Observation of Mixing Angle θ_{13}

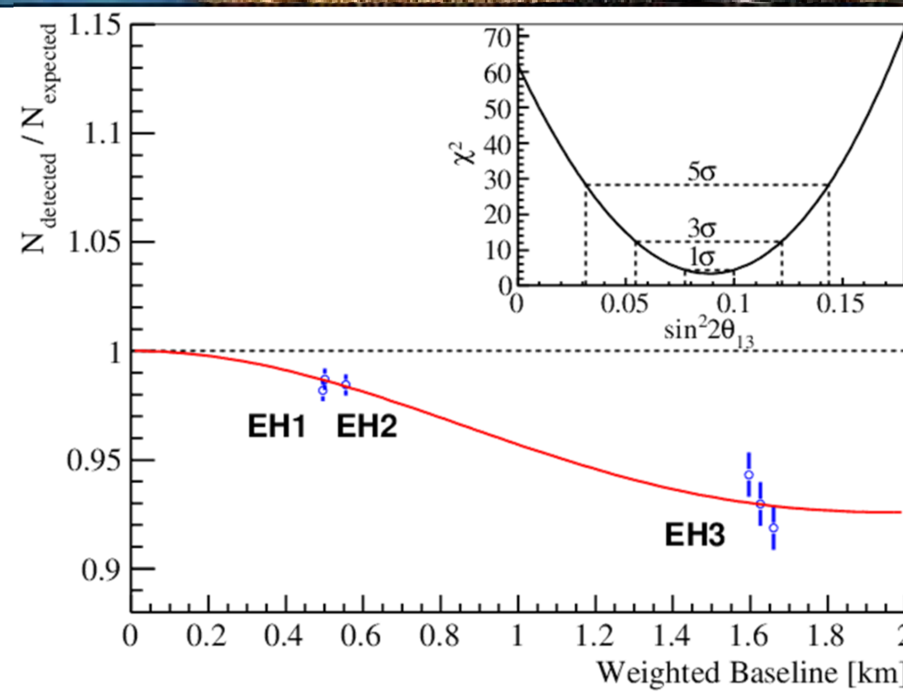
in the Daya Bay Reactor Antineutrino Experiment

Kirk T McDonald
Princeton U
(updated June 1, 2012)
on behalf of the Daya Bay Collaboration

We observe that
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat.) ± 0.005 (syst.)
after 55 days of operation with 6 detectors
at 3 sites close to 3 pairs of ~ 3 GW reactors.

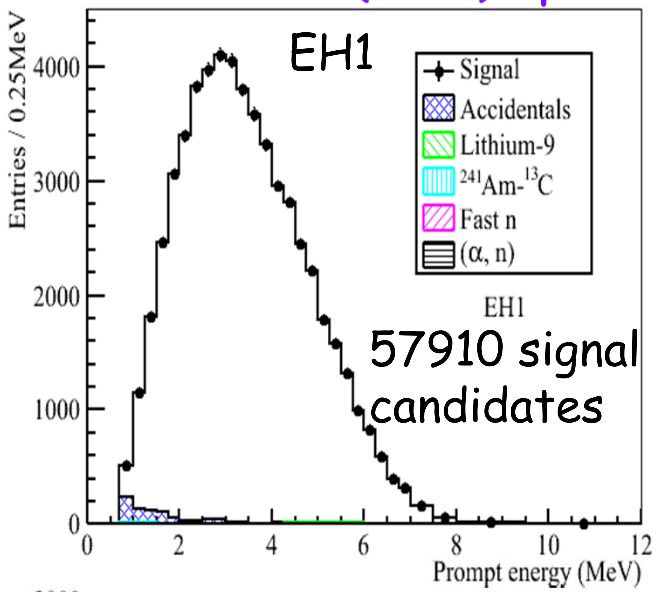
F.P. Ahn *et al.*, Phys. Rev. Lett. **108**, 171803 (2012).

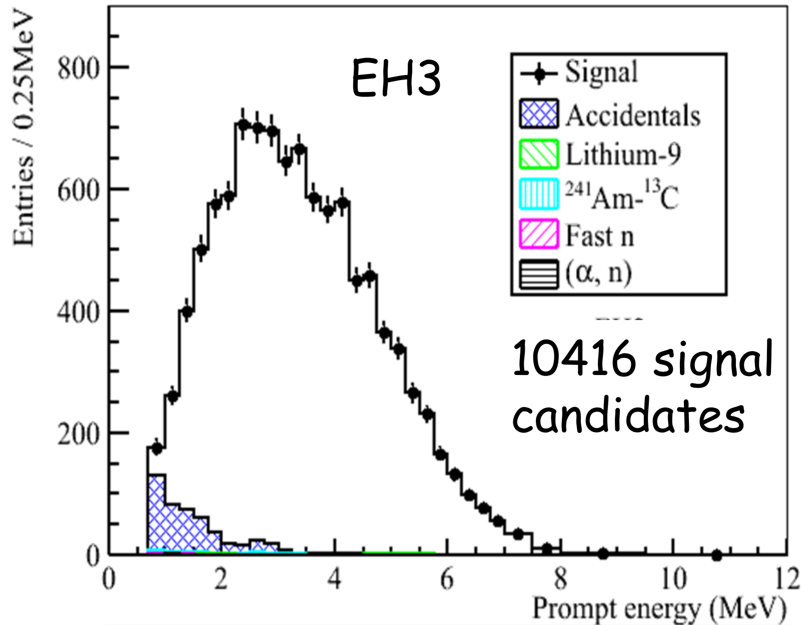
After 110 days of running,
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat.) ± 0.005 (syst.)

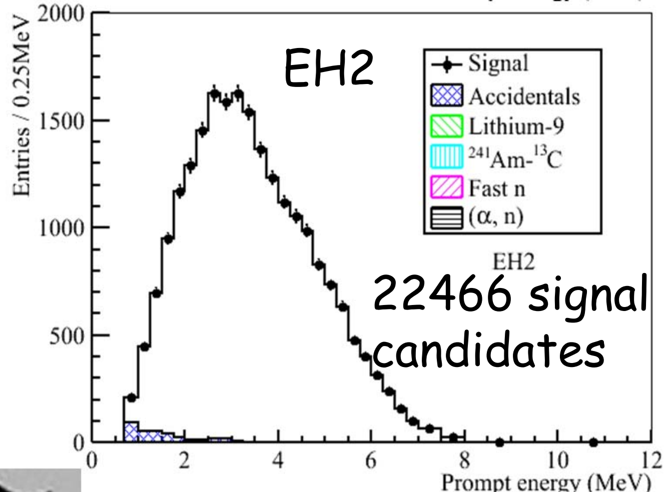


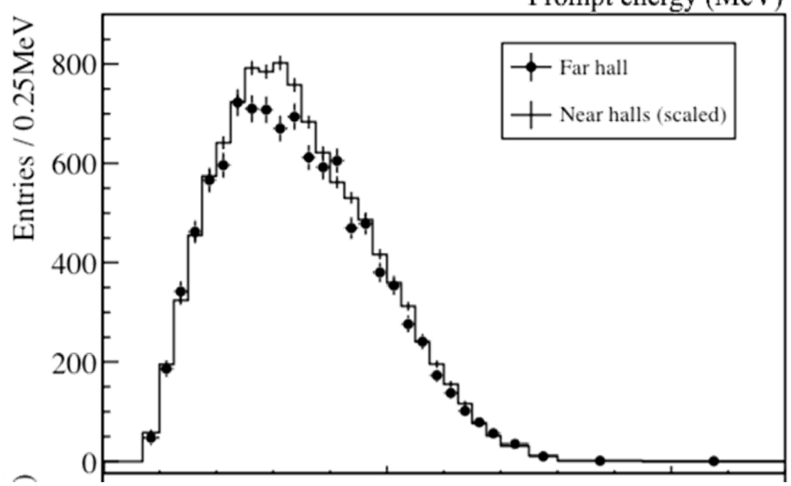
Independent Evidence via Spectral Analysis

Neutrino oscillations at Daya Bay deplete the e^+ energy spectrum near 3 MeV,
$\Rightarrow$ Far-detector (EH3) spectrum will be "flatter" if oscillations have occurred.









In predicting the Far (EH3) spectrum from the Near (EH1 and EH2) detectors, EH2 is weighted 7 times EH1.

~ 3-σ difference in near-far spectral shapes (preliminary).

Backup Slides

The Neutrino Mixing Matrix

- The MNS matrix relates the mass eigenstates (ν_1, ν_2, ν_3) to the flavor eigenstates ν_e, ν_μ, ν_τ):

MNS = Maki-Nakagawa-Sakata, who (1962) extended Ponetcorvo's prediction (1957) from 2 to 3 neutrinos.

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

U_{e3} is last unknown matrix element

$\sin^2\theta_{12} \sim 0.31$
$\sin^2\theta_{23} \sim 0.43$

- It can be described by three 2D rotations:

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

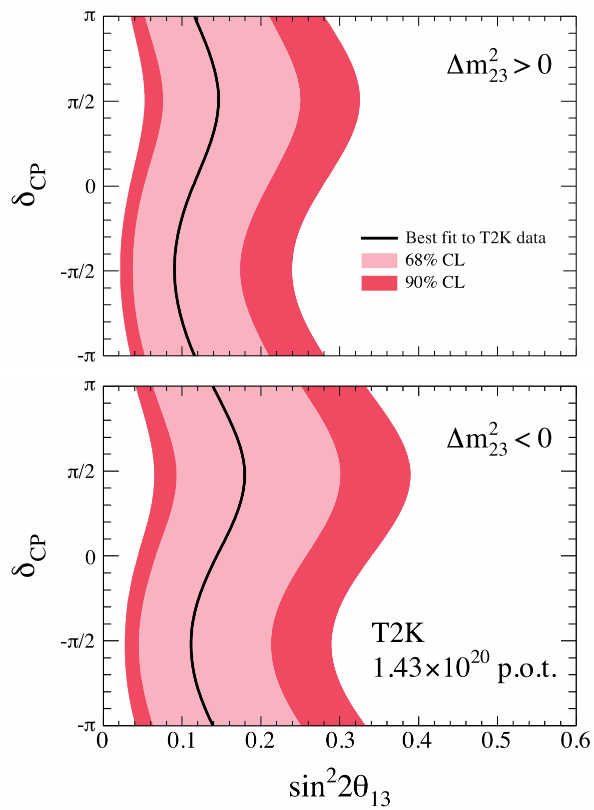
Atmospheric — Reactor — Solar — Majorana Phases

Measurement of the last unknown mixing angle, θ_{13}, is going to have a substantial impact on the future of neutrino physics.

Recent Experimental Results (2011): θ_{13} may be large

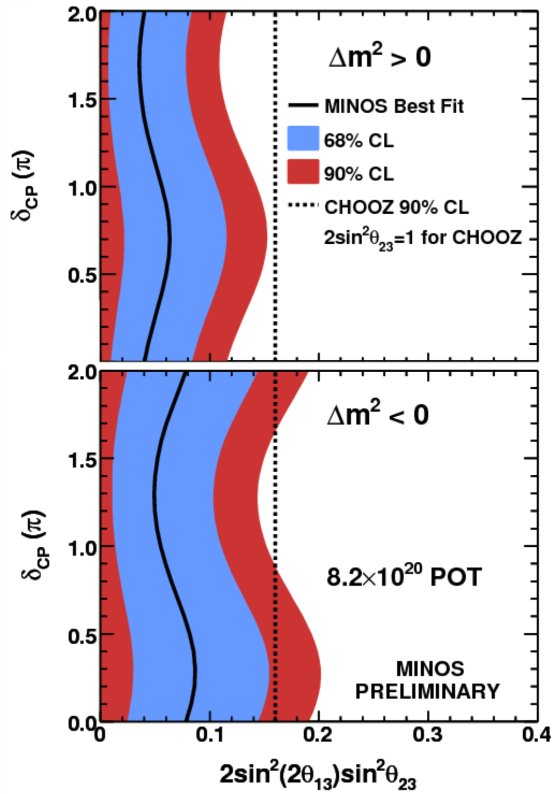
Accelerator-based appearance expts. Reactor-based disappearance expt.

T2K



PRL **107**, 041801 (2011)

MINOS



PRL **107**, 181802 (2011)

Double Chooz

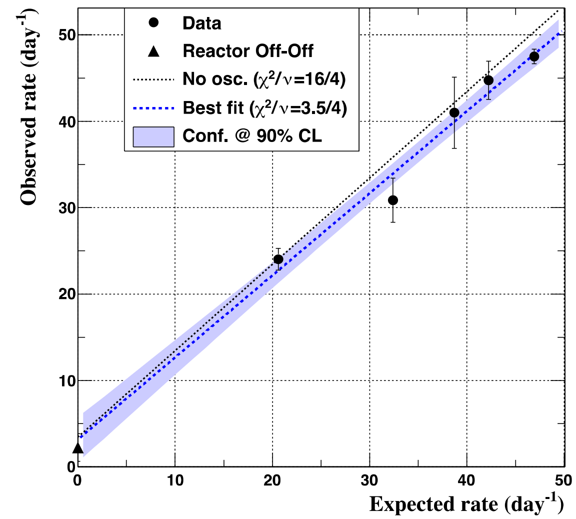


FIG. 2. Daily number of $\bar{\nu}_e$ candidates as a function of the expected number of $\bar{\nu}_e$. The dashed line is a fit to the data, the band is the 90% CL of this fit. The dotted line is the expectation in the no-oscillation scenario. The triangle indicates the one day measurement with both reactors off.

arXiv:1112.6353v1

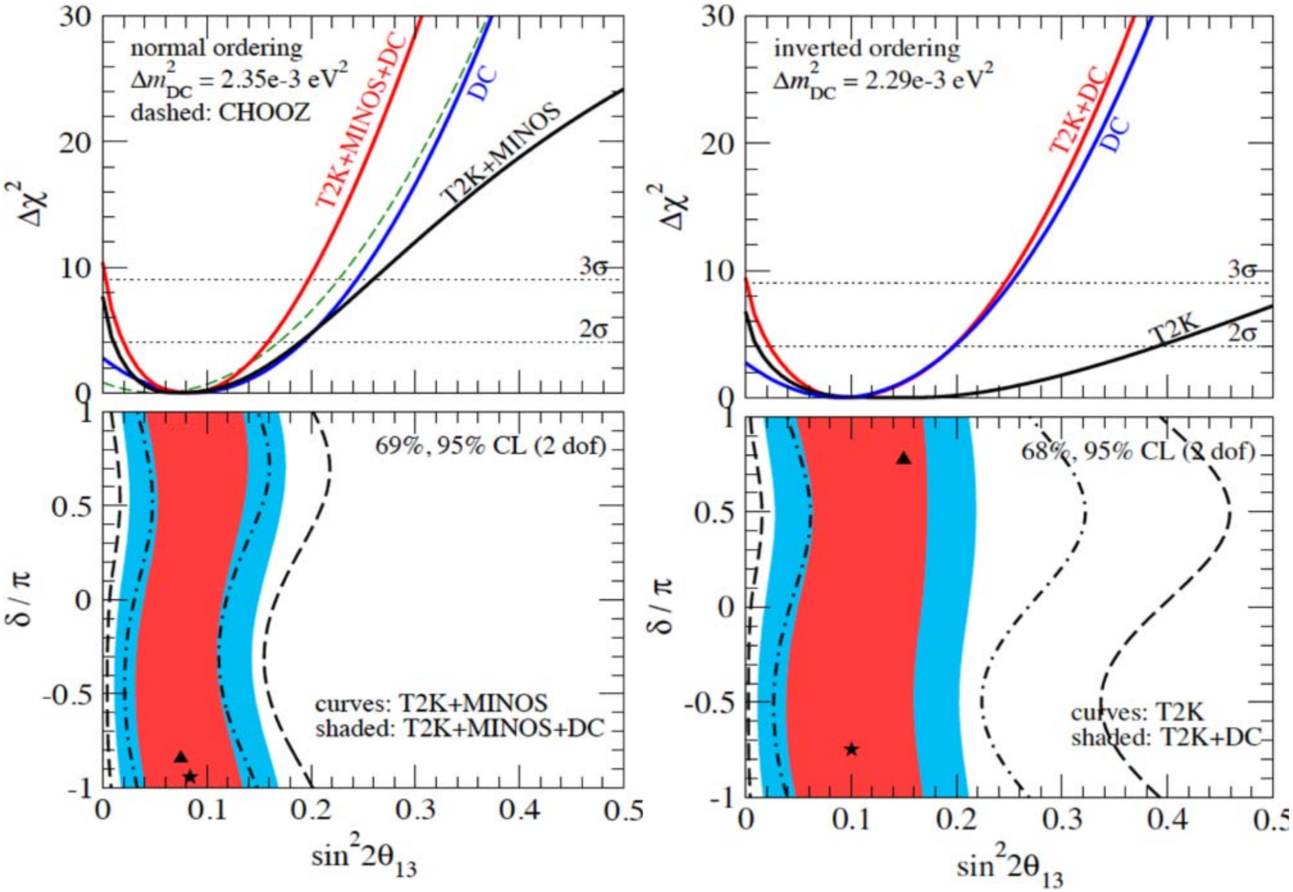
$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ at 90% CL

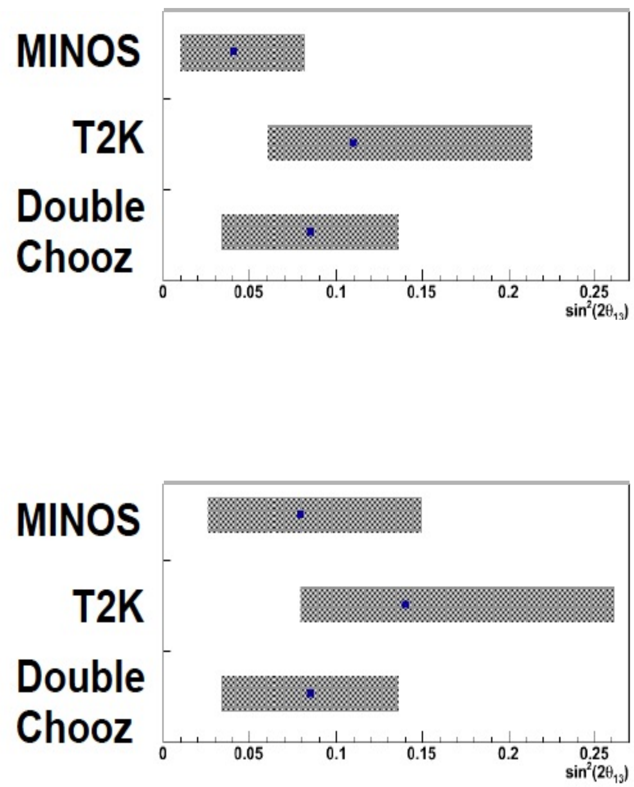
$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{sys})$
$(0.015 < \sin^2 2\theta_{13} < 0.16$ at 90% CL)

T2K has 6 candidate electron-appearance events, all close to the beam-entry side of the Super-K detector.

Combined Analysis

http://arxiv.org/abs/1111.3330 Machado *et al.*

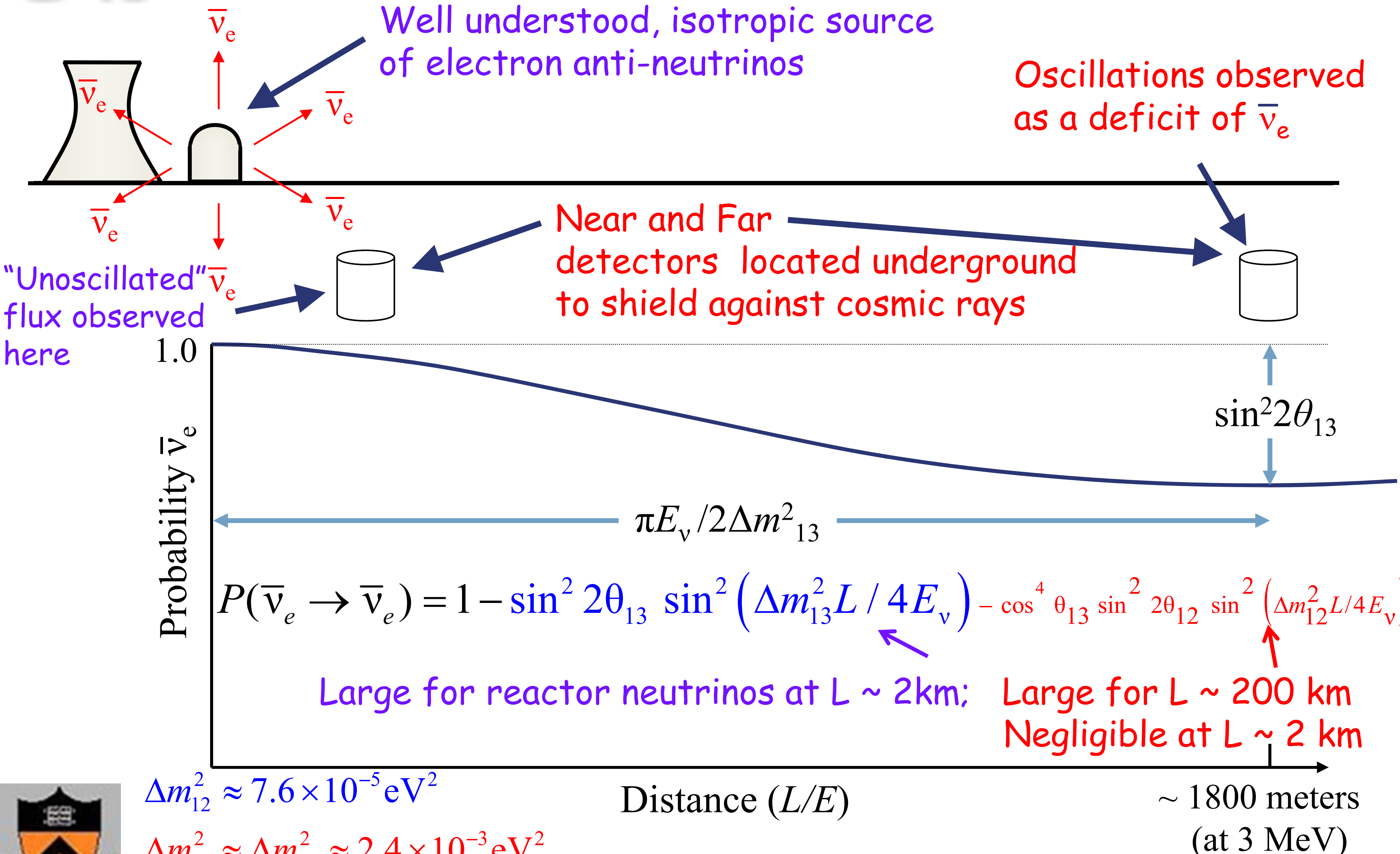




$\sin^2 2\theta_{13}$	best fit	1σ	2σ	3σ	$\Delta\chi^2(\theta_{13}=0)$
normal ordering:	0.092	0.051–0.140	0.021–0.186	0.002–0.233	9.50
inverted ordering:	0.092	0.056–0.146	0.024–0.198	0.002–0.246	9.43

Combined measurements exclude θ_{13} = 0 at greater than 3 σ, but no single experiment has this sensitivity.

