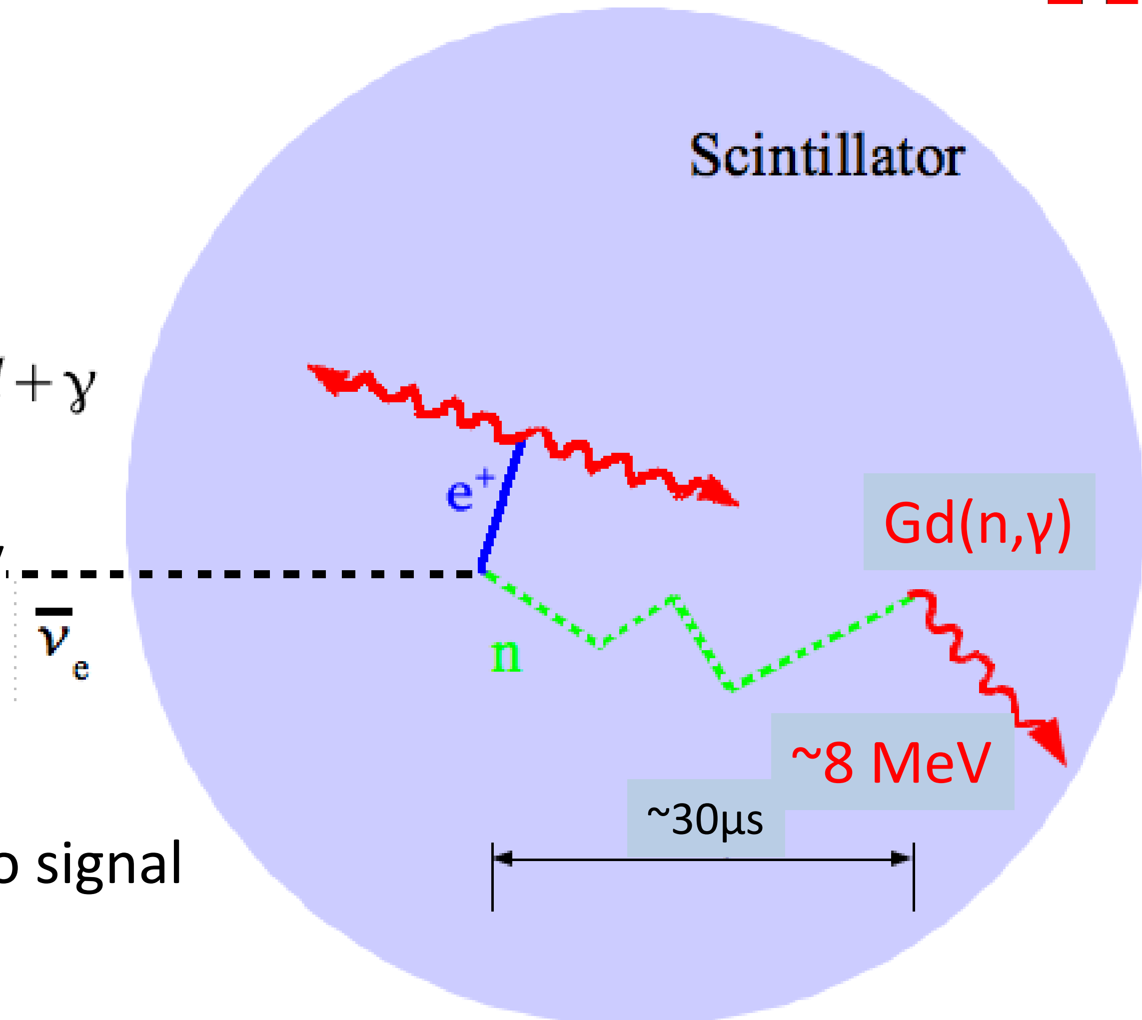
Prompt positron:

Carries antineutrino energy

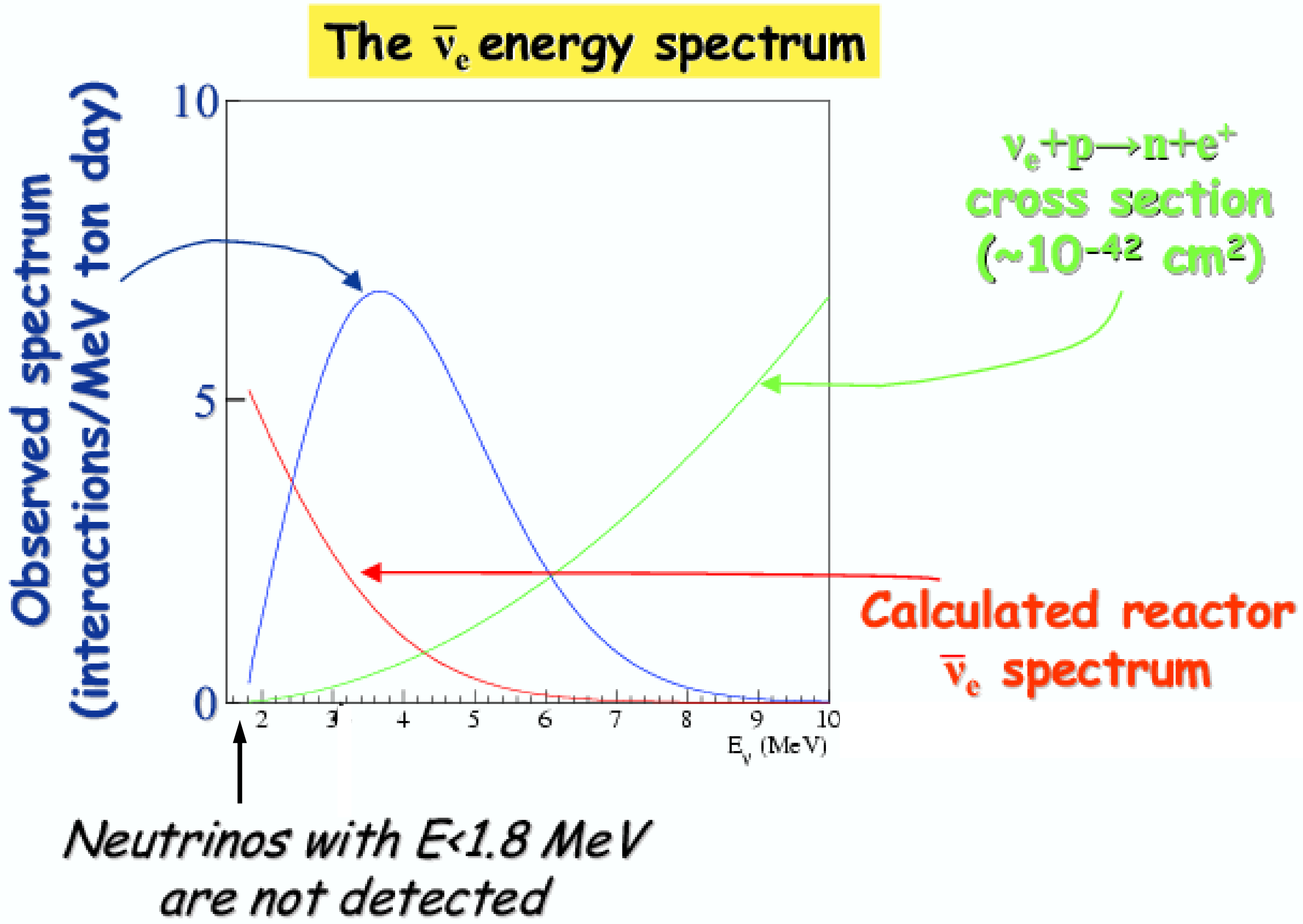
$E_{e+} \approx E_{\nu} - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature


The $\bar{\nu}_e$ energy spectrum
Observed spectrum
(interactions/MeV ton day)
10
5
0
2
3
4
5
6
7
8
9
10
E_ν (MeV)
$\nu_e + p \rightarrow n + e^+$
cross section
($\sim 10^{-42}$ cm^2)
Calculated reactor
$\bar{\nu}_e$ spectrum
Neutrinos with E<1.8 MeV
are not detected

Brief summary of θ_{13} reactor experiments

Experiment	Daya Bay	Double Chooz	RENO
Number of reactors & total power	3 (17.4 GW)	2 (9.4 GW)	6 (16.5 GW)
Reactor configuration	3	2	6 inline
Detector configuration	2 N +1 F	1 N +1 F	1 N +1F
Baseline (meter)	(364, 480, 1912)	(400, 1050)	(290,1380)
Overburden (mwe)	(280, 300, 880)	(120, 300)	(110, 450)
Detector medium	Gd-doped liquid scintillator (GdLS)		
Detector geometry	Concentric cylinders of GdLS, γ-catcher and Oil buffer		
Target mass (ton)	(40, 40, 80)	(10, 10)	(16.5, 16.5)
Outer shield	2.5 m water	0.50 m of LS + 0.15 m of Steel	1.5 of water
Muon veto	Water Cerenkov + RPC Cover	LS + Scintillator Strip Cover	Water Cerenkov

The Daya Bay Neutrino Experiment

A large international collaboration of about 230 members was formed to build and deploy eight modules, each with 20-t target mass, inside a mountain next to the Daya Bay Nuclear Power Plant Complex, 4 in two near halls and 4 in the far hall at distances of about 2km.

Daya Bay: An Ideal Location

17.4 GW (thermal) reactor power adjacent to mountains.

Daya Bay NPP 2.9GW×2

LingAo NPP 2.9GW×2

LingAo II NPP 2.9GW×2

Mountains shield detectors from cosmic ray backgrounds

Reactors produce ~2×10^{20} antineutrinos / s / GW

The Daya Bay Collaboration

~ 230 collaborators, 37 institutions

Europe (2) (~10)

Charles University, Czech Republic, JINR, Dubna, Russia

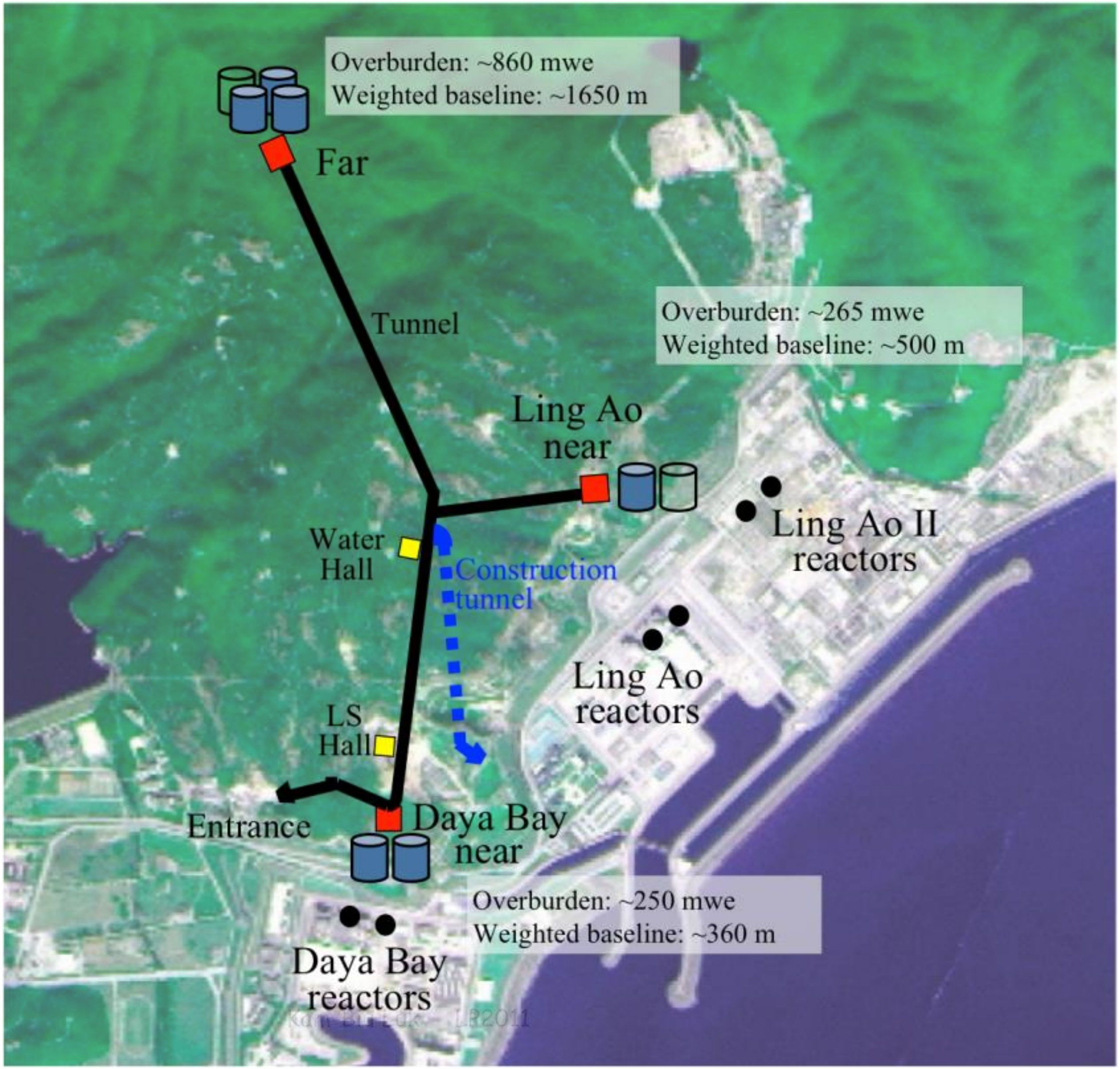
North America (16) (~100)

BNL, Caltech, Illinois Inst. Tech., Iowa State Univ., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Illinois-Urbana-Champaign, Univ. of Wisconsin-Madison, Virginia Tech., William and Mary

Asia (19) (~140)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., IHEP, Nanjing Univ., Nankai Univ., Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

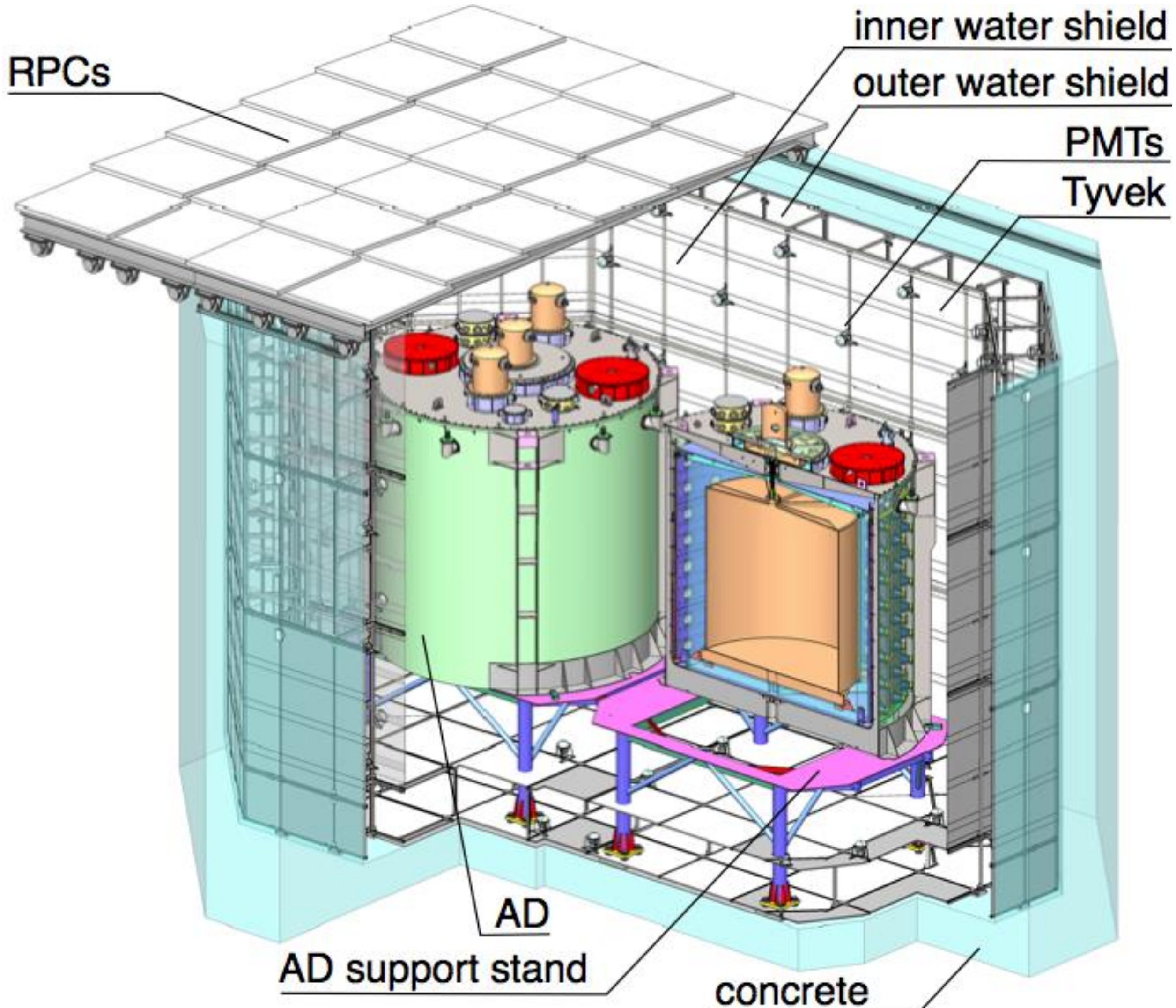
Experiment Layout



The Daya Bay Detector

ADs surrounded by > 2.5-meter thick two-section water shield and RPCs

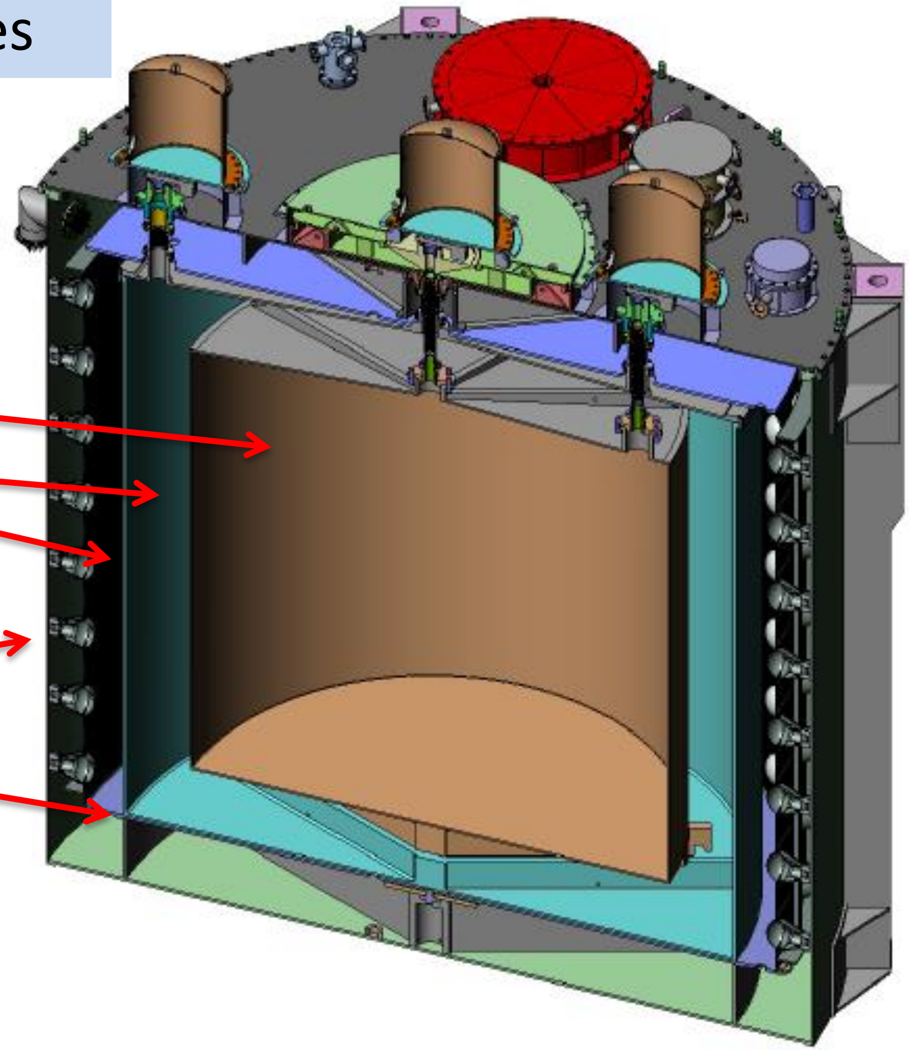
- Antineutrino detectors (ADs) are concentric acrylic tanks filled with liquid scintillator or mineral oil
- Inner and outer water shields are instrumented with
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall



Antineutrino Detectors

6 'functionally identical' detectors:
Reduce systematic uncertainties

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$



3 nested cylinders:

Inner: 20 tons Gd-doped LS (d=3m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:

192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution

Interior of Antineutrino Detector

Antineutrino IBD Event Selection

Use IBD Prompt + Delayed correlated signal to select antineutrinos

Selection:

- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  No other signal > 0.7 MeV
  in ±200 μs of IBD.