Reactor-Based θ_{13} Experiments

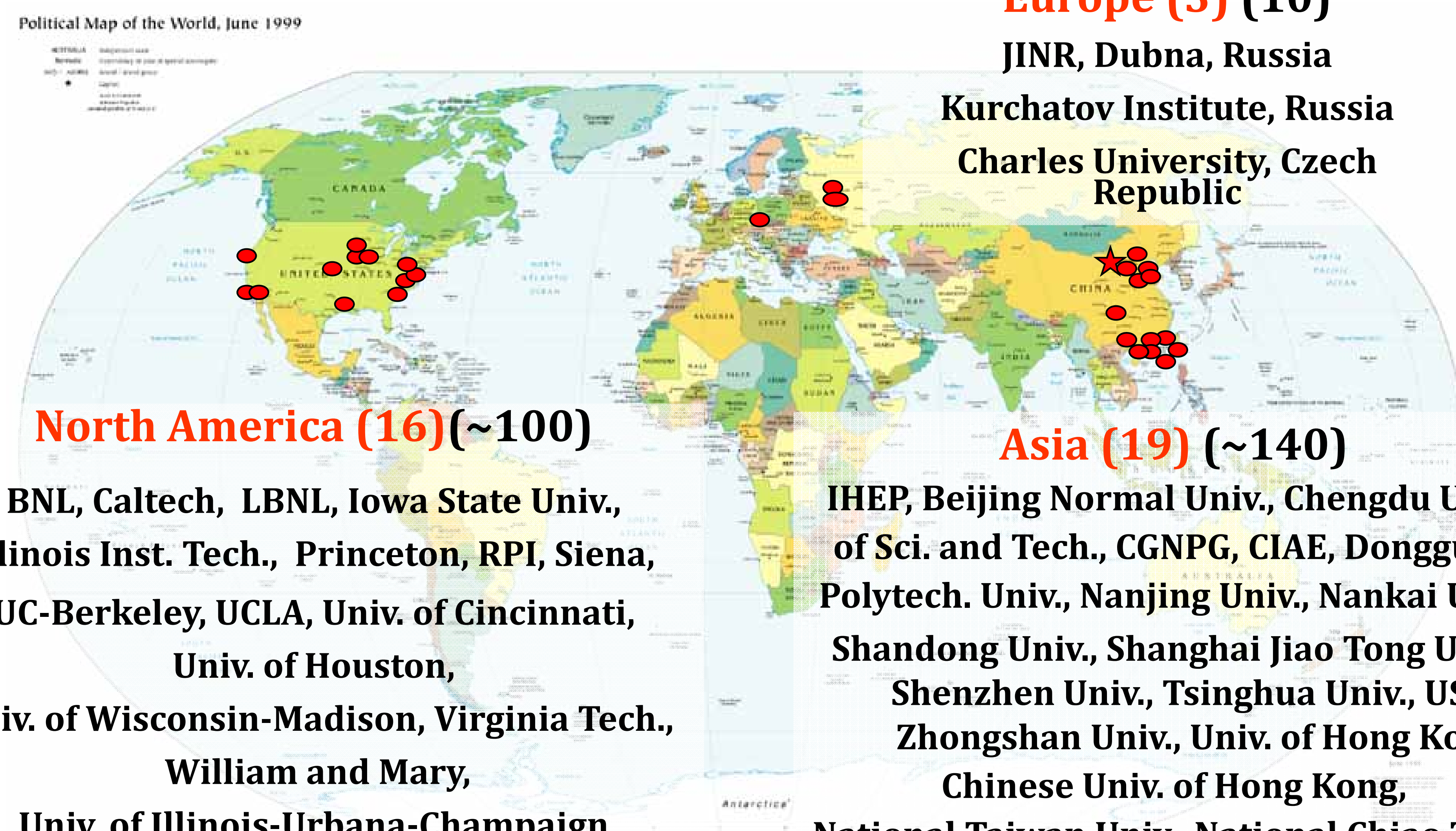


$\Delta m^2_{12} \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2$

$\Delta m^2_{13} \approx \Delta m^2_{23} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2$

The Daya Bay Collaboration

~ 250 collaborators, 38 institutions



Europe (3) (10)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (16)(~100)

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

Asia (19) (~140)

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

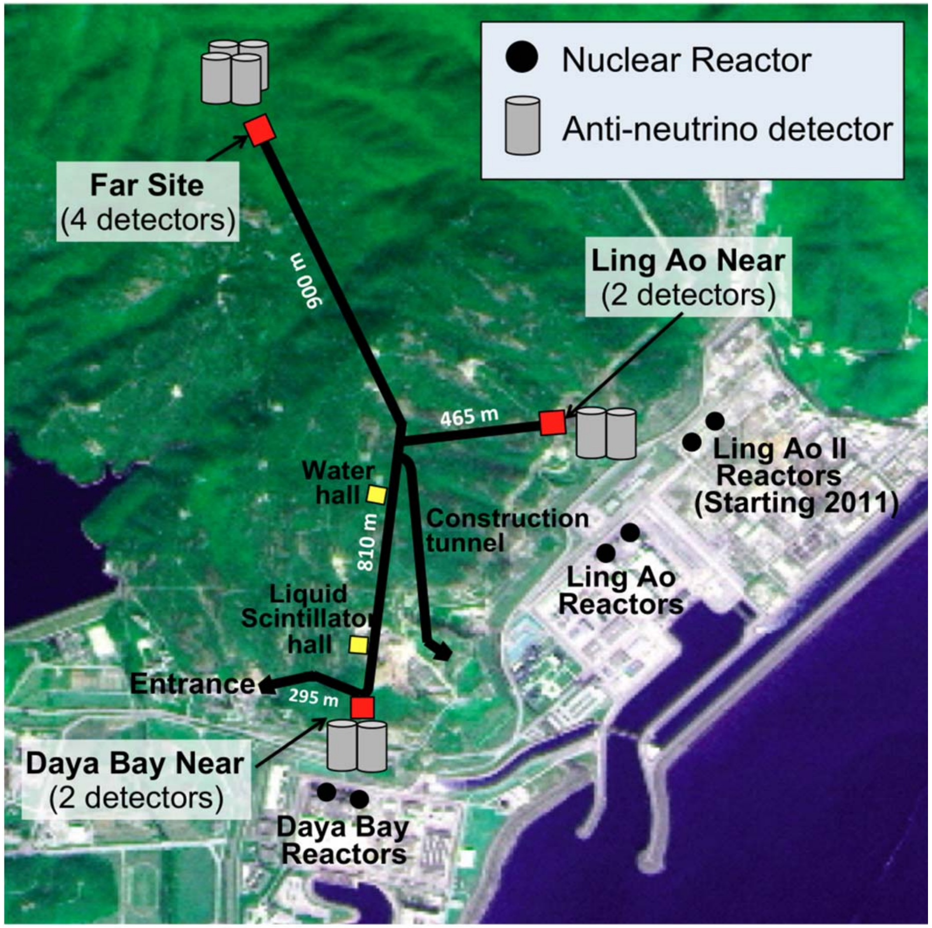
Daya Bay Experiment Design Principles

- Identical near and far detectors cancel many systematic errors
- Multiple detectors at 3 locations boost statistics while reducing systematic errors with multiple independent measurements
- Three-zone detector design eliminates the need for spatial cuts which can introduce systematic uncertainties
- Shielding from cosmic rays and natural radioactivity reduces background rates
- Movable detectors allow possible cross calibration between near and far detectors to further reduce systematic errors

Experimental Layout

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548
	mwe	Hz/m^2	GeV	m	m	m

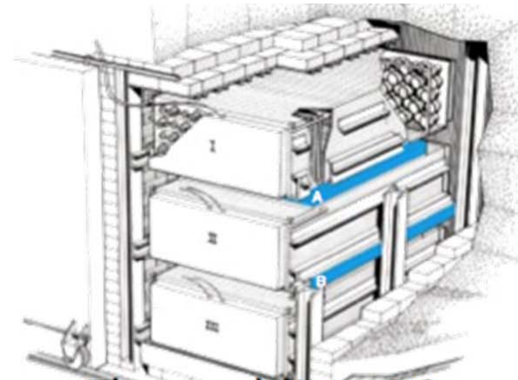
EH = Experimental Hall
D.B. = Daya Bay reactor cores
L.A. = Ling Ao reactor cores
L.A. II = Ling Ao II reactor cores



Antineutrino Detection

Daya Bay: 0.1% Gd doped liquid scintillator as target

Reines *et al.*, Phys. Rev. **117**, 159 (1960)



The world's 1st LS reactor neutrino det.

Inverse beta decay = IBD

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

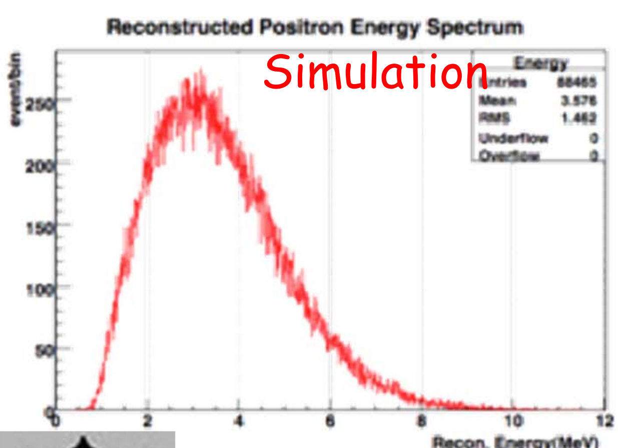
0.3b

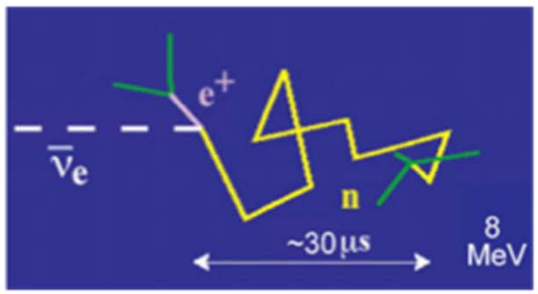
$$n + p \rightarrow D + \gamma(2.2\,\mathrm{MeV})$$

~49,000b

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma(\sim 8\,\mathrm{MeV})$$

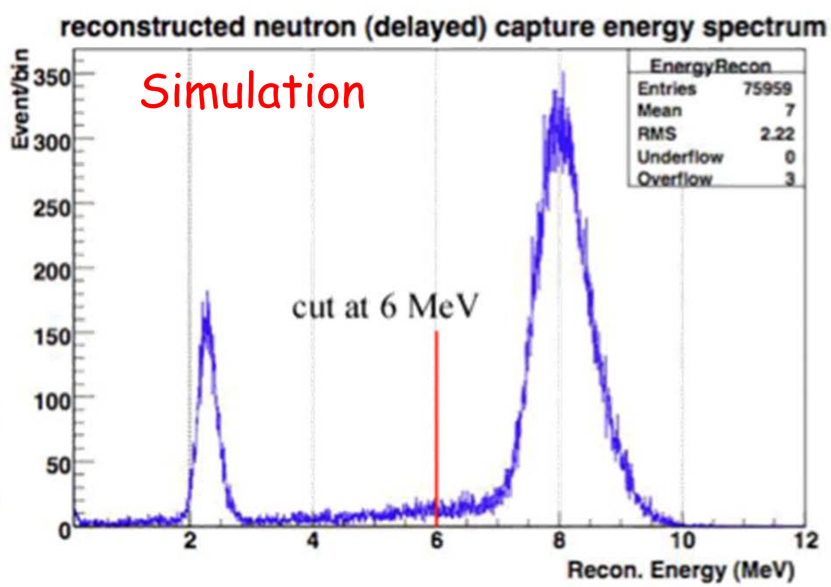
$$E_{\bar{\nu}_e} \approx E_{e^+} + m_n - m_p$$





Correlated Signals

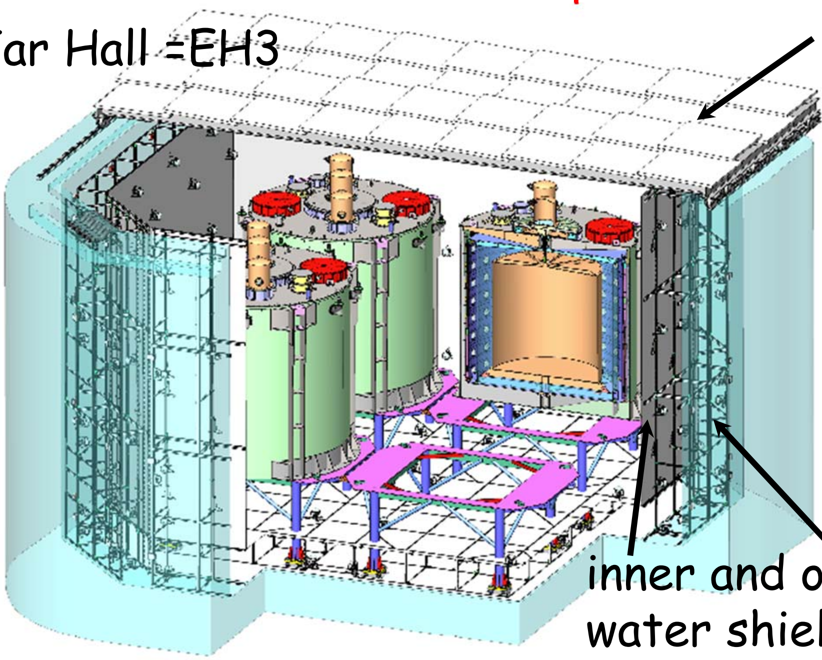
- background suppression
- well-defined target zone

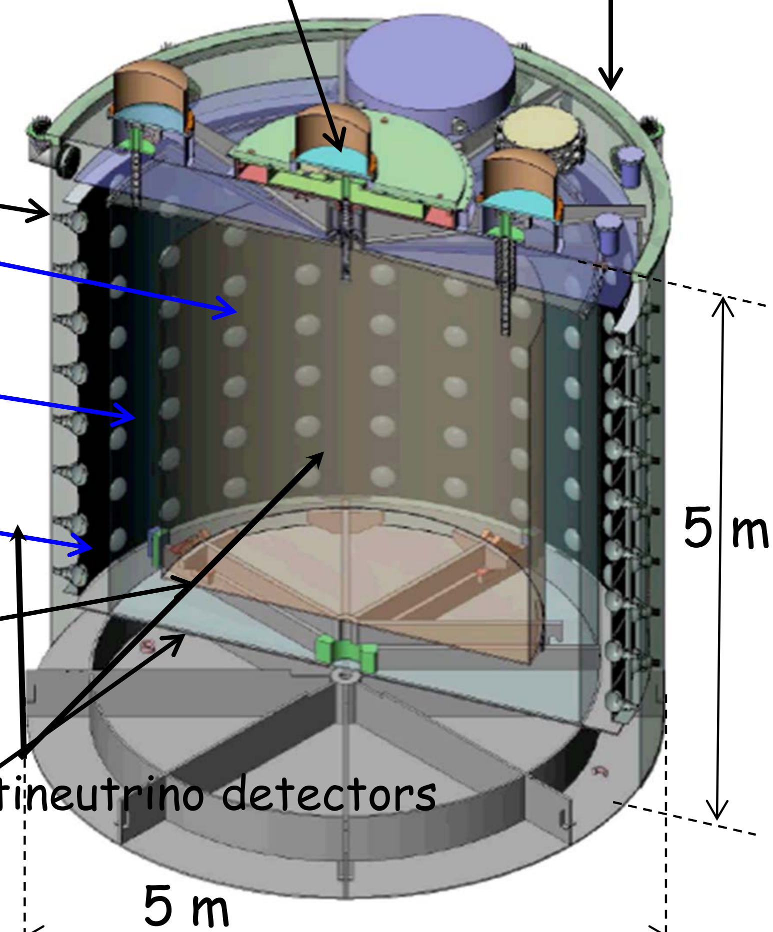


Daya Bay: 8 Identical Antineutrino Detectors

Only 6 detectors installed at present.

- Three-zone cylindrical design:
  1. Target: 20 t (0.1% Gd-based liquid scintillator)
  2. Gamma catcher: 20-t LS (no Gd, so no 8-MeV neutrons detected here)
  3. Buffer : 40-t (mineral oil; no scintillator, so no e, n or γ detected here)
- Detector mass ~ 110 ton ($\Rightarrow$ need big crane to lift!)
- 192 low-background 8" photomultiplier tubes
- Reflectors at top and bottom
- Detectors sit in a pool of water, covered by RPCs





PMT = PhotoMultiplier Tube
AD = Antineutrino Detector
RPC = Resistive Plate Chamber

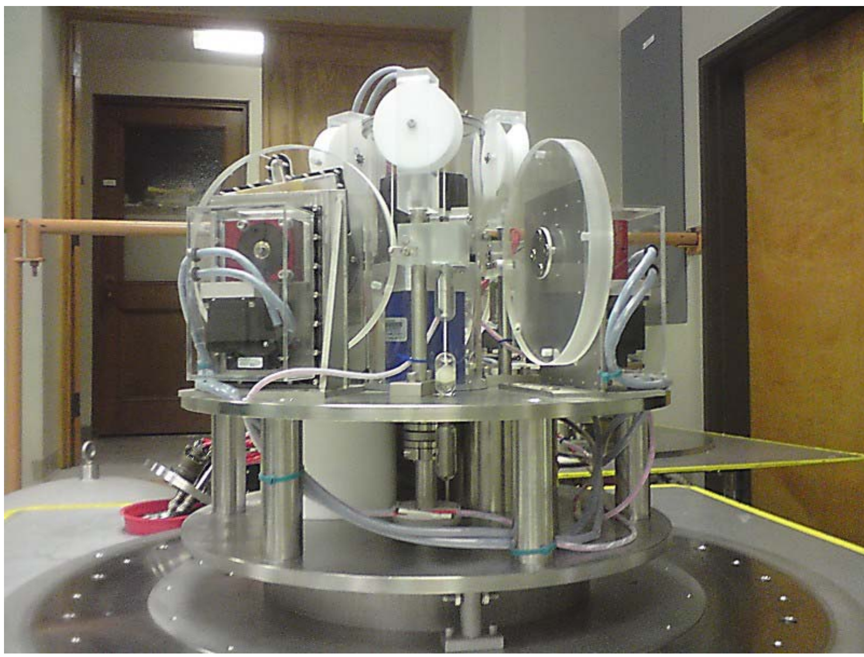
Antineutrino Detector Calibration System

Automated calibration system
→ Routine weekly deployment of sources, lowered into any of the 3 liquid zones.

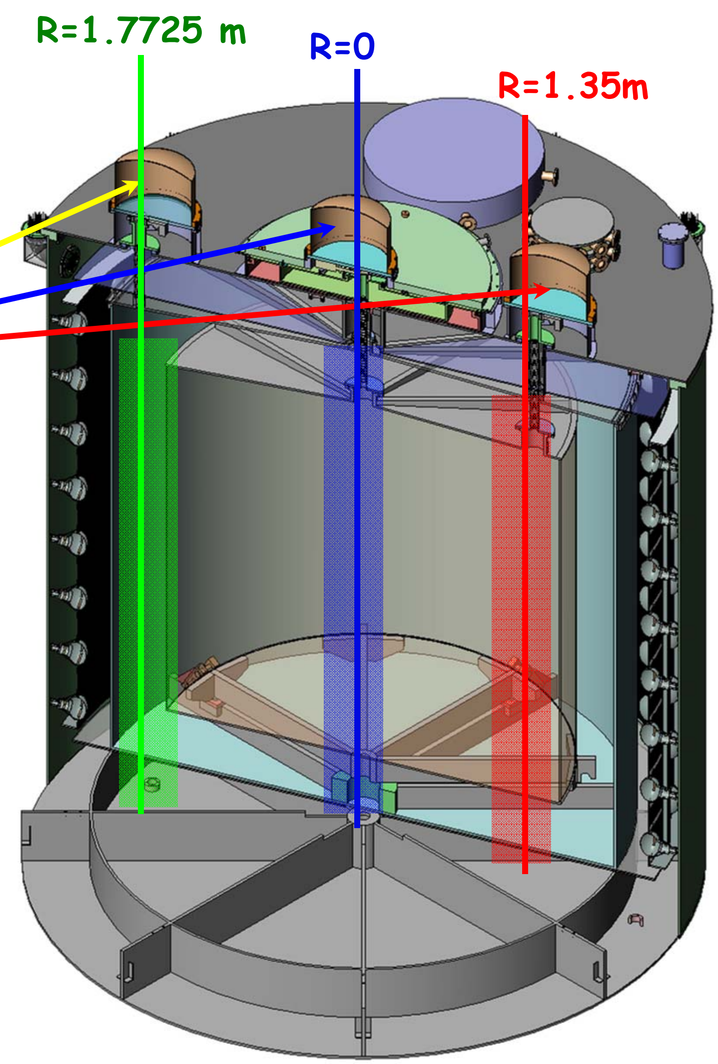
- ^{68}Ge source
- Am-^{13}C + ^{60}Co source
- LED diffuser ball

LED light sources
→ Monitoring optical properties

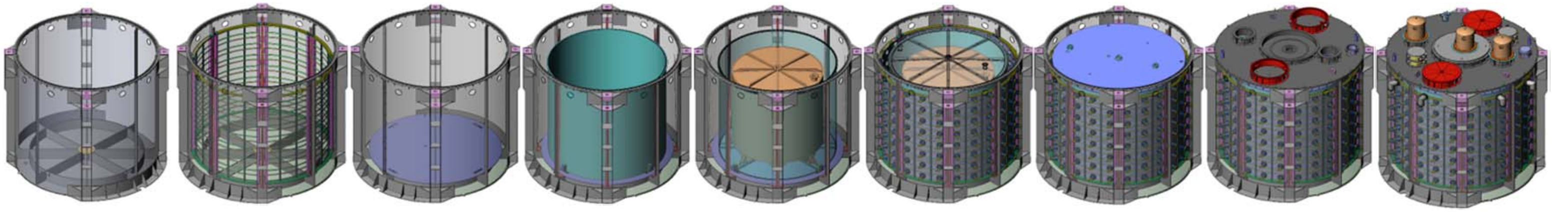
e^+ and n radioactive sources (fixed energy)
→ Energy calibration

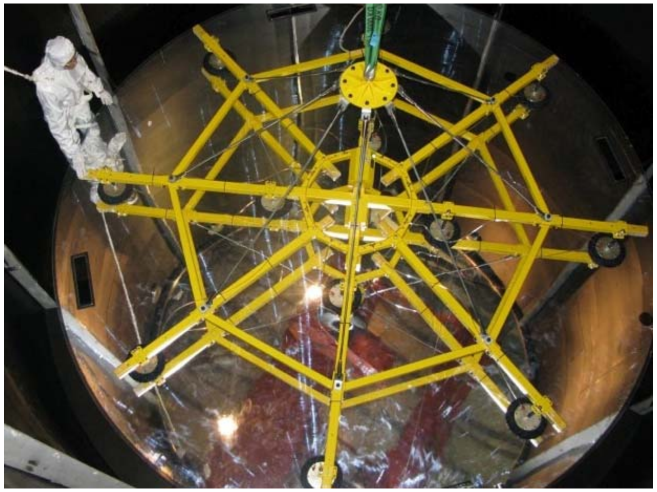


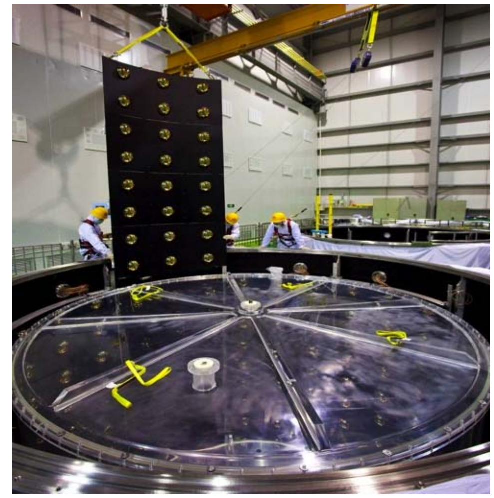
Automated calibration system

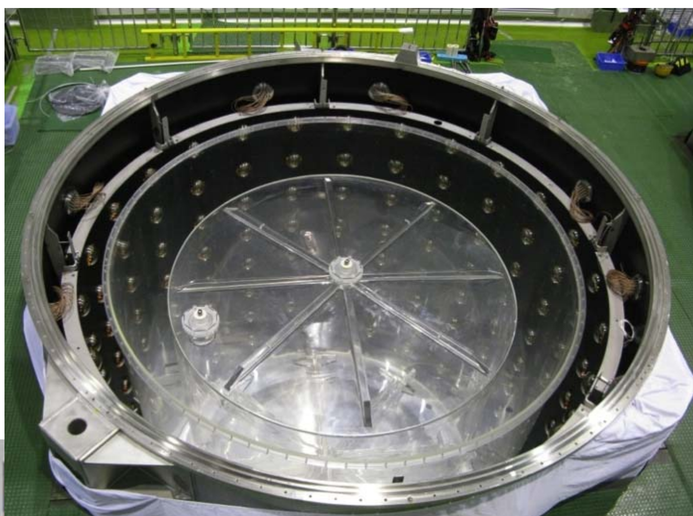


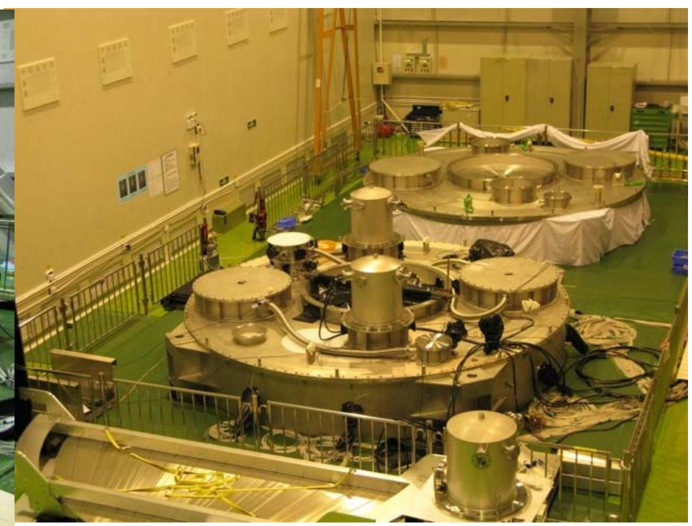
Antineutrino Detector Assembly







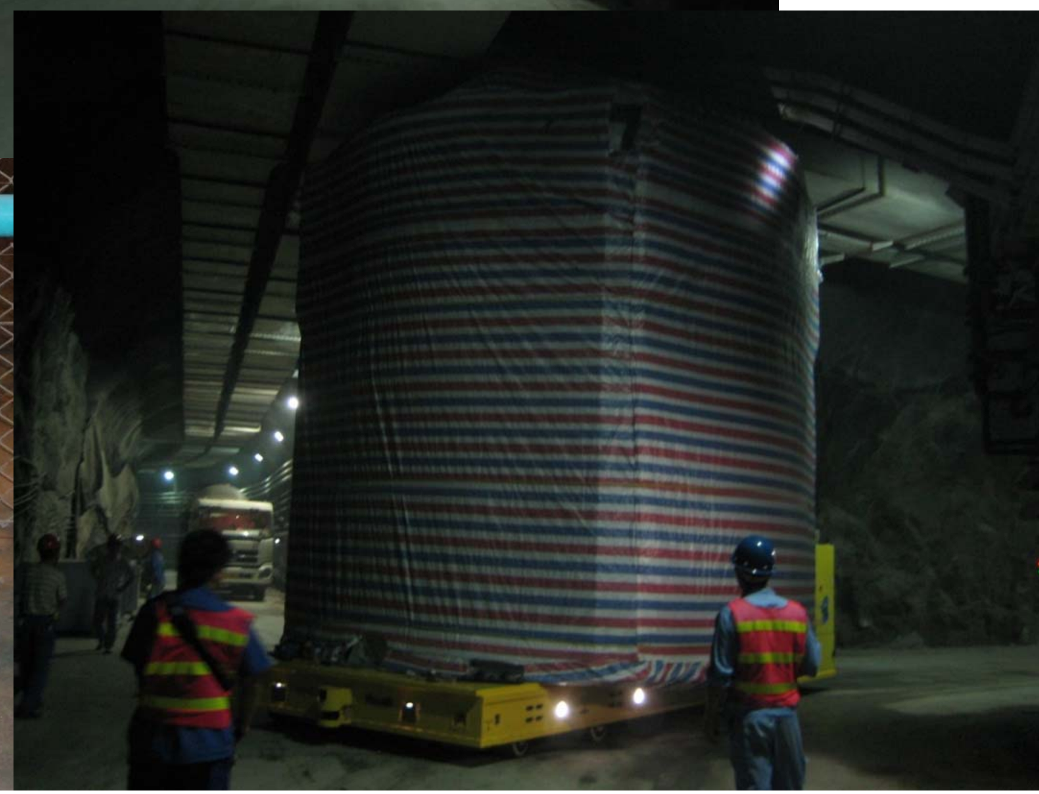




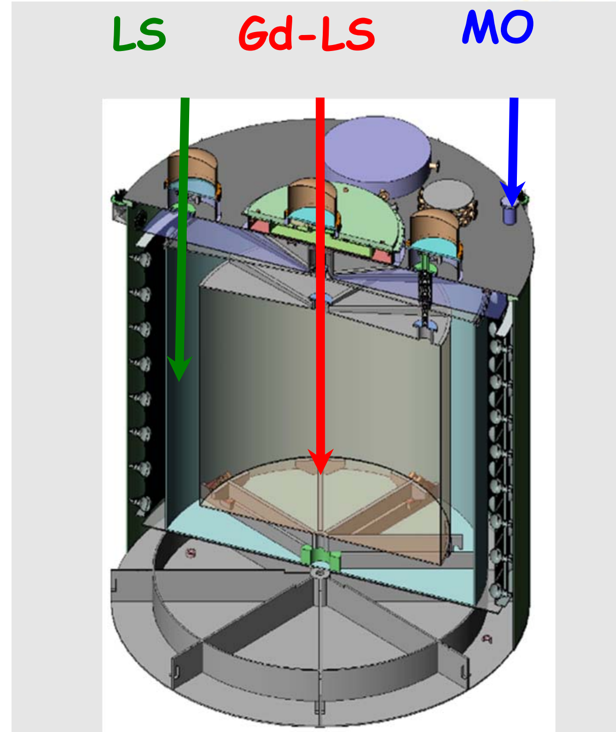
Transporting the Antineutrino Detectors

AGV = automated guided vehicle, 120 ton capacity

Cobra

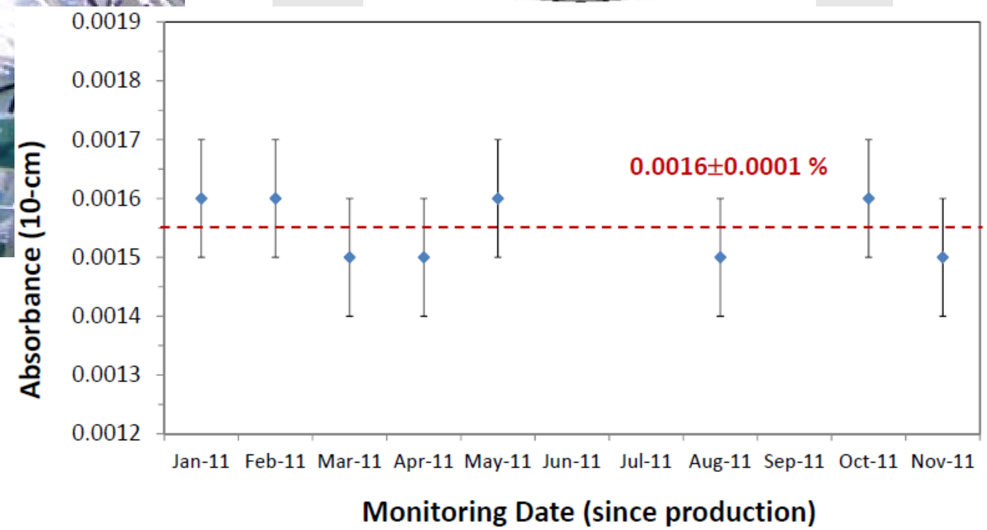


Detector Filling and Target Mass Measurement



Detectors are filled from same reservoirs "in-pairs" within < 2 weeks.