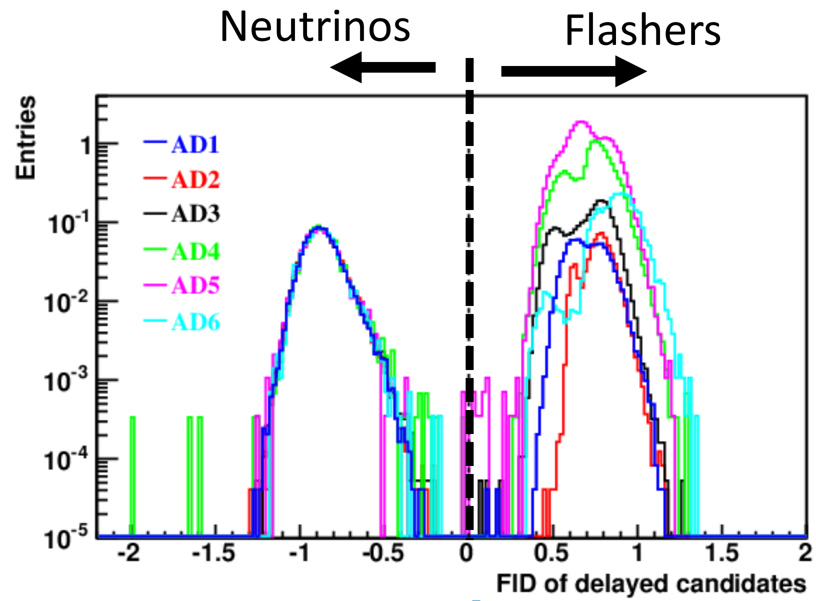
Selection driven by uncertainty in relative detector efficiency

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

PMT Light Emission (Flashing)

Flashing PMTs:

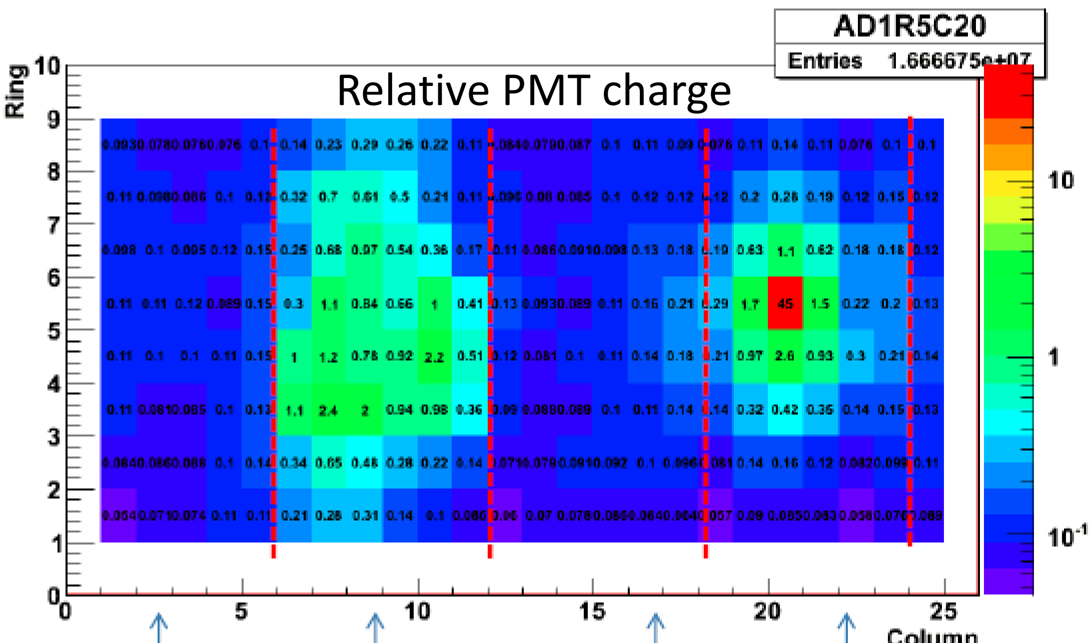
- Instrumental background from ~5% of PMTS
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals



$$FID = \log_{10}\left[\left(\frac{\text{Quadrant}}{1.0}\right)^2 + \left(\frac{\text{MaxQ}}{0.45}\right)^2\right] < 0$$

Quadrant = Q3/(Q2+Q4)

MaxQ = maxQ/sumQ

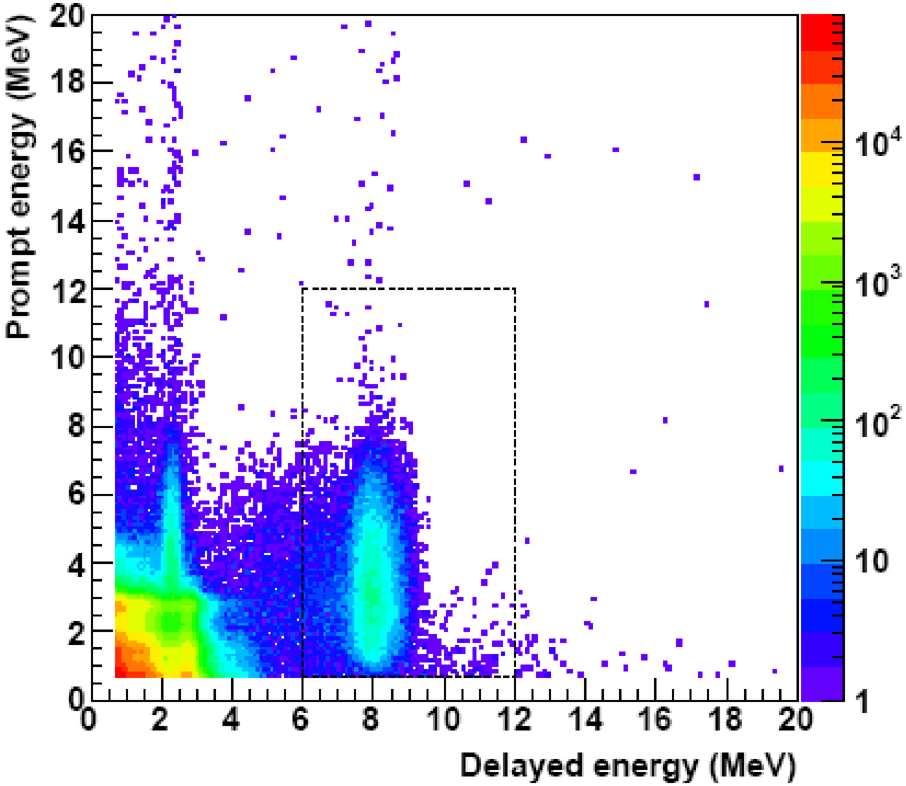


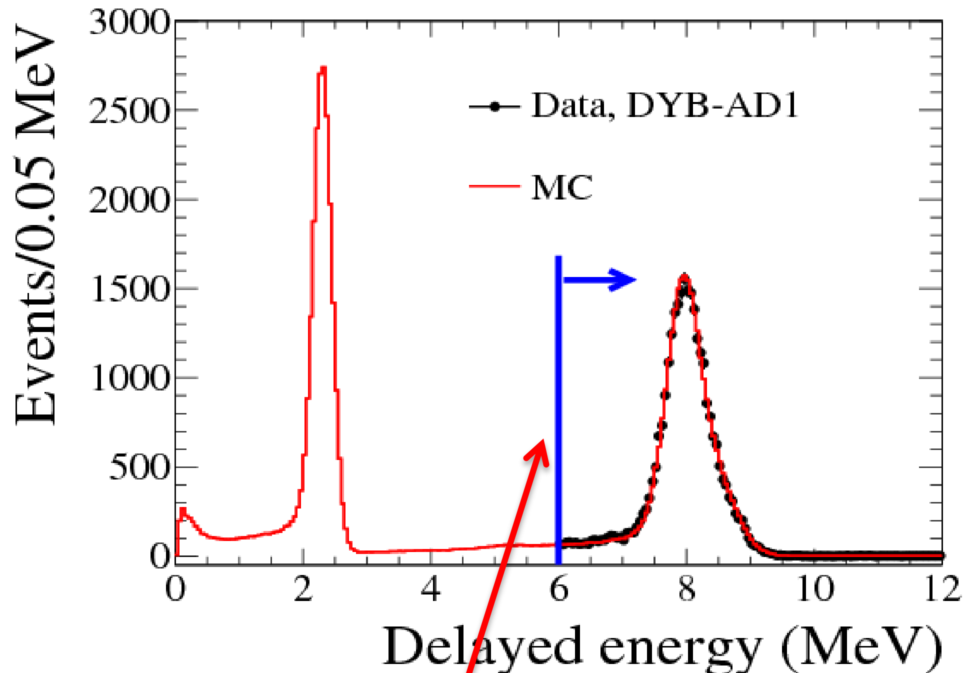
Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1
(contains ‘hottest’ PMT)

Inefficiency to antineutrinos signal:
$0.024\% \pm 0.006\%$(stat)
Contamination: < 0.01%

Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals

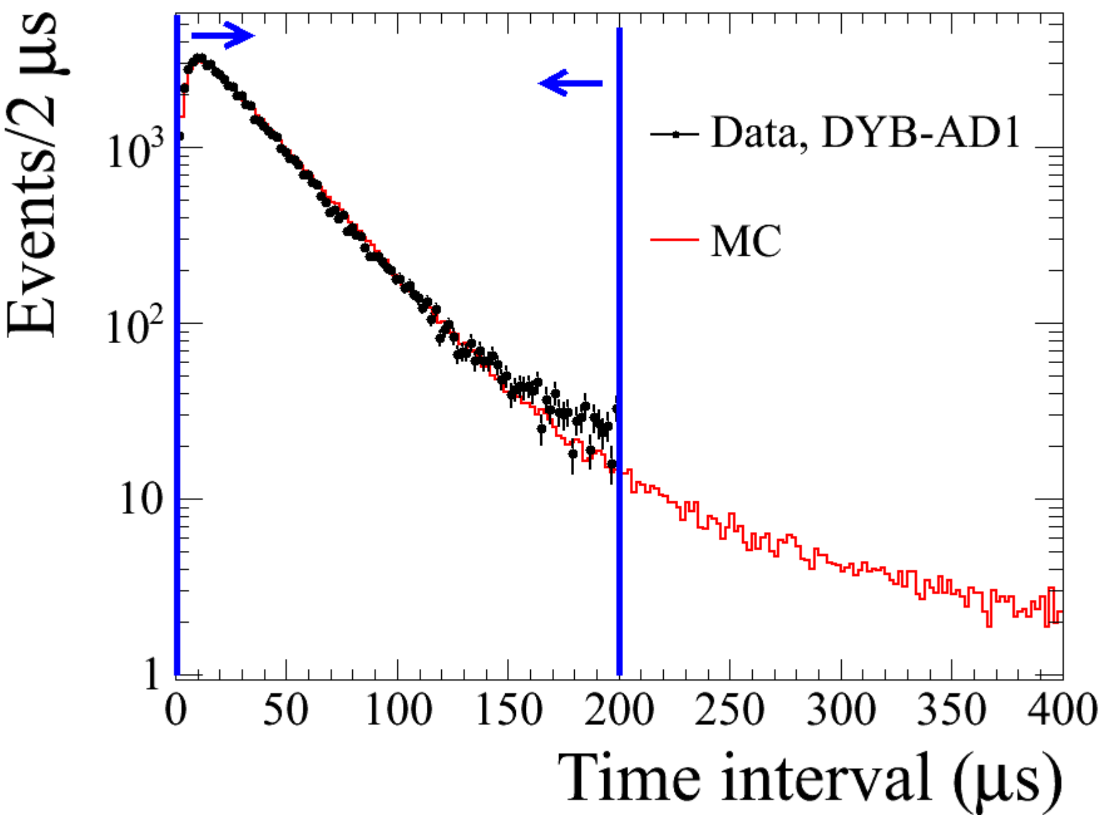




Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

Capture Time

Consistent IBD capture time measured in all detectors



Relative detector efficiency estimated within 0.02% by considering possible variations in Gd concentration.

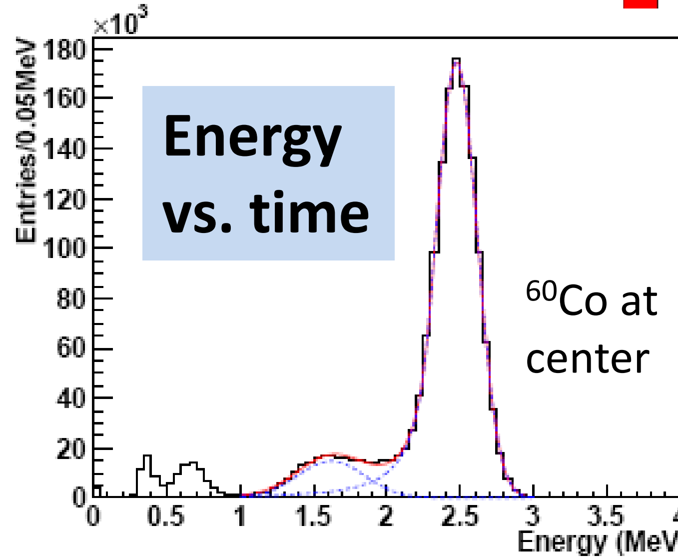
Simulation contains no background (deviates from data at >150 μs)

Calibration

Calibration driven by uncertainty in relative detector efficiency

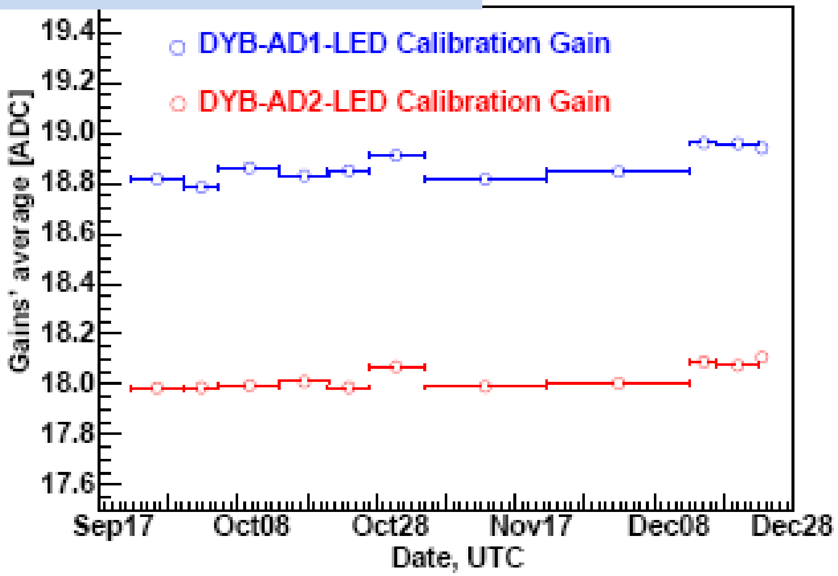
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E,L_{\mathrm{f}})}{P_{\mathrm{sur}}(E,L_{\mathrm{n}})}\right]$$

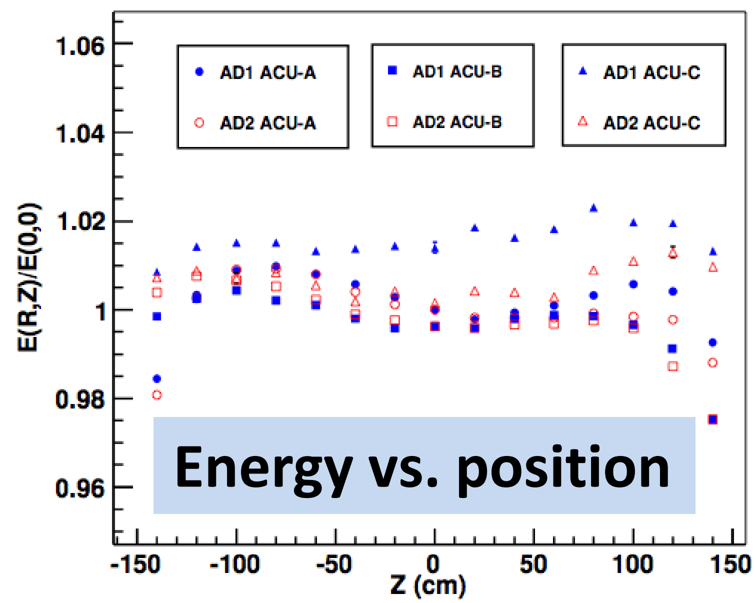
Energy vs. time



^{60}Co at center

PMT gain vs. time





Energy vs. position

Singles Spectrum

Uncorrelated signals dominated by low-energy radioactivity

Measured Rates:

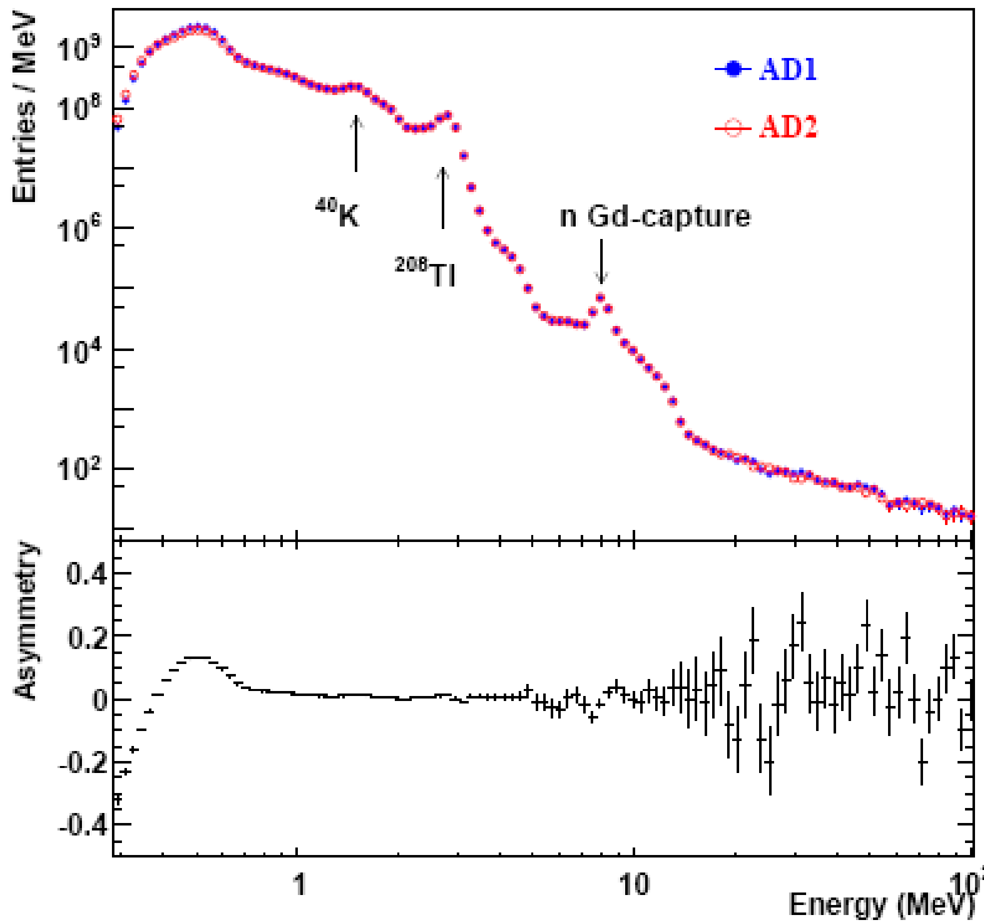
~65 Hz in each detector (>0.7 MeV)

Sources:

Stainless Steel: U/Th chains

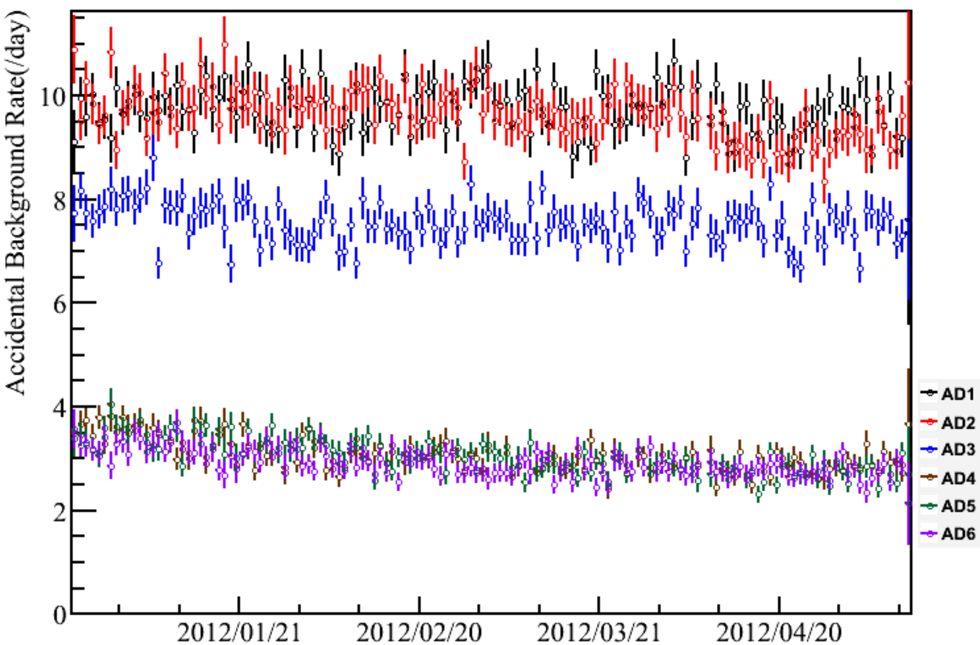
PMTs: ^{40}K, U/Th chains

Scintillator: Radon/U/Th chains



Accidental Background

- Calculation:
  - Random coincidence of neutron-like singles and prompt signals
- Cross check:
  - Prompt-delayed distance distribution. Check the fraction of prompt-delayed with distance >2m.