Target mass determined to ± 3kg out of 20,000 or < 0.02%.

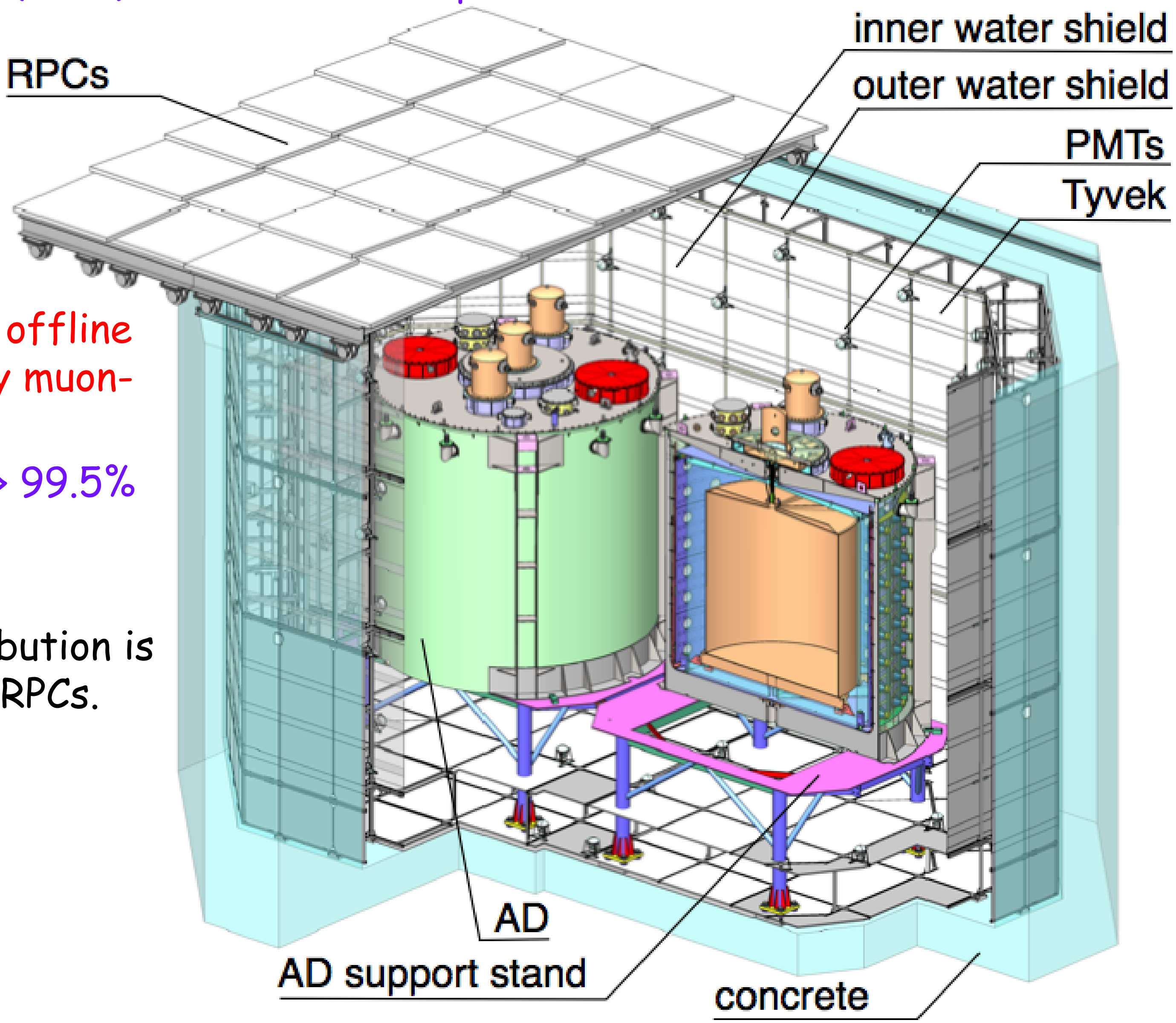


Gd-loaded scintillator shows good stability with time.

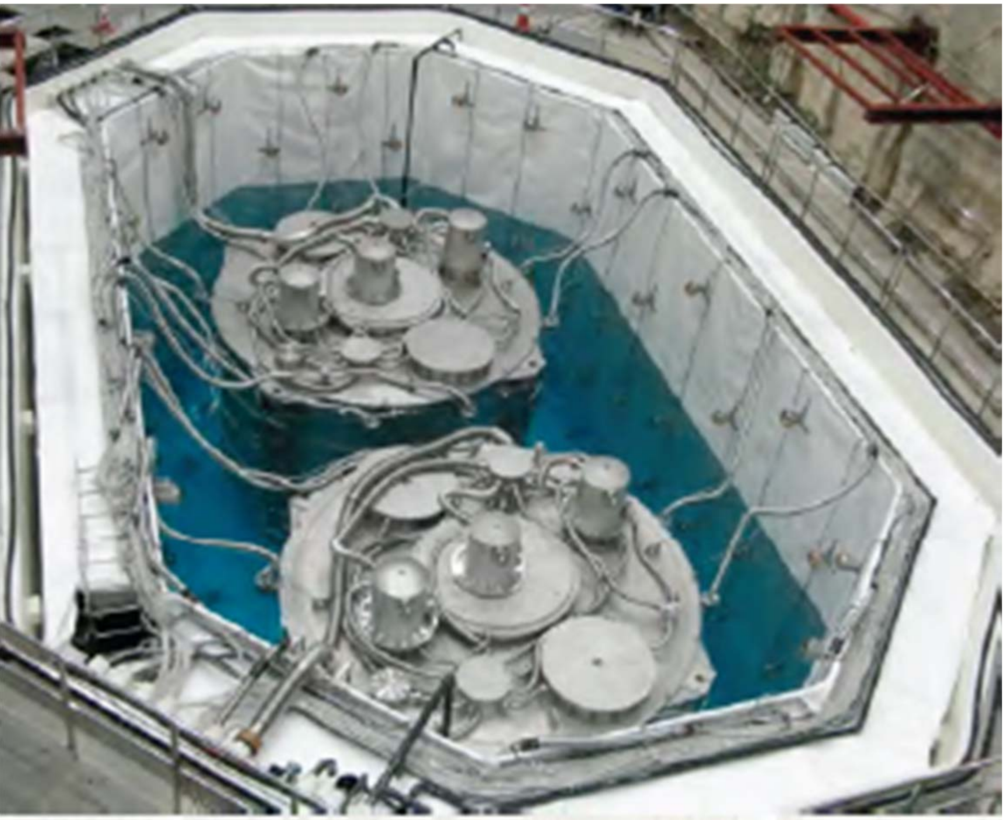
The Muon Tagging System

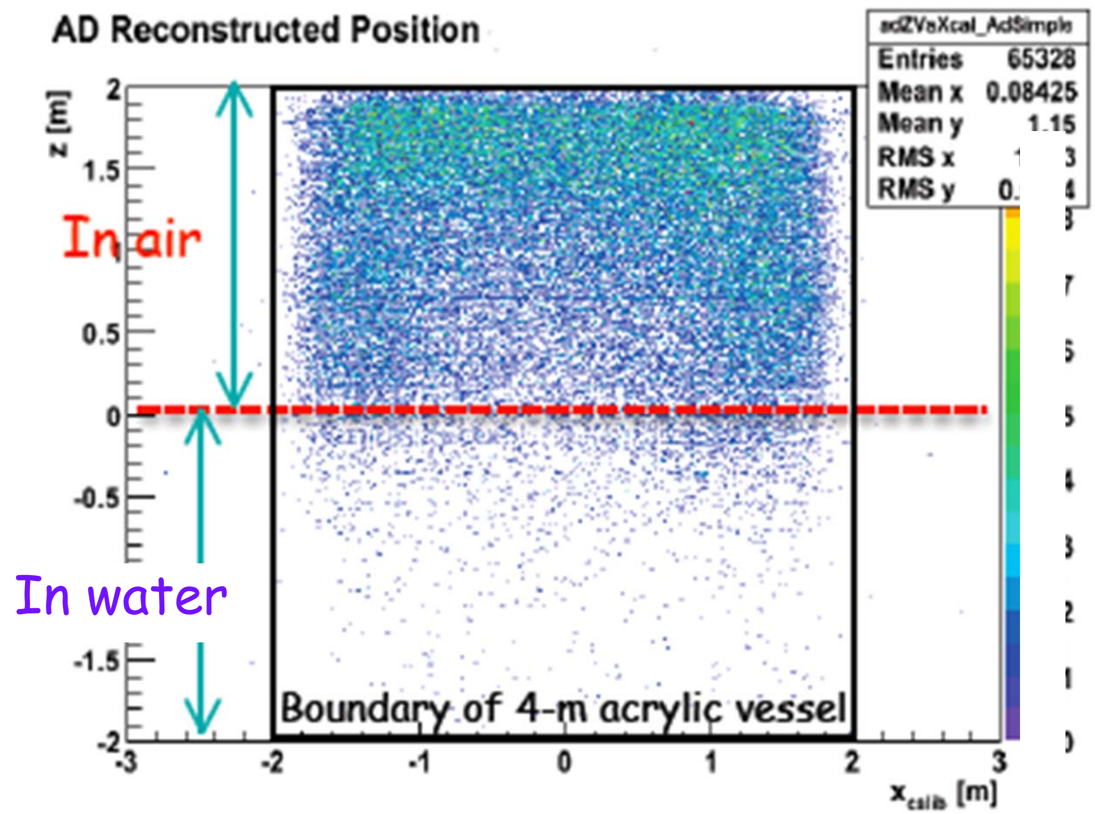
Dual tagging systems: 2.5-m thick, two-zone water shield, instrumented with PMTs, + resistive plate chambers (RPCs) above the water pool.

- No online veto, but rather offline tagging/veto of cosmic-ray muon-induced events.
- Design tagging efficiency > 99.5% with uncertainty < 0.25%.
- Princeton hardware contribution is to the gas system for the RPCs.



Water Shield Suppresses Background Radioactivity

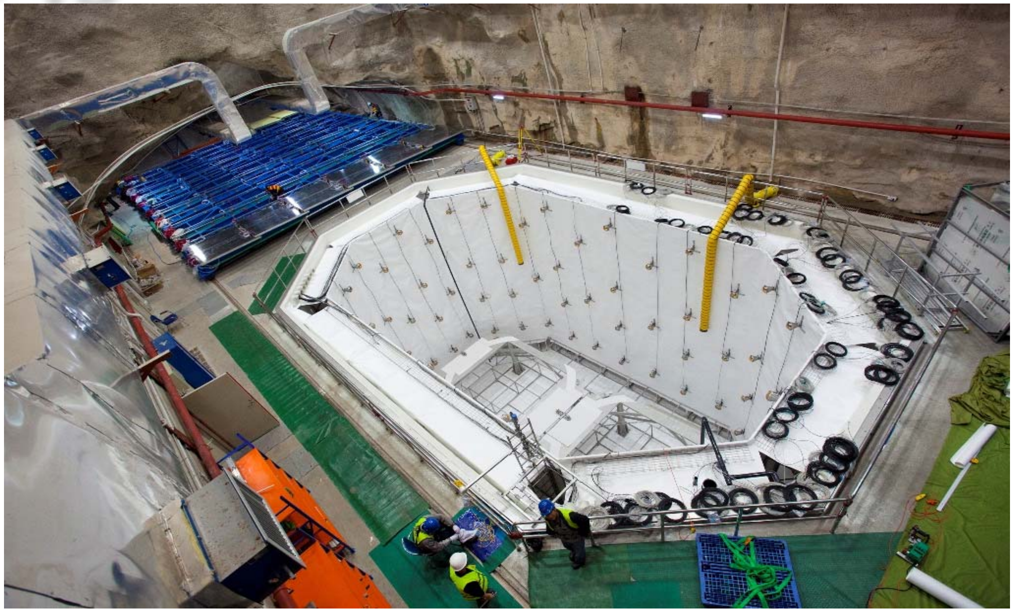


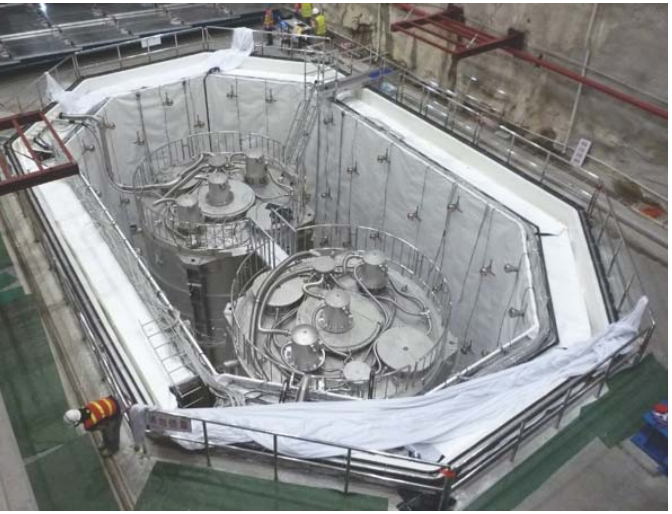
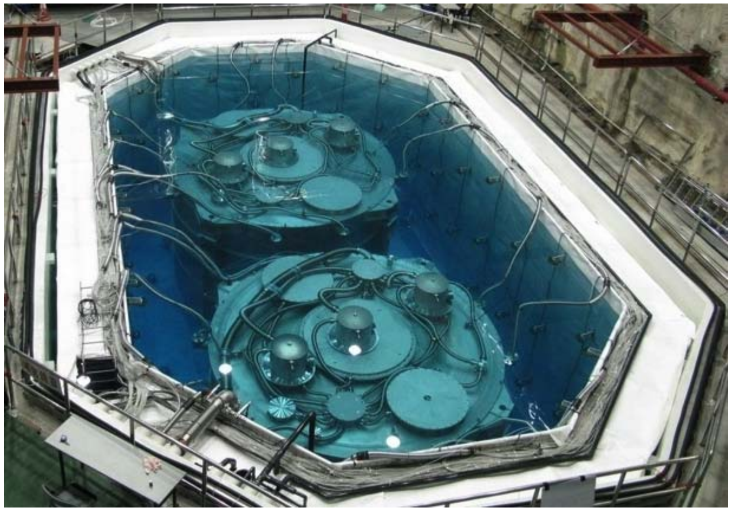
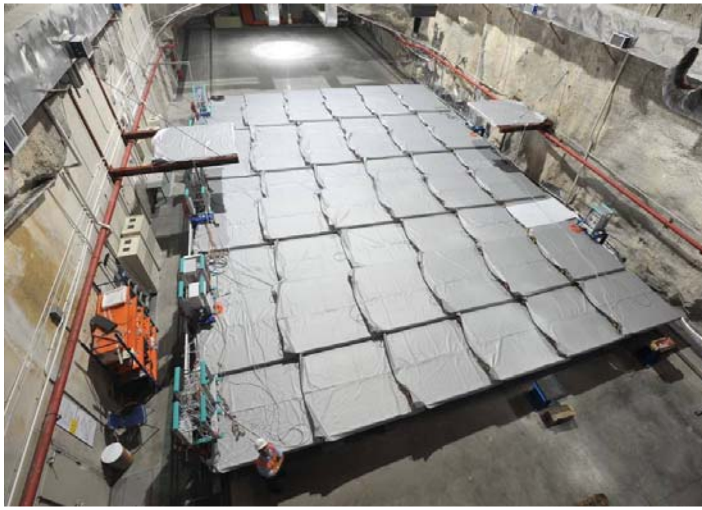


Singles rates *vs.* height in the partially filled pool show the suppression of radioactive backgrounds (due to the rock and/or radon) by the water shield.

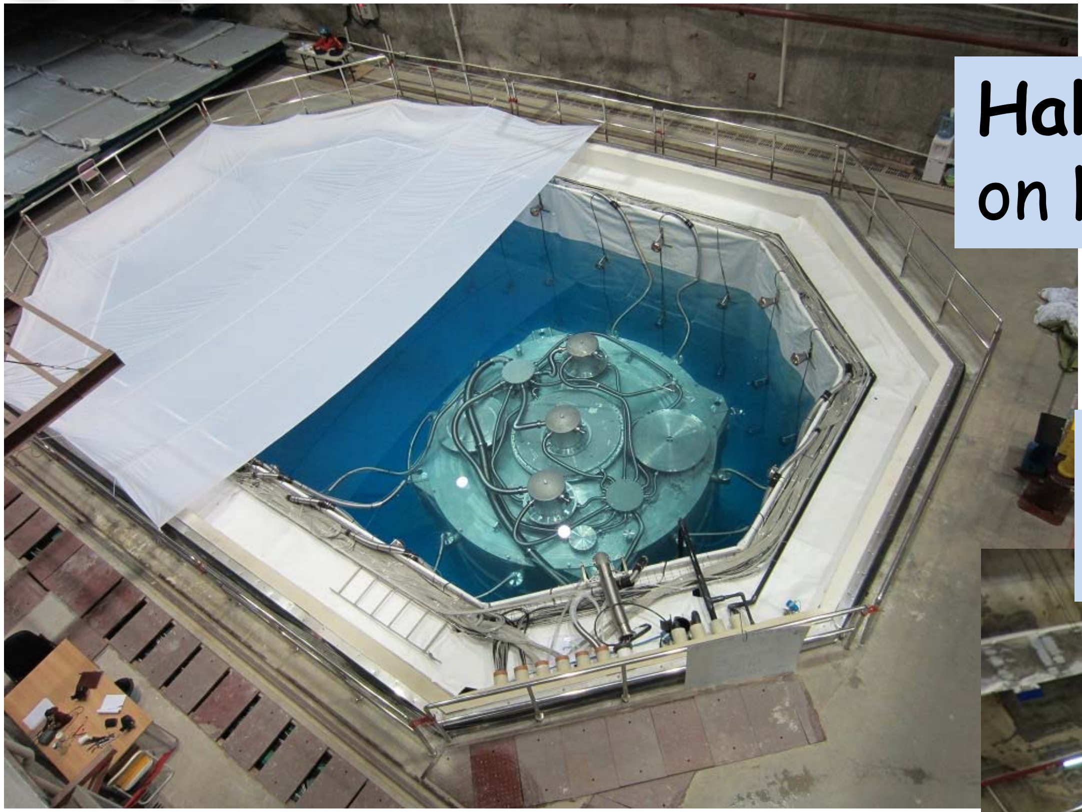
[PMT coverage in the water pool is poor at the top, where the RPC array augments the muon coverage – but not that for rock radioactivity.]

EH1 Data-Taking since August 15, 2011



Installation in EH2 and EH3



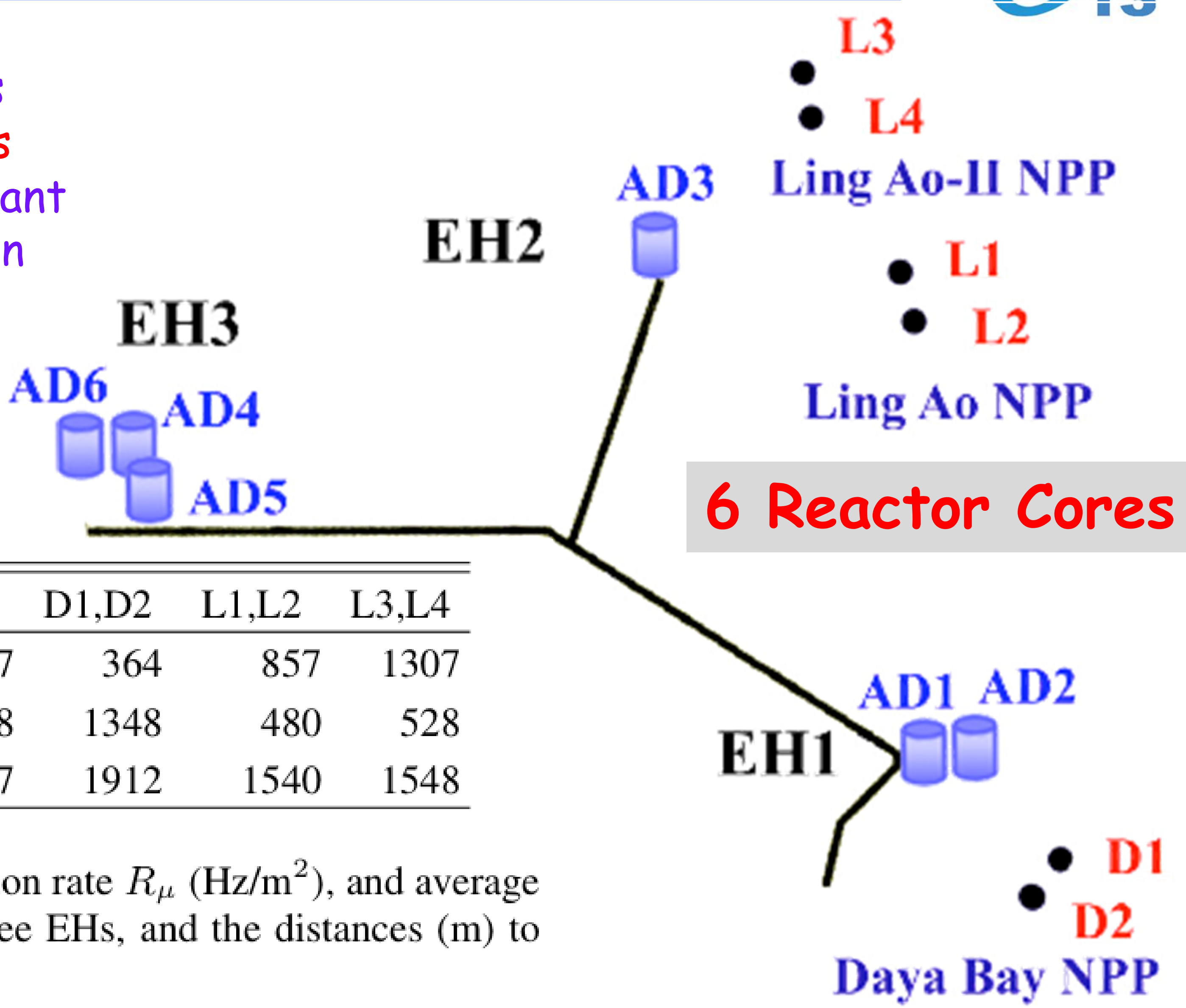
Hall 2: Began 1 AD operation on Nov. 5, 2011

Hall 3: Began 3 AD operation on Dec. 24, 2011

2 more ADs still in assembly; installation planned for Summer 2012

6 Antineutrino Detectors in 3 Halls

EH1 is close to 2 reactors
EH2 is close to 4 reactors
⇒ EH2 much more important in the near/far comparison



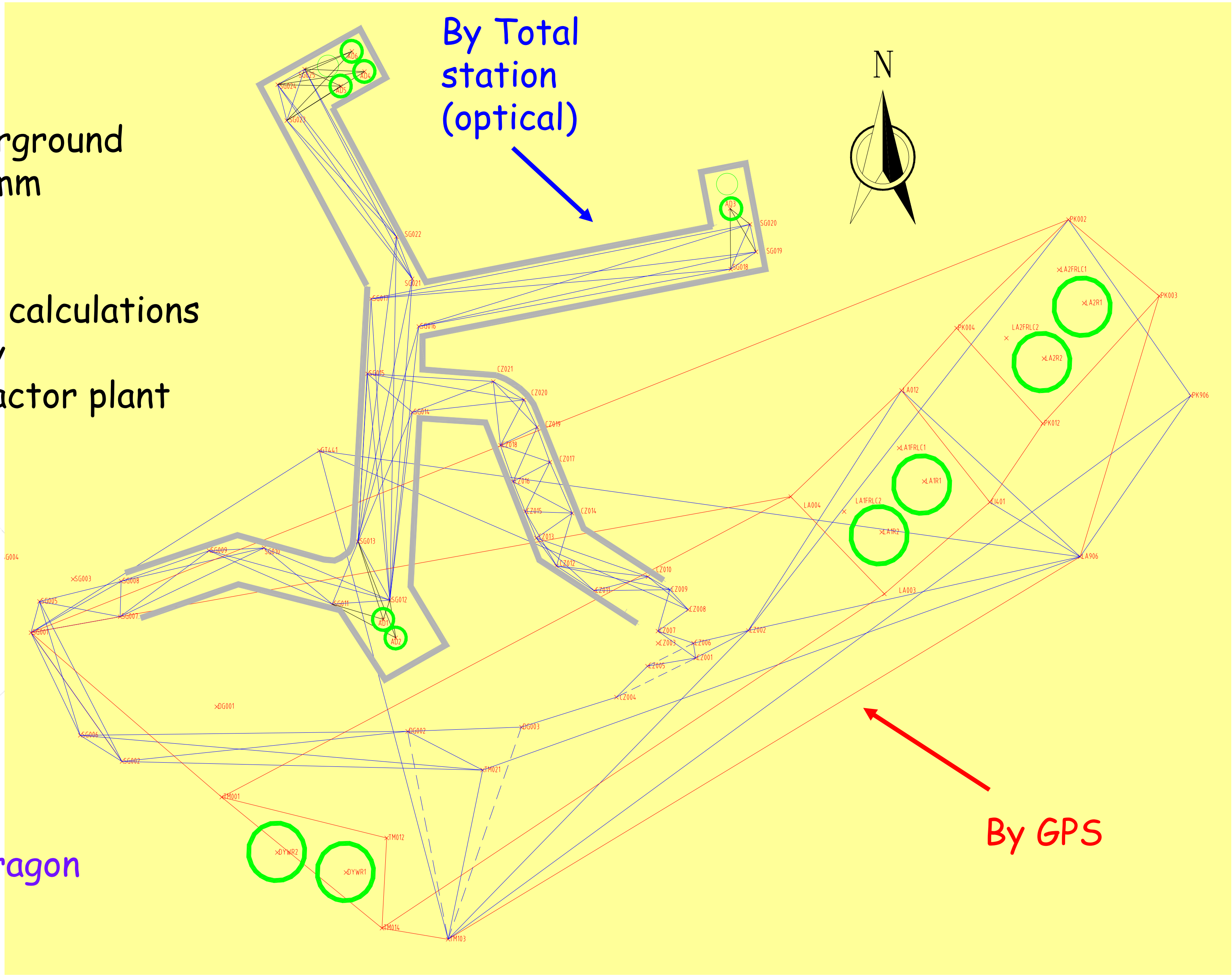
	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

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.