Accidental background rates (per day), muon veto and multiplicity cut eff corrected

	AD1	AD2	AD3	AD4	AD5	AD6
Accidentals (per day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03

Fast neutron Background

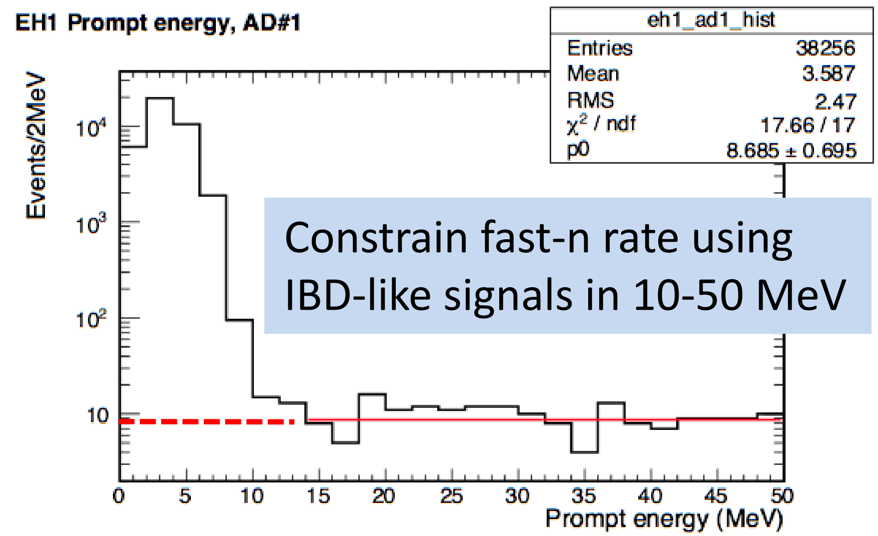
Fast Neutrons:

Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

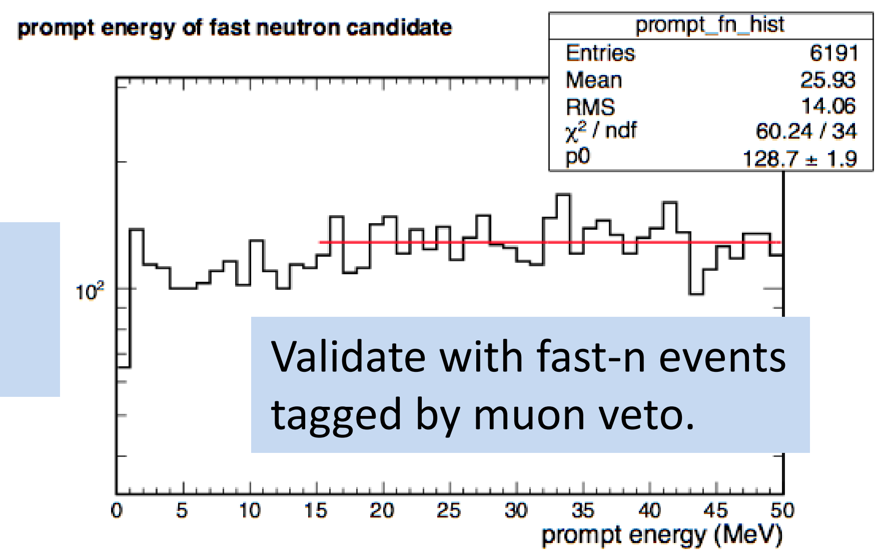
Mimics antineutrino (IBD) signal:

- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

Background uncertainties are 0.3% (0.2%) in far (near) halls.



Constrain fast-n rate using IBD-like signals in 10-50 MeV

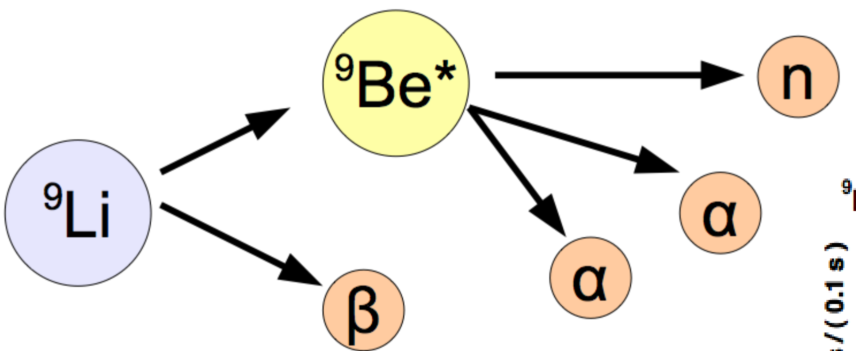


Validate with fast-n events tagged by muon veto.

β-n decay Background

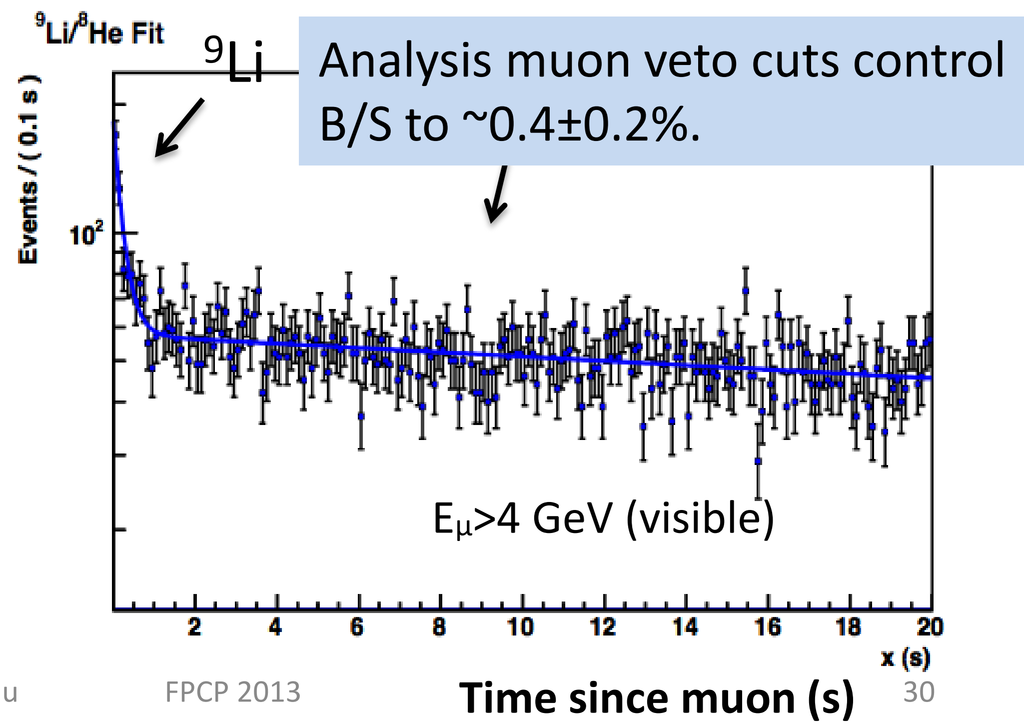
- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal
- Estimate ^{9}Li rate using time-correlation with muon

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{1/2} = 178$ ms, Q = 13.6 MeV

^{8}He: $\tau_{1/2} = 119$ ms, Q = 10.6 MeV



Summary of Backgrounds

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
^{9}Li/^{8}He	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
^{13}C(α, n)^{16}O	0.01	0.006	0.05	0.03

Total backgrounds are 5% (2%) in far (near) halls.

Data Set Summary

> 200k antineutrino interactions!

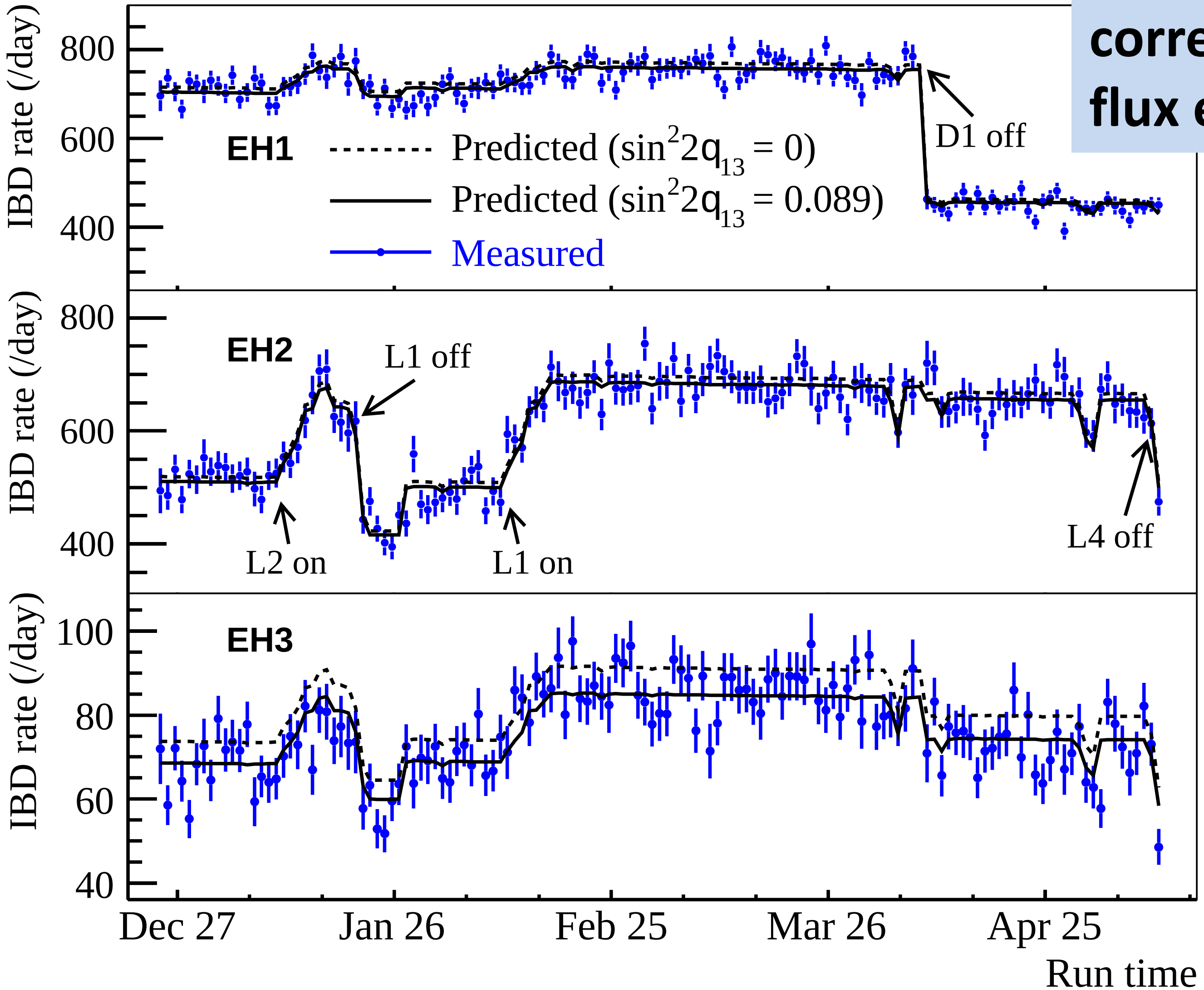
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763		126.2646	
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73 ± 0.10	9.61 ± 0.10	7.55 ± 0.08	3.05 ± 0.04	3.04 ± 0.04	2.93 ± 0.03
Fast neutron (/day)	0.77 ± 0.24	0.77 ± 0.24	0.58 ± 0.33	0.05 ± 0.02	0.05 ± 0.02	0.05 ± 0.02
^{8}He/^{9}Li (/day)	2.9 ± 1.5		2.0 ± 1.1		0.22 ± 0.12	
Am-C corr. (/day)	0.2 ± 0.2					
^{13}C(α, n)^{16}O (/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
Antineutrino rate (/day)	**662.47 $\pm$3.00**	**670.87 $\pm$3.01**	**613.53 $\pm$2.69**	**77.57 $\pm$0.85**	**76.62 $\pm$0.85**	**74.97 $\pm$0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

Daya Bay IBD Daily Rates

Detected rate strongly correlated with reactor flux expectations.

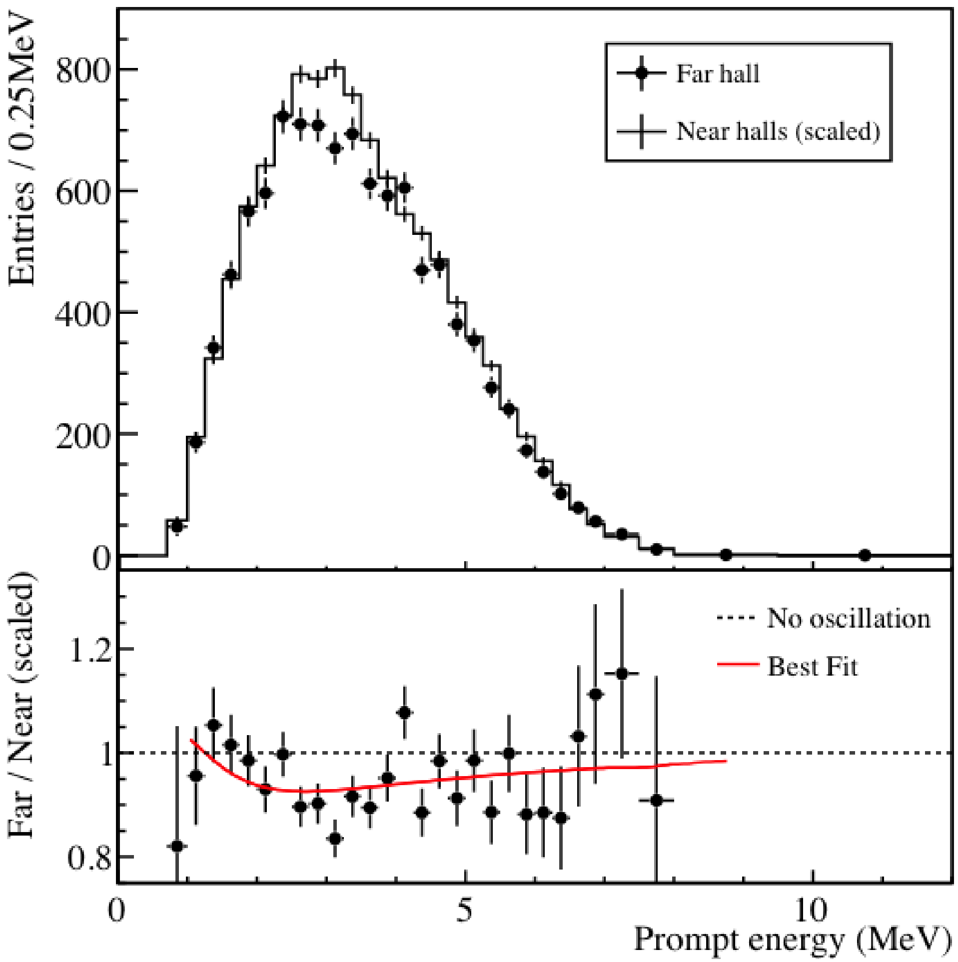


Predicted Rate:

- Normalization is determined by data fit.
- Absolute normalization is within a few percent of expectations.

Far vs. Near Comparison

Compare the far/near measured rates and spectra



$$R = \frac{\mathrm{Far}_{\mathrm{measured}}}{\mathrm{Far}_{\mathrm{expected}}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6} (\alpha_i (M_1 + M_2) + \beta_i M_3}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

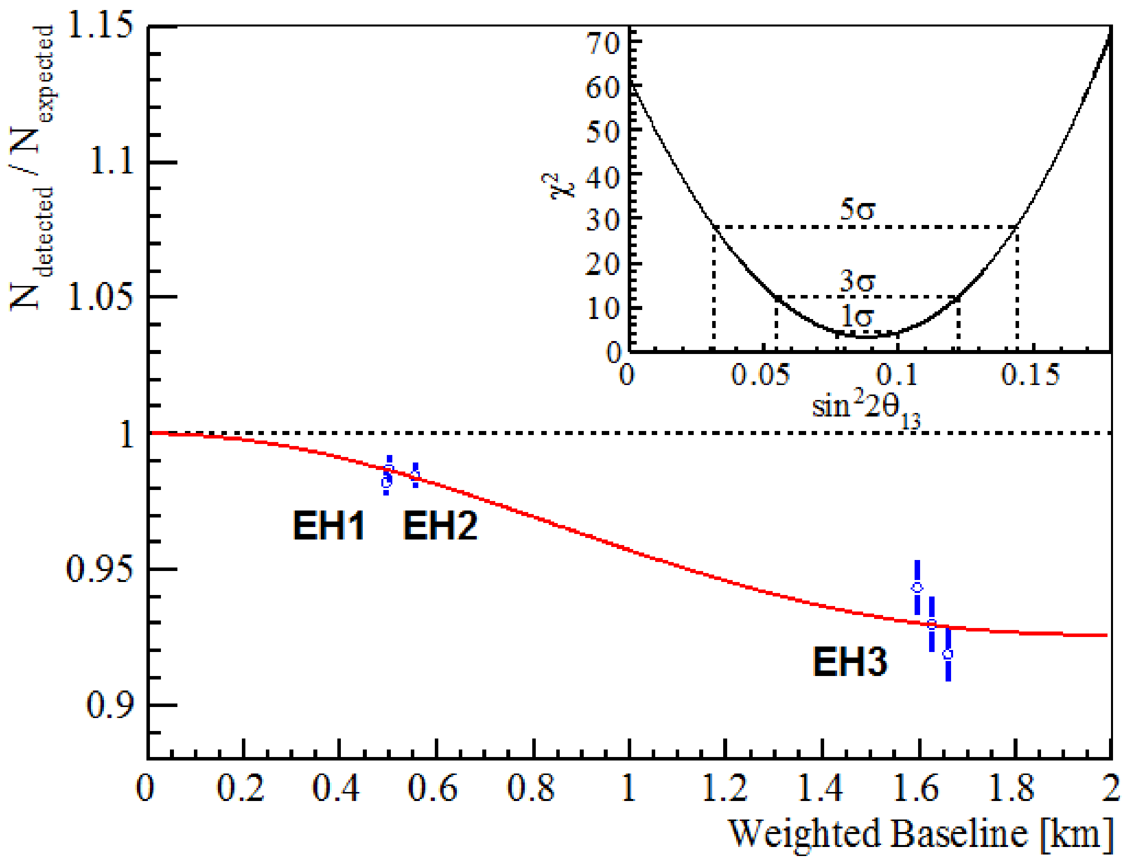
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

Far vs. near relative measurement.
[Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.

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

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

RENO

A collaboration of about 40 members from 12 Korean institutions. The antineutrinos are from 6 reactors on a straight line. There are 1 far and 1 near detectors, 16.5 tons of Gd-loaded liquid scintillator each, both located inside a mountain.

RENO Collaboration

(12 institutions and 40 physicists)

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

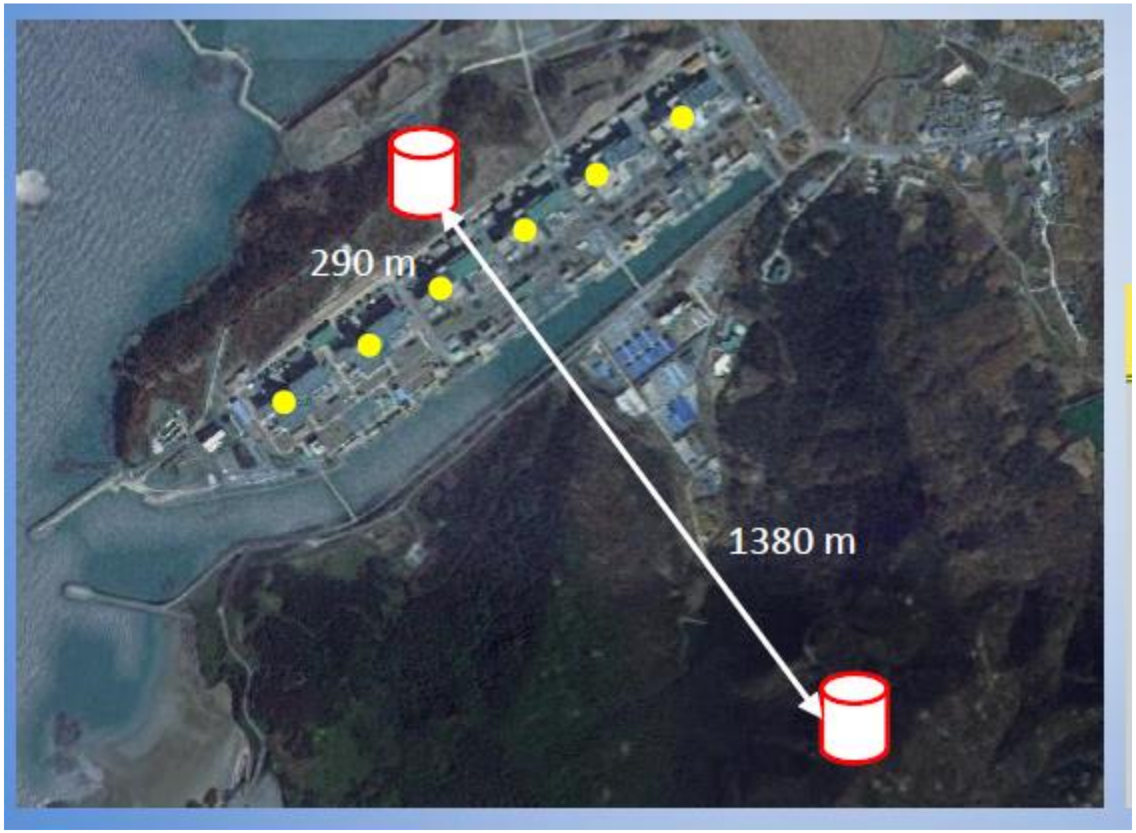
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

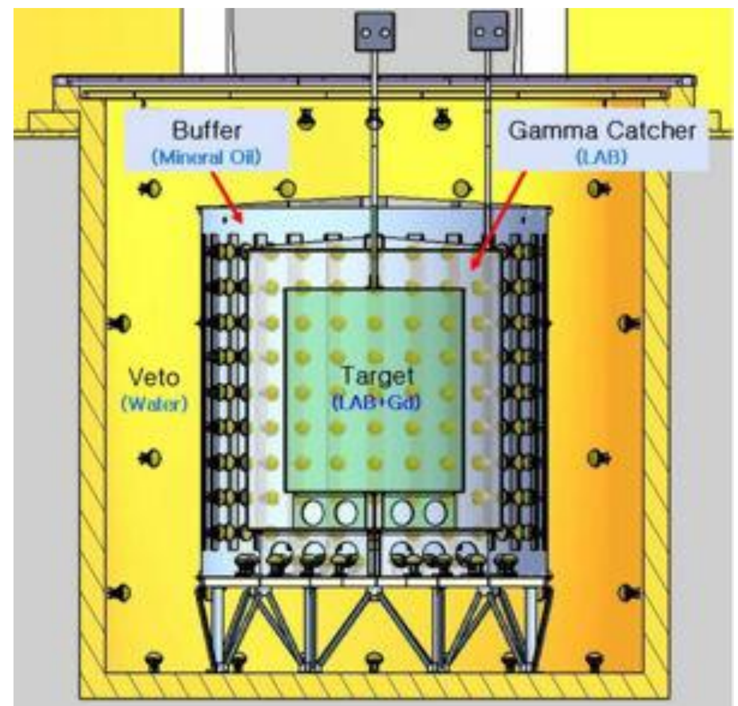
YongGwang (靈光) :

RENO Experiment

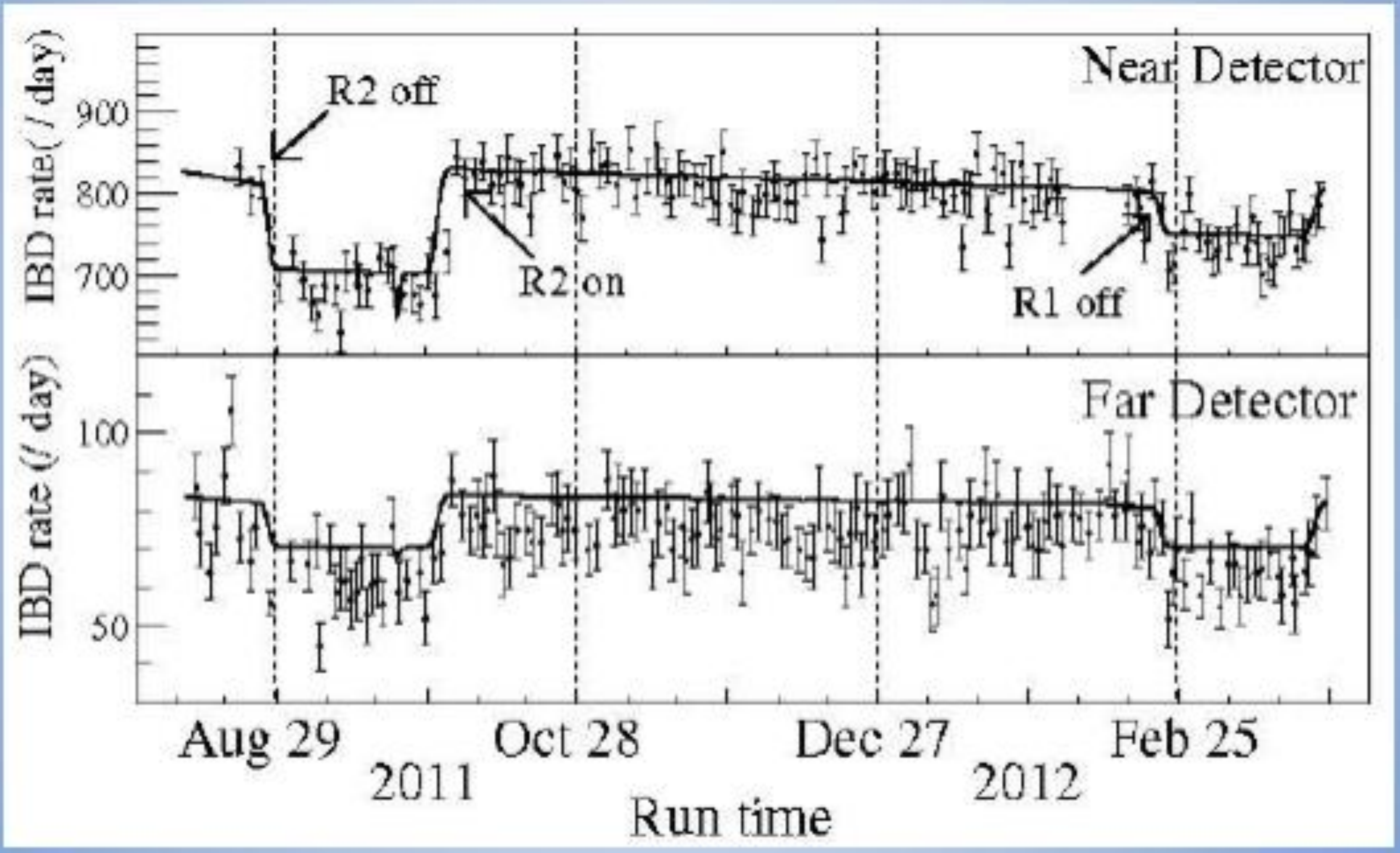
Reactors: 6 x 2.8 GW_{th}

Detectors: Near and Far
- Each 16.5 t Gd loaded scintillator



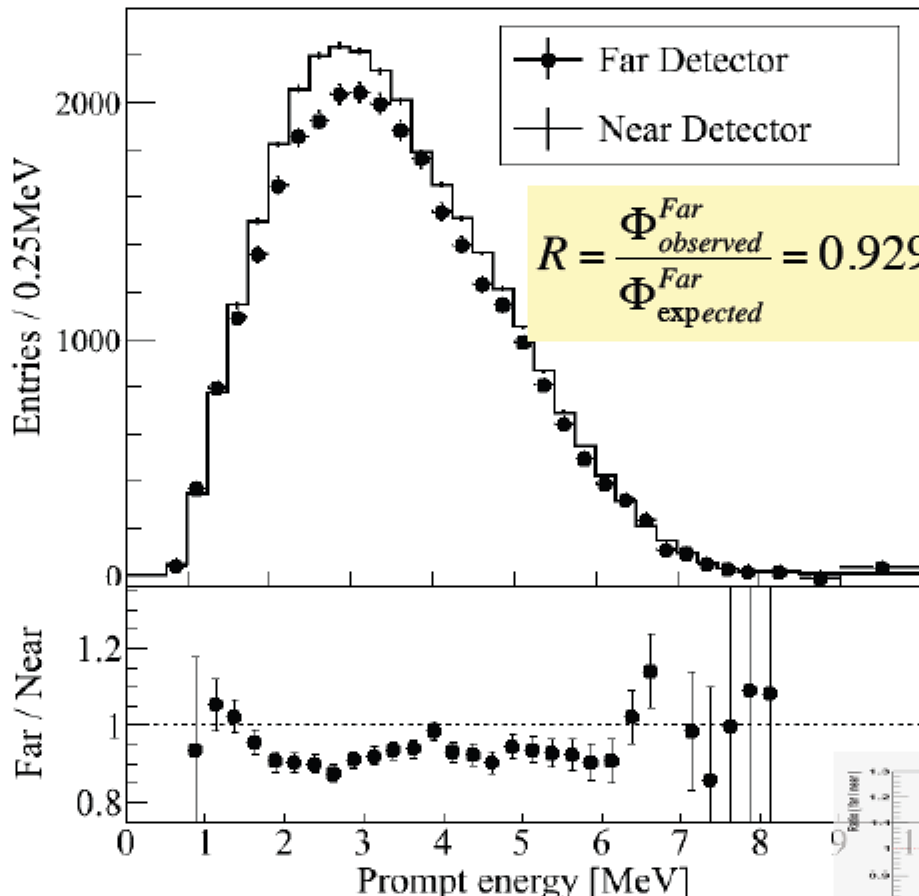


Reno Daily IBD Rate



RENO (NuTel 2013 Seon-Hee Seo)

Reactor Antineutrino Disappearance

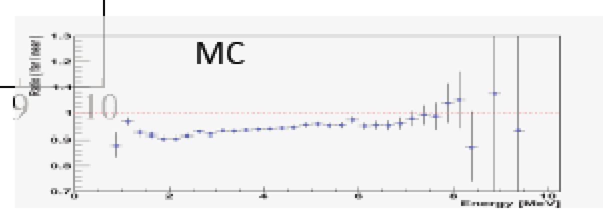


preliminary

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat.) \pm 0.009(syst.)$$

- A clear deficit in rate

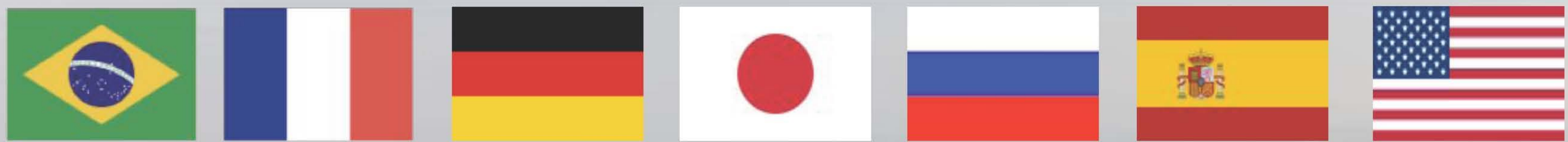
  (7 % reduction)
- Consistent with neutrino oscillation in the spectral distortion



Double Chooz

A large international collaboration of about 200 members. Both far and near detectors are 10 m^3 of Gd-loaded liquid scintillator. The far detector was completed in April 2011, while the near detector is still under construction with expected completion date in2013.

Double Chooz collaboration



Brazil
- CBPF
- UNICAMP
- UFABC

France
- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

Japan
- Tohoku U.
- Tokyo Inst. Tech.
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst. Tech.

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

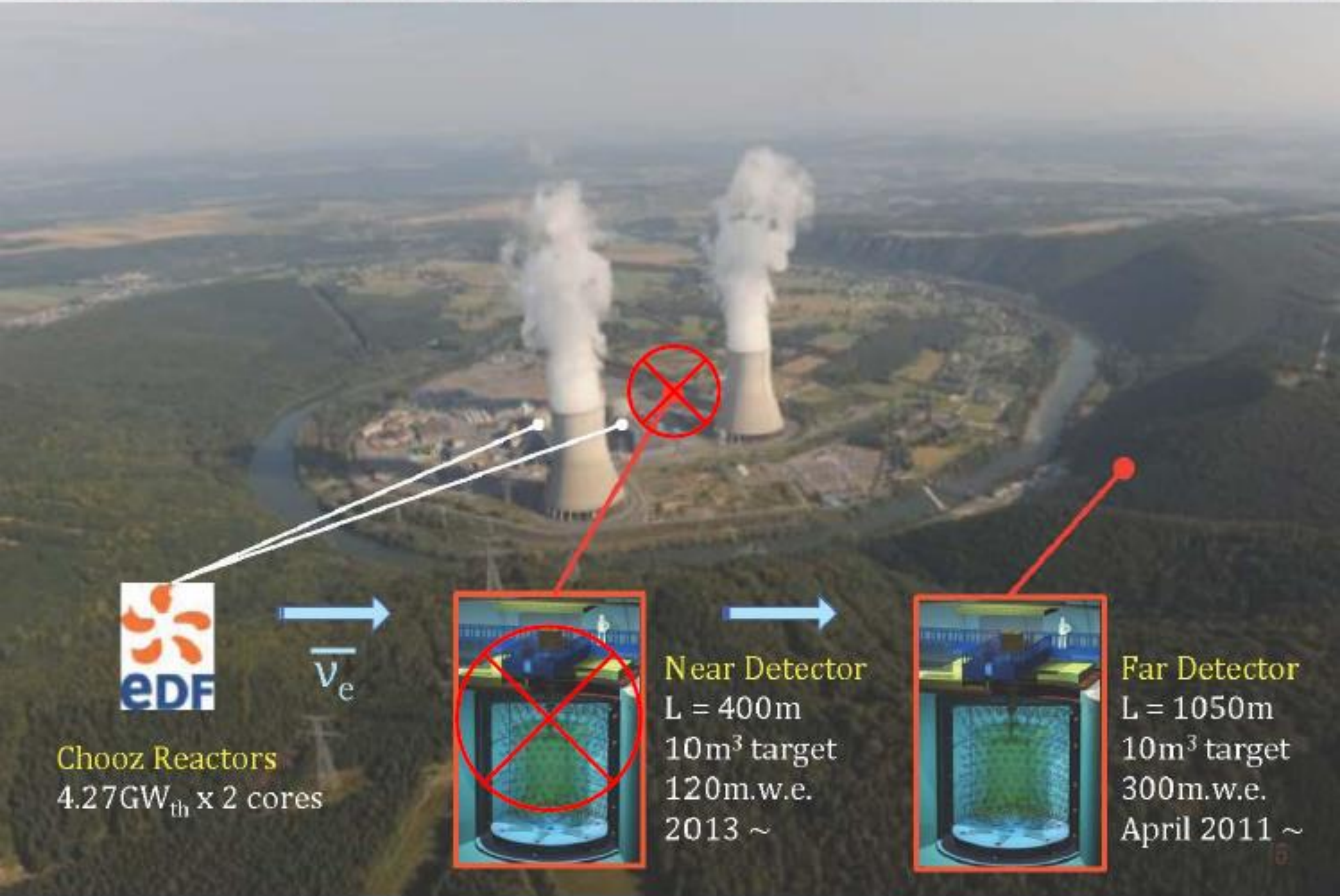
USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

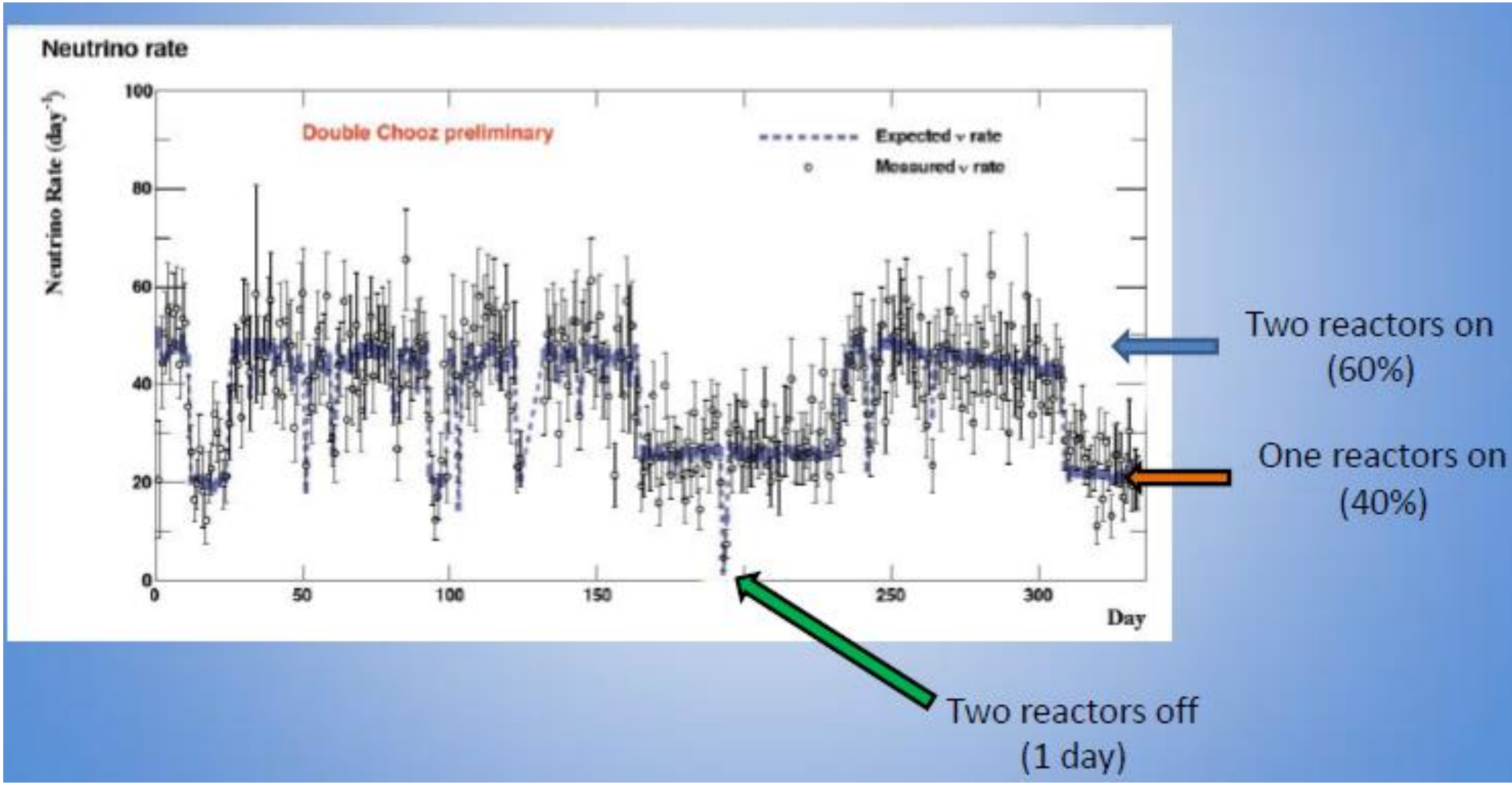
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