Survey

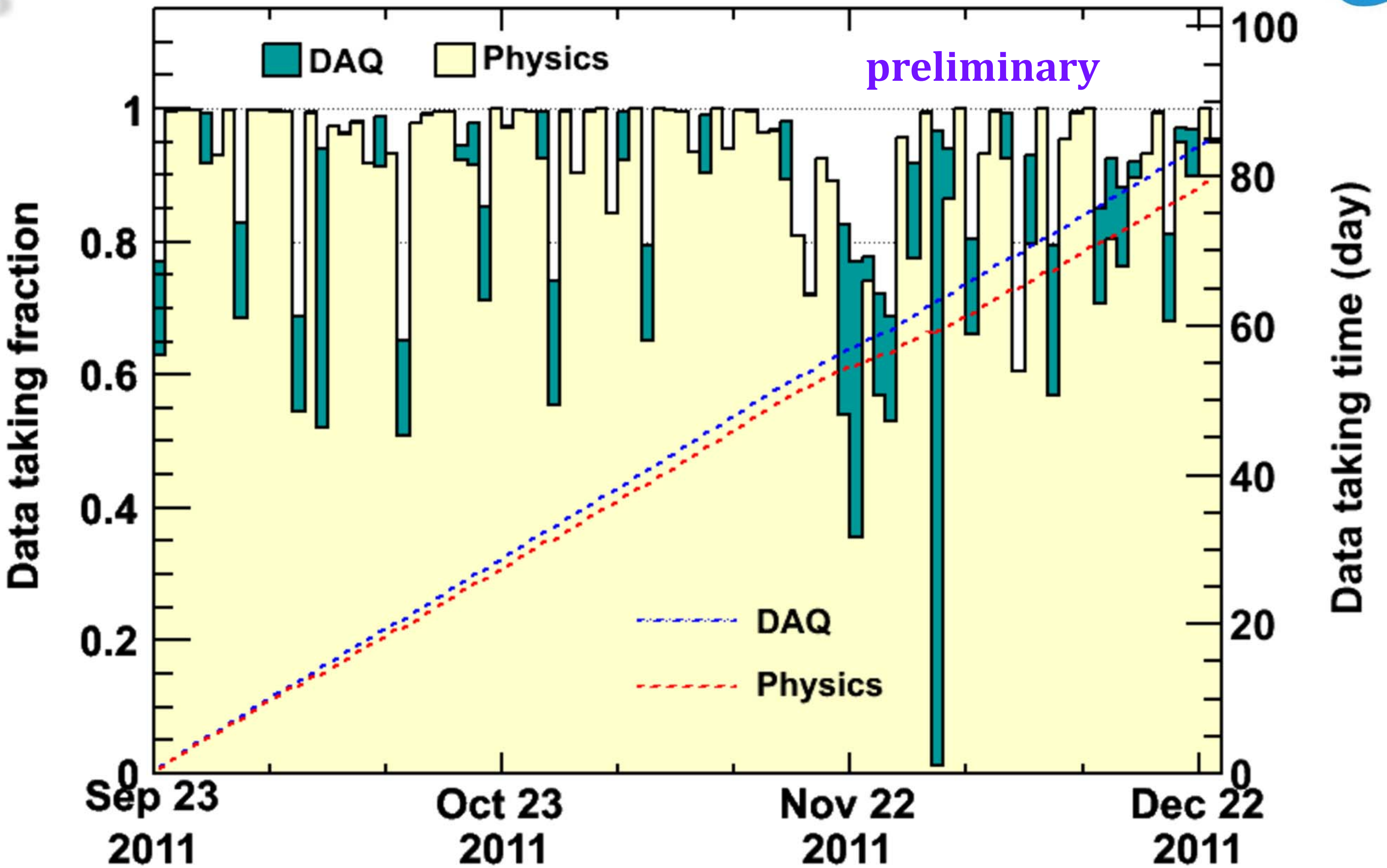
Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 28mm

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



2012 = year of the dragon

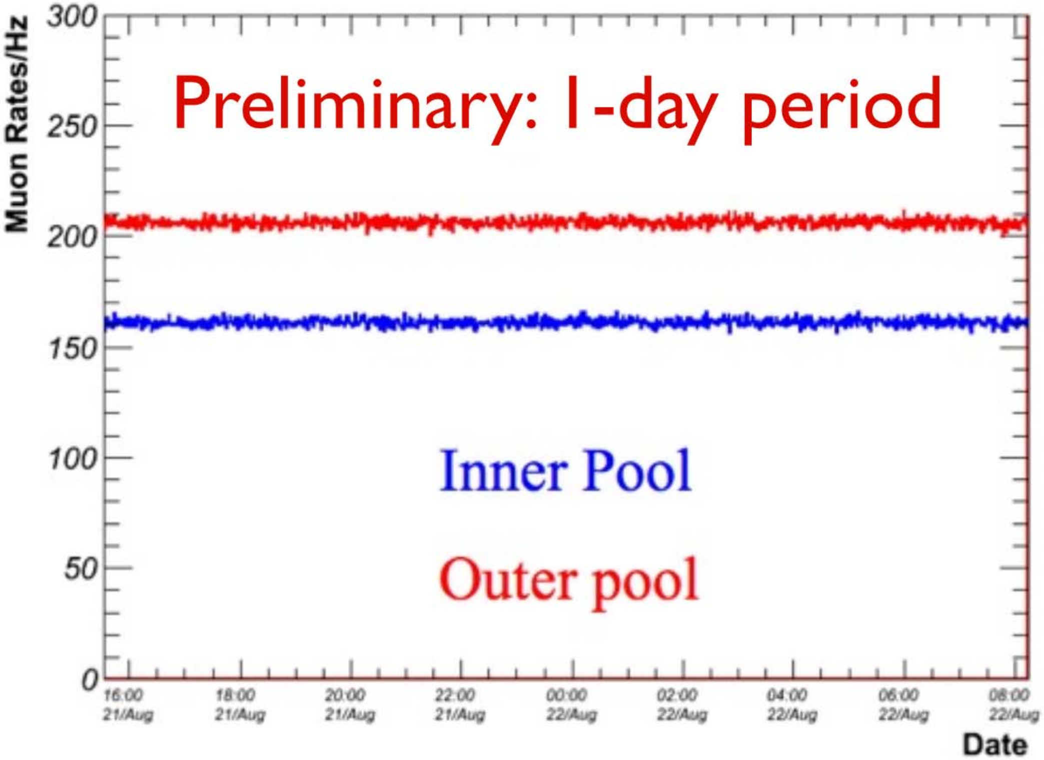
Live Time of First Two Detectors (EH1)

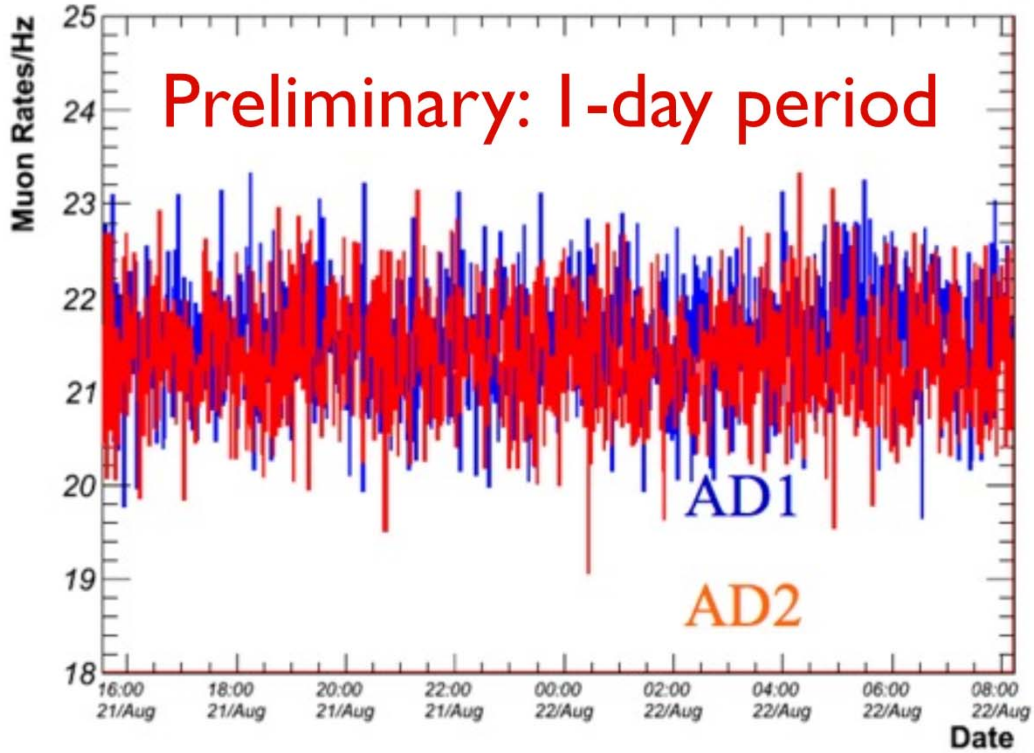


We have used the 3 months of data for side-by-side comparison of first two detectors.

Detailed comparison of AD1 and 2: F.P. An *et al.*, http://arxiv.org/abs/1202.6181

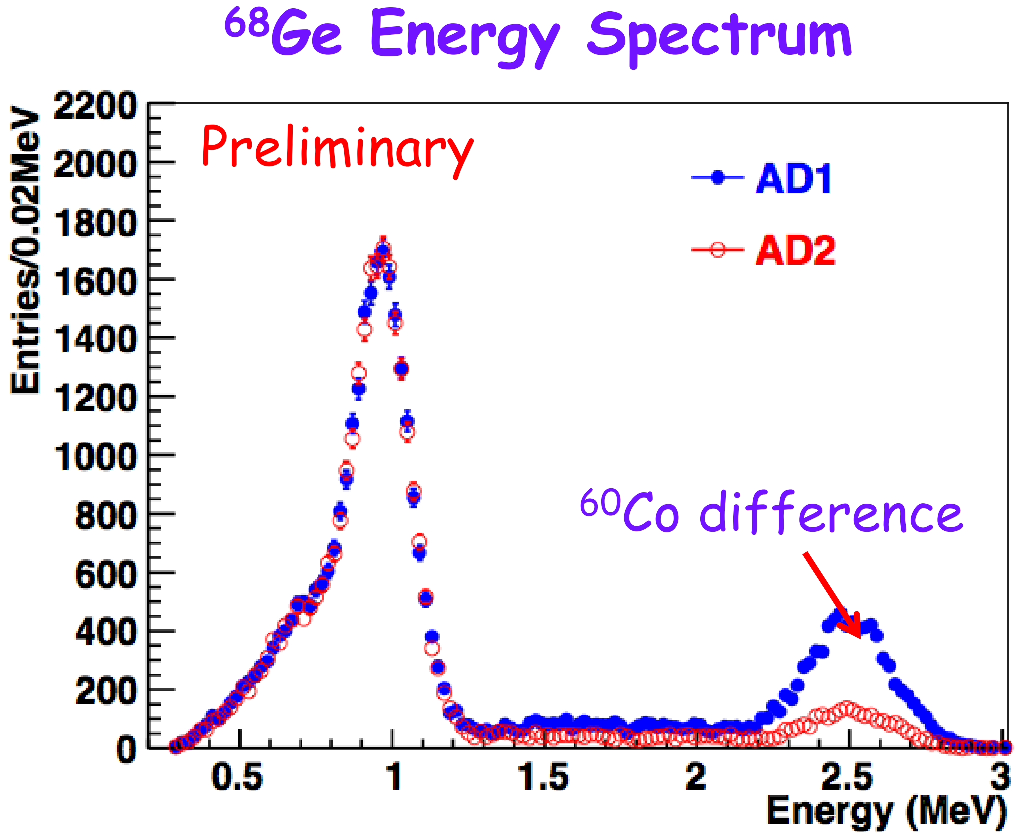
Muon Rates at EH1

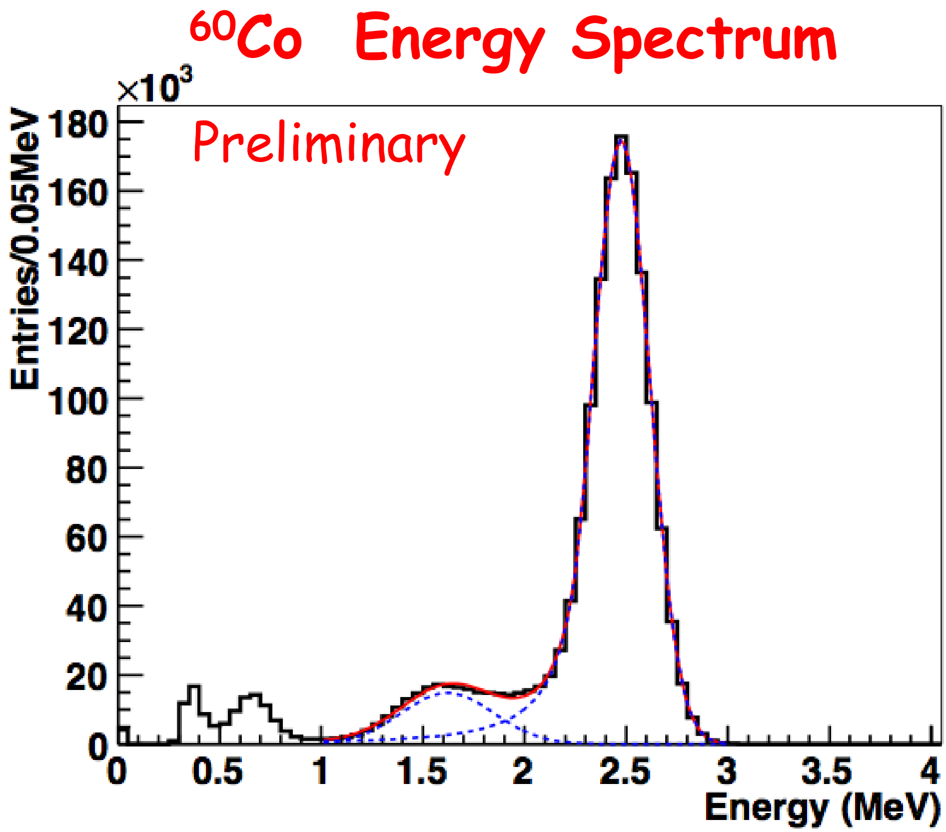




- Measured rates are consistent with expected ~ 20 Hz for each AD at the Daya Bay near site (EH1).

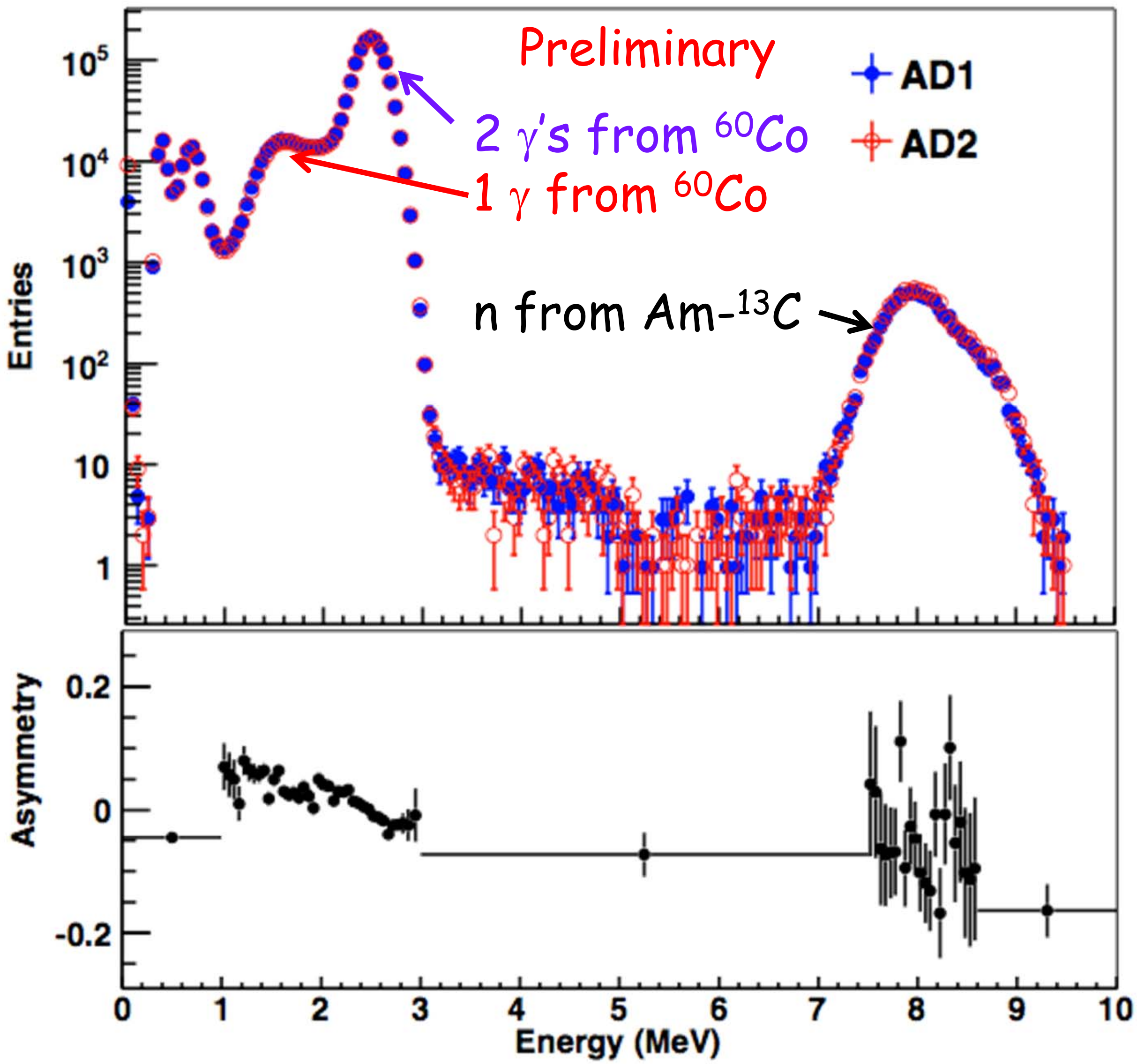
Energy Response with Calibration Sources: ^{68}Ge and ^{60}Co





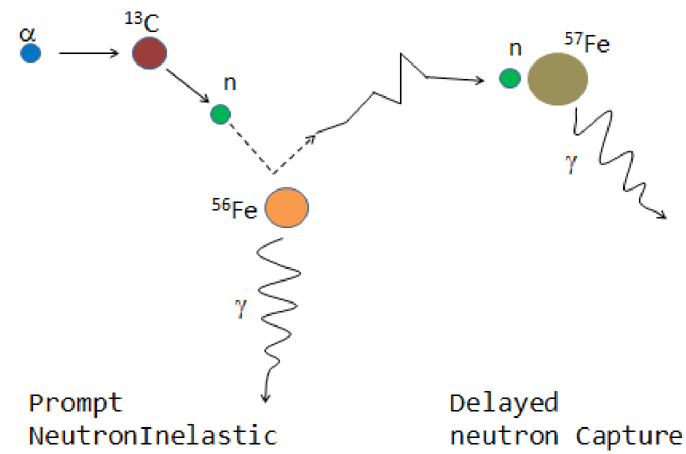
- Weekly automatic detector calibration.
- Energy responses of the detectors are studied with ^{68}Ge, ^{60}Co and Am-^{13}C.