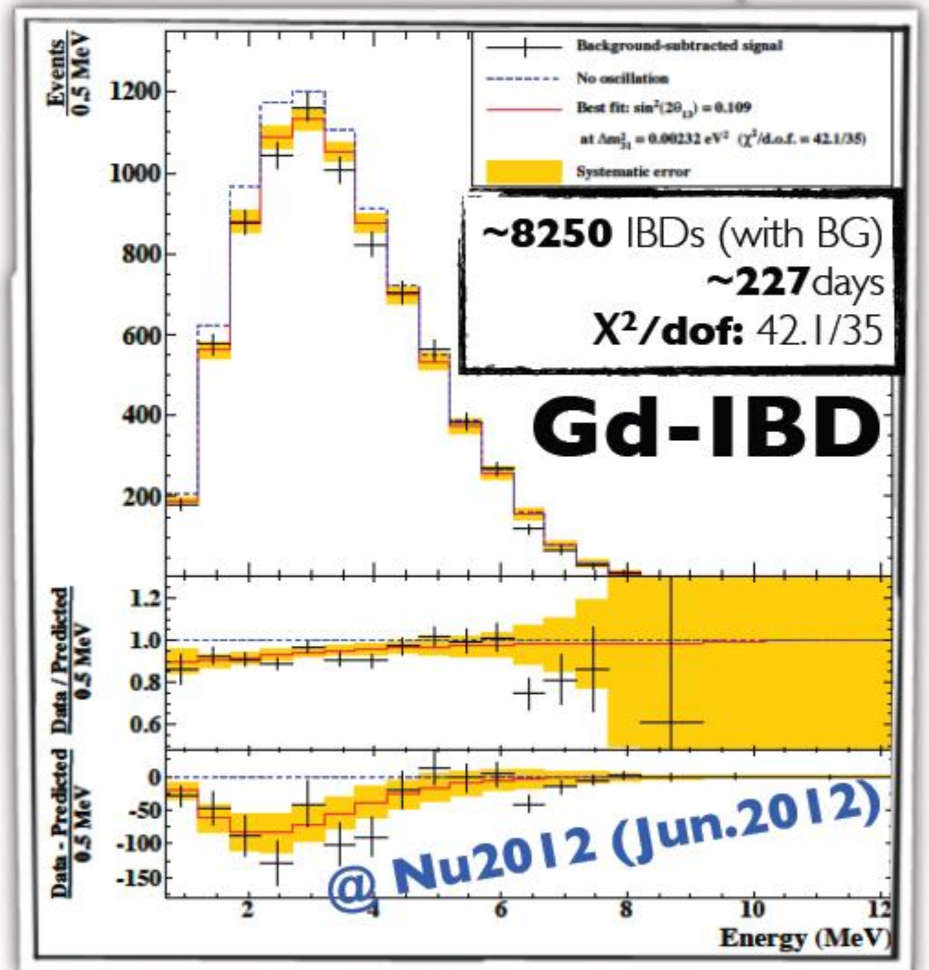
Double Chooz experiment

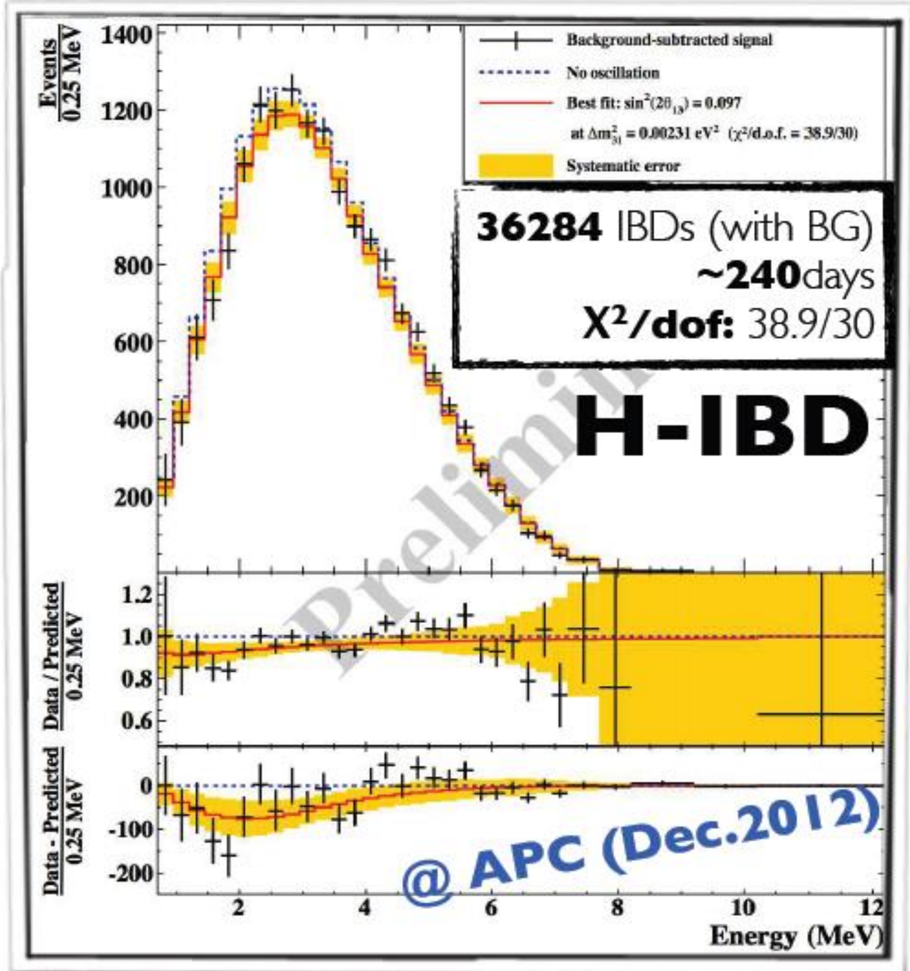


Double Chooz Daily IBD Rate



two independent measurements of θ_{13}...





rate+shape analysis→ clear θ_{13} E/L pattern & BG constrains

DC-II(Gd): $\sin^2(2\theta_{13})=0.109\pm0.04\ [0.030^{stat}\pm0.025^{syst}]$

DC-II(H): $\sin^2(2\theta_{13})=0.097\pm0.05\ [0.034^{stat}\pm0.034^{syst}]$

Anatael Cabrera (CNRS-IN2P3 & APC)

Summary of θ_{13} results

Reactor-based neutrino experiments have measured θ_{13} to a precision better than the other 2 angles. Continuation of current measurements will begin to constrain the unitarity of the 3-flavor paradigm of neutrinos, and provide help to CP violation measurements.

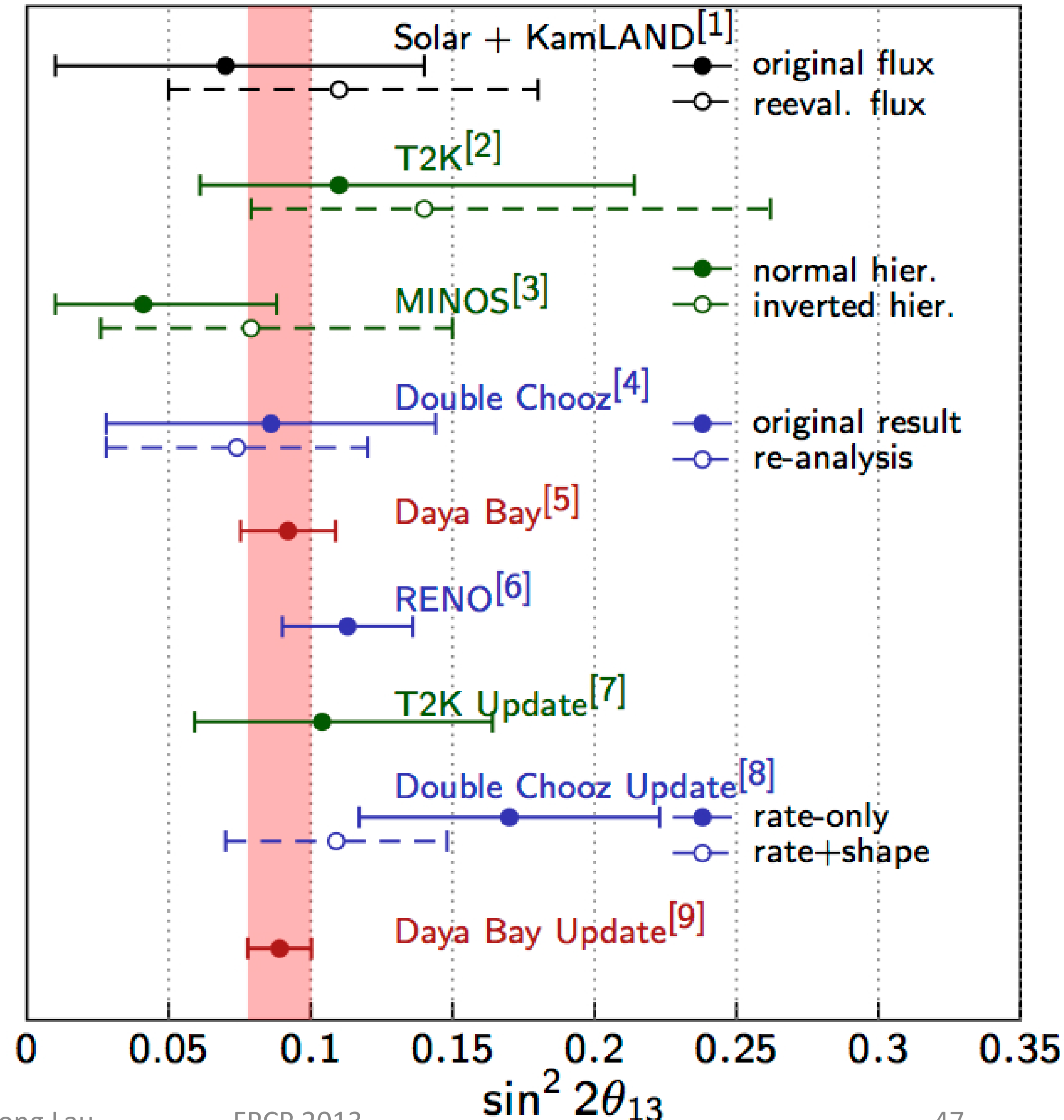
Current θ_{13} Landscape

[5] Daya Bay:
Phys. Rev. Lett. **108**, 171803 (2012)
$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

[6] RENO:
Phys. Rev. Lett. **108**, 191802 (2012)
$\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) ± 0.019 (syst)

[8] Double Chooz:
Phys. Rev. D, 86, 052008 (2012)
$\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) ± 0.025 (syst)

[9] Daya Bay:
Chinese Physics C, 37, 011001(2013)
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)



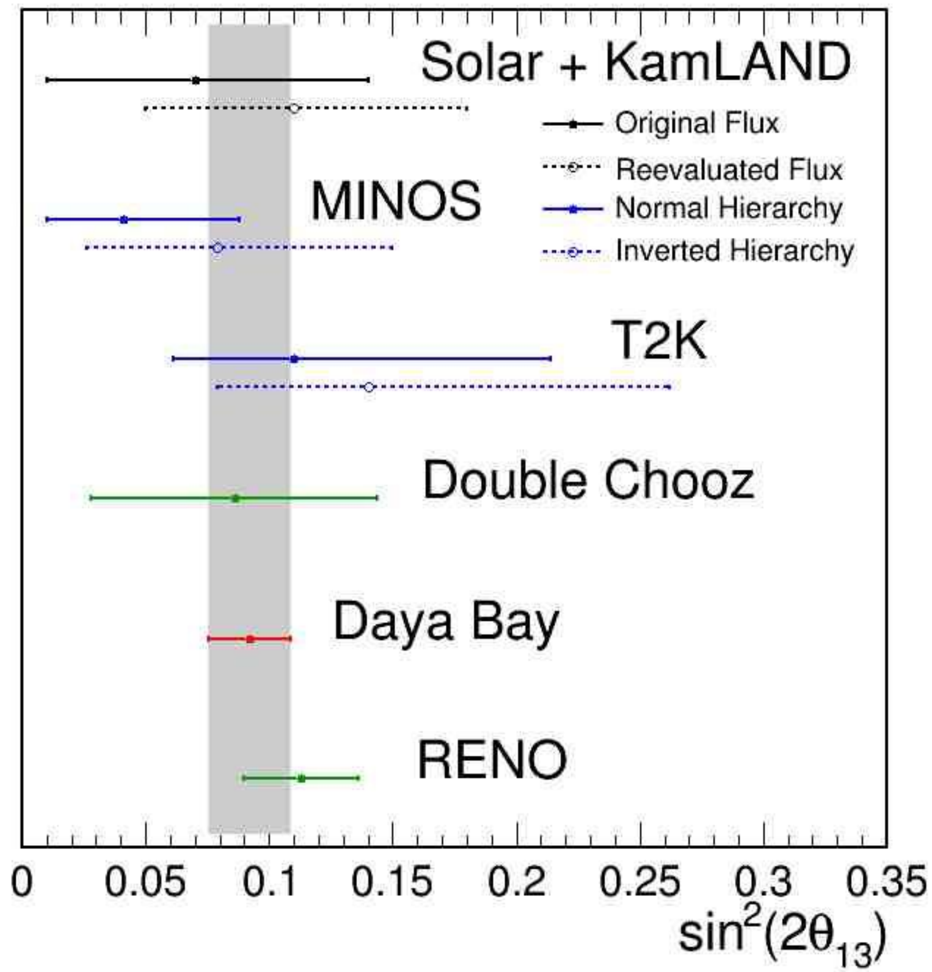
Backup

Some backup slides

Non-zero measurements of θ_{13}

Daya Bay:
Phys. Rev. Lett. **108**, 171803 (2012)
$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)
Result announced simultaneous by all collaborating institutions on March 8, 2012

RENO:
Phys. Rev. Lett. **108**, 191802 (2012)
$\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) ± 0.019 (syst)



Background: $^{13}C(\alpha,n)^{16}O$

$^{13}C\,(\alpha, n)\,^{16}O$ 1.1% natural abundance ^{13}C

$\to n + p \longrightarrow n + p$ (1)

$\to n + {}^{12}C \longrightarrow n + {}^{12}C^*(4.4\ \mathrm{MeV})$

$\to {}^{12}C + \gamma$ (2)

$^{13}C\,(\alpha, n)\,^{16}O^*(6.05\ \mathrm{MeV})$

$\to {}^{16}O + \gamma$ (3)

$^{13}C\,(\alpha, n)\,^{16}O^*(6.13\ \mathrm{MeV})$

$\to {}^{16}O + e^+ + e^-$ (4)

Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Potential alpha source:

^{238}U, ^{232}Th, ^{235}U, ^{210}Po:

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) – Po – Pb

^{210}Po: spectrum fitting

Combining (α,n) cross-section, correlated background rate is determined.

Near Site: 0.04+-0.02 per day, B/S (0.006±0.004)%

Far Site: 0.03+-0.02 per day, B/S (0.04±0.02)%

Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:
- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

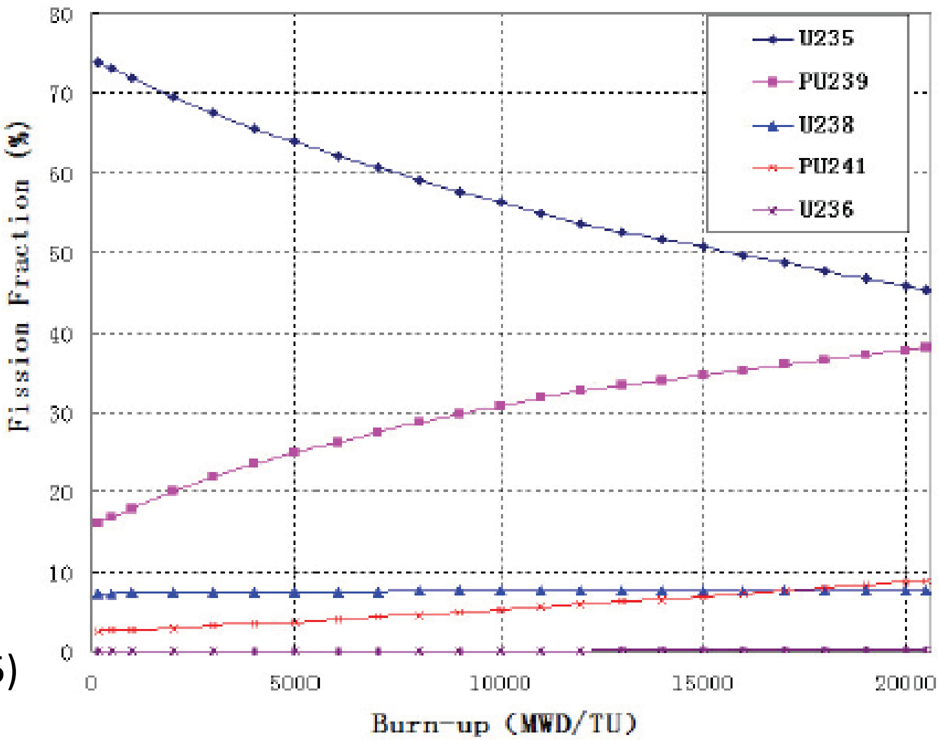
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

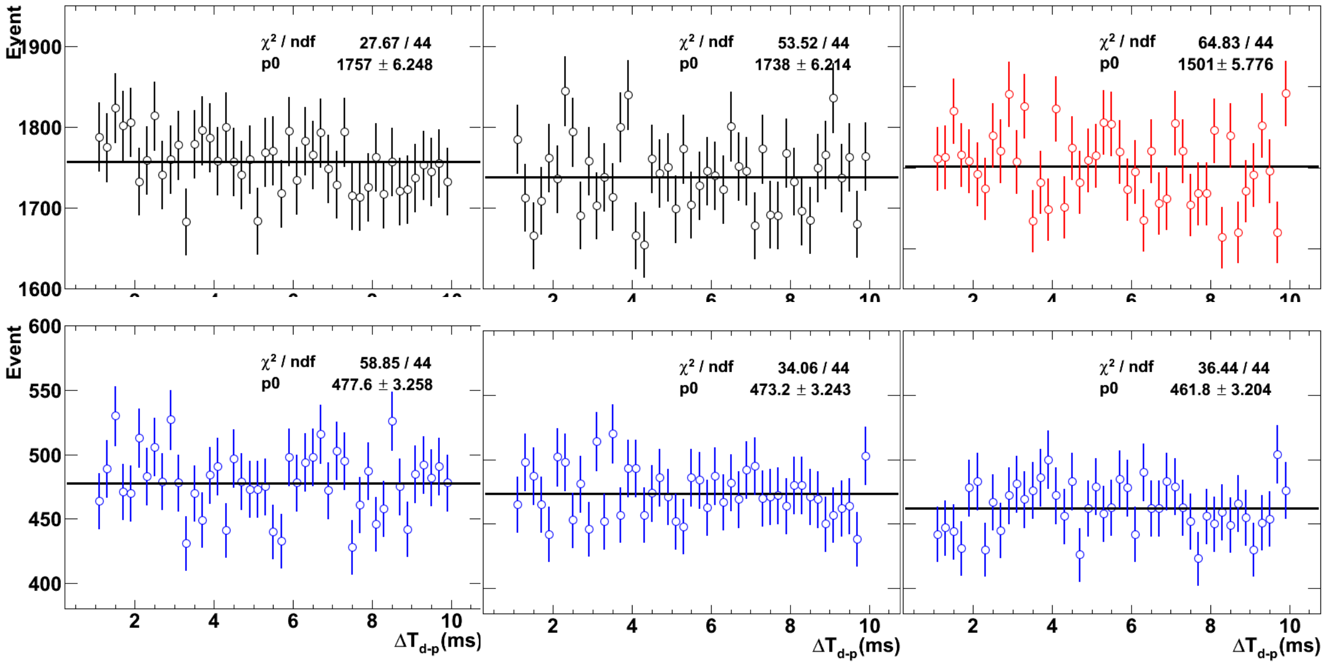
Isotope fission rates vs. reactor burnup



Flux model has negligible impact on far vs. near oscillation measurement

Accidental Background (Method II)

- An alternative method
  - Off-window fits with two choices of windows
- Based on the difference between two methods, the systematic error is below 1%. No systematic error is assigned to the accidental background.



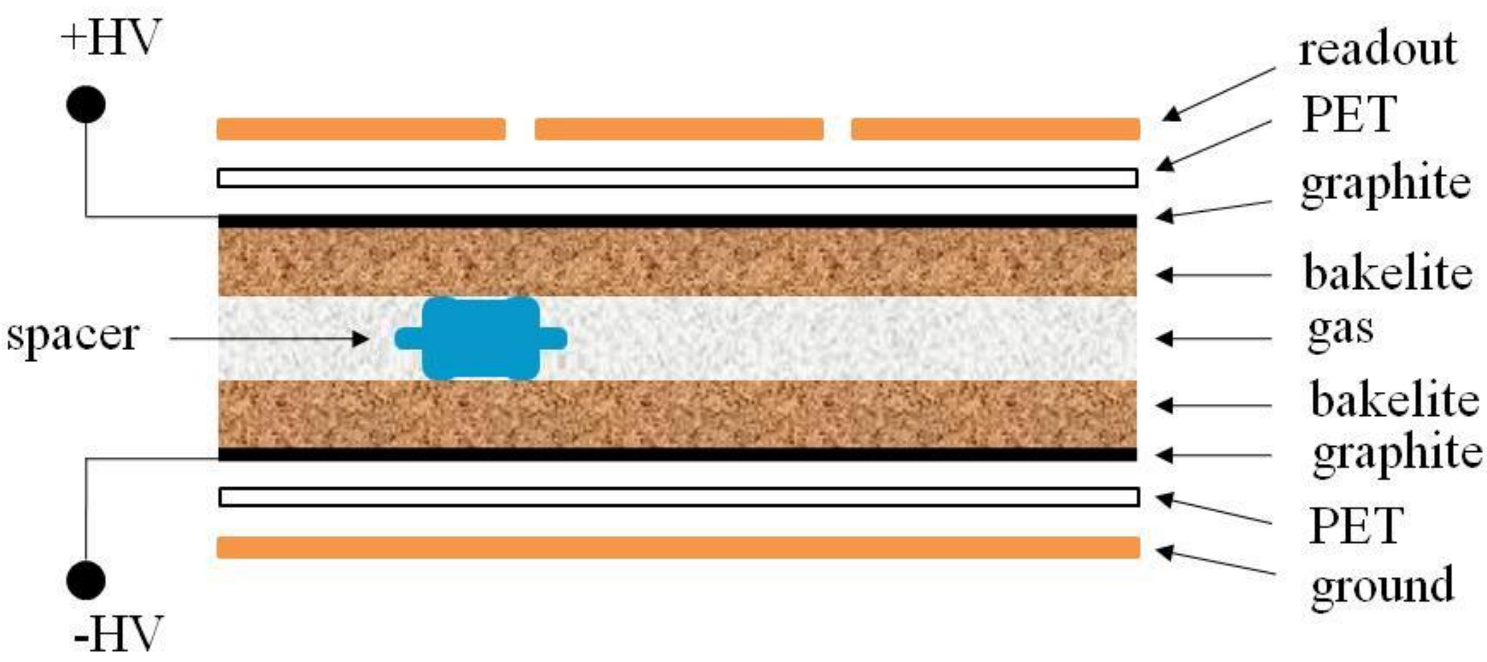
Comparison of accidental rates (per day) among different methods

	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Theoretical	9.73±0.03	9.61±0.03	7.55±0.03	3.05±0.02	3.04±0.02	2.93±0.02
Off-window1	9.69±0.03	9.59±0.03	7.54±0.03	3.06±0.02	3.03±0.02	2.95±0.02
Rel. diff.	-0.4%	-0.5%	-0.2%	0.2%	-0.2%	0.6%
Off-window2	9.77±0.05	9.66±0.05	7.61±0.04	3.05±0.02	3.02±0.02	2.94±0.02
Rel. diff.	0.4%	0.5%	0.8%	0.0%	-0.6%	0.5%

The RPC muon detector

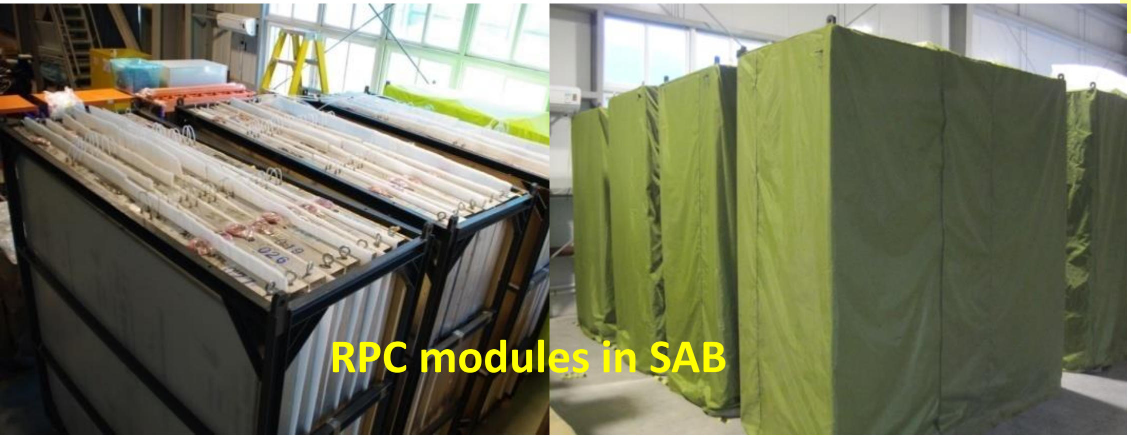
Resistive Plate Chambers (RPCs) are placed above the water pools to detect muons entering the pool with high efficiency. The RPC system, combined with the water pool instrumented as a Cerenkov detector, will allow us to measure muon-induced background to reach the ultimate sensitivity.

Resistive Plate Chambers



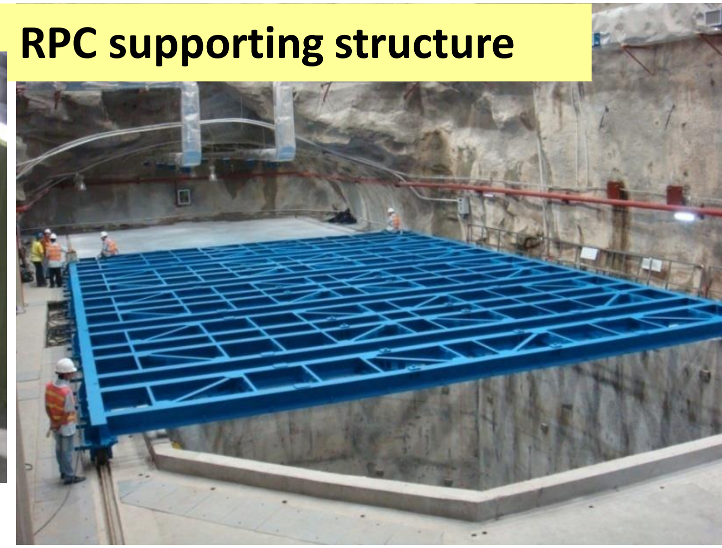
- Streamers are formed in the gas gap between two resistive electrodes with a gas gain of ~ 10^9.
- The Daya Bay RPCs are made from Bakelite with resistivity controlled to 0.5 - 2.5 X 10^{12} Ω.cm.
- The gas mixture is Argon, R134a, Isobutane and a trace amount of SF6.
- The signal is read out from outside using strips at a threshold of 40 mV.

RPC installation



RPC modules in SAB

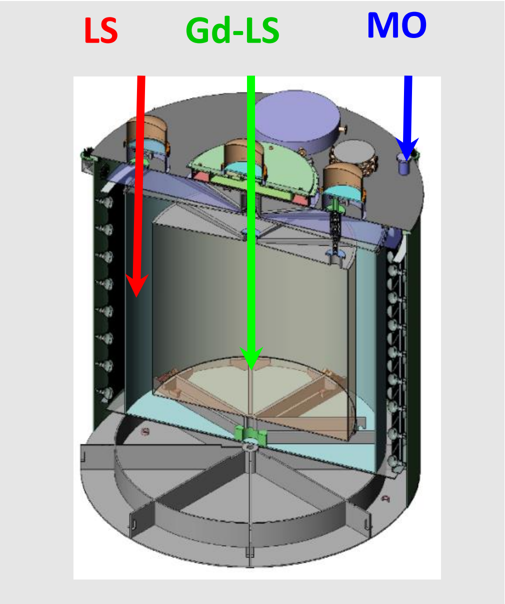
RPC supporting structure

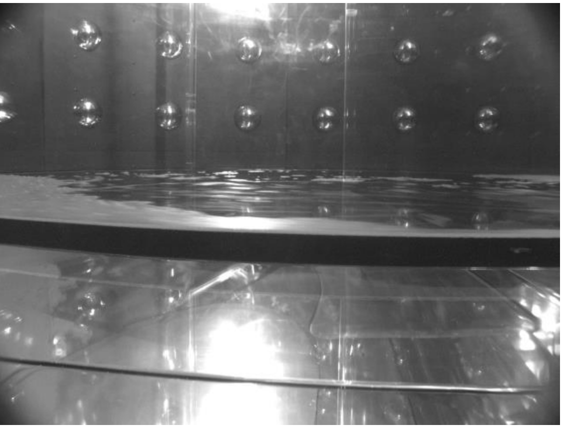


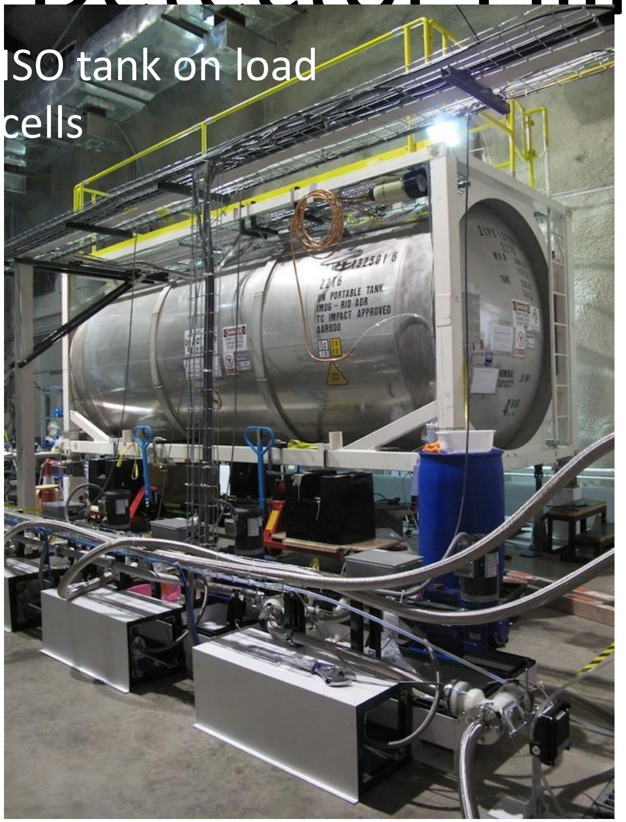
Gas system

Fully installed RPC

Detector Filling







Detector target filled from GdLS in ISO tank.

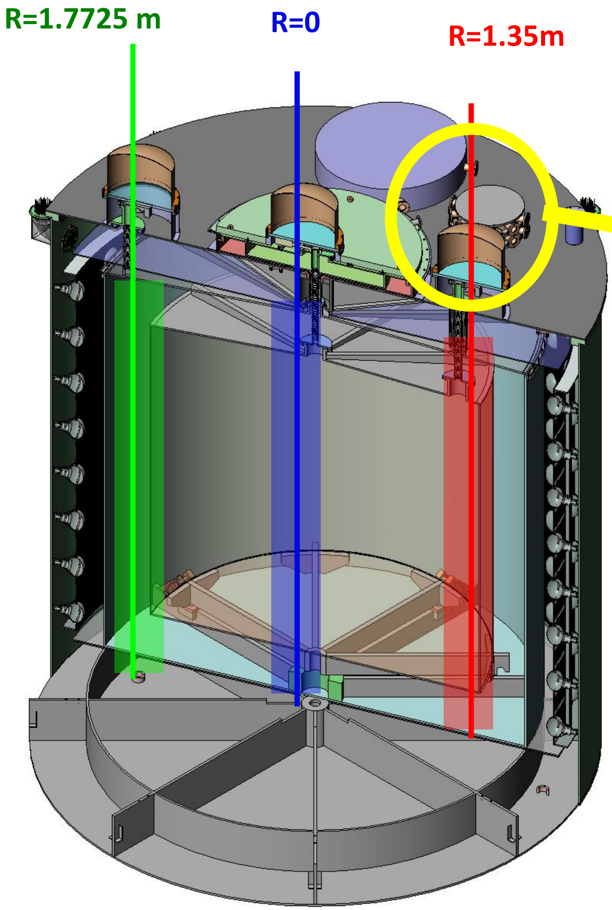
Load cells measure 20 ton target mass to 3 kg (0.015%)

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

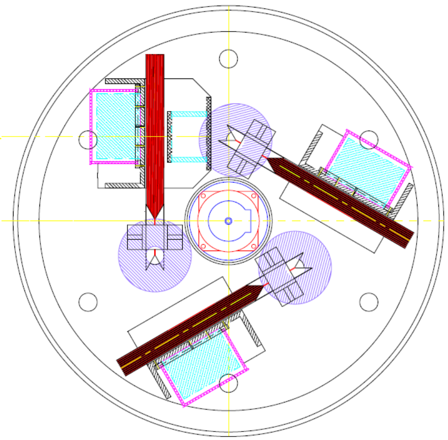
3 fluids filled simultaneously, with heights matched to minimize stress on acrylic vessels
- **Gadolinium-doped Liquid Scintillator (GdLS)**
- **Liquid Scintillator (LS)**
- **Mineral Oil (MO)**

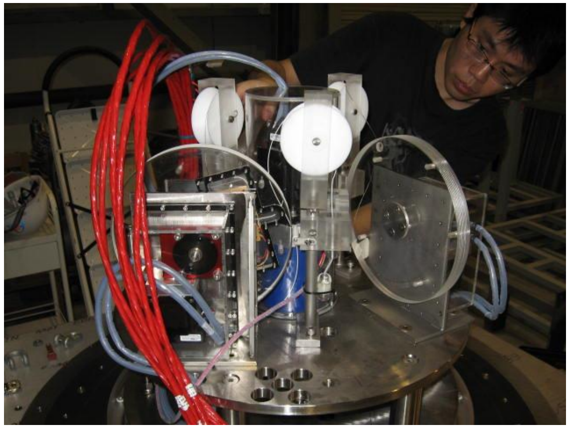
Automated Calibration System

3 Automated calibration 'robots' (ACUs) on each detector



Top view





Three axes: center, edge of target, middle of gamma catcher

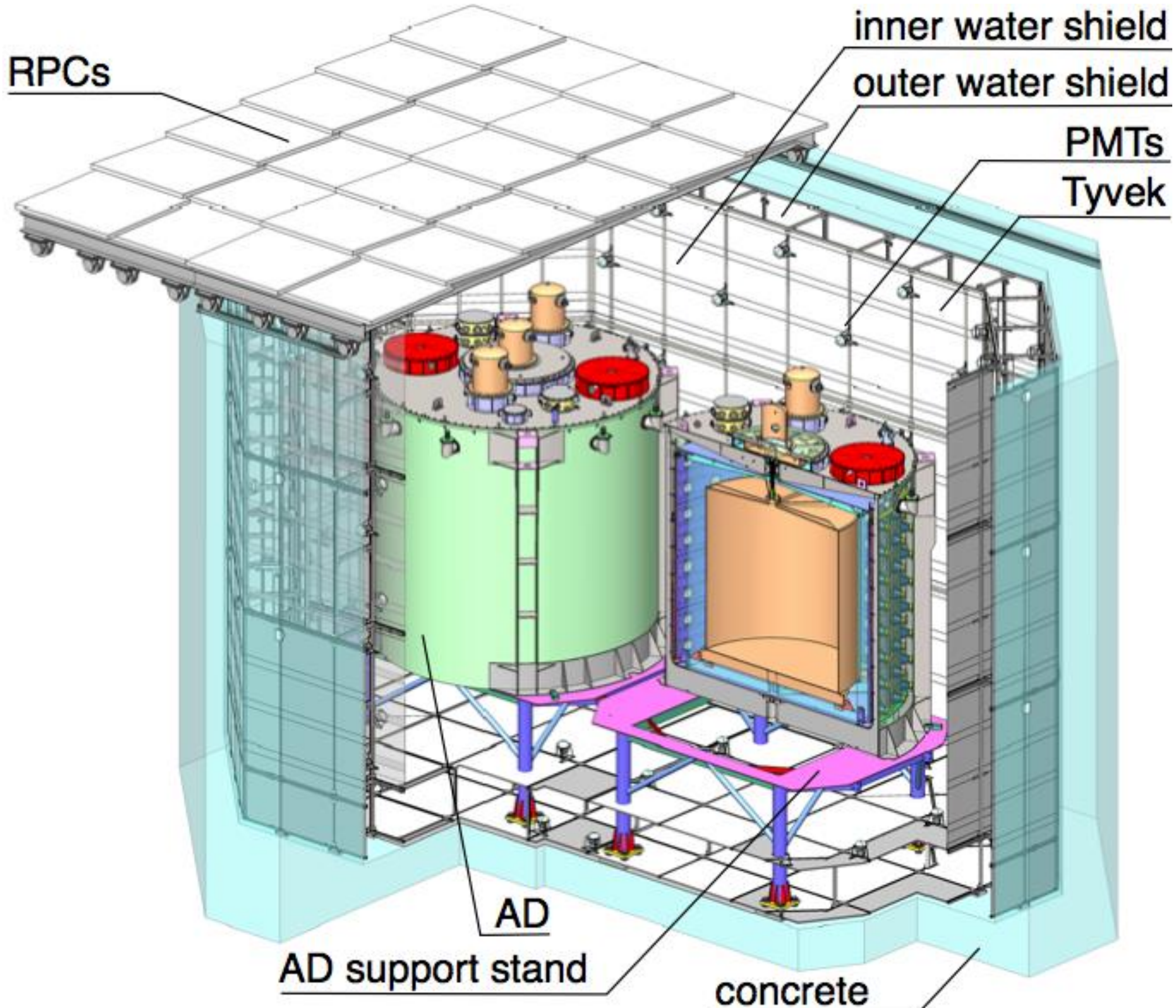
3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for T_0 and gain

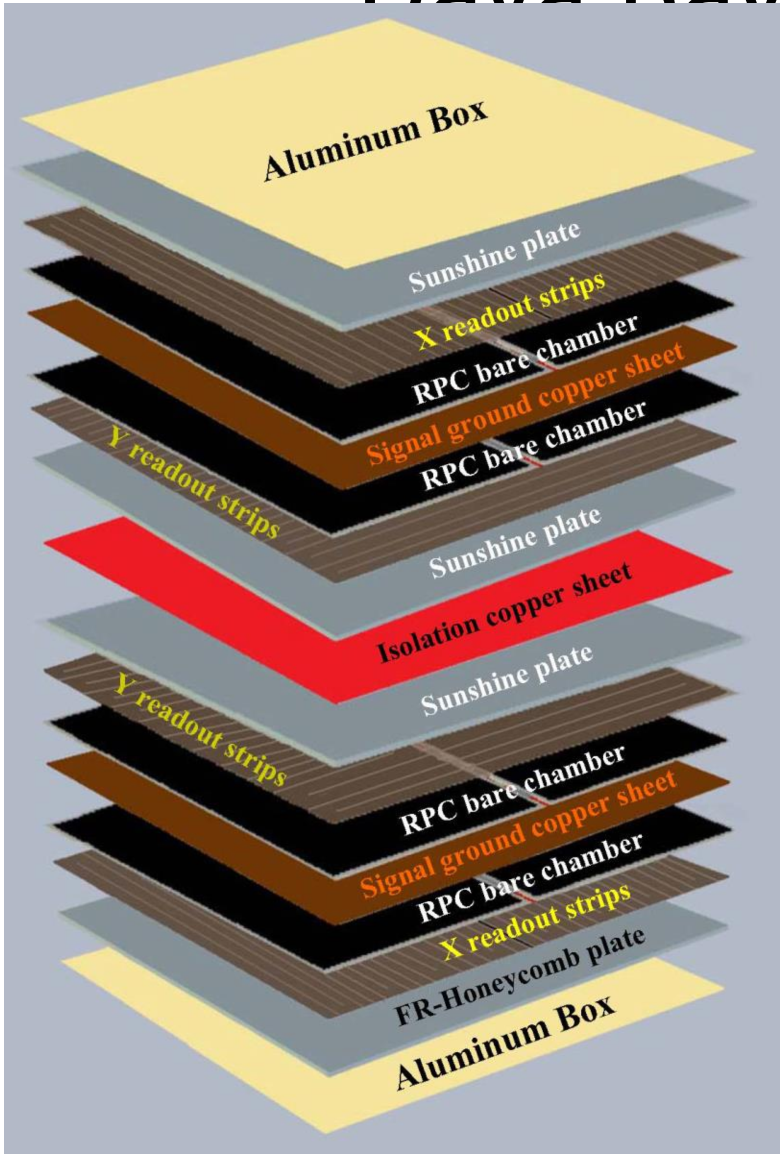
Muon Tagging System

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

- 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
- Goal efficiency: > 99.5% with uncertainty <0.25%



Daya Bay RPC Modules



- The Daya Bay RPC Modules are 2 m x 2 m
- There are 4 layers of bare RPCs, each with 1 readout plane, inside an Al box
- There are 2 x and 2 y 25-cm wide strips per module
- The spatial resolution is about 8 cm per coordinate
- There are 54 modules each in EH1 and EH2, and 81 In EH3.
- The RPCs are triggered by having 3 out of 4 layers hit per module
- The muon detection efficiency based on RPCs alone is > 95%.