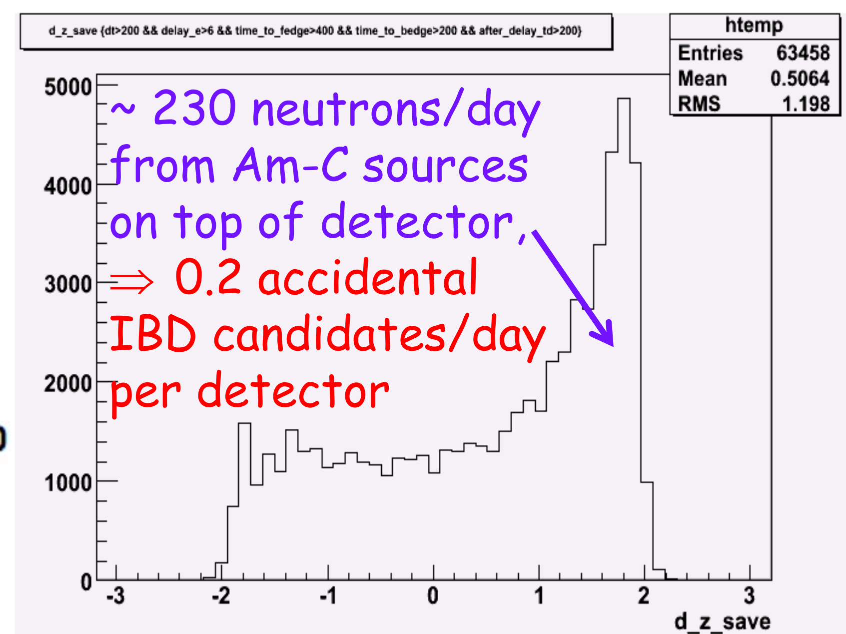
Energy Spectrum with Am-^{13}C/^{60}Co Source



$$\text{Asymmetry} = \frac{N_{\text{AD1}} - N_{\text{AD2}}}{(N_{\text{AD1}} + N_{\text{AD2}})/2}$$

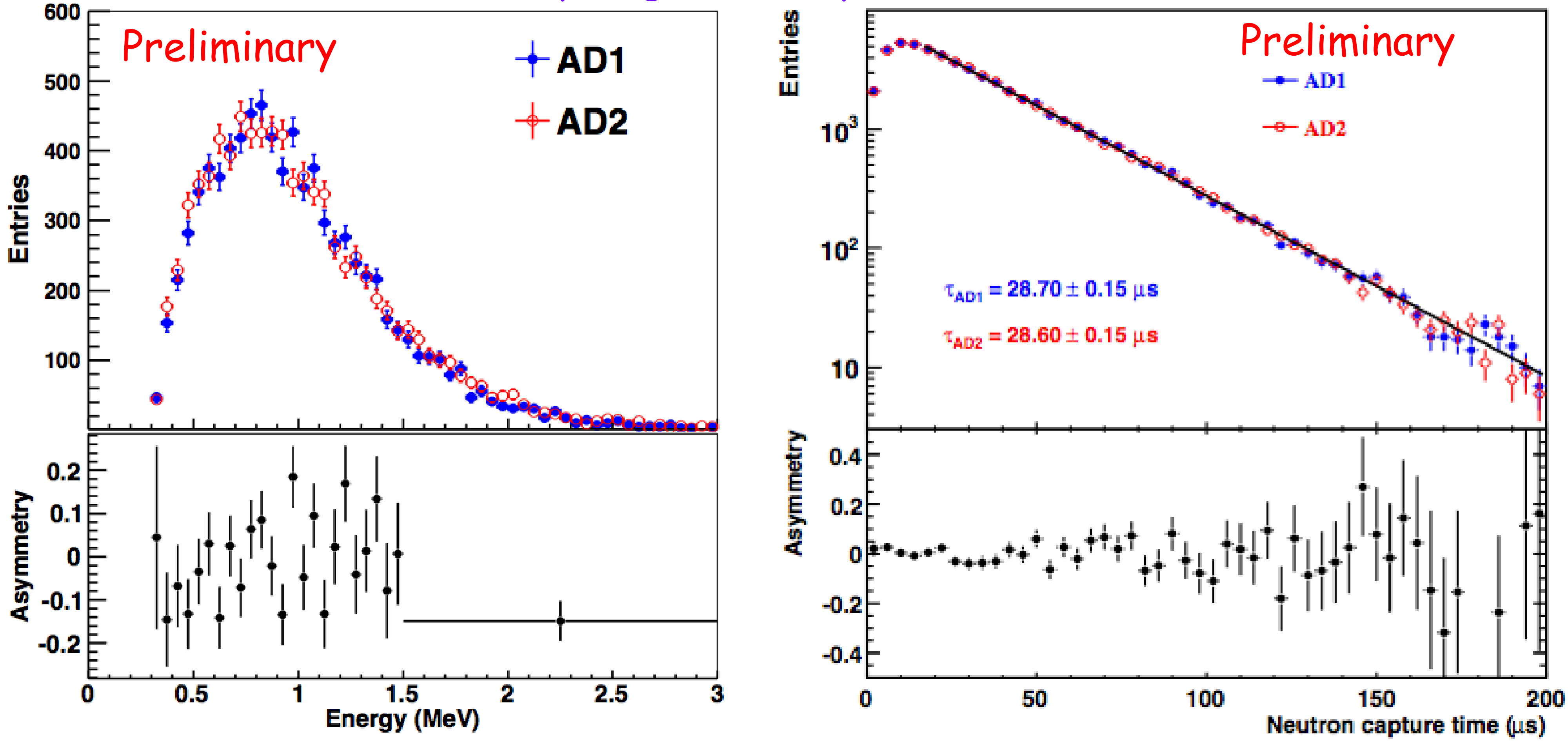
$N_{AD1,2}$ is the bin content for AD1 or 2





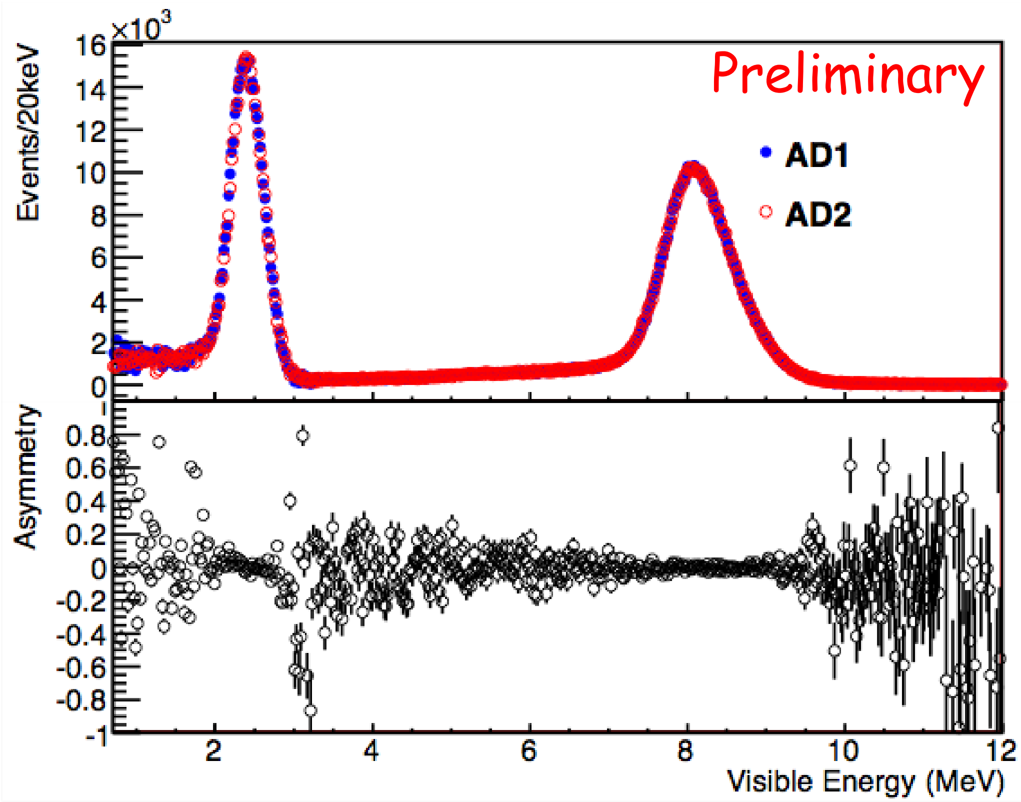
Calibration with Am-^{13}C Source

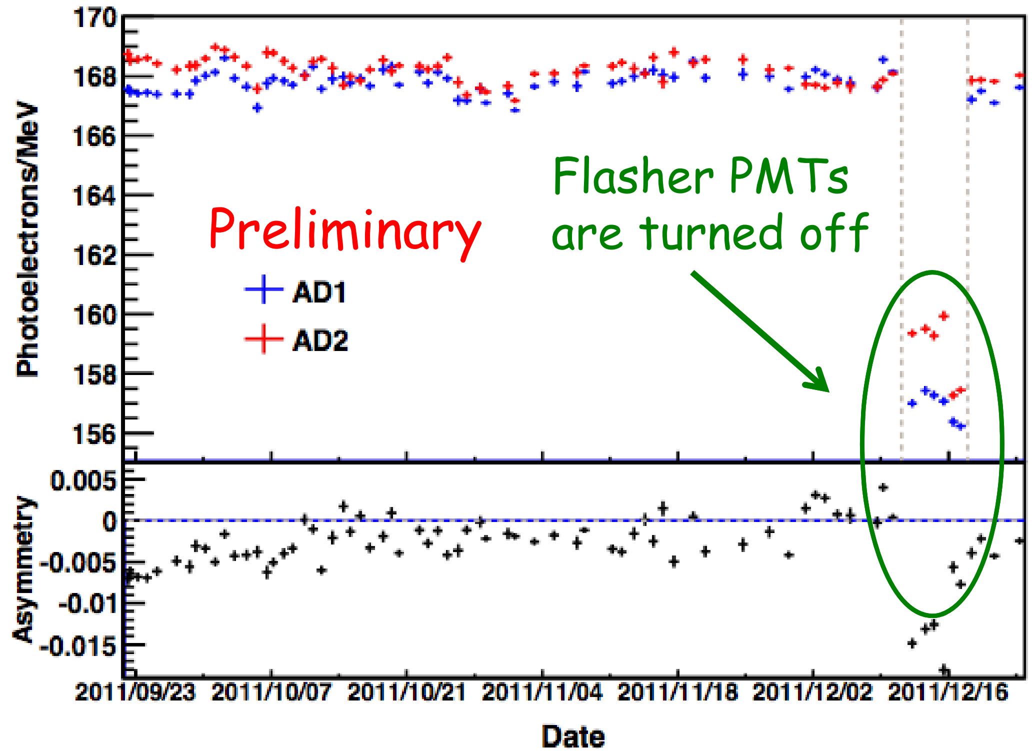
Prompt signal from proton recoil



- Two ADs with similar energy responses (~ 0.5%)
- Consistent response in capture time measurements

Spallation-Neutron Energy Spectrum





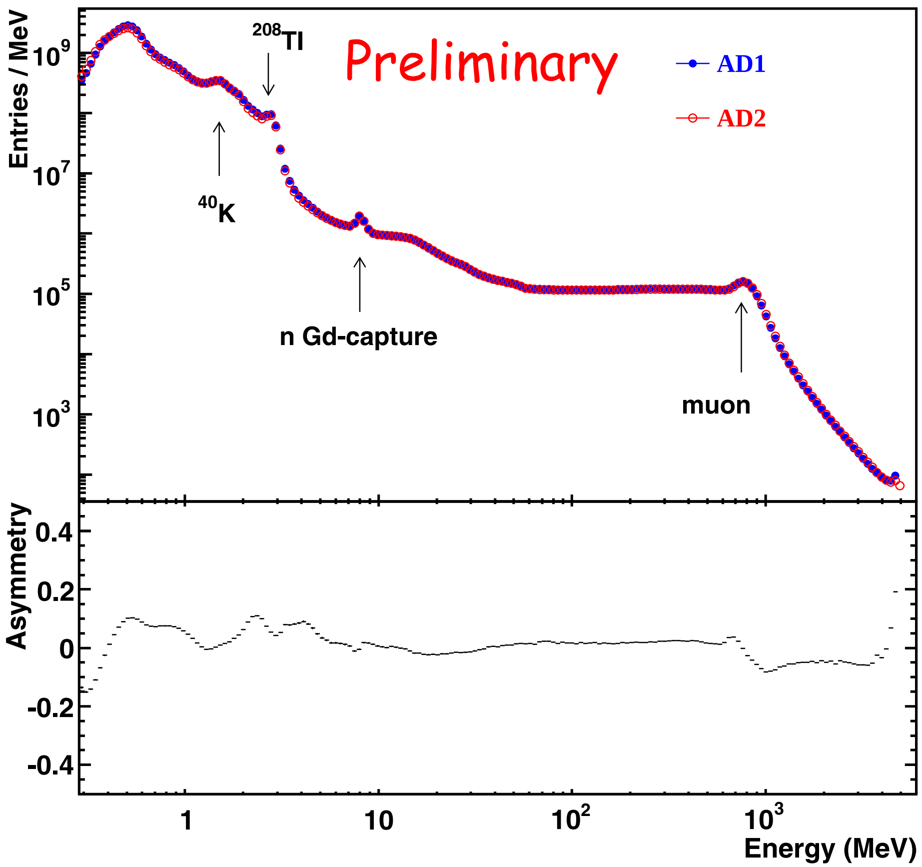
- Run-by-run calibration of detectors using spallation neutrons
  - ~ 168 p.e./MeV for AD1
  - ~ 169 p.e./MeV for AD2

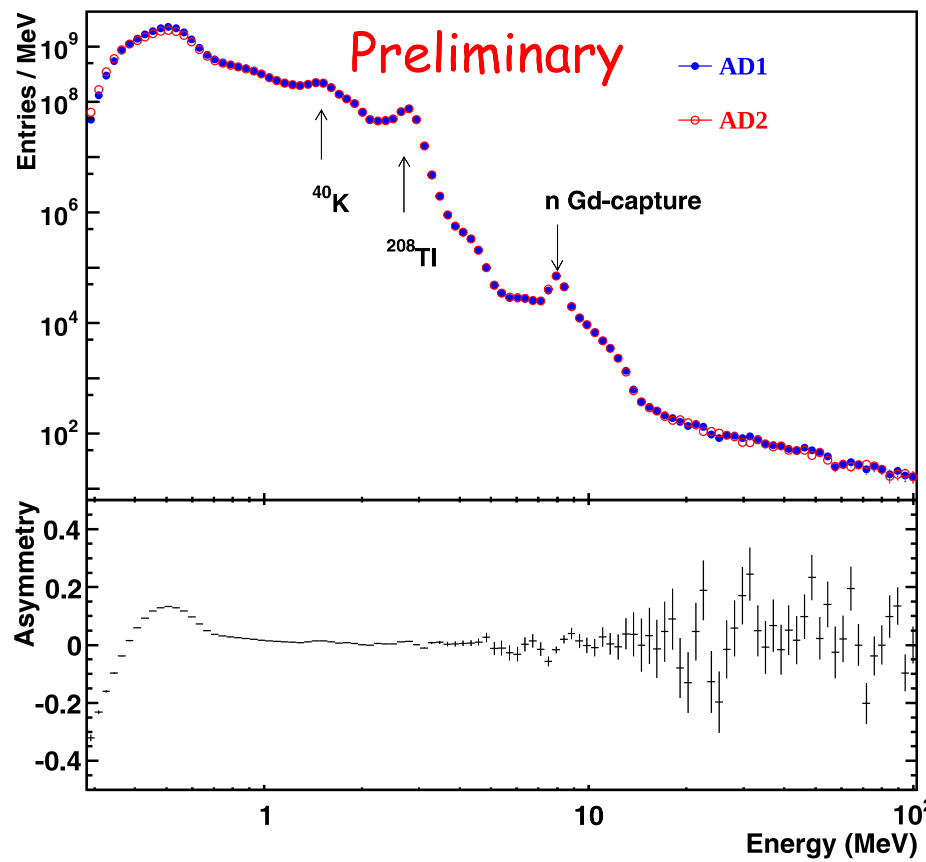
p.e. = photoelectrons detected in a photomultiplier tube.

Singles Energy Spectrum of AD Triggers

Before muon (offline) veto,
~ 65 kHz with E > 0.7 MeV

After muon veto,
⇒ low-energy events due to radioactivity (mostly in PMTs)





- The difference in AD1 and AD2 triggers is mostly due to after-pulsing in the PMTs immediately following a muon event (which leads to a relatively large signal).

Selection of Inverse Beta Decay Candidates, 1

Reject "flashers" = emission of light by a PMT, due to secondary emission processes in its dynodes during photoelectron signal amplification.

Prompt "positron": 0.7 MeV < E_p < 12 MeV

Delayed "neutron": 6.0 MeV < E_d < 12 MeV

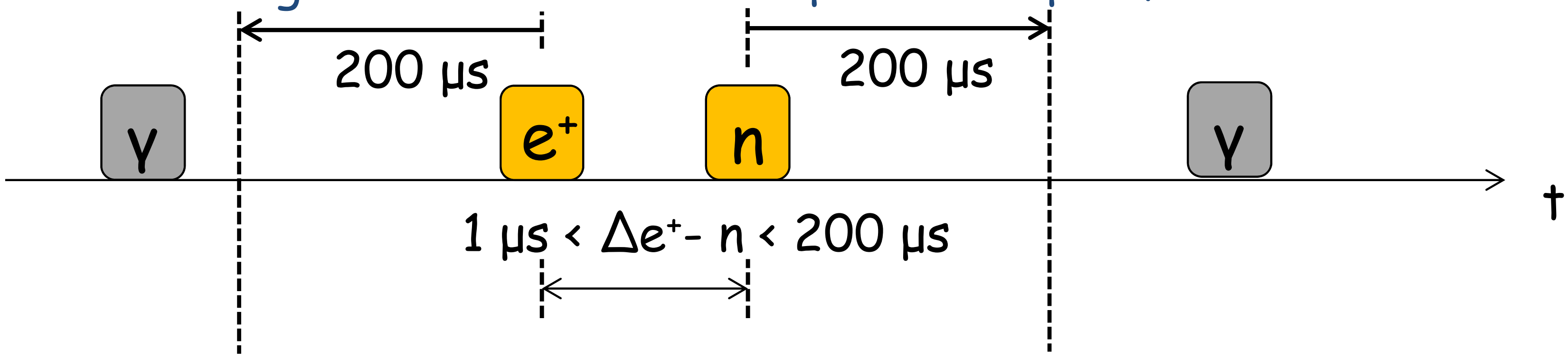
Neutron capture time: 1 μs < Δt < 200 μs

Muon Veto:

- Pool Muon: Reject IBD candidate if < 0.6 ms after pool muon
- AD Muon (> 20 MeV): Reject if < 1 ms before IBD candidate
- AD Shower Muon (> 2.5GeV): Reject if < 1 s before

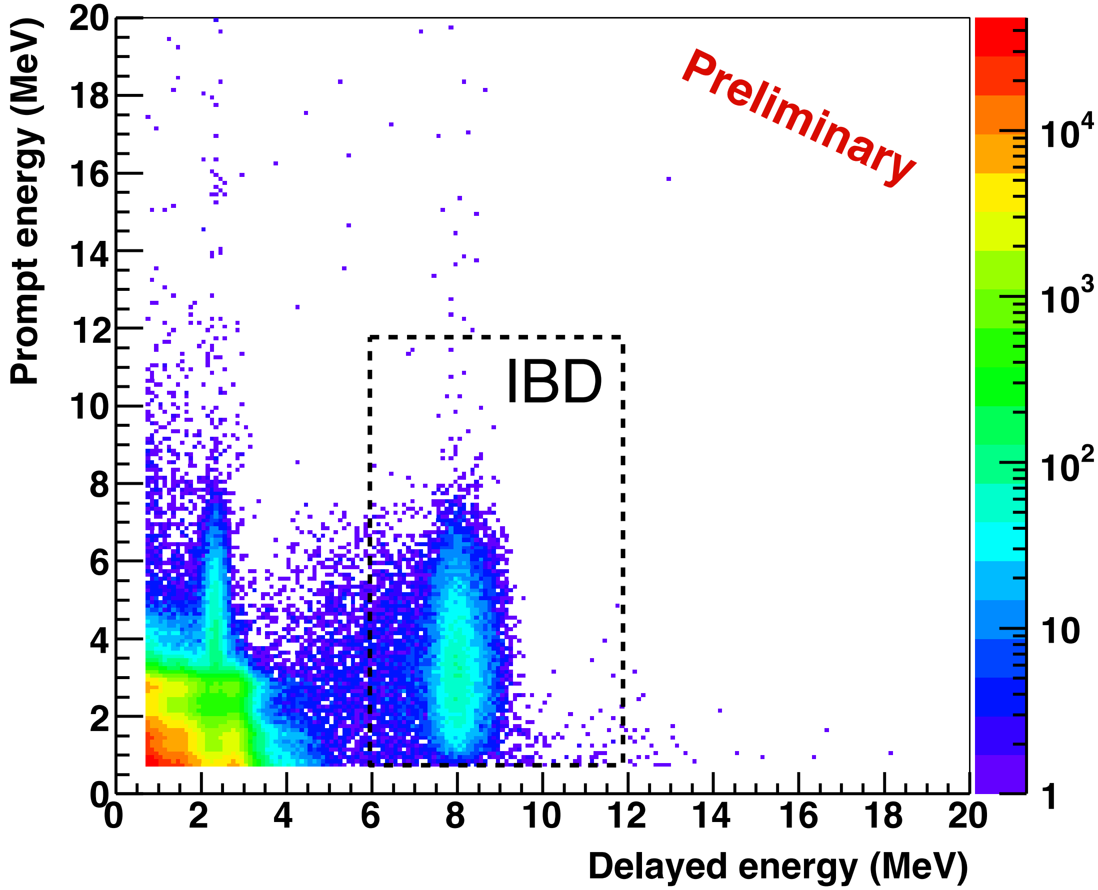
Multiplicity cut:

No other AD signal > 0.7 MeV in -200 μs to 200 μs of IBD.

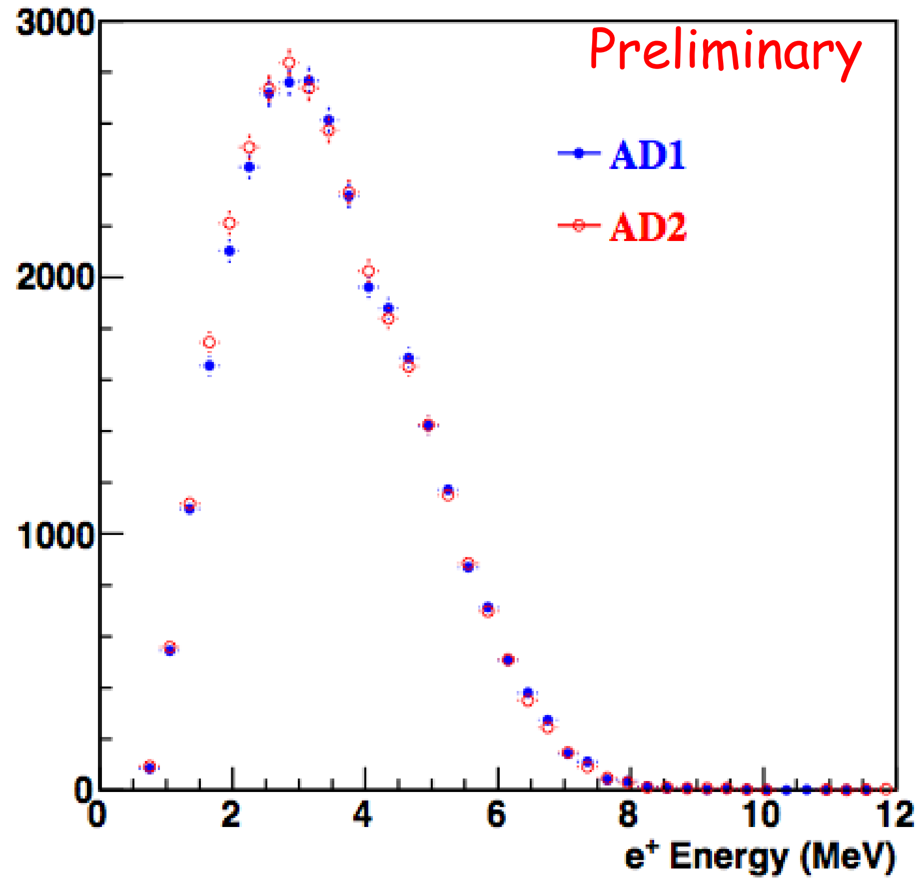


Selection of Inverse Beta Decay Candidates, 2

IBD = Inverse beta decay = $\nu + p \rightarrow n + e$



Prompt Energy Spectrum



With Flasher cut, Muon veto, Prompt Energy, Delayed Energy, Time correlation and Multiplicity cuts.

Flasher Cut

A PMT "flash" leads to light collected near that PMT, and on the opposite side of the detector.

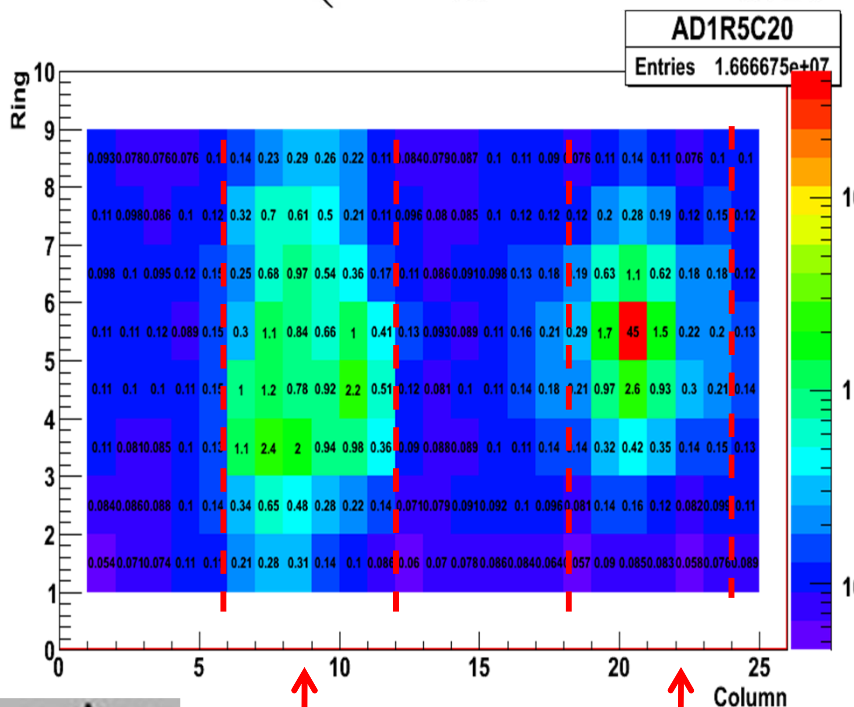
Q = charge collected from PMT anode

MaxQ = $Q_{max} / \Sigma Q$

Define Quadrant 1 as that which contains the "hottest" PMT

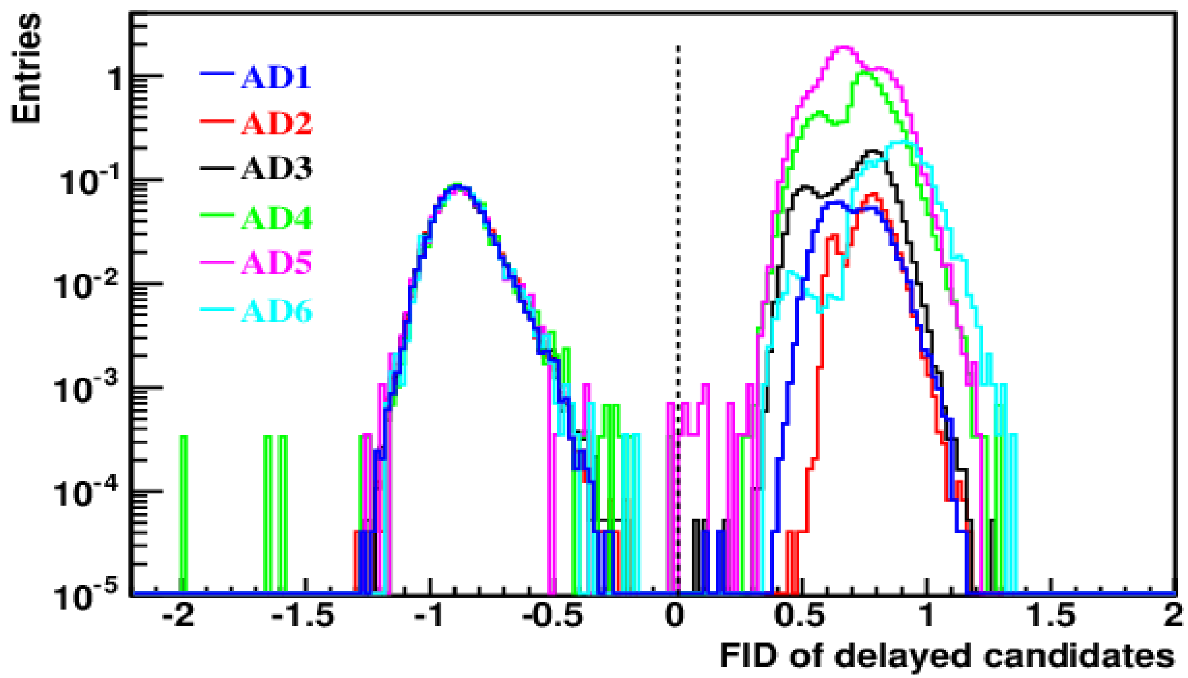
Quadrant = $Q_{Quadrant3} / (Q_{Quadrant2} + Q_{Quadrant4})$

FID = $\log\left((\frac{Quadrant}{1.})^2 + (\frac{MaxQ}{0.45})^2 \right) < 0$ for IBD candidates, > 0 for "flashers"



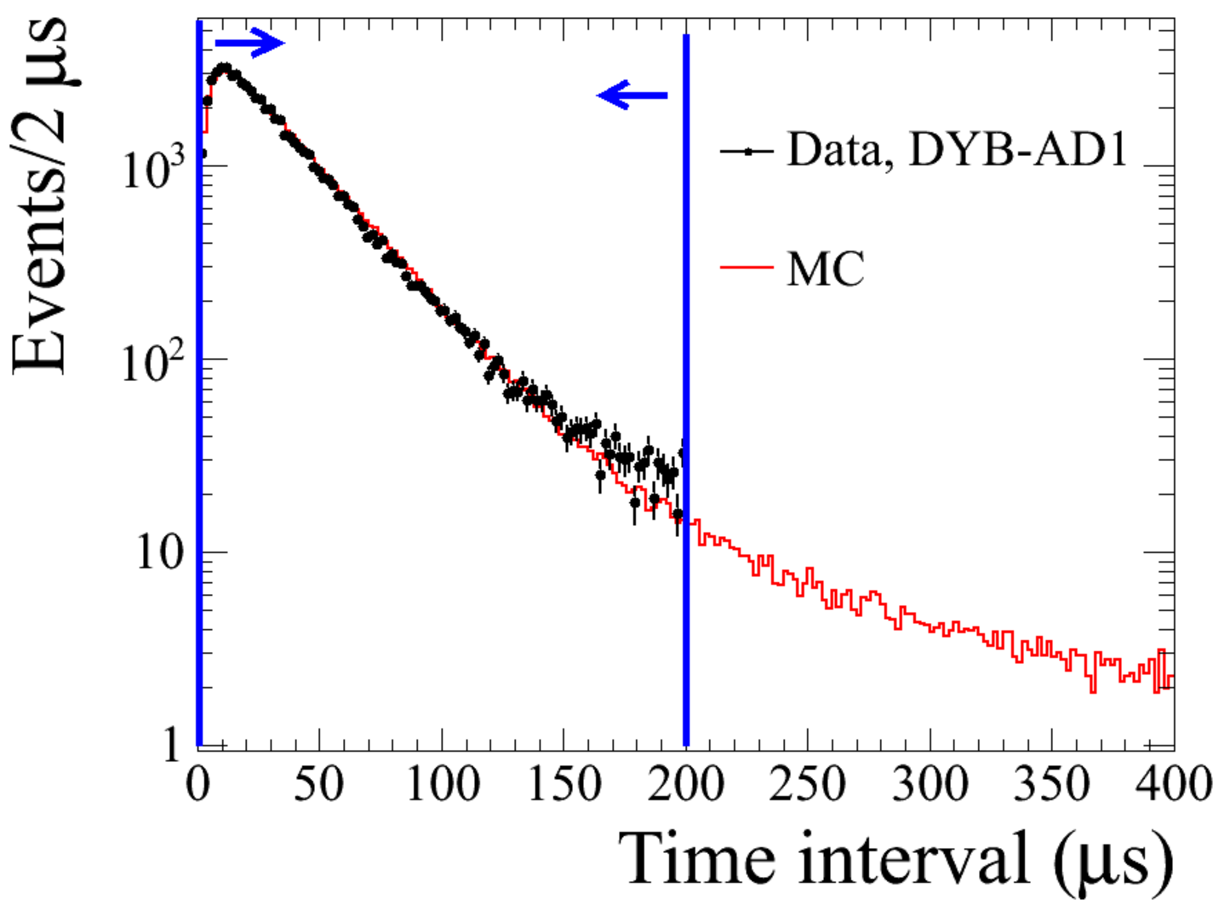
Quadrant 3

Quadrant 1 with the flasher PMT



Neutron Capture Time

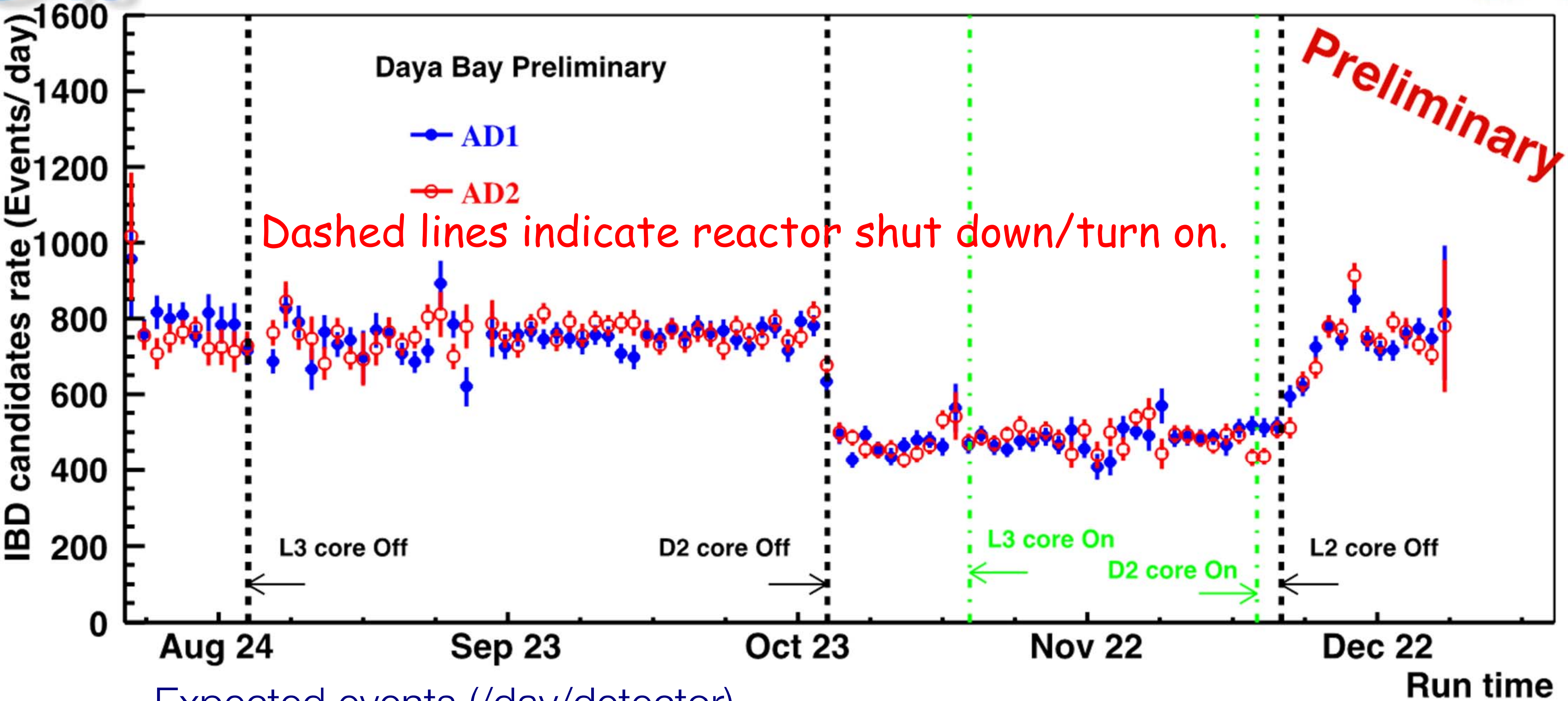
Consistent IBD capture time measured in all detectors



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

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

Inverse-Beta-Decay Candidate Rate

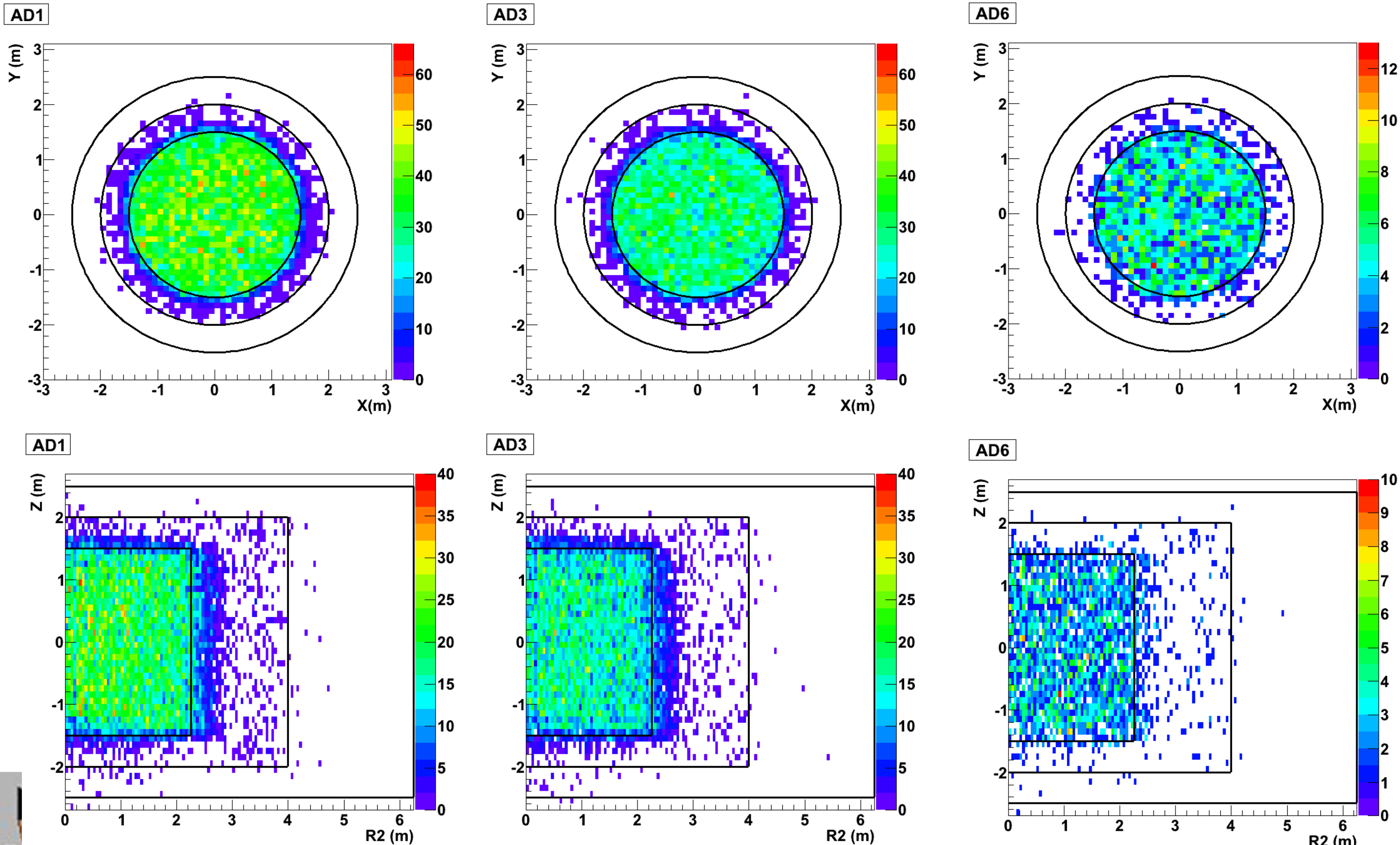


Expected events (/day/detector)

	DYB Site	LA Site	Far Site
IBD Evts	840	760	90
BKG Evts	<0.6%	<0.5%	<0.4%

Expected events with all cores ON

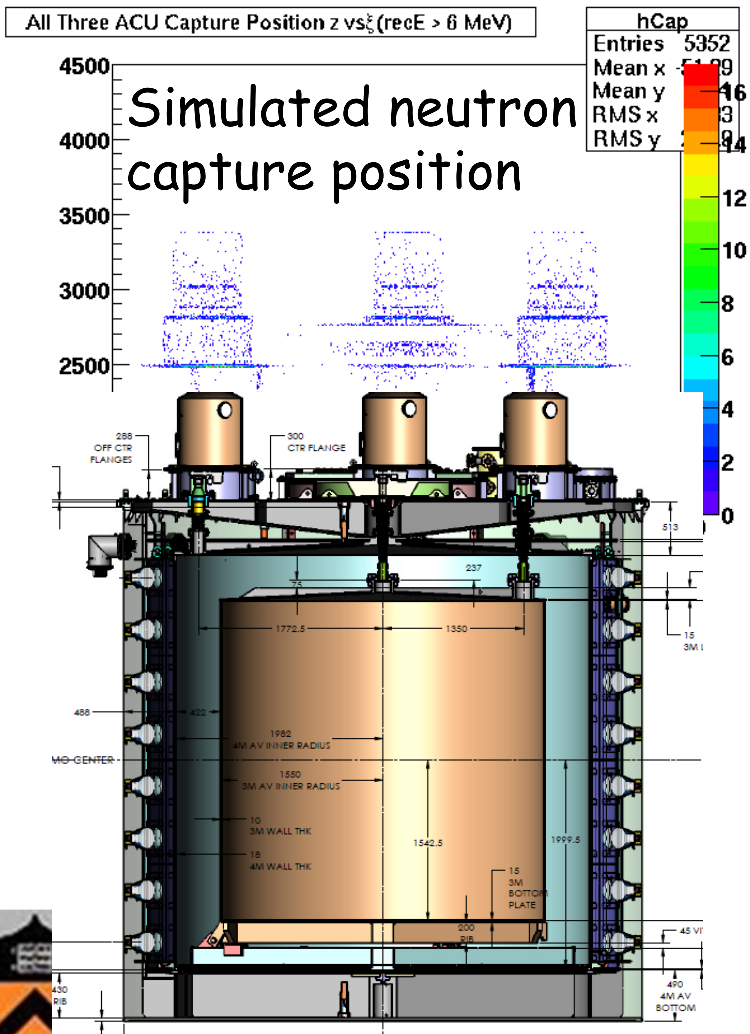
Inverse-Beta-Decay Positron Positions in AD1, 3, 6

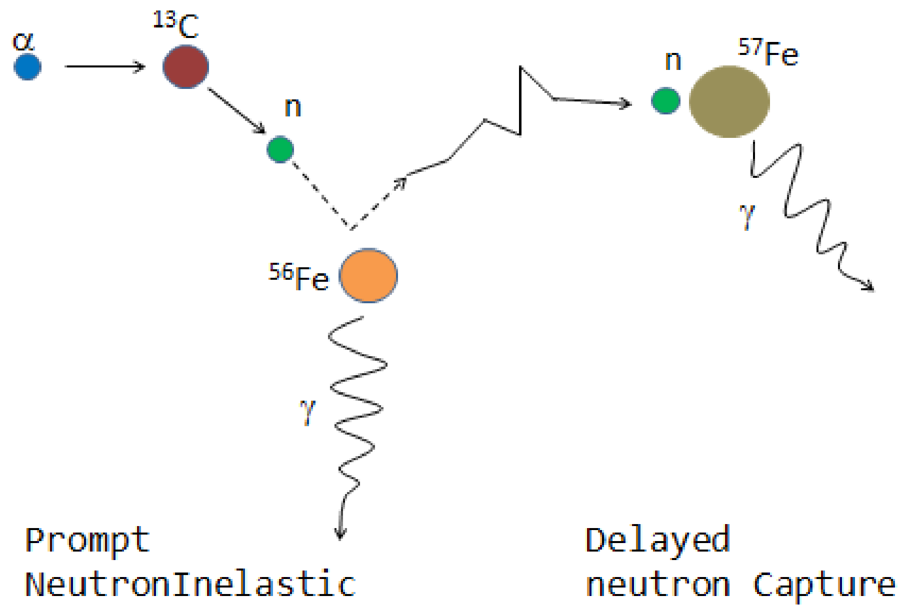


Background: ^{241}Am-^{13}C neutrons

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

Simulated neutron capture position





Constrain far site B/S to 0.3 ± 0.3%:

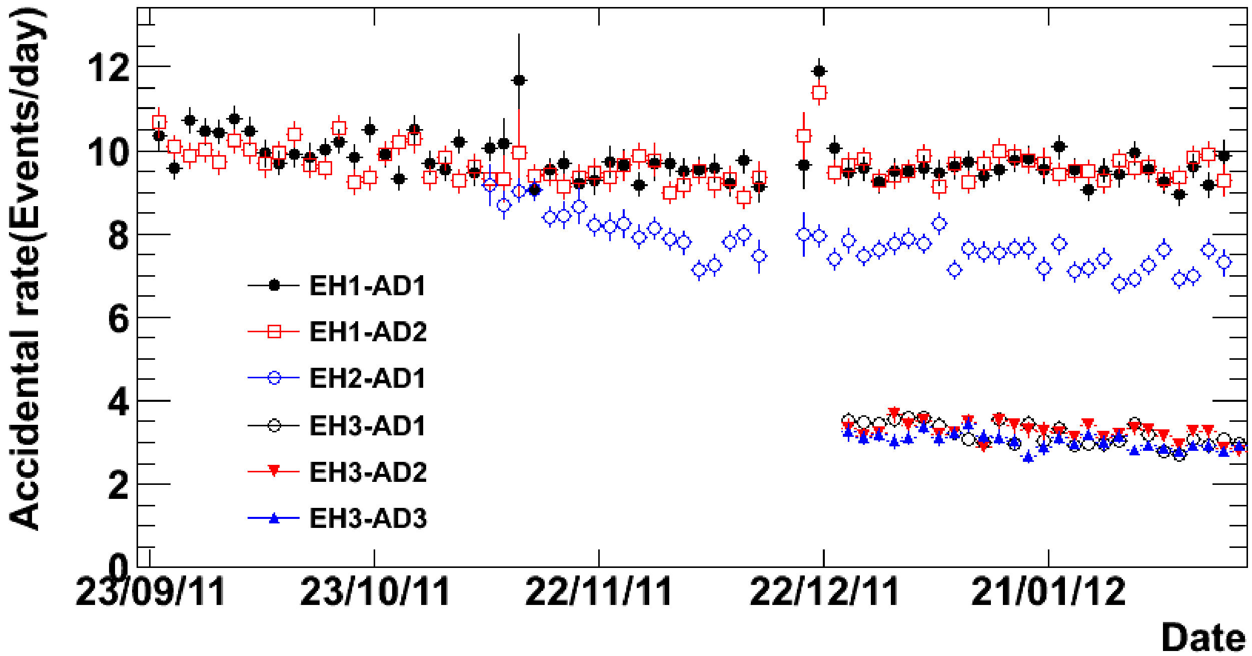
- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

Background: Accidentals

Two random single signals can accidentally mimic a prompt-delayed IBD signal

Accidental rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.

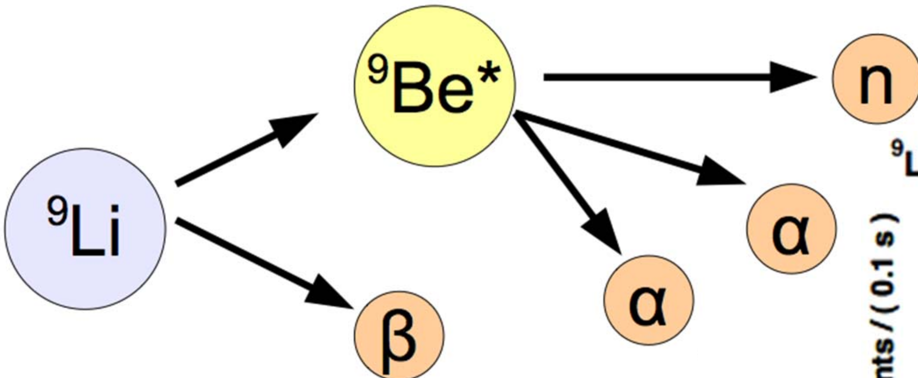


	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
B/S	1.37%	1.38%	1.44%	4.58%	4.77%	4.43%

Lower rate of accidentals in EH3 is due to the lower rate of neutrons from cosmic-ray muons (although rate of neutrons from the retracted Am-C source is the same).

Background: β-n Decay

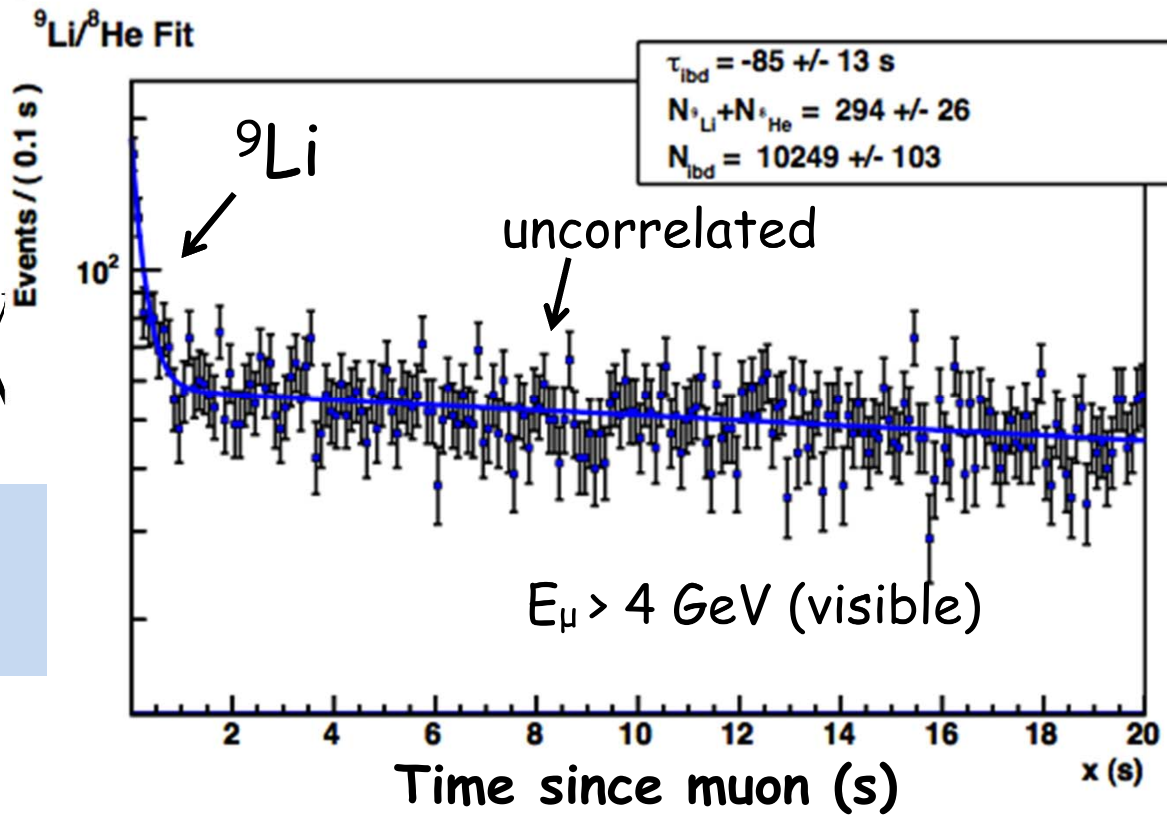
β-n decay:
- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{1/2} = 178$ ms, Q = 13. 6 MeV
^{8}He: $\tau_{1/2} = 119$ ms, Q = 10.6 MeV

Analysis muon-veto cuts control B/S to ~0.4±0.2%.