Data acquisition and analysis

Antineutrino interactions are selected based on their characteristic time sequence of a prompt signal followed by delayed energetic neutron capture signal by Gadolinium. Relative detection efficiencies are known to high precision via calibration and Monte Carlo simulation.

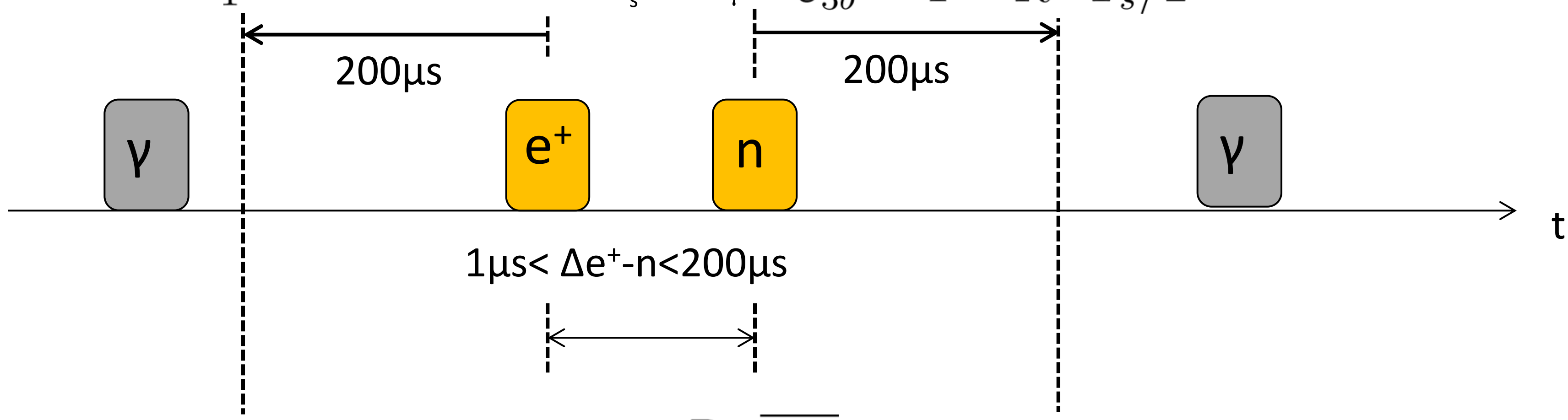
Multiplicity

Ensure exactly one prompt-delayed coincidence

If $T_s \geq 200\ \mu s$ $\quad \varepsilon_{3a} = 1 - R \cdot 200\mu s \cdot (1 - 100\mu s/\Delta T_s)$

If $T_s < 200\ \mu s$ $\quad \varepsilon_{3b} = 1 - R \cdot T_s/2$

$$\varepsilon_1 = e^{-R \cdot 200\mu s}$$

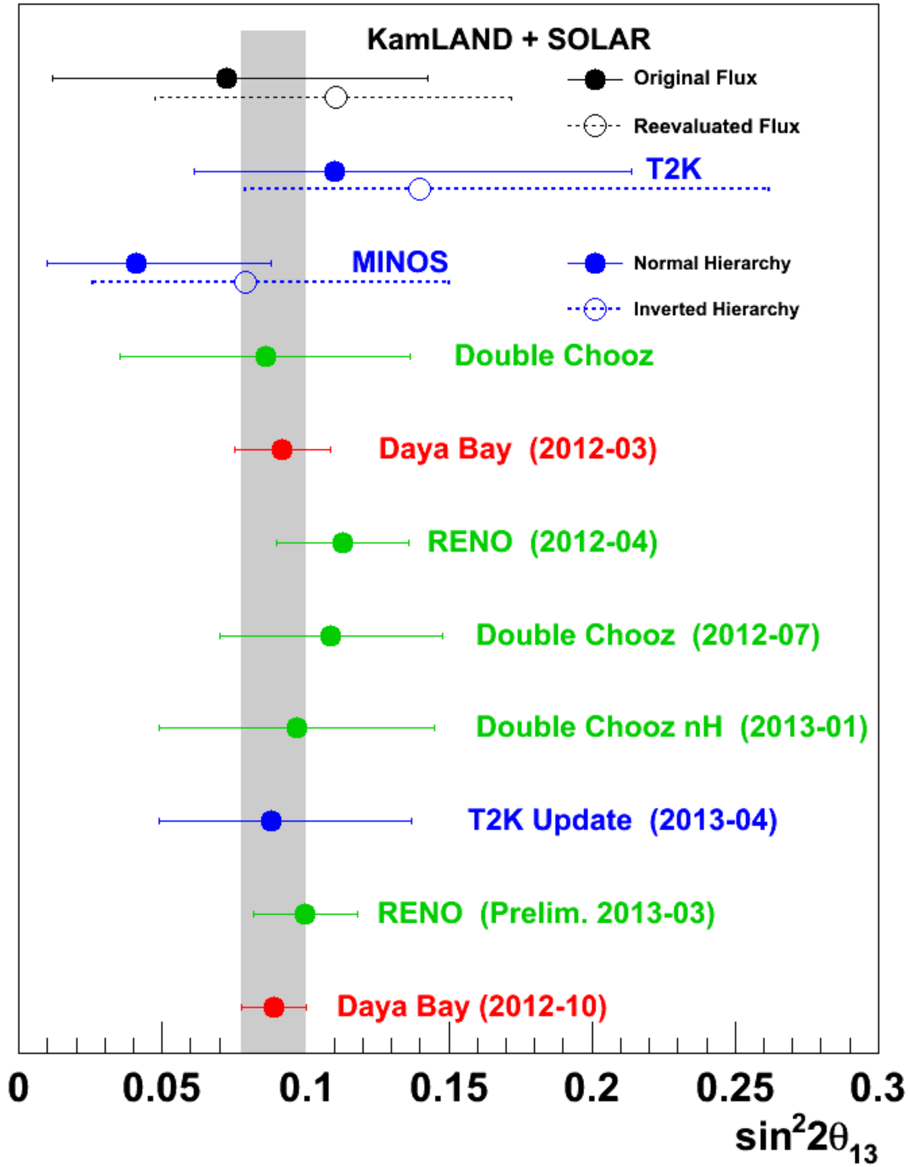


$$\varepsilon_2 = 1 - R \cdot \overline{t_{cap}}$$

Uncorrelated background and IBD signals result in ambiguous prompt, delayed signals.

-> Reject all IBD with >2 triggers above 0.7 MeV in -200μs to +200μs.
Introduces ~2.5% IBD inefficiency, with negligible uncertainty

Current θ_{13} Landscape



Slide by R. McKeown

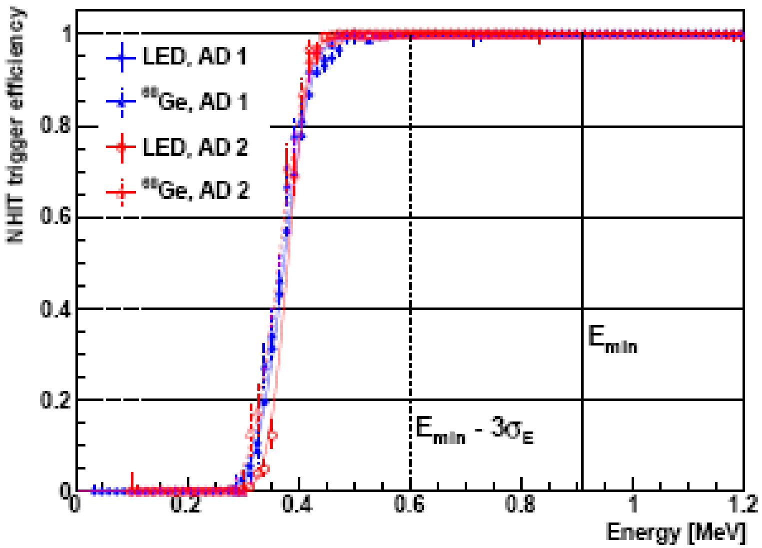
Trigger Perf

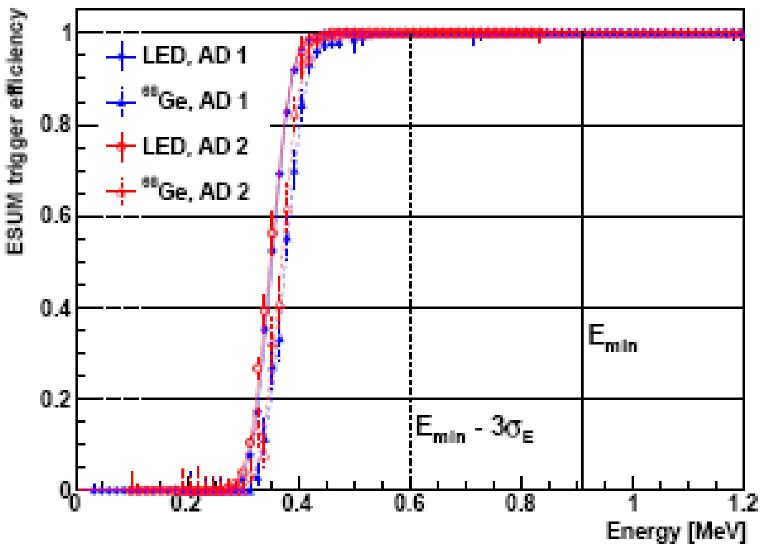
Trigger Thresholds:

- AD: >45 PMTs (digital trigger)
  >0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: 3/4 layers in module

Trigger Efficiency:

- No measureable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.





Background

Background rates are determined from data whenever possible or from data and simulation.

Result

The efficiency-corrected background-subtracted yields at the far hall are compared to predictions from those of near halls. A 6.0 % deficit at the far site was observed. Our analysis with the increased statistics (2.5 X) showed that θ_{13} is large and consistent with our RPL result.

Experiment Survey

Negligible reactor flux uncertainty (<0.02%) from precise survey.

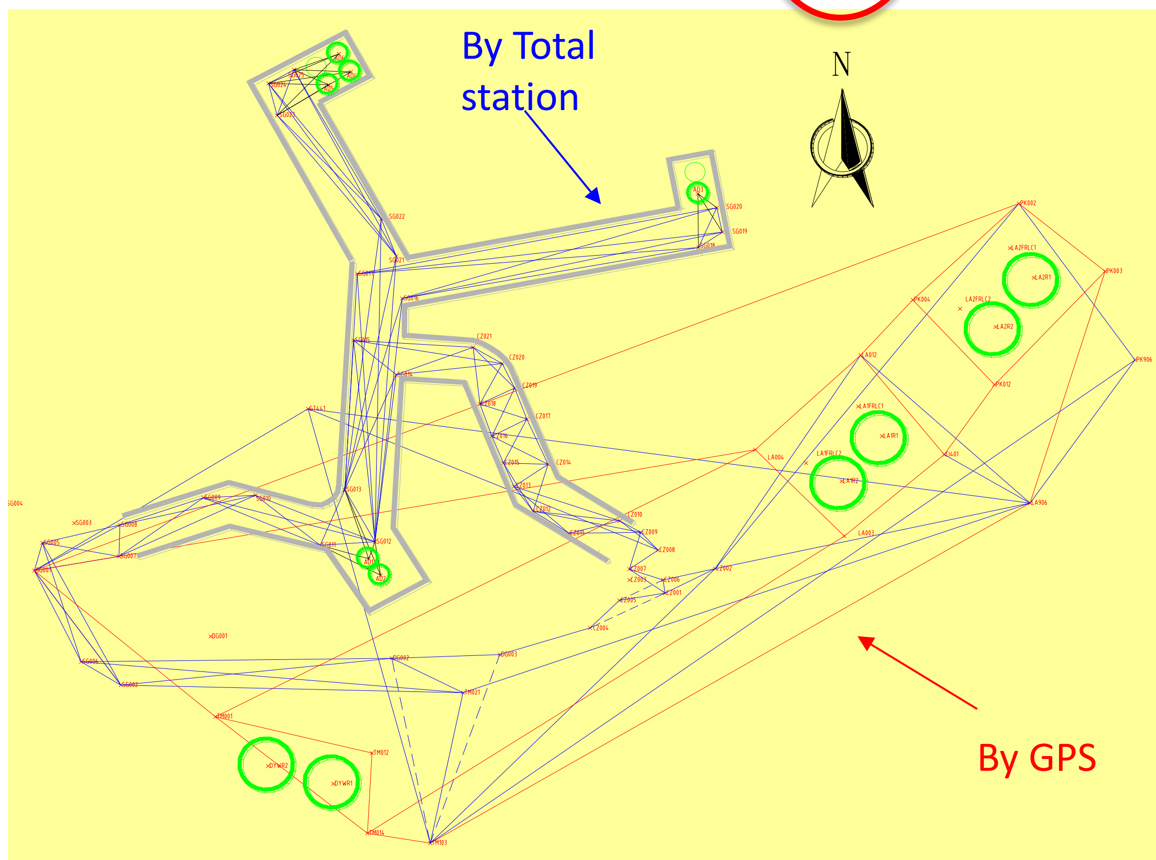
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

Detailed Survey:

- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:

- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



The Daya Bay Detector

Eight neutrino detectors, each holding 20 tons of liquid scintillator doped with Gadolinium, are deployed to measure the energy and time of antineutrino interactions electronically. The detectors are submerged in water to shield them from ambient radioactivity background. Active muon detectors are installed to veto residual cosmic muons which can produce cosmogenic background.

Summary

- With 2.5x more data, the Daya Bay reactor neutrino experiment measures a far/near antineutrino deficit at ~2 km:

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

[PRL value: R = 0.940 ± 0.011 (stat) ± 0.004 (syst)]

- Interpretation of disappearance as neutrino oscillation yields:

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

[PRL value: $\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)]

- Installation of final two antineutrino detectors this year

Gateway to Leptonic CP violation wide open!

Stay tuned for more results from Daya Bay

Data Period

A. Two Detector Comparison: arXiv:1202:6181

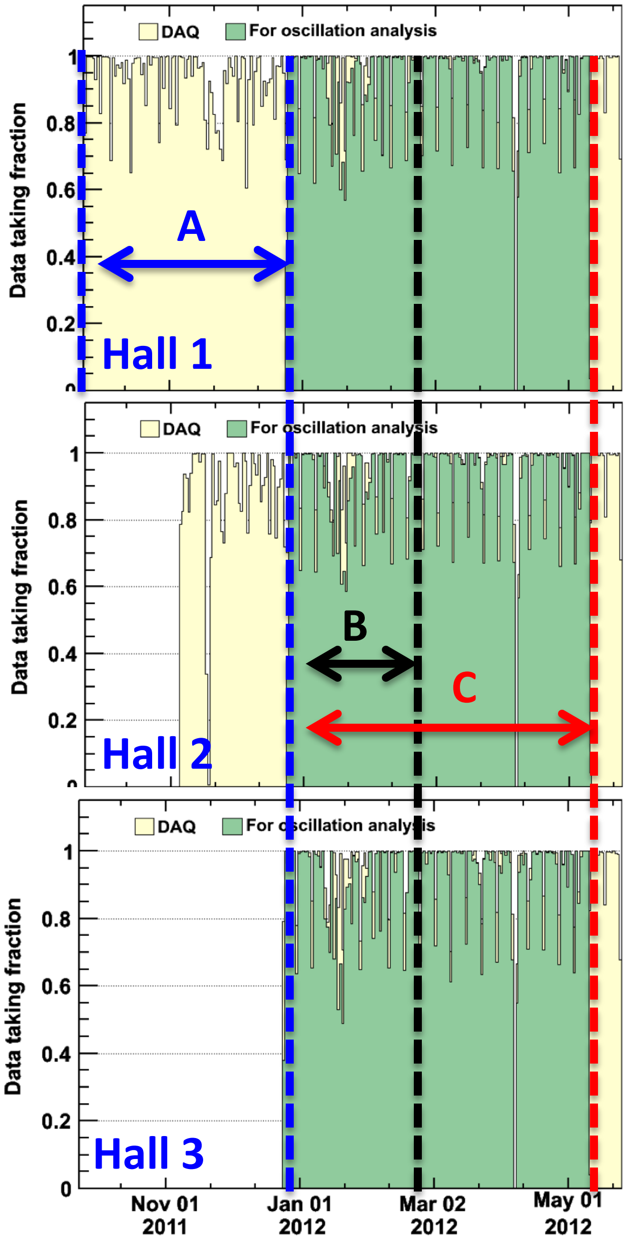
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- To be published in Nucl. Inst. and Meth.