- Generated by cosmic rays
- Long-lived
- Mimics antineutrino signal



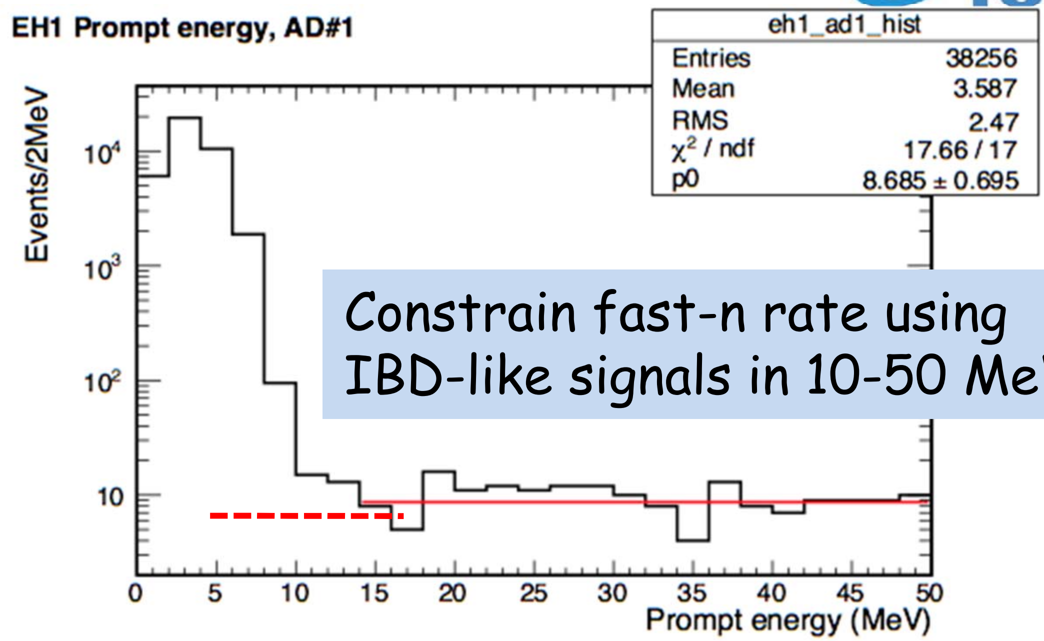
Background: Fast neutrons

Fast Neutrons:

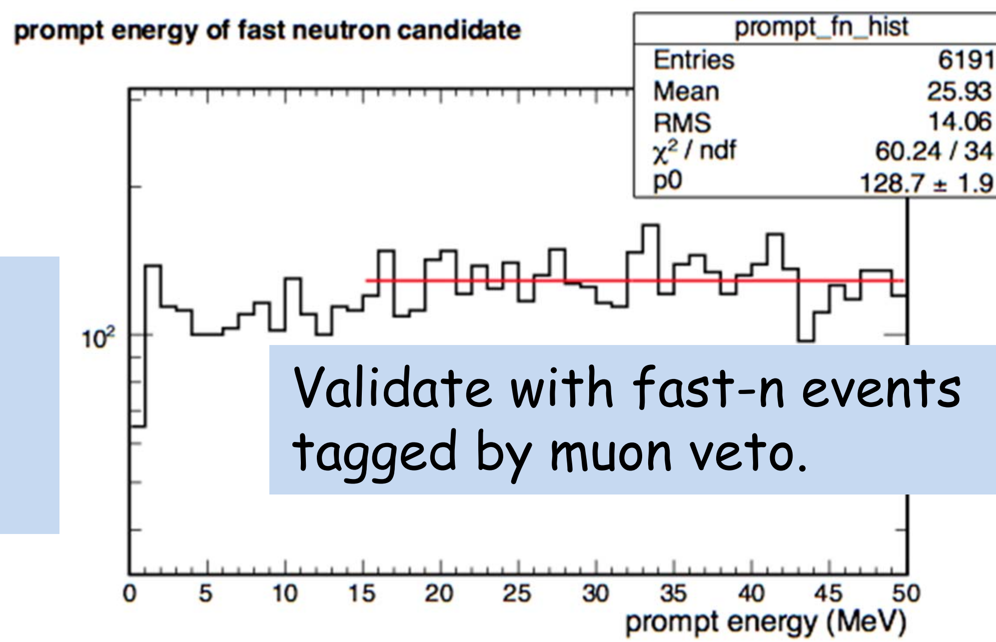
Energetic neutrons produced by cosmic rays (inside and outside of muon-veto system)

Mimics antineutrino (IBD) signal:

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



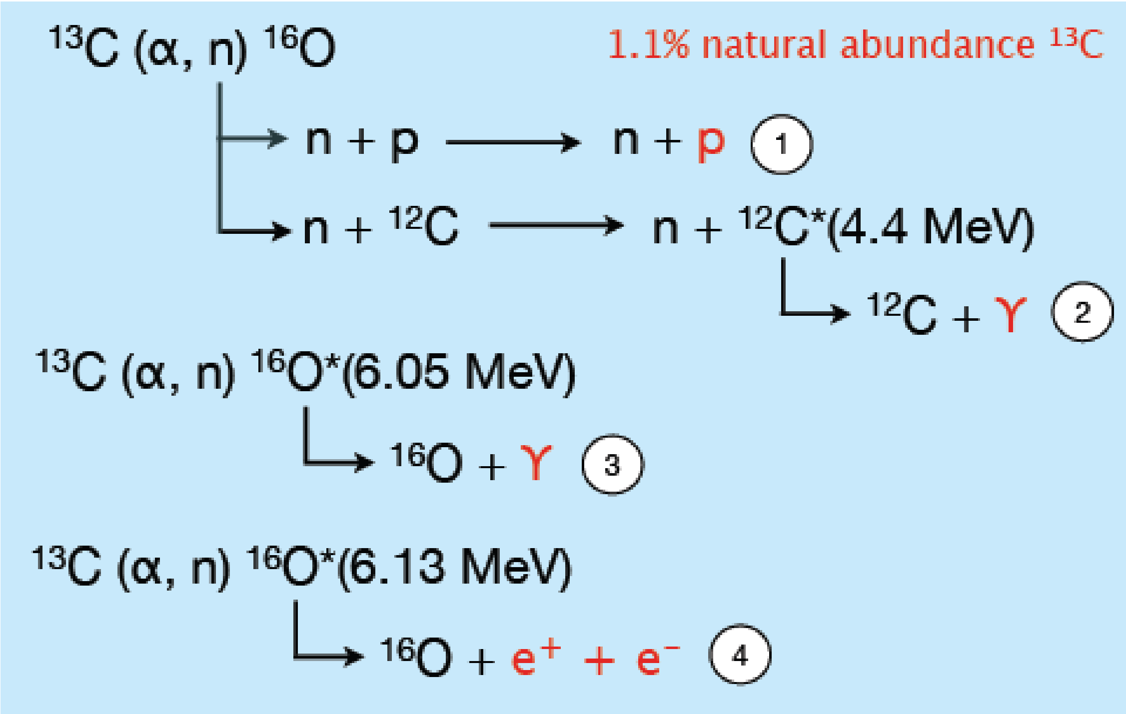
Constrain fast-n rate using IBD-like signals in 10-50 MeV



Validate with fast-n events tagged by muon veto.

Analysis muon-veto cuts control B/S to 0.06% (0.1%) of far (near) signal.

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



Potential alpha sources:

^{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

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

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)%

Data Set Summary

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Veto time (day)	8.7418	8.9109	7.0389	0.8785	0. 8800	0.8952
Efficiency	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{8}He/^{9}Li (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
Antineutrino rate (/day)	**714.17 ±4.58**	**717.86 ±4.60**	**532.29 ±3.82**	**71.78 ±1.29**	**69.80 ±1.28**	**70.39 ±1.28**

Reactor Flux Expectations

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

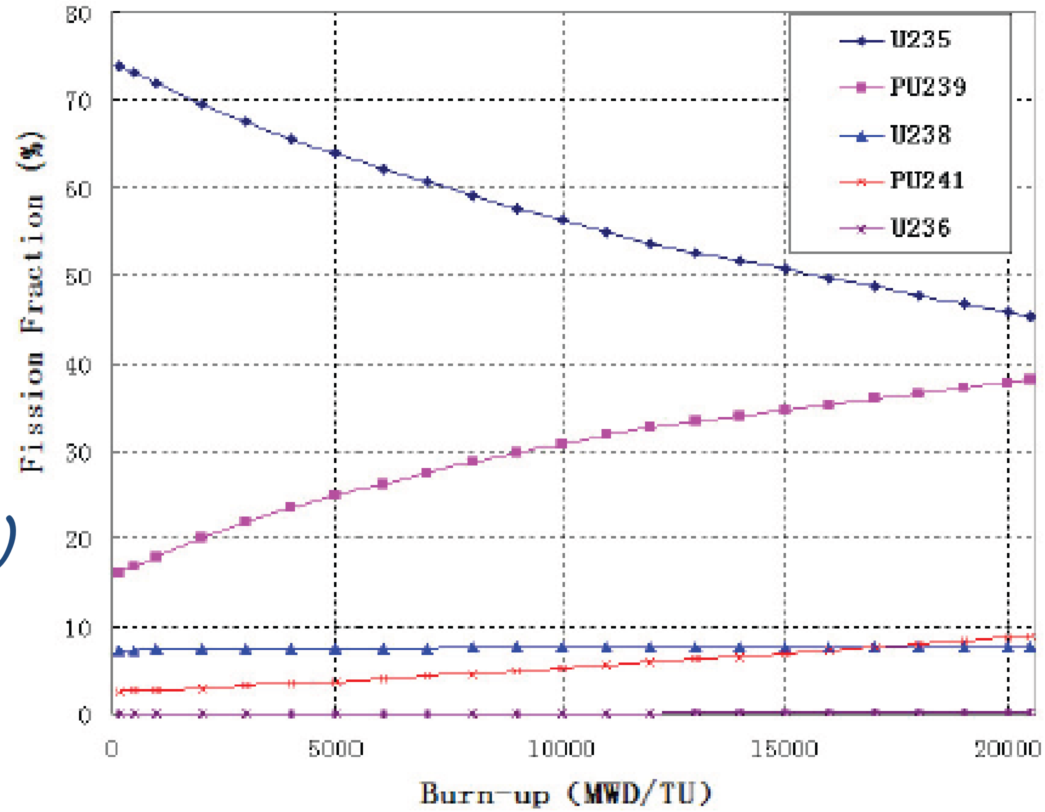
Energy released per fission: e_i

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

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

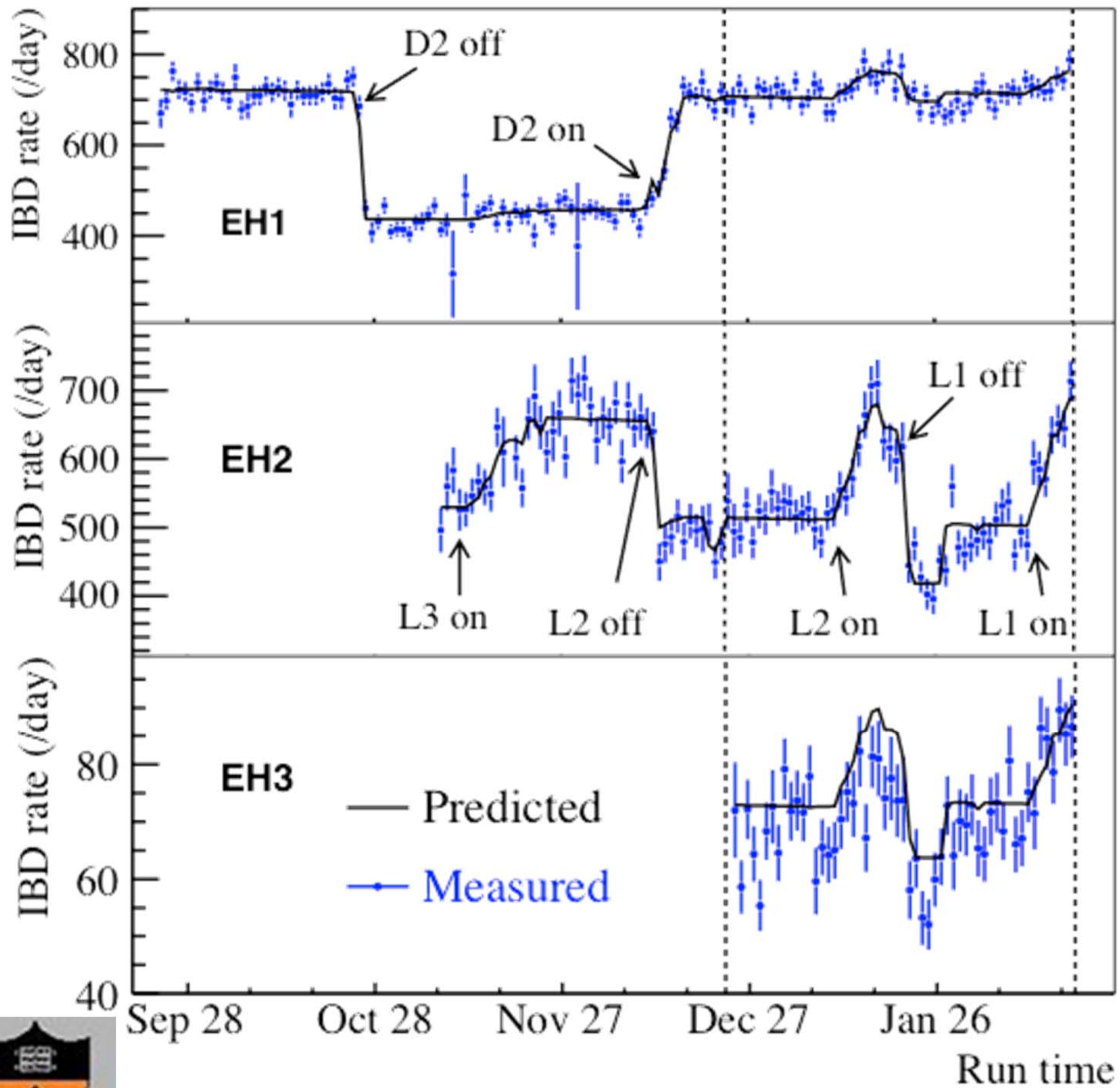
K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Isotope fission rates *vs.* reactor burnup



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

Antineutrino Detection Rate *vs.* Time



Detected rates strongly correlated with reactor flux expectations.

Predicted Rates: (in figure)

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

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%

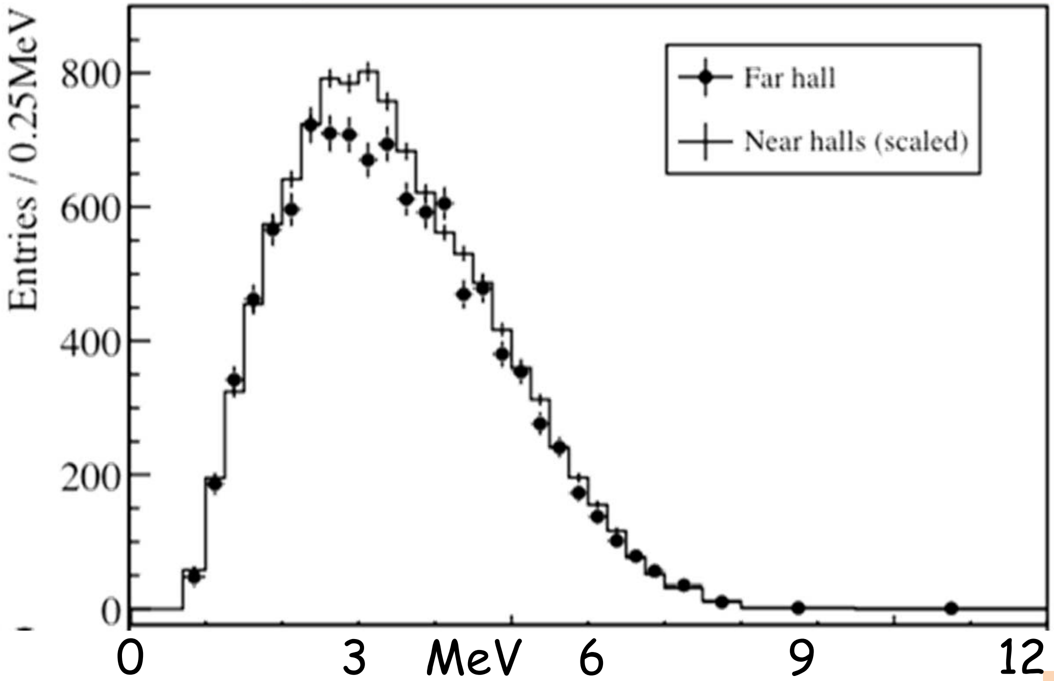
For near/far rate analysis , only uncorrelated uncertainties are relevant.

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

Influence of uncorrelated reactor systematics reduced (~1/20) by far *vs.* near measurement.

Far vs. Near Rate Analysis

Compare the far/near measured rates (and spectra)



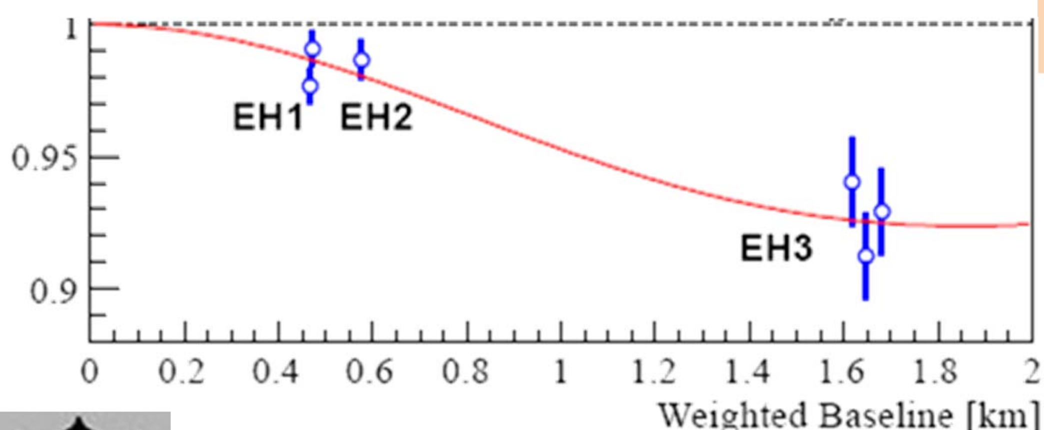
$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n is the measured IBD rate in detector n.

Weights α_i, β_i are determined from baselines and reactor fluxes.

$\alpha \sim 0.014$, $\beta \sim 0.10$

$\Rightarrow$ EH2 weighted 7 times EH1



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.

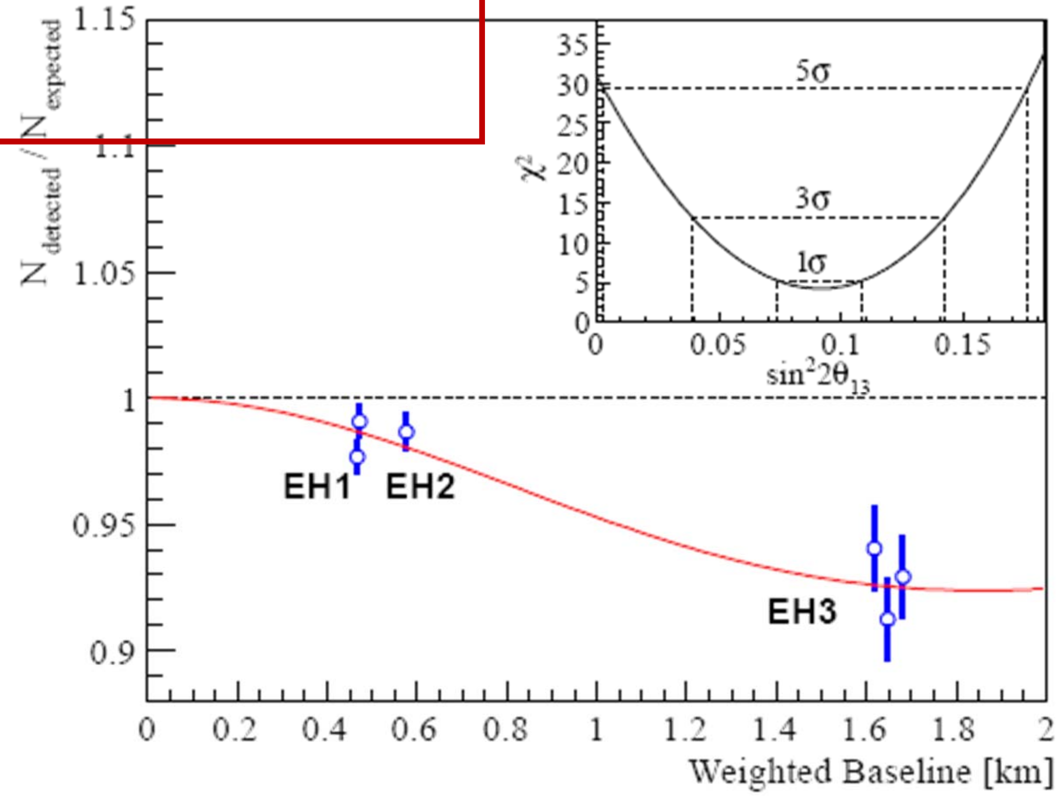
χ^2 Rate Analysis

$$\chi^2 = \min_{\gamma} \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \sum_r \omega_r^d \epsilon_r + \epsilon + \epsilon_d\right) - B_d\left(1 + \eta_d\right)\right]^2}{M_d}$$

$$+ \sum_r \frac{\epsilon_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left[\frac{\epsilon_d^2}{\sigma_d^2} + \left(\frac{\eta_d}{\sigma_B^d}\right)^2\right] + \cancel{\frac{\epsilon^2}{\sigma^2}}$$

"Pull" χ^2 analysis.
No constraint on absolute normalization.
Fit on the near-far relative measurement.

$\mathrm{Sin}^2 2\theta_{13}$ = 0.092 ± 0.016(stat) ± 0.005(syst)
χ^2/NDF = 4.26/4
5.2 σ for non-zero θ_{13}



Summary

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron-antineutrino disappearance at ~ 2 km for E_ν ~ 3 MeV:

$$R_{far/near} = 0.940 \pm 0.011\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst})$$

- Interpretation of this disappearance as neutrino oscillation in a 3-neutrino context yields, via a χ^2 analysis:

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\mathrm{stat}) \pm 0.005\ (\mathrm{syst})$$

ruling out zero at 5.2 standard deviations.

$\theta_{13} = 8.8°$ (or 81.2°?), $\sin^2\theta_{13} = 0.024$

- Installation of final pair of antineutrino detectors this Summer

Could θ_{13} Be Near 90°?

In the 3-ν context, taking $\Delta m^2_{13} \sim \Delta m^2_{23}$, the ν_e survival probability is

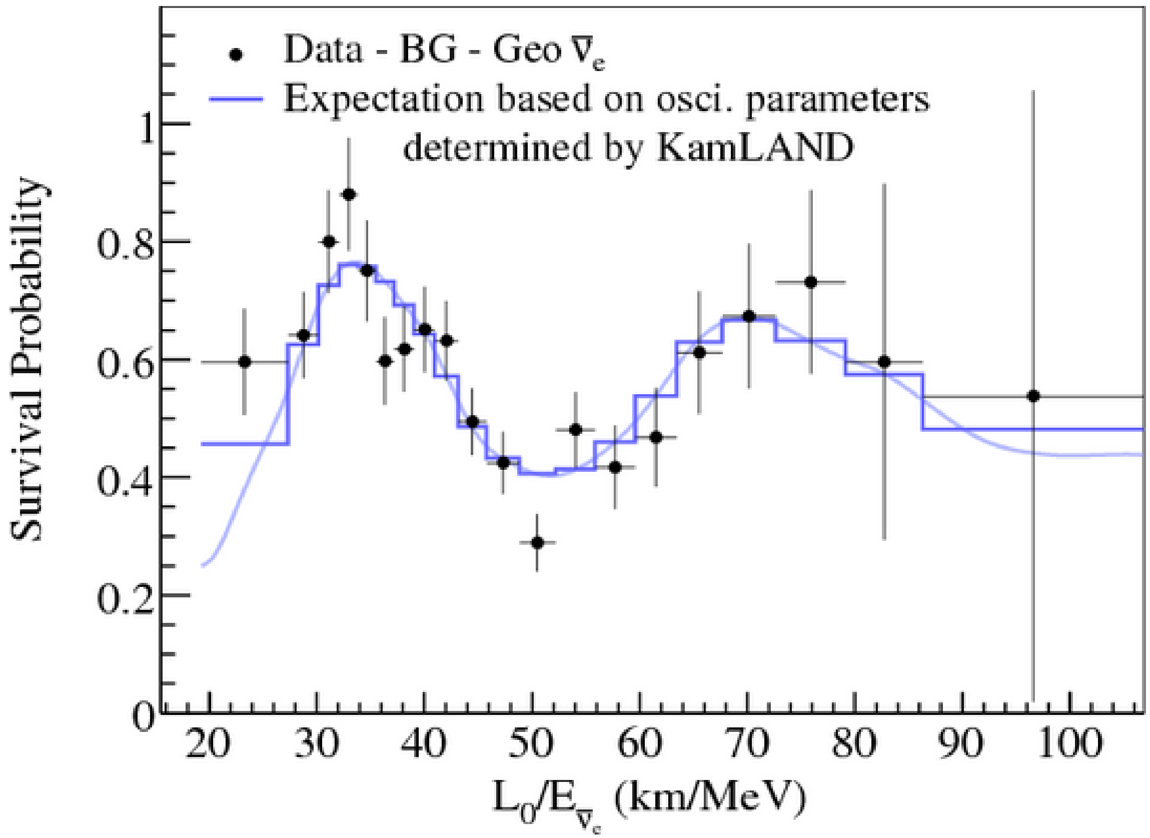
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\, \sin^2\left(\Delta m^2_{13} L / 4E_\nu\right) - \cos^4\theta_{13} \sin^2 2\theta_{12}\, \sin^2\left(\Delta m^2_{12} L / 4E_\nu\right)$$

For large L, the 2nd term averages to $(1/2)\sin^2 2\theta_{13} \sim 0.04$, such that

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 0.96 - \cos^4\theta_{13} \sin^2 2\theta_{12}\, \sin^2\left(\Delta m^2_{12} L / 4E_\nu\right)$$

If $\theta_{13} \sim 81°$, then no oscillations could be seen in long baseline experiments with reactor or solar neutrinos.

The clear evidence for oscillations in the KamLAND experiment excludes that θ_{13} is near 90°.
Phys. Rev. Lett. **100**, 221803 (2008)

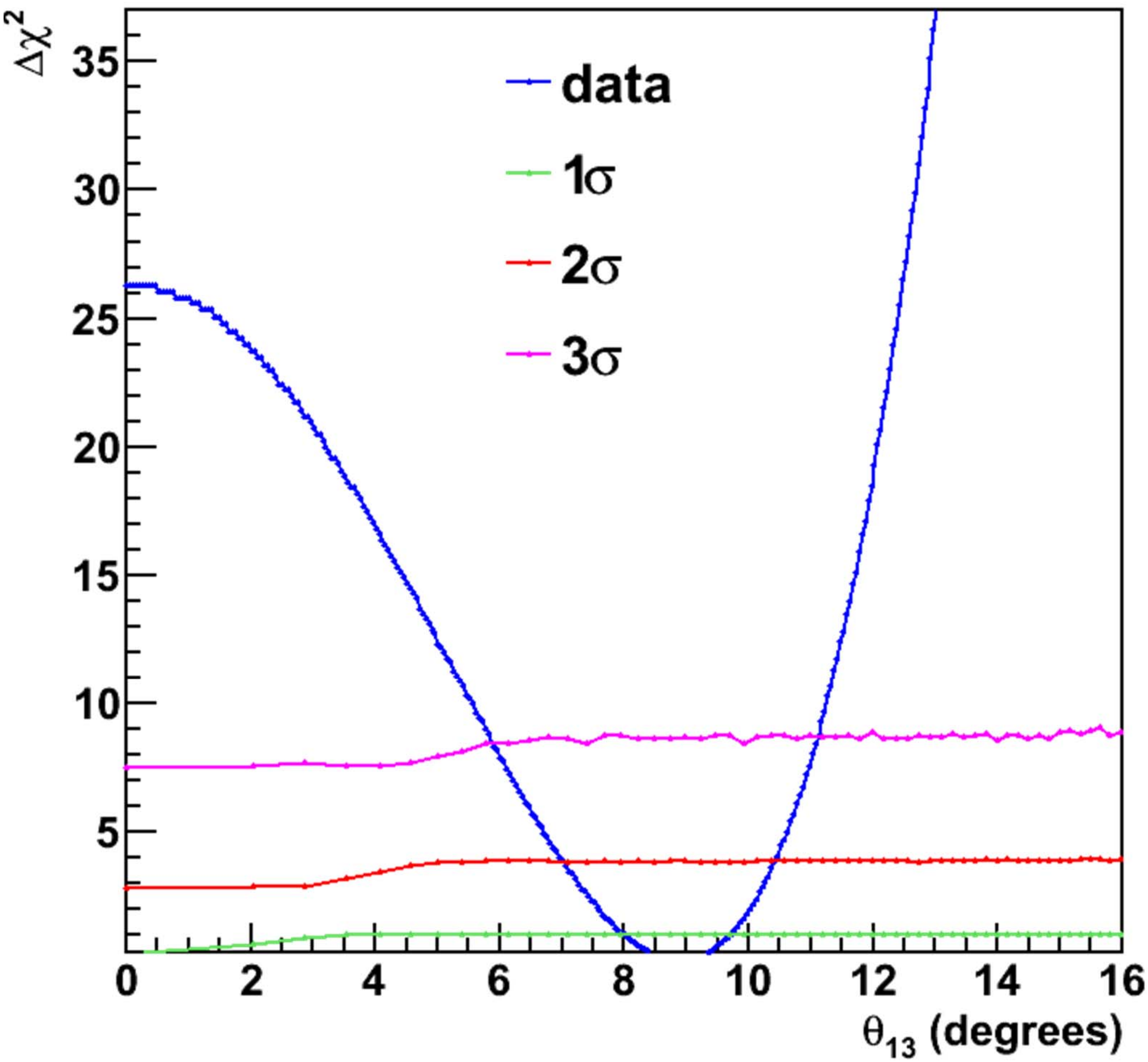


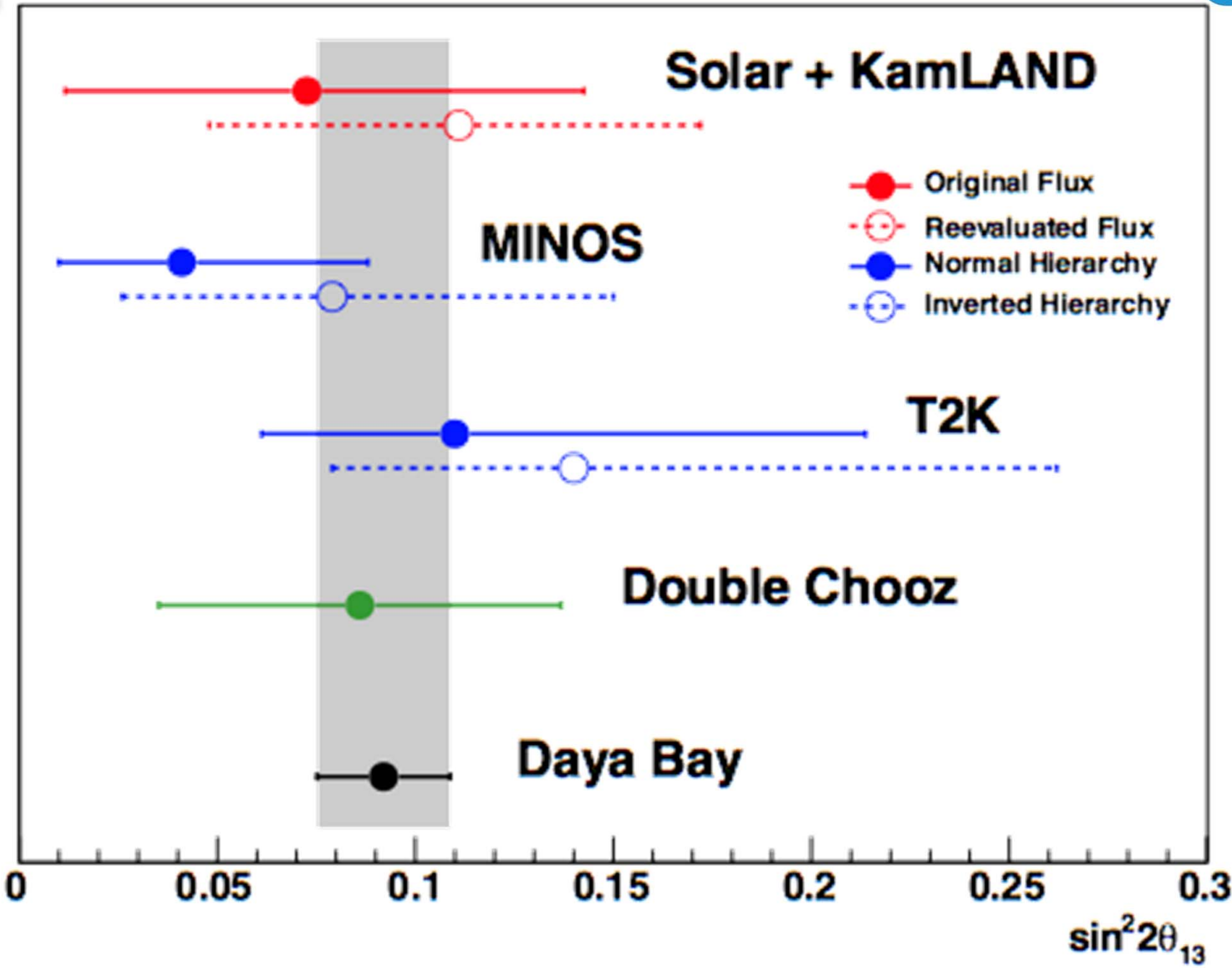
Using our value for θ_{13} = 8.8°,

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 0.96 - 0.95 \sin^2 2\theta_{12}\, \sin^2\left(\Delta m^2_{12} L / 4E_\nu\right)$$

⇒ 5% increase in $\sin^2\theta_{12}$ compared to previous fits.

Asymmetric Confidence Intervals in θ_{13}




Solar + KamLAND
Original Flux
Reevaluated Flux
Normal Hierarchy
Inverted Hierarchy
MINOS
T2K
Double Chooz
Daya Bay
0
0.05
0.1
0.15
0.2
0.25
0.3
sin²2θ13

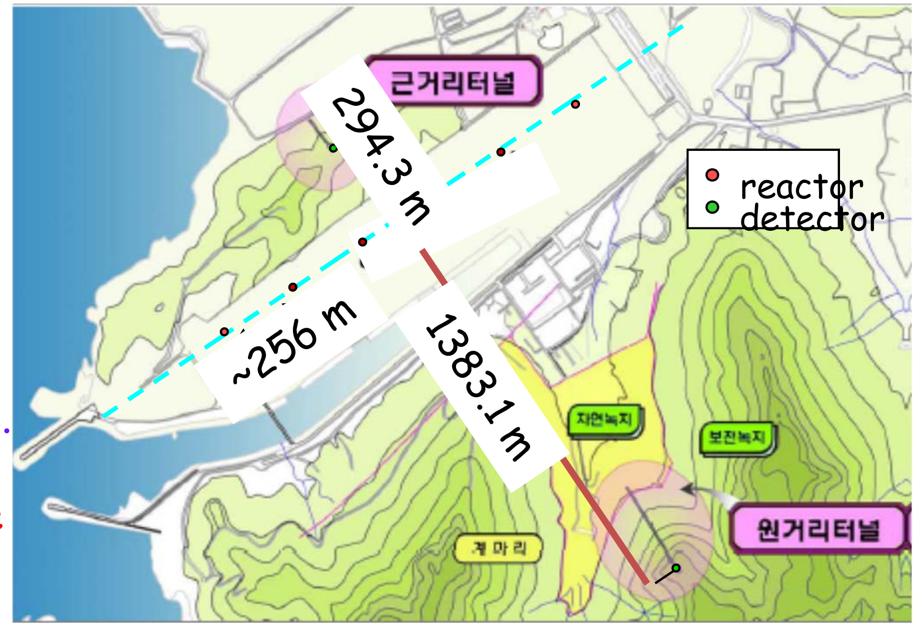
RENO Experiment

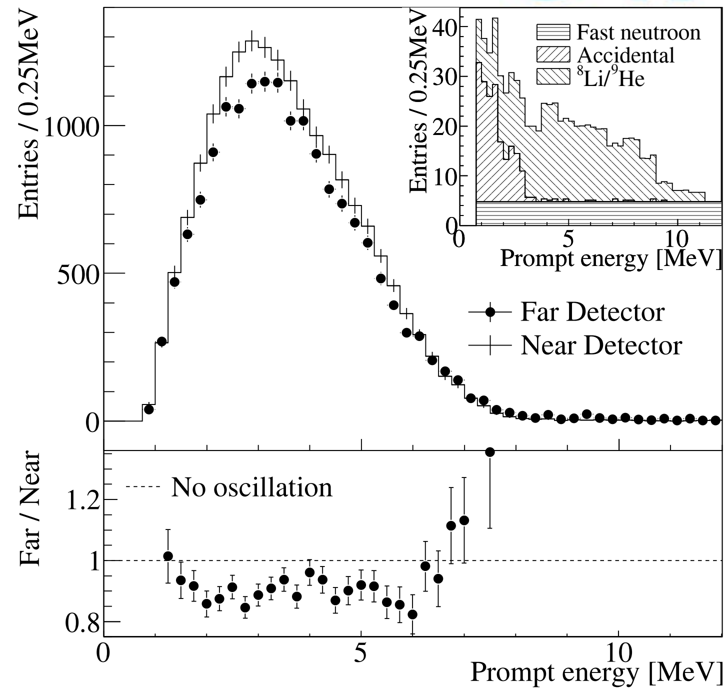
Yonggwang Nuclear Power Plant

Six ~ 3 GW_e reactors along a line.

1 Near and 1 Far detector, each 16 tons.

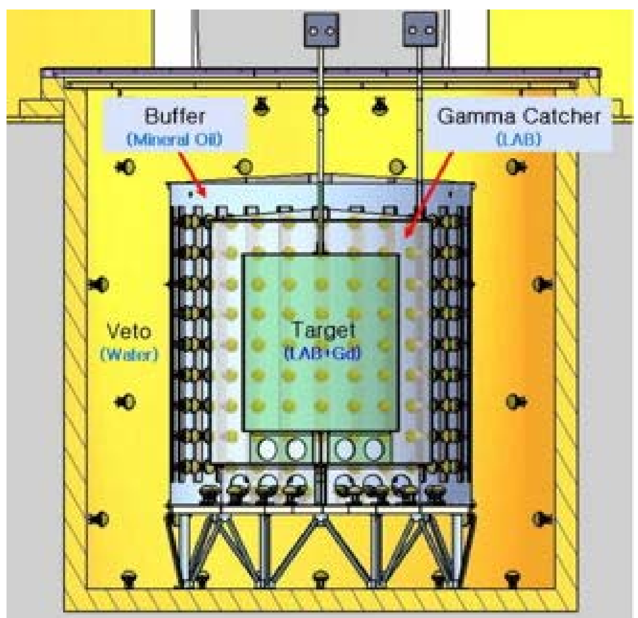
229 days of data since August 2011.

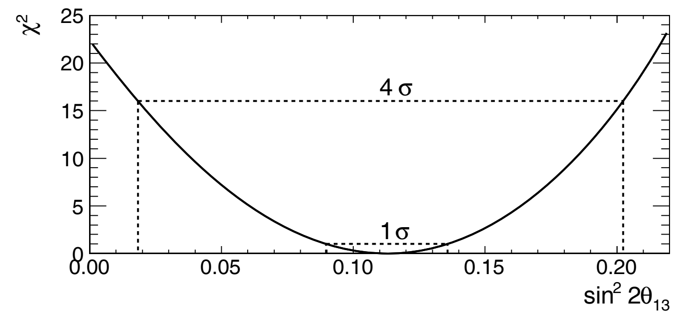


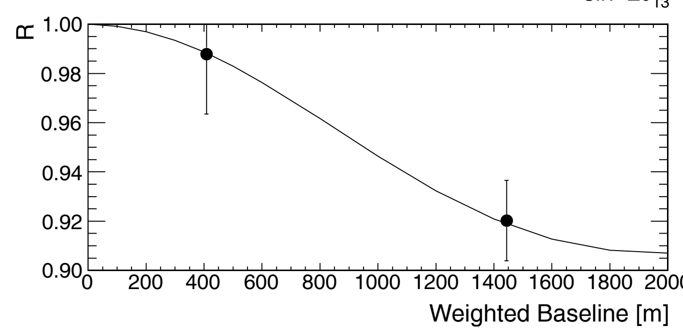


$\sin^2 2\theta_{13}$ = 0.113 ± 0.013 (stat) ± 0.019 (syst.)

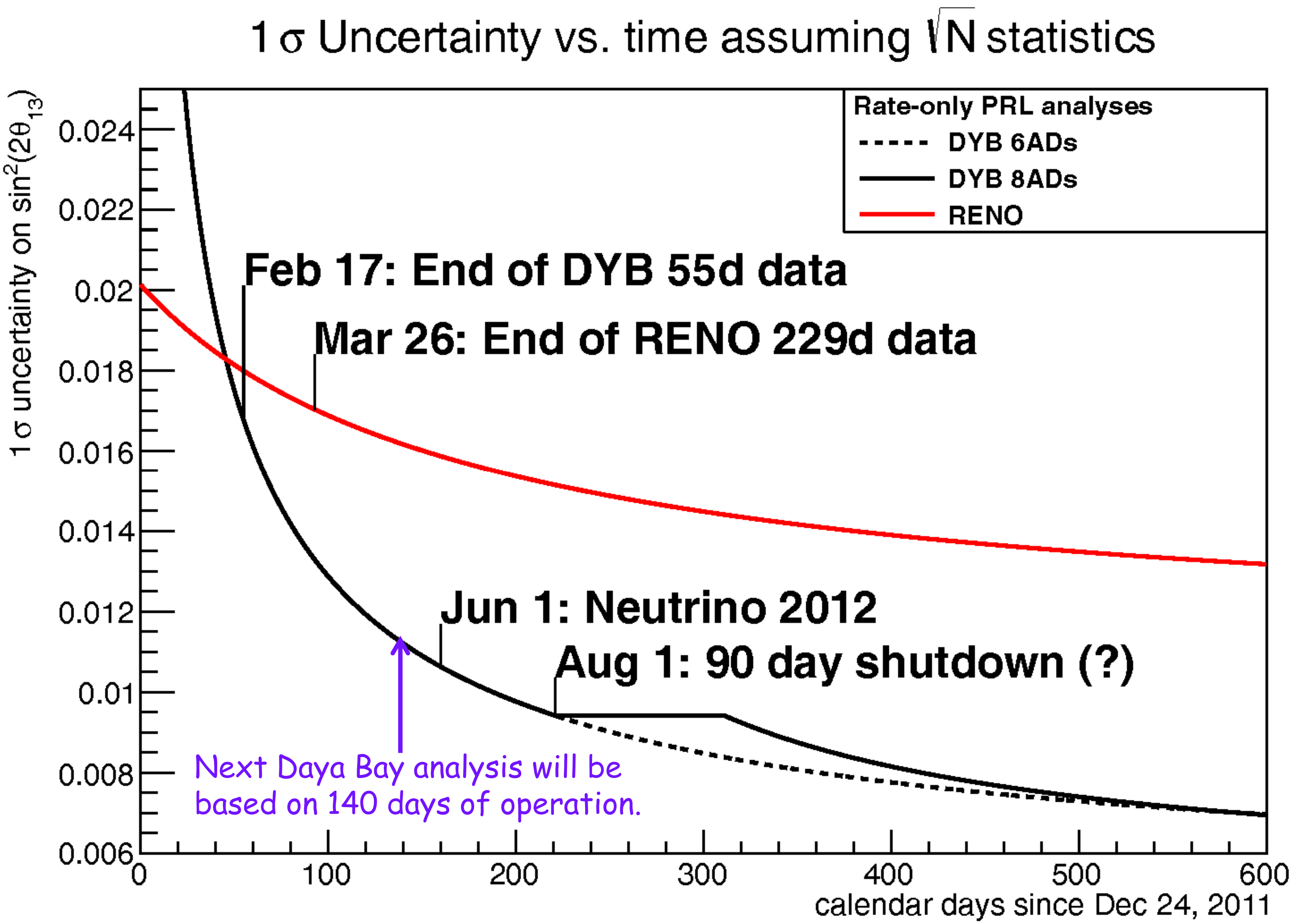
http://arxiv.org/abs/1204.0626
(Apr. 8 ,2012)





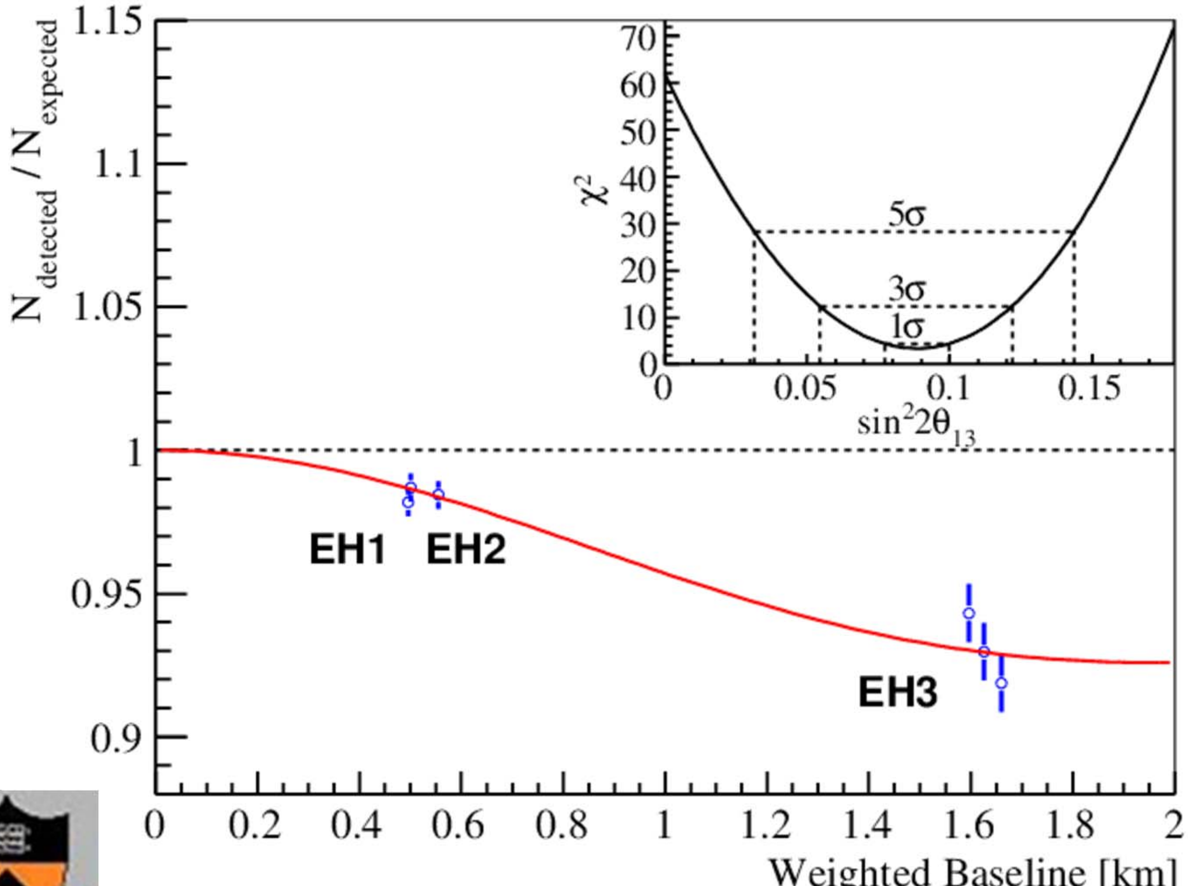


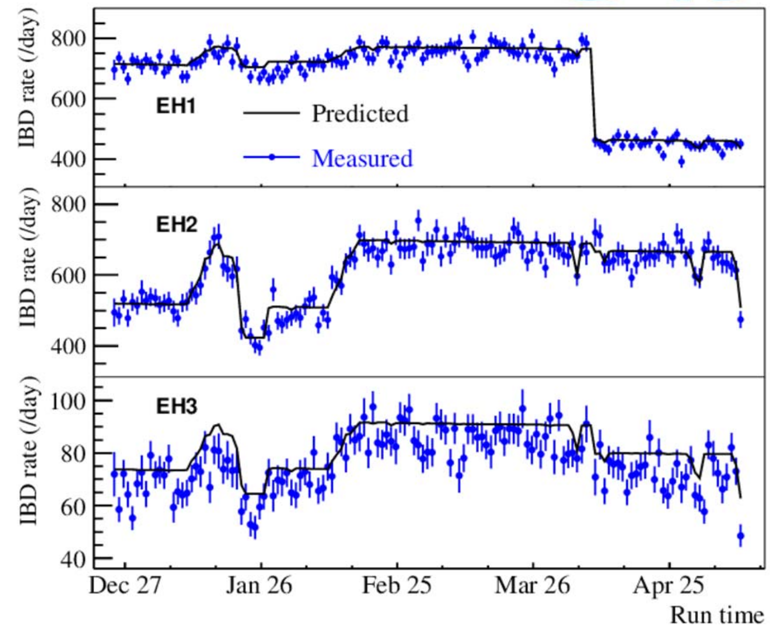
Projected Uncertainty for Future Running of the Daya Bay and RENO Experiments

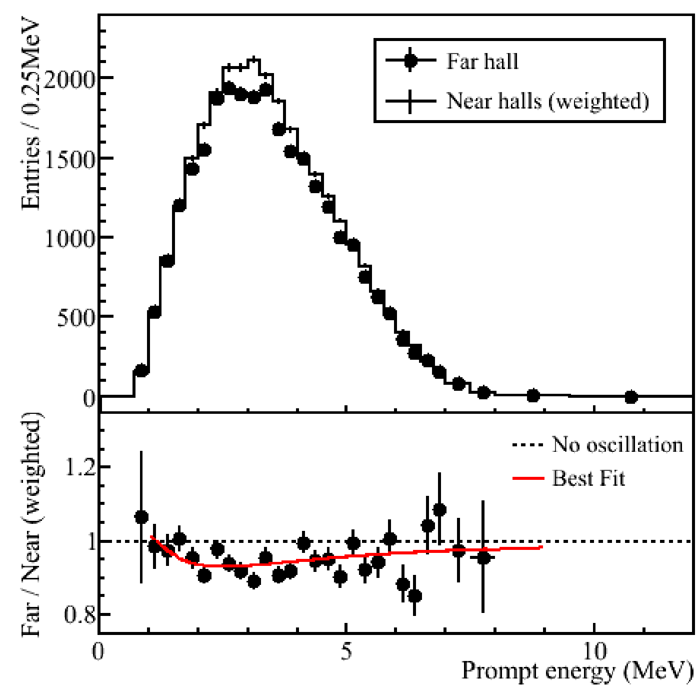


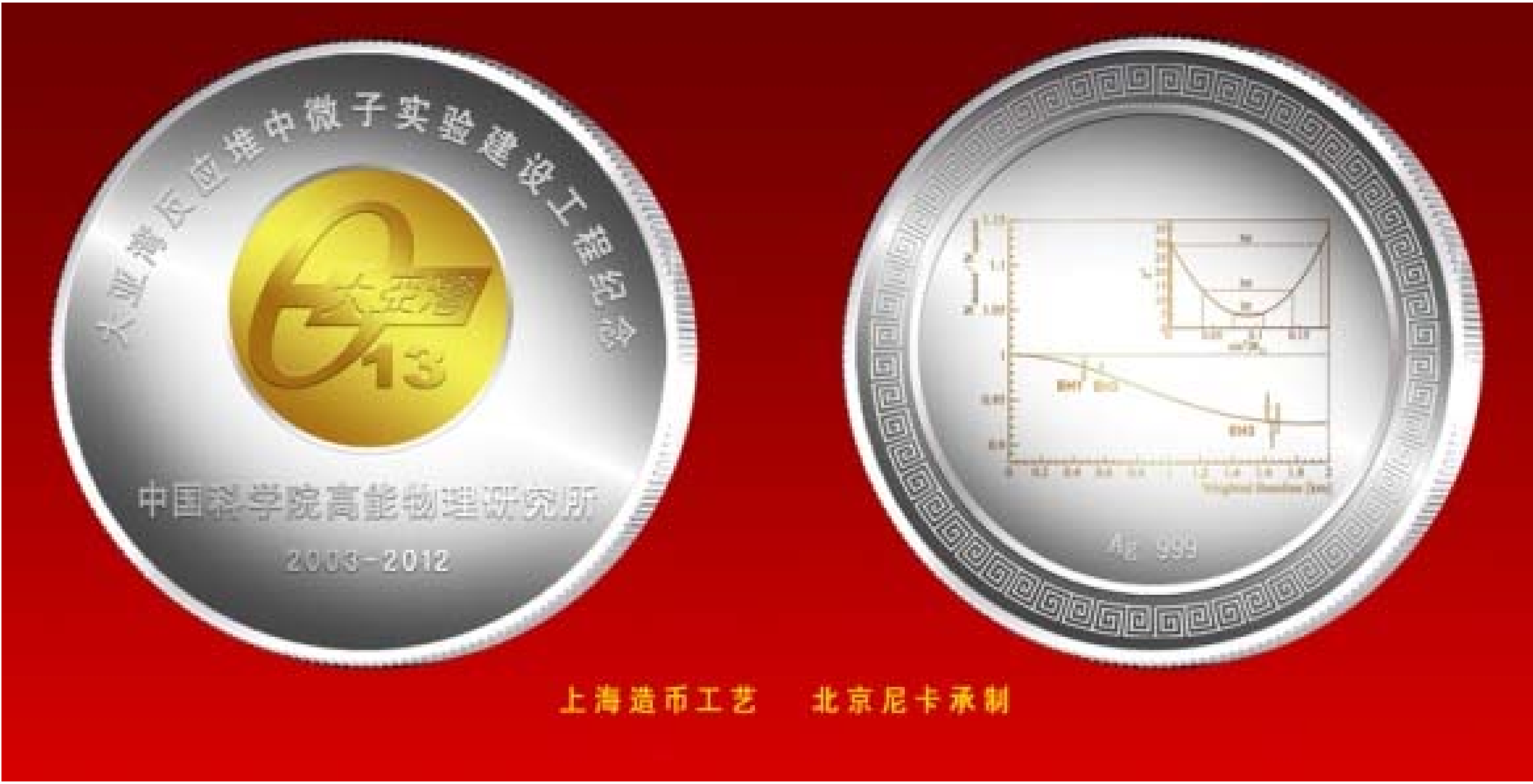
Update of Daya Bay Analysis through May 17, 2012

- χ^2 fit result: $\sin^2 2\theta_{13}$ = 0.089 ±0.010(stat) ±0.005(syst)
- χ^2_{min} = 3.4
- 7.7σ non-zero








大亚湾反应堆中微子实验建设工程纪念
中国科学院高能物理研究所
2003-2012
Ag 999
上海造币工艺 北京尼卡承制