B. First Oscillation Result: arXiv:1203:1669

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- First observation of $\bar{\nu}_e$ disappearance
- Phys. Rev. Lett. **108**, 171803 (2012)

C. This Update:

- Dec. 24, 2011 – May 11, 2012
- More than 2.5x the previous data set



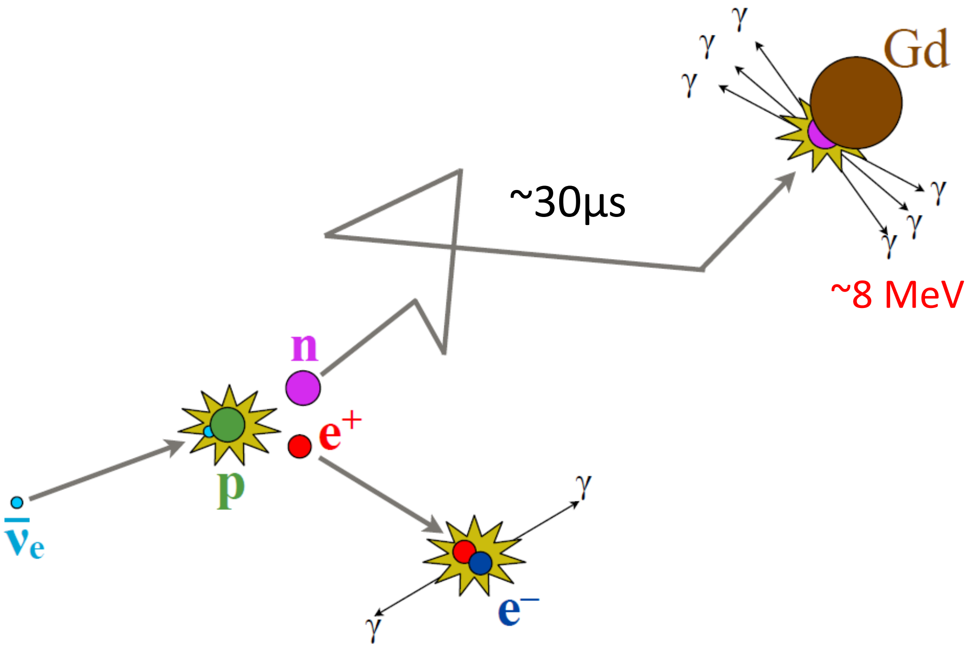
Inverse beta decay has a distinctive signature

Inverse β-decay (IBD):

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

$$\downarrow$$

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



Prompt positron:

Carries antineutrino energy

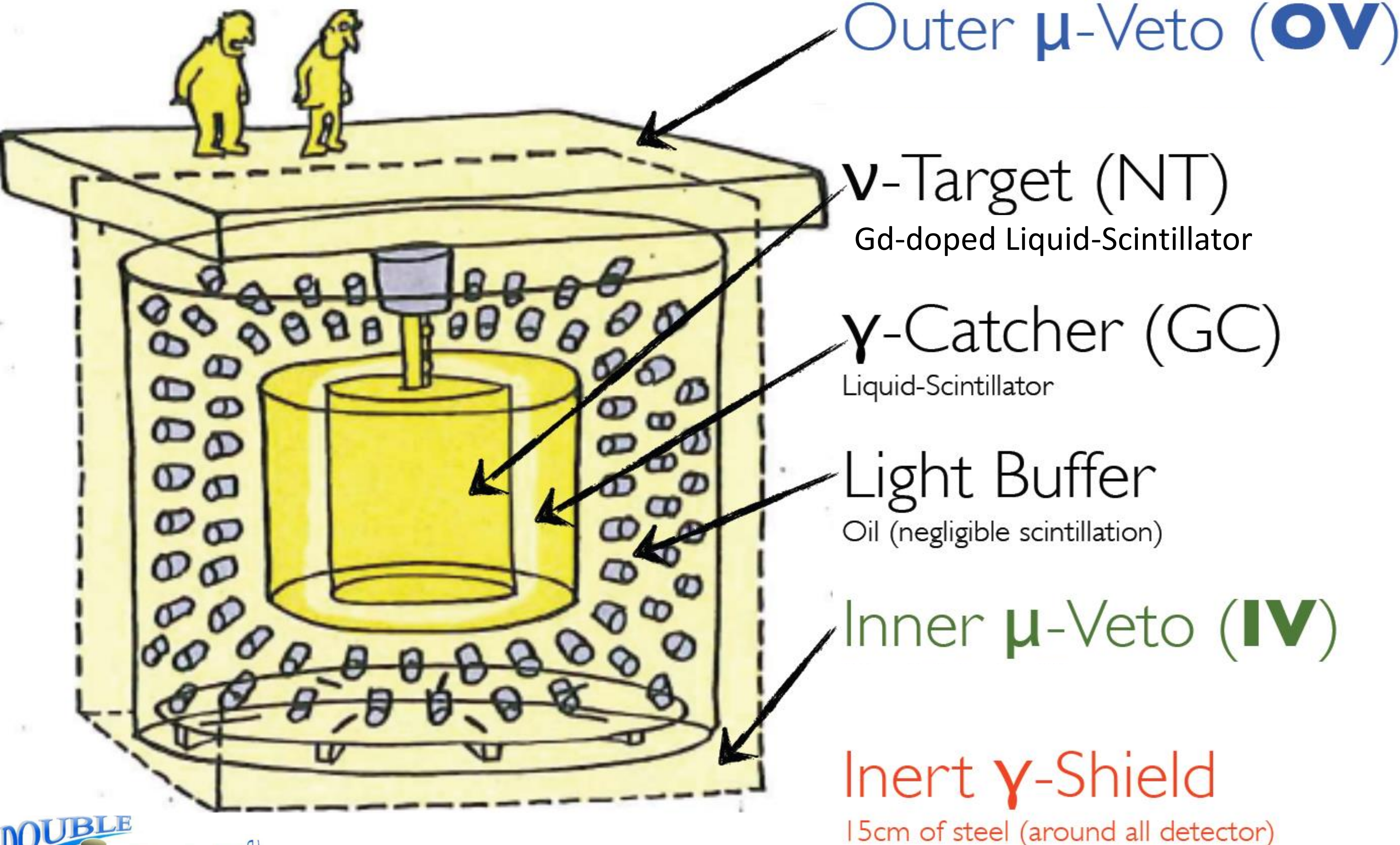
$E_{e+} \approx E_\nu - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature

Detectors are optimized for inverse beta decay observation



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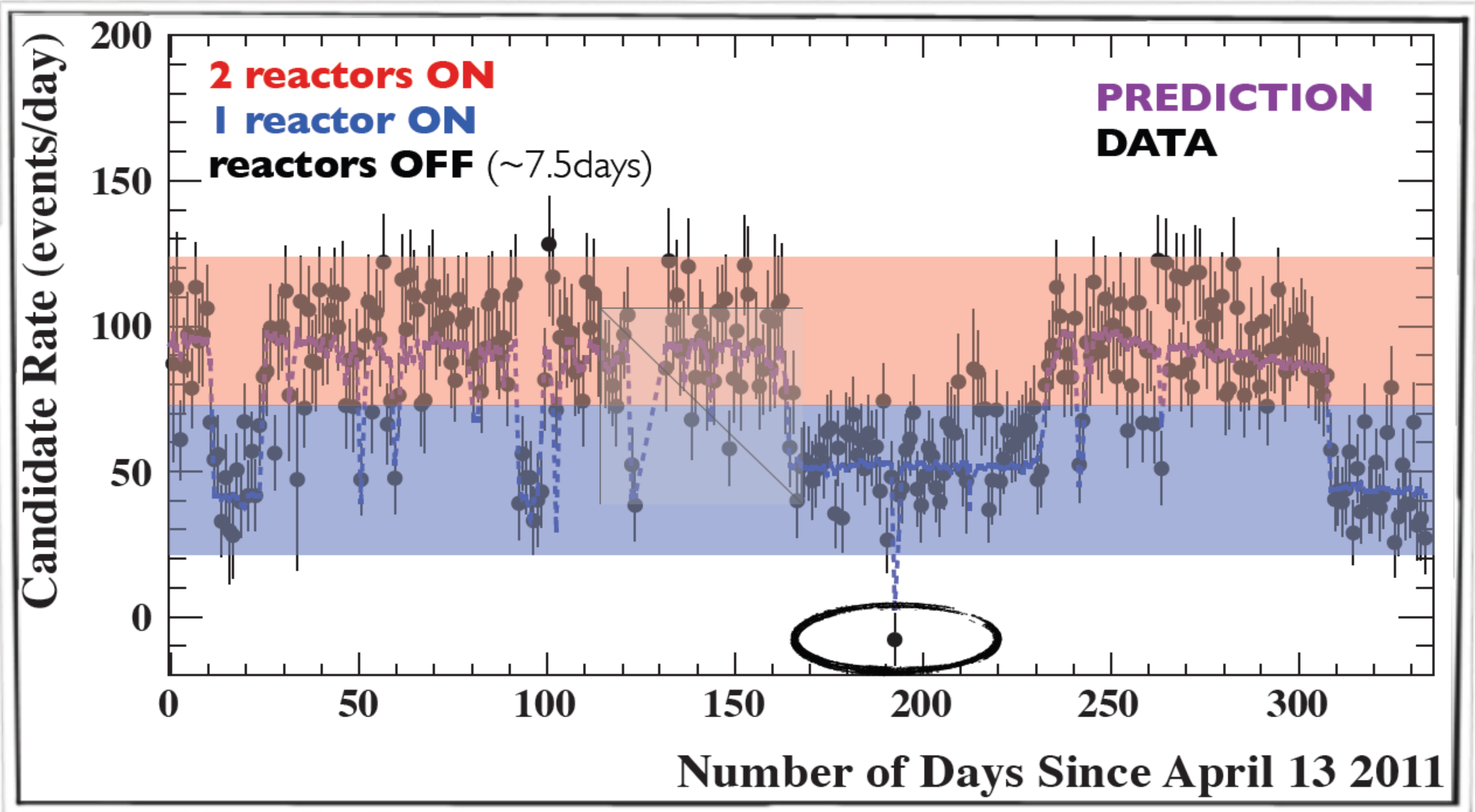
observed vs expected rate…



next: plot observed vs expected IBD rate per day

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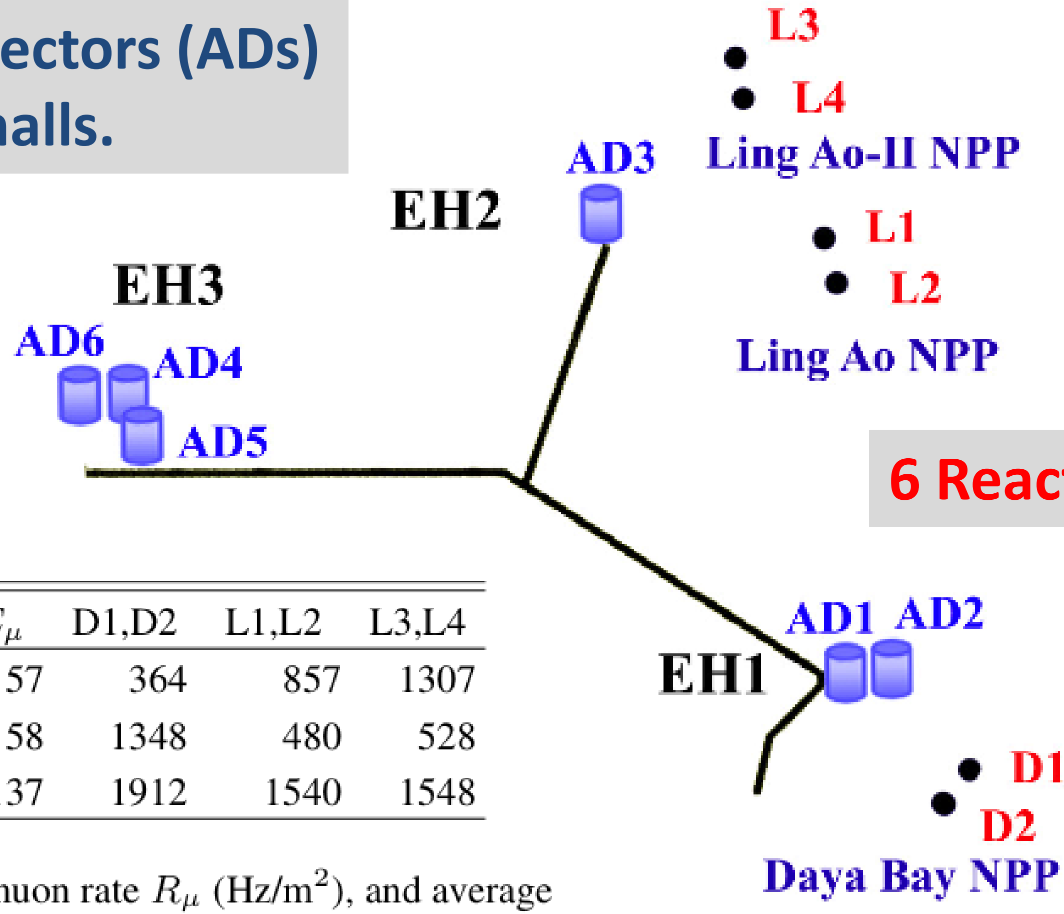
Experiment Layout

6 Antineutrino Detectors (ADs) in 3 underground halls.



6 Reactor Cores

	Overburden	R_μ	E_μ	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

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Uncertainty Summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

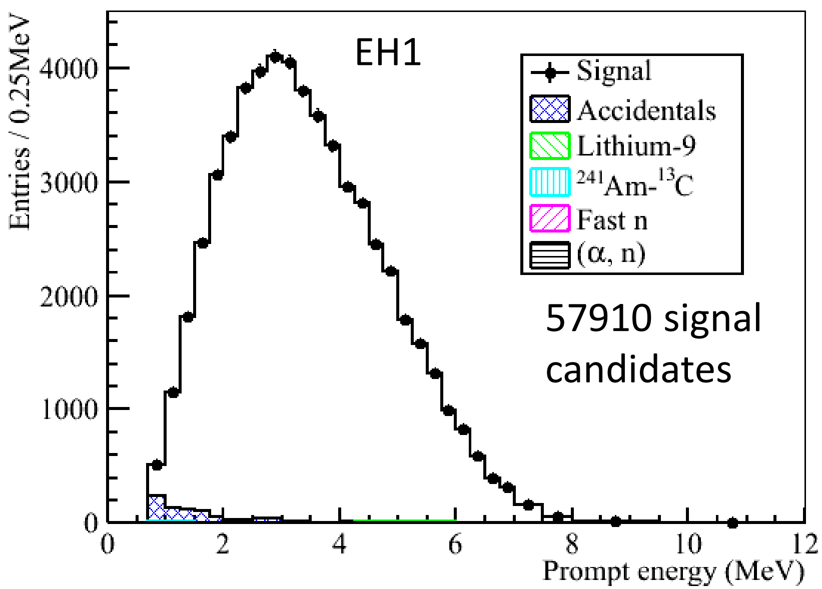
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

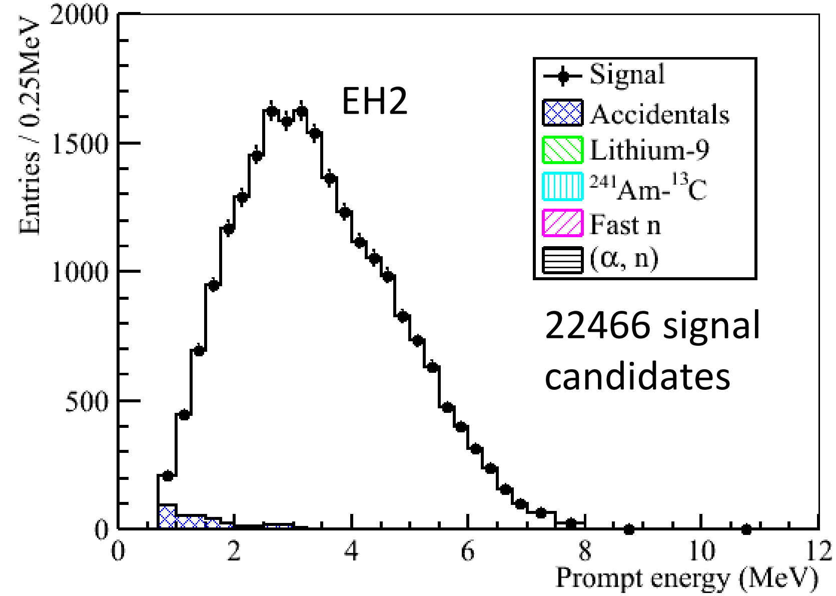
For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

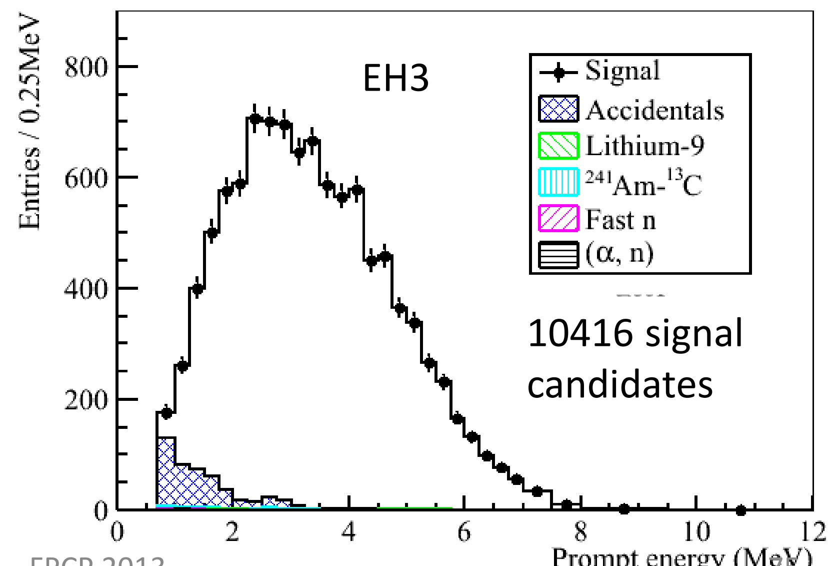
Prompt Positron Spectra





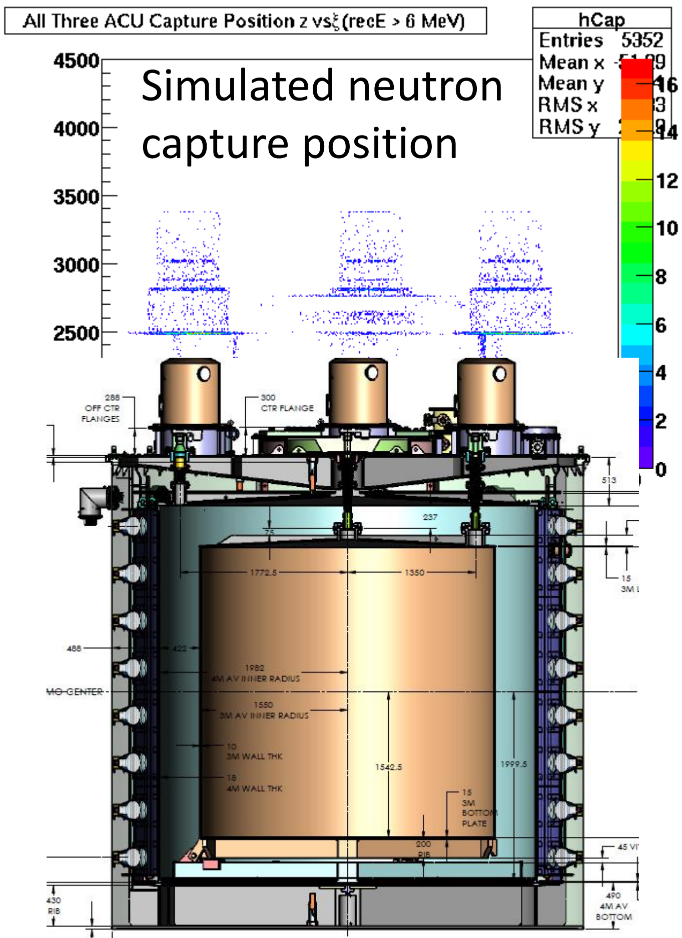
High-statistics reactor antineutrino spectra.

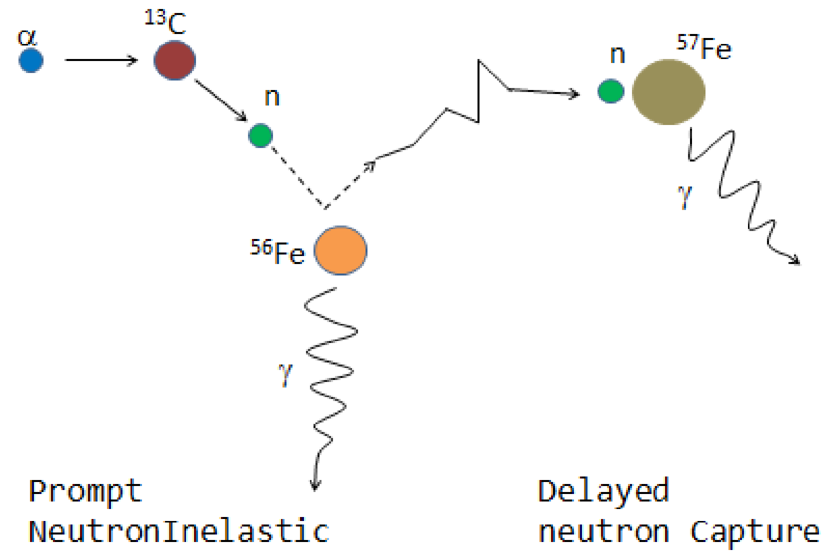
B/S ratio is 5% (2%) at far (near) sites.



Background: ^{241}Am-^{13}C neutrons

Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.





Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation