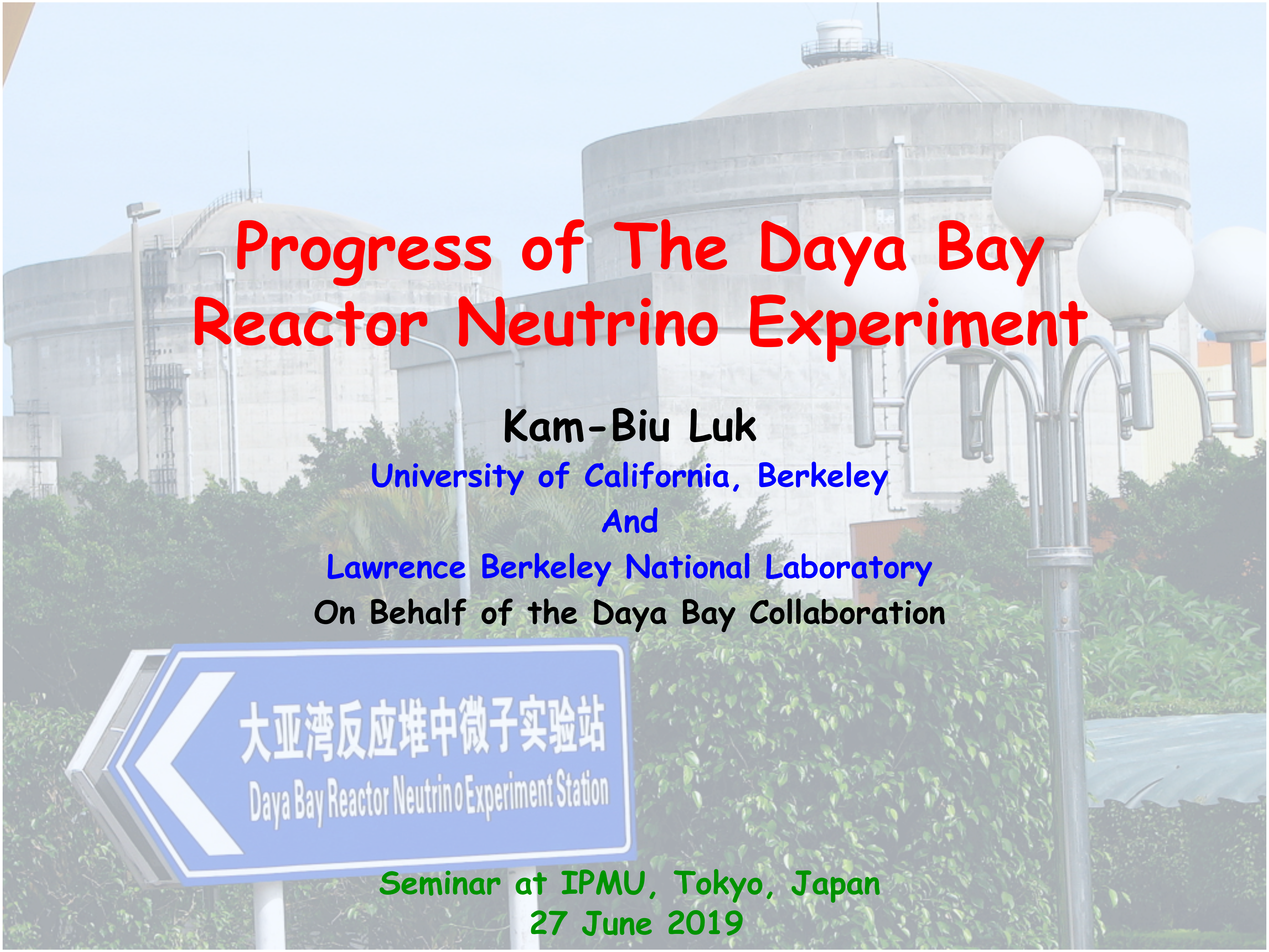


Progress of The Daya Bay Reactor Neutrino Experiment

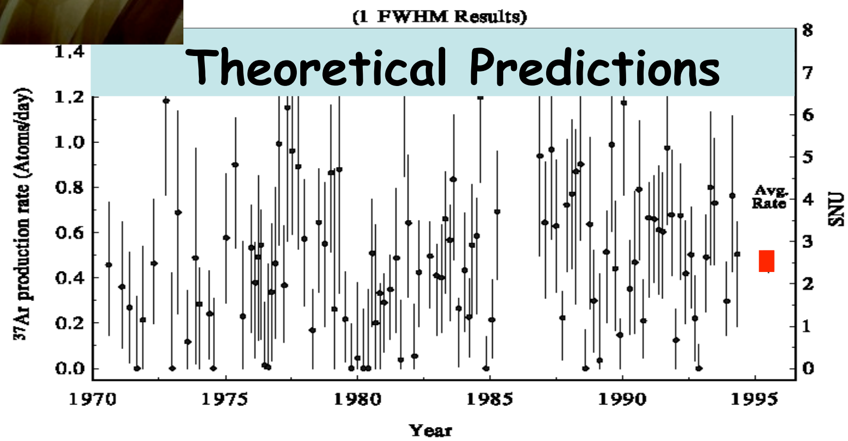
Kam-Biu Luk
University of California, Berkeley
And
Lawrence Berkeley National Laboratory
On Behalf of the Daya Bay Collaboration

Seminar at IPMU, Tokyo, Japan
27 June 2019

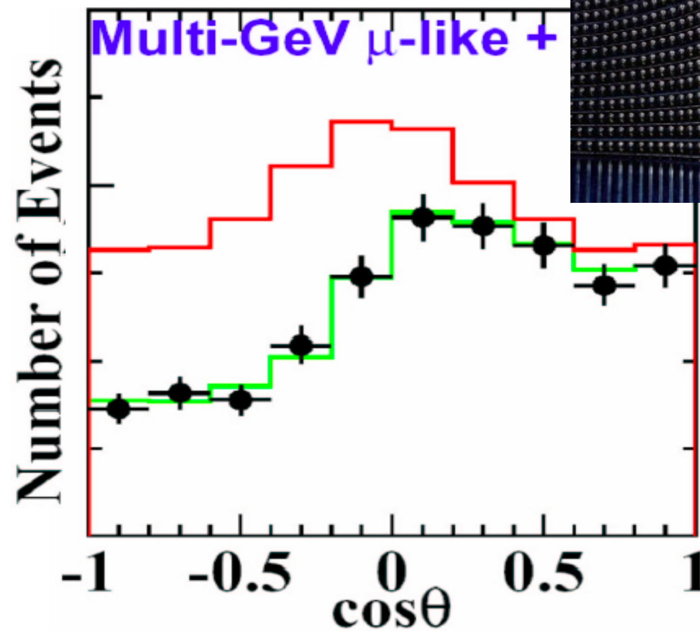
Outline

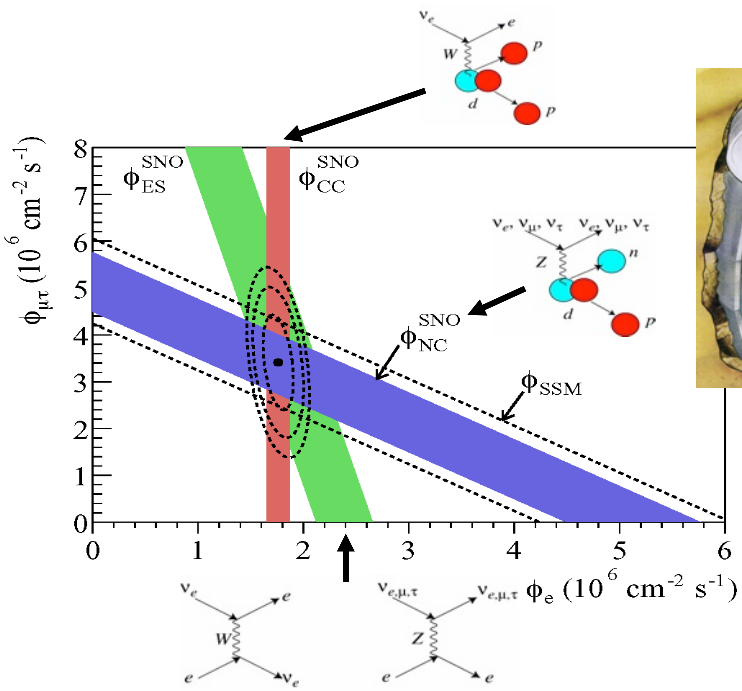
- Introduction
  - Motivation
  - The Daya Bay experiment
- Neutrino oscillation
  - Latest measurements of θ_{13} and Δm^2_{ee} using nGd samples
  - Search for a light sterile neutrino
- Absolute measurement of reactor antineutrinos
  - Flux
  - Energy spectrum

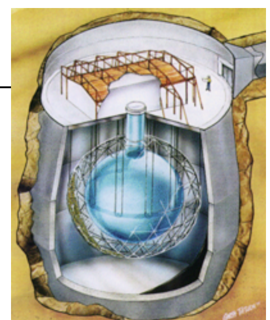
Discoveries of Neutrino Oscillation

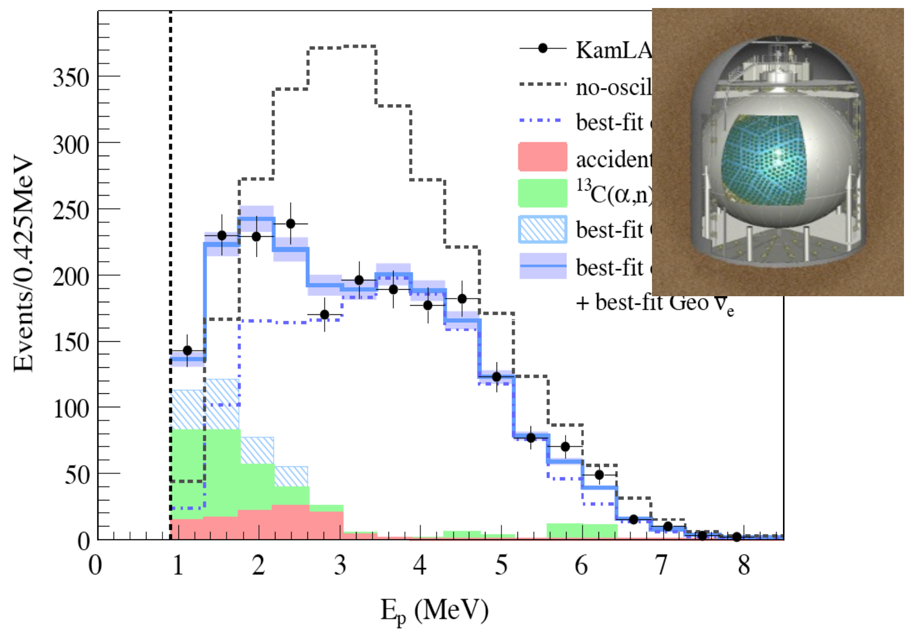


1 SNU = 10^{-36} interaction/atom/s





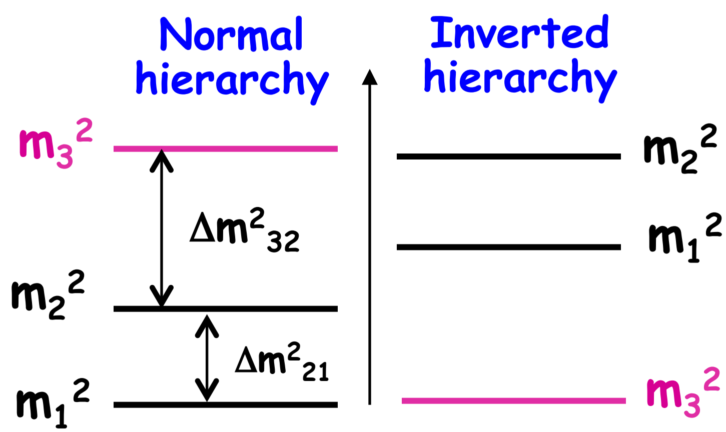




Neutrino Mixing Circa 2011

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

$\theta_{12} = 33° \pm 1°$ θ_{13} and δ ? $\theta_{23} \approx 42° \pm 3°$



Which one ?

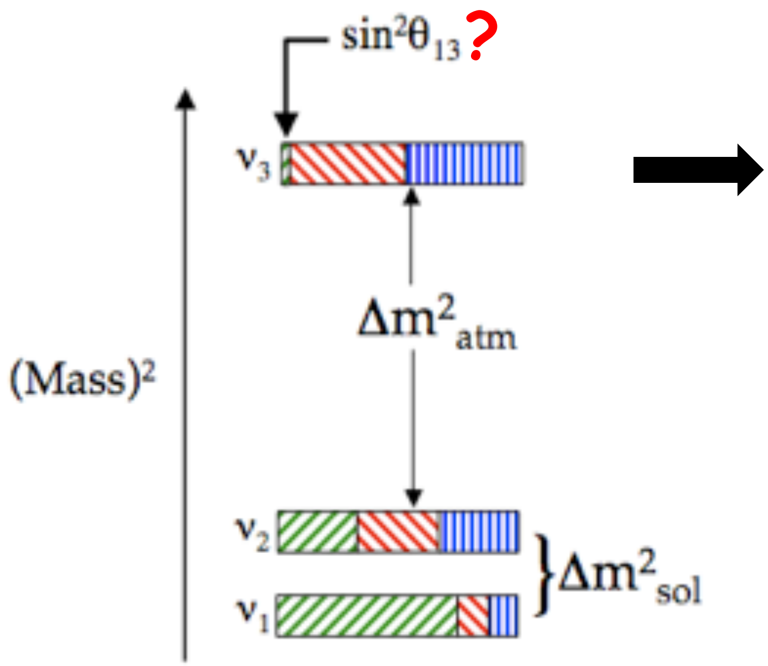
$$|\Delta m^2_{31}| = |\Delta m^2_{32}| \pm |\Delta m^2_{21}| \approx |\Delta m^2_{32}|$$

$(2.45 \pm 0.09) \times 10^{-3}$ eV^2 $(7.6 \pm 0.2) \times 10^{-5}$ eV^2

New J. Phys. **13**(2011)063004

Significance of Knowing θ_{13}

- Complete the determination of the mixing matrix
  - guide model-building
- Determine ν_e fraction of ν_3



reduce uncertainties in predicting neutrino-related phenomena

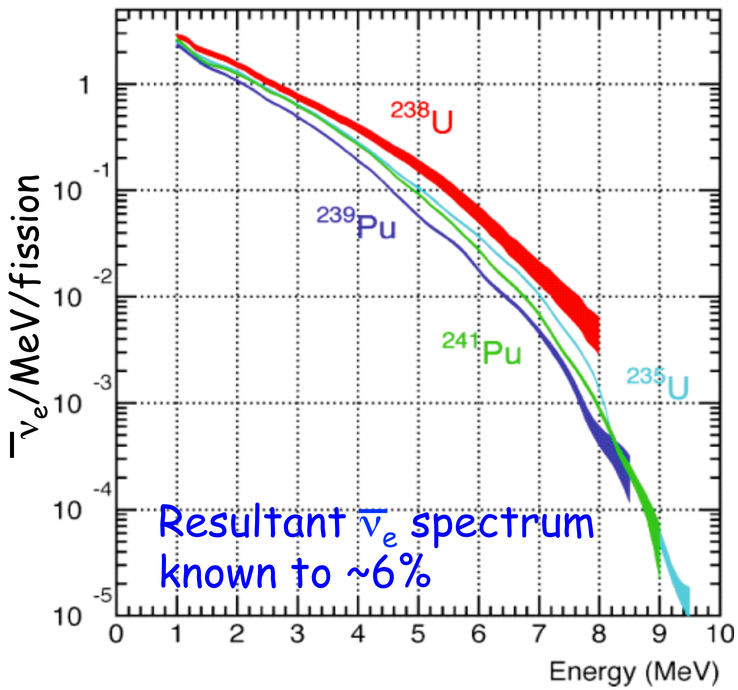
- θ_{13} is the gateway to CP violation in the neutrino sector:

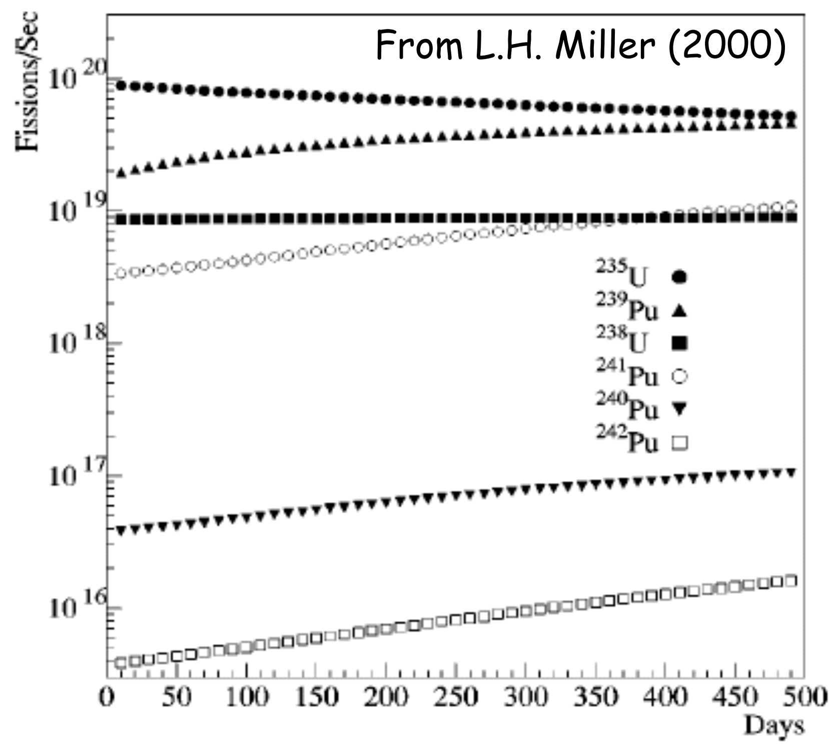
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Production of Reactor $\bar{\nu}_e$

- A pure, intense source of low-energy $\bar{\nu}_e$:

  3 GW_{th} generates 6×10^{20} $\bar{\nu}_e$ per sec





- $\bar{\nu}_e$ related to ^{235}U, ^{239}U, and ^{241}Pu :
  - measure β spectrum using thermal neutron induced fission on the isotope
  - convert β spectrum to $\bar{\nu}_e$ spectrum
- $\bar{\nu}_e$ related to ^{238}U :
  - $\bar{\nu}_e$ spectrum is based on calculation, now measurement as well.

- Uncertainty in $\bar{\nu}_e$ yield, ~2%, due to
  - Thermal power (0.5%)
  - Sampling of fuel
  - Analysis of fractions of isotopes in samples

Detecting Reactor $\bar{\nu}_e$

- Detect inverse β-decay reaction (IBD) in liquid scintillator:

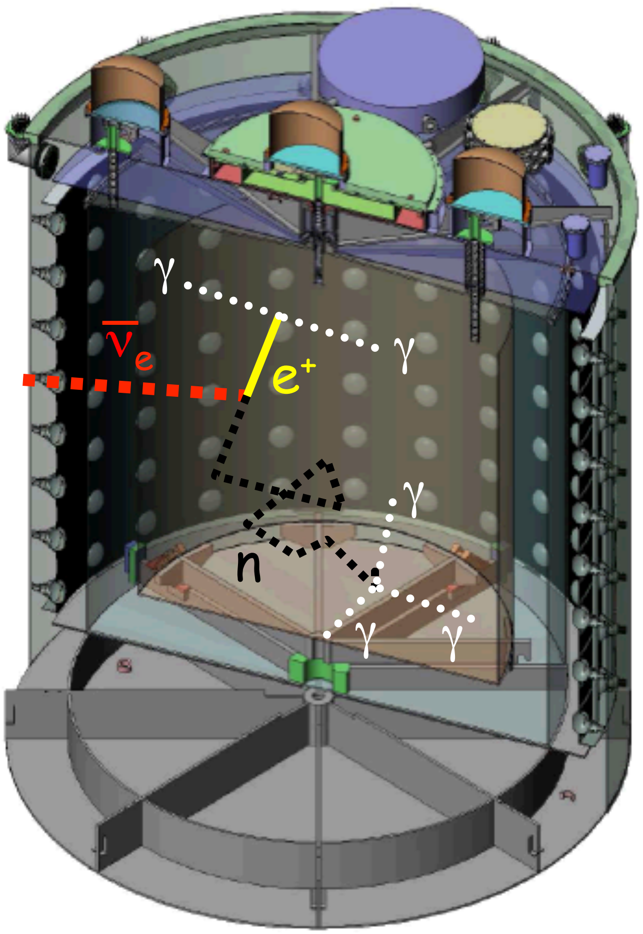
$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

~180μs → $+ p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed signal)

→ $+ Gd \rightarrow Gd^*$

~30μs for 0.1% Gd

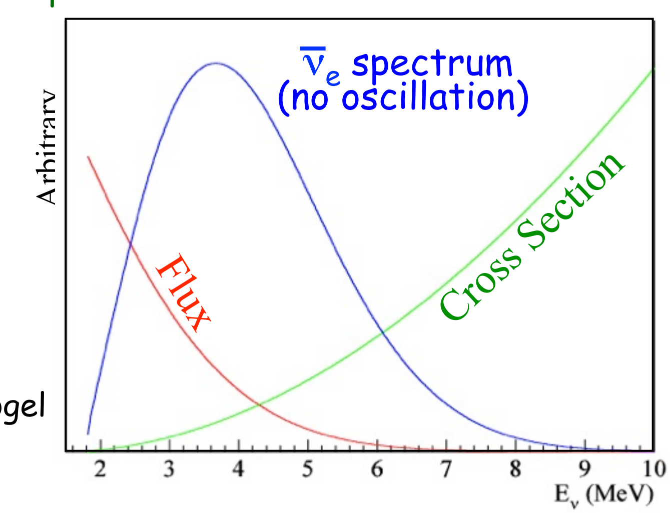
↳ $Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed signal)



- Time- and energy-tagged signal is a good tool to suppress background events.
- Energy of $\bar{\nu}_e$ is given by:

$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

tens of keV



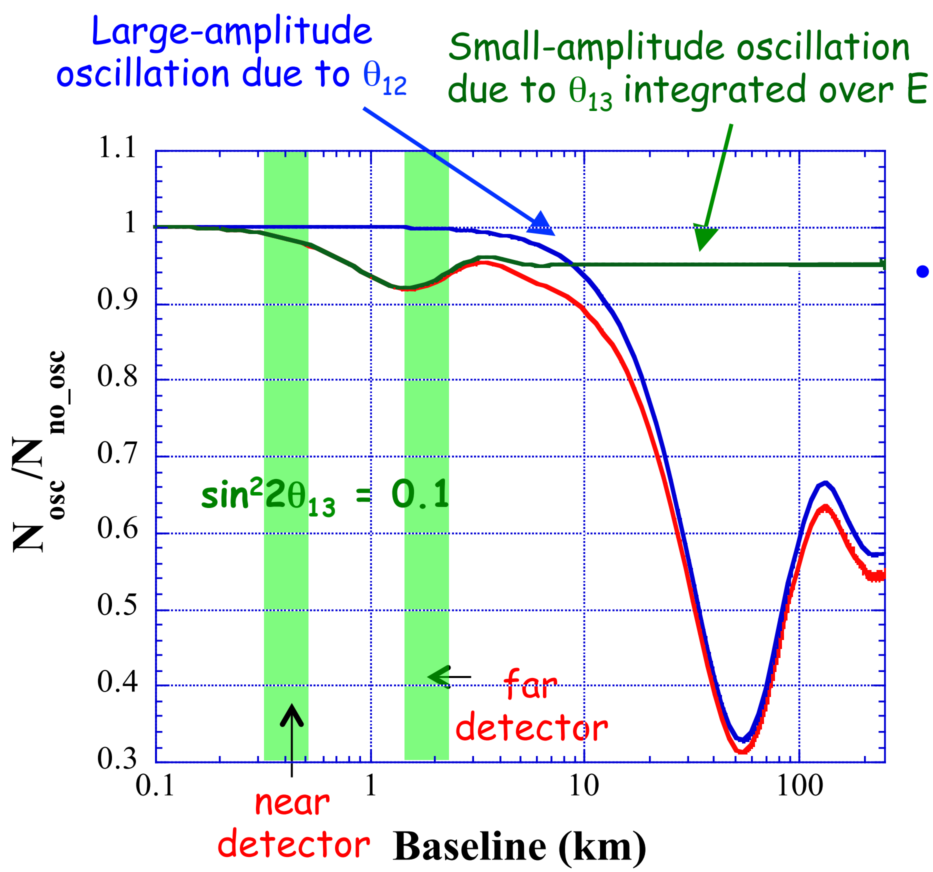
From Bemporad, Gratta and Vogel

Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of electron antineutrinos from reactors:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right) \leftrightarrow \cos^2\theta_{12}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$



- Perform relative measurement, for a given E :

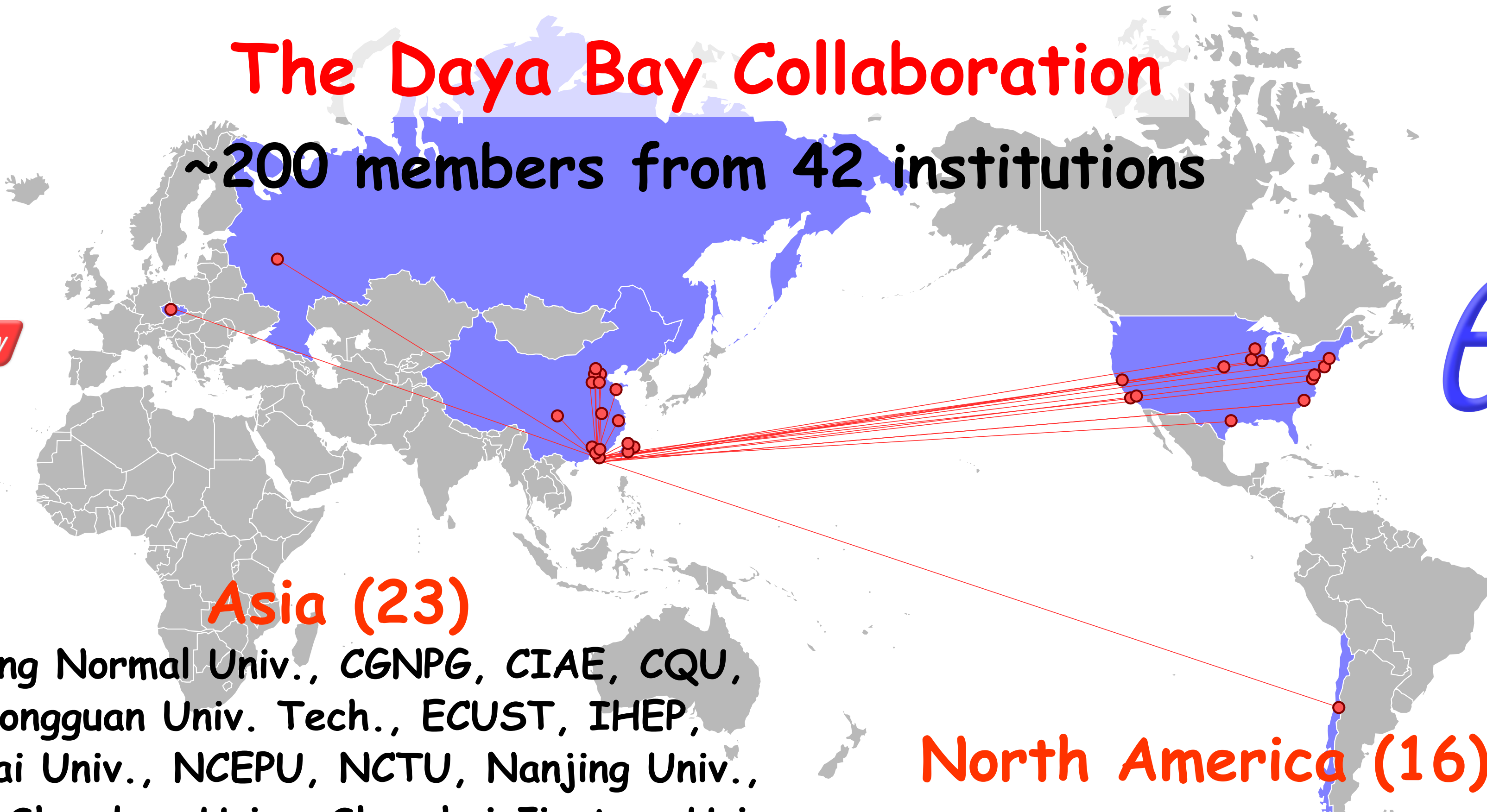
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{P_{Far}}{P_{Near}}\right)$$

$\bar{\nu}_e$ rate	number of protons	detection efficiency	$1/r^2$	yield $\sin^2 2\theta_{13}$

Correlated errors are cancelled & enable precise measurement.

The Daya Bay Collaboration

~200 members from 42 institutions



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, CQU, Dongguan Univ. Tech., ECUST, IHEP, Nankai Univ., NCEPU, NCTU, Nanjing Univ., NUDT, Shandong Univ., Shanghai Jiaotong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Chin. Univ. of Hong Kong, Univ. of Hong Kong, Nat. Taiwan Univ., Nat. Chiao Tung Univ., National United Univ.

Europe (2)

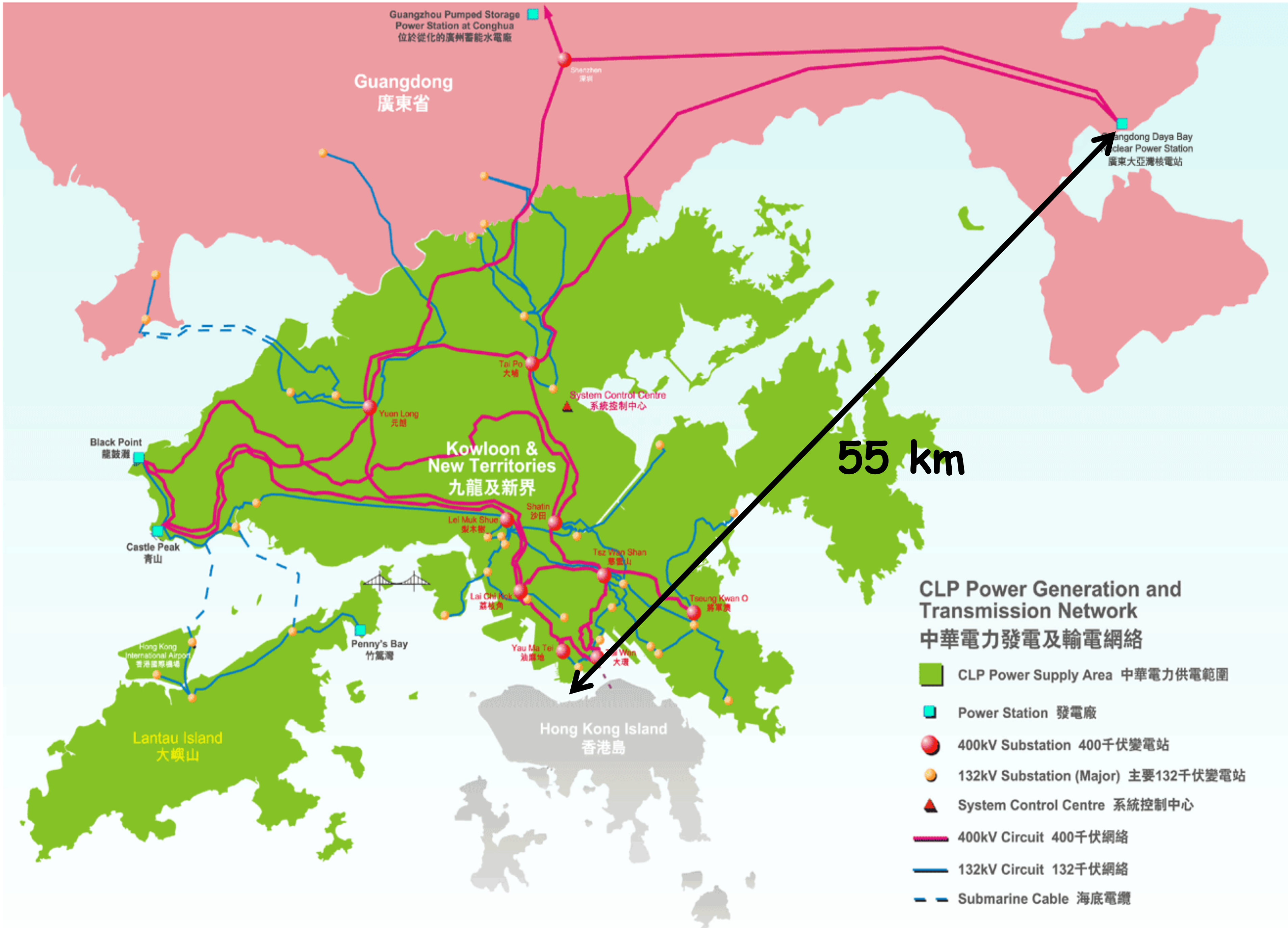
JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

BNL, Illinois Inst. Tech., Iowa State Univ., LBNL, Princeton, RPI, Siena, Temple, UC-Berkeley, UC-Irvine, Univ. of Cincinnati, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary, Yale

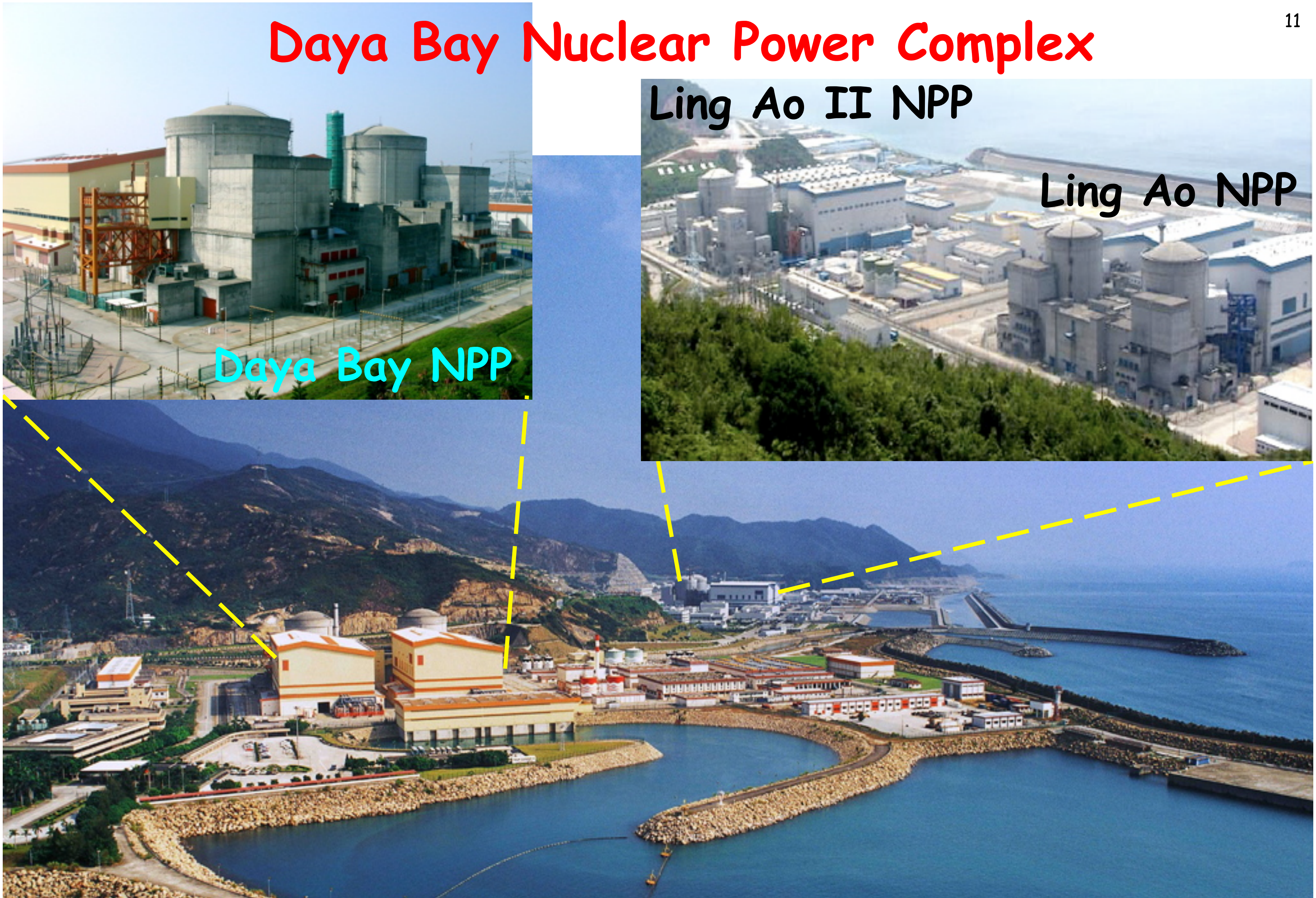
South America (1)

Cath. Univ. of Chile



Guangzhou Pumped Storage Power Station at Conghua
位於從化的廣州蓄能水電廠
Guangdong
廣東省
Guangdong Daya Bay Nuclear Power Station
廣東大亞灣核電站
55 km
Black Point
龍鼓灘
Castle Peak
青山
Yuen Long
元朗
Tai Po
大埔
System Control Centre
系統控制中心
Kowloon & New Territories
九龍及新界
Shatin
沙田
Lai Chi Kok
荔枝角
Tsz Wan Shan
慈雲山
Tseung Kwan O
將軍澳
Yau Ma Tei
油麻地
Penny's Bay
竹篙灣
Hong Kong International Airport
香港國際機場
Lantau Island
大嶼山
Hong Kong Island
香港島
CLP Power Generation and Transmission Network
中華電力發電及輸電網絡
CLP Power Supply Area 中華電力供電範圍
Power Station 發電廠
400kV Substation 400千伏變電站
132kV Substation (Major) 主要132千伏變電站
System Control Centre 系統控制中心
400kV Circuit 400千伏網絡
132kV Circuit 132千伏網絡
Submarine Cable 海底電纜

Daya Bay Nuclear Power Complex



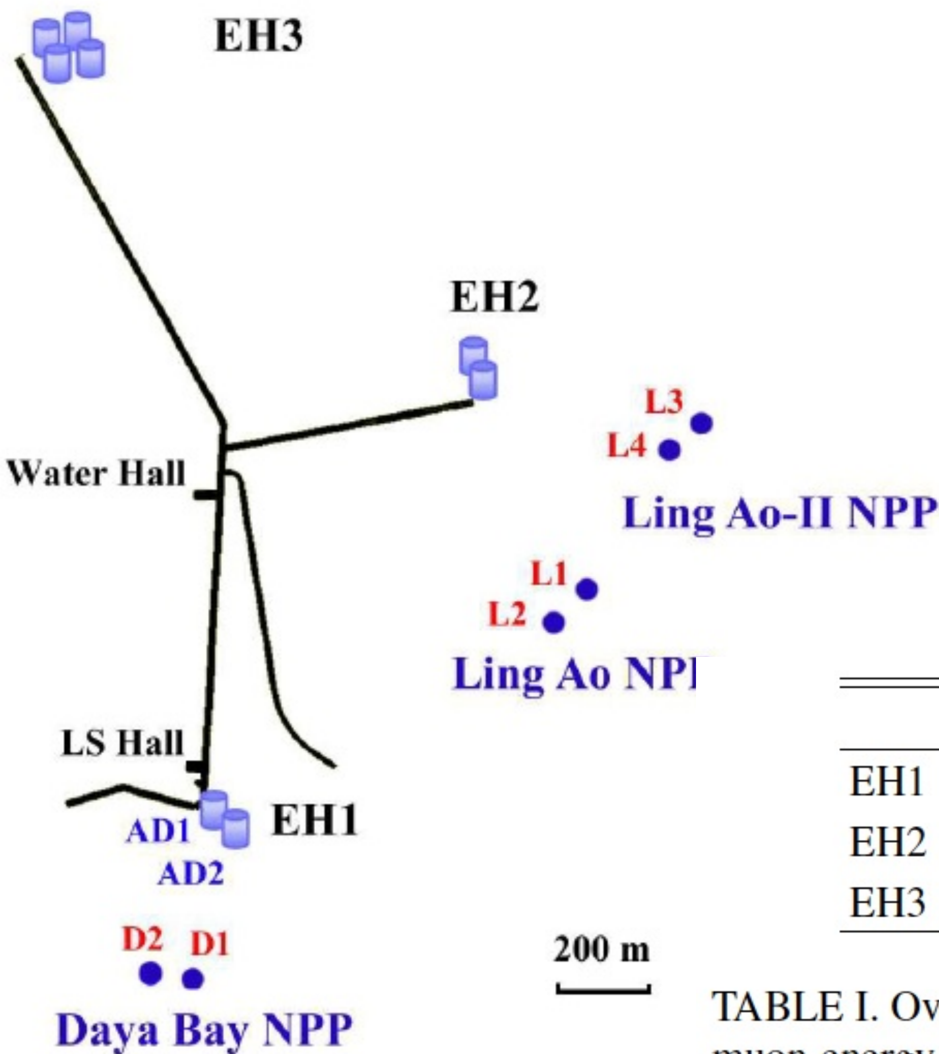
Maximum thermal power: $6 \times 2.9\ GW_{th}$

Far Hall (EH3)
Tunnel
Ling Ao near Hall (EH2)
Ling Ao II reactors
Water Hall
Ling Ao reactors
LS Hall
Daya Bay Near Hall (EH1)
Entrance
Daya Bay reactors
m
Control Building
Surface Assembly Building (SAB)

Baselines

Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 18mm

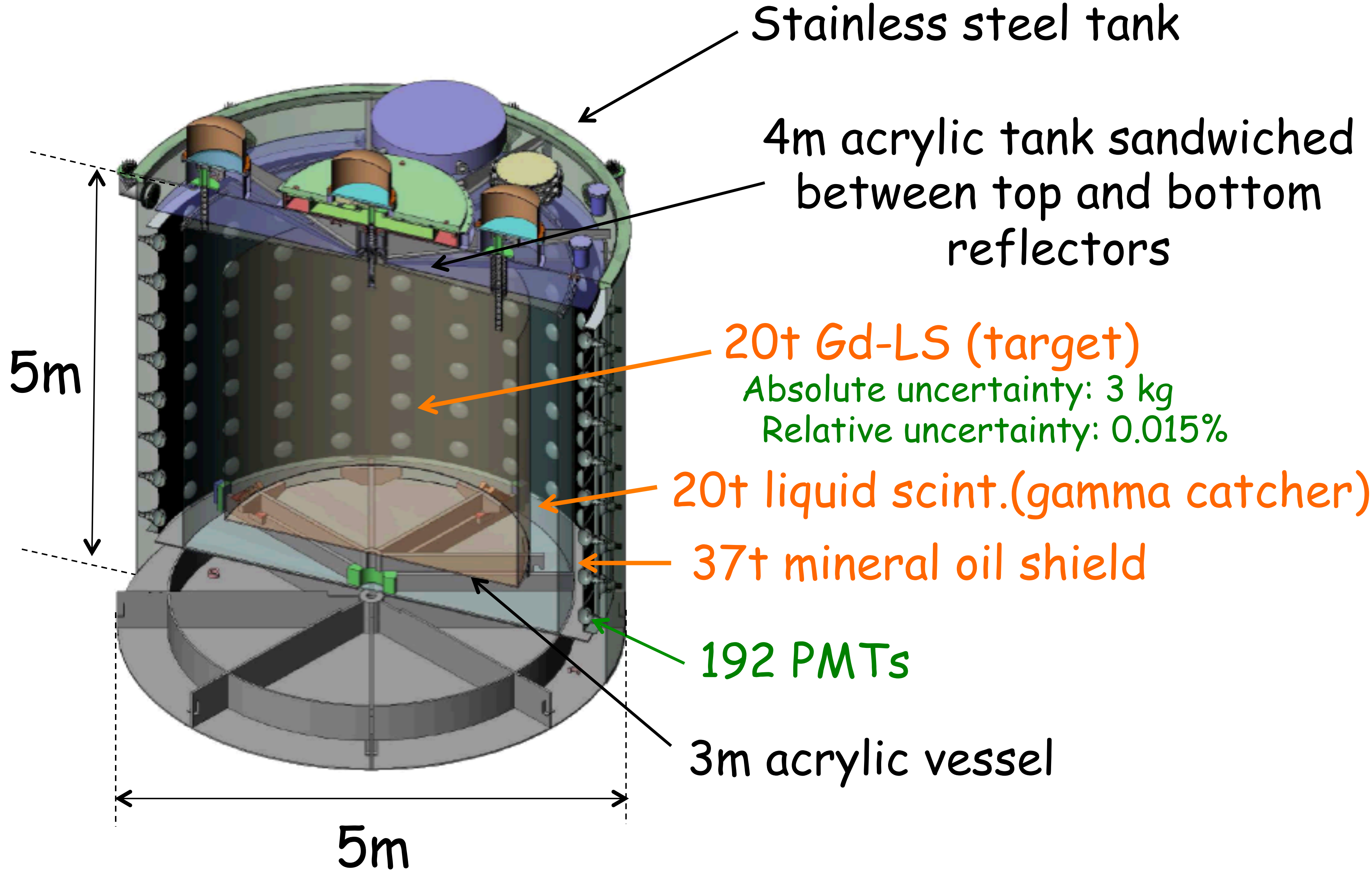
Validation:
- 3 independent calculations
- Cross-check survey
- Consistent with power plant and design plans



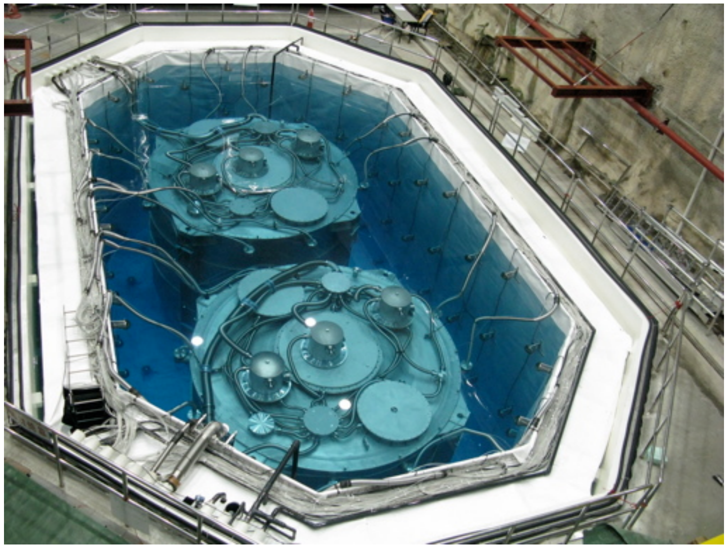
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

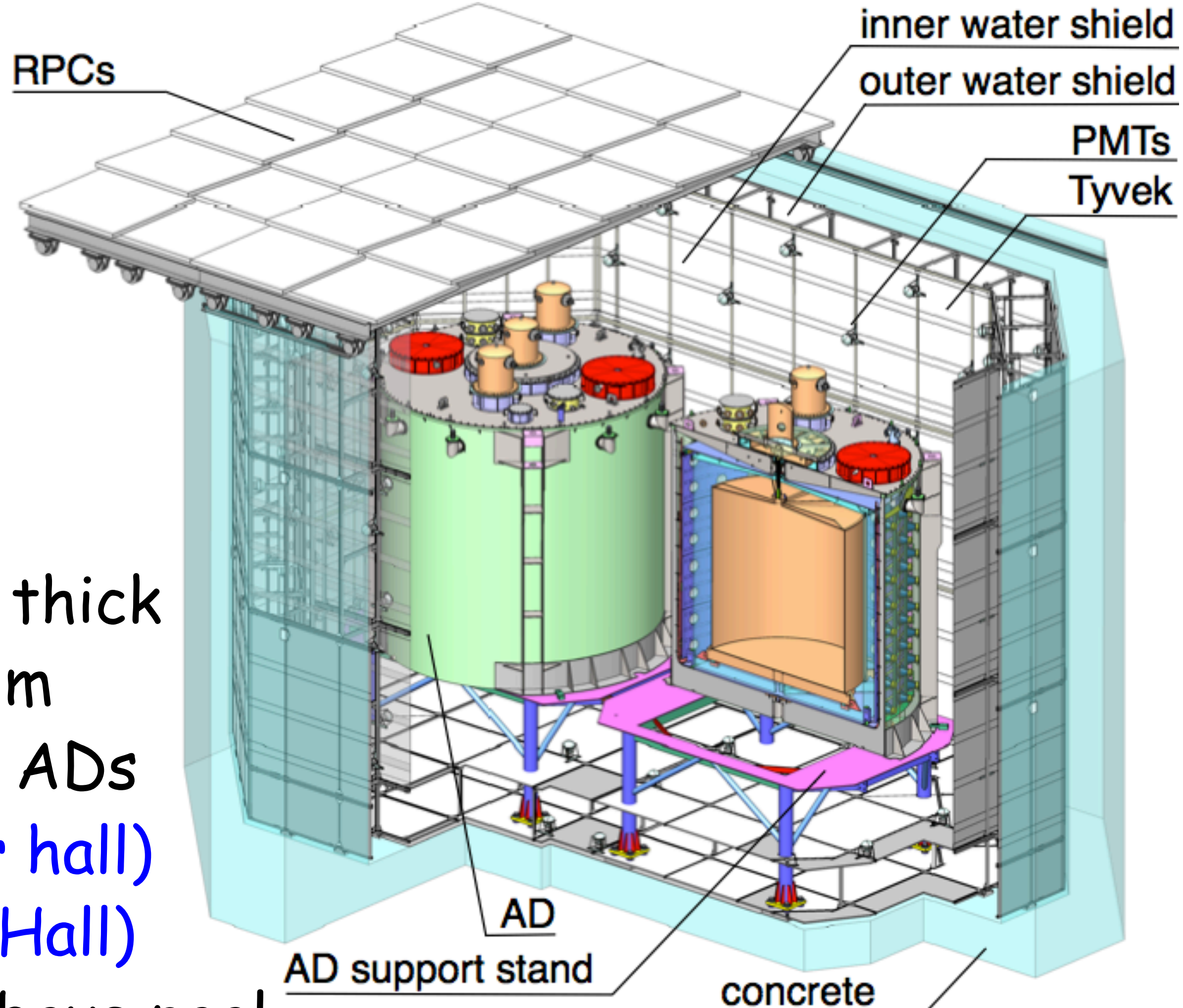
TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Antineutrino Detector (AD)



Muon Tagging System





- Outer Cherenkov: 1-m thick
  Inner Cherenkov: 1.5 m
  2.5 m of water above ADs
  - 288 8" PMTs (near hall)
  - 384 8" PMTs (Far Hall)
- 4-layer RPC modules above pool
  - 54 modules (near hall)
  - 81 modules (Far Hall)

Operation of Daya Bay

Date	Operation
24 December 2011	Data taking with 6 ADs EH1: 2 ADs EH2: 1 AD EH3: 3 ADs
28 July – 19 October 2012	Special calibration runs Installation of last 2 ADs
19 October 2012	Data taking with 8 ADs
20 Dec 2016 – 26 Jan 2017	Special calibration runs EH1 AD1 used for LS studies
26 January 2017	Data taking with 7 ADs EH1: 1 ADs EH2: 2 AD EH3: 4 ADs

Triggers & Their Performance

Discriminator threshold:

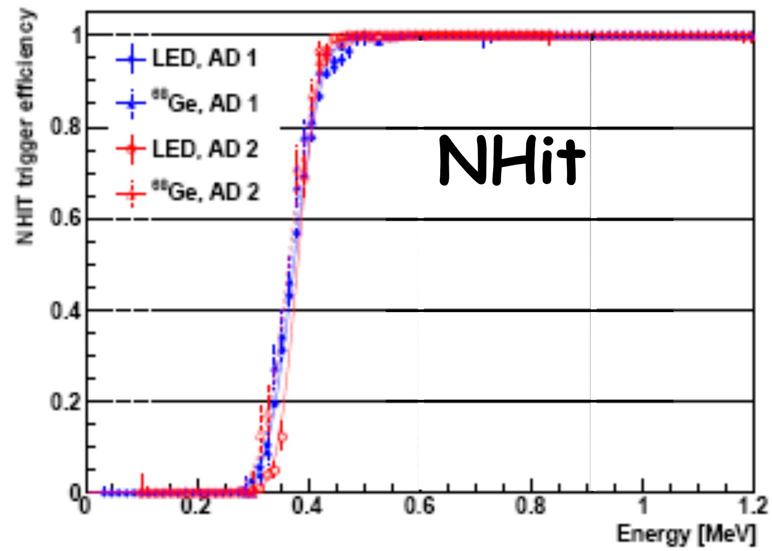
- ~0.25 p.e. for PMT signal

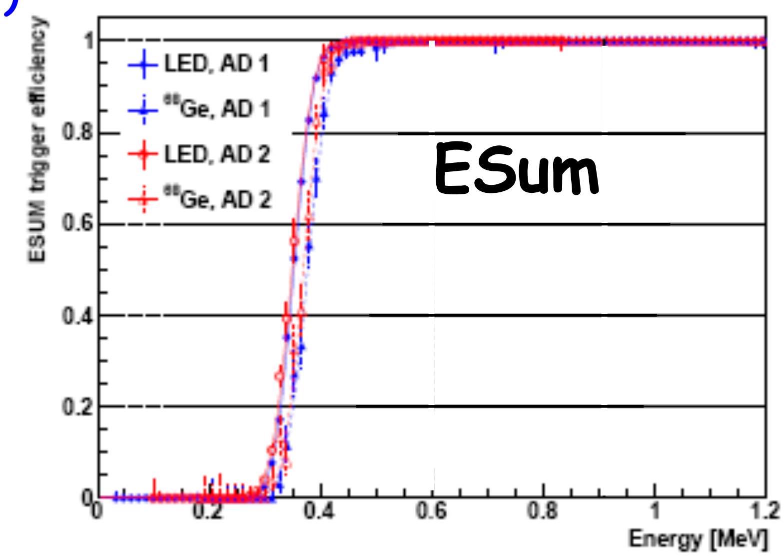
Triggers:

- AD: ≥ 45 PMTs (digital trigger)
  ≥ 0.4 MeV (analog trigger)
- Inner Water Cherenkov: ≥ 6 PMTs
- Outer Water Cherenkov: ≥ 7 PMTs (near)
  ≥ 8 PMTs (far)

Trigger rate:

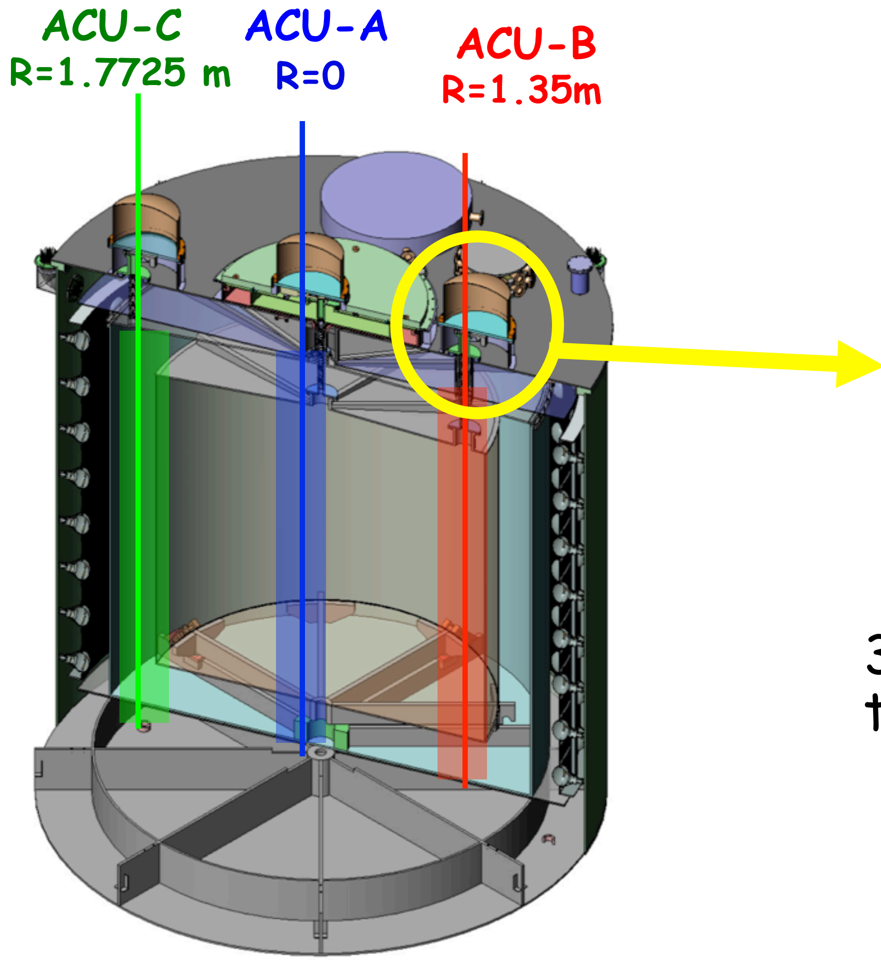
- AD: < 280 Hz
- Inner Water Cherenkov: < 250 Hz
- Outer Water Cherenkov: < 330 Hz
- Periodic: 10 Hz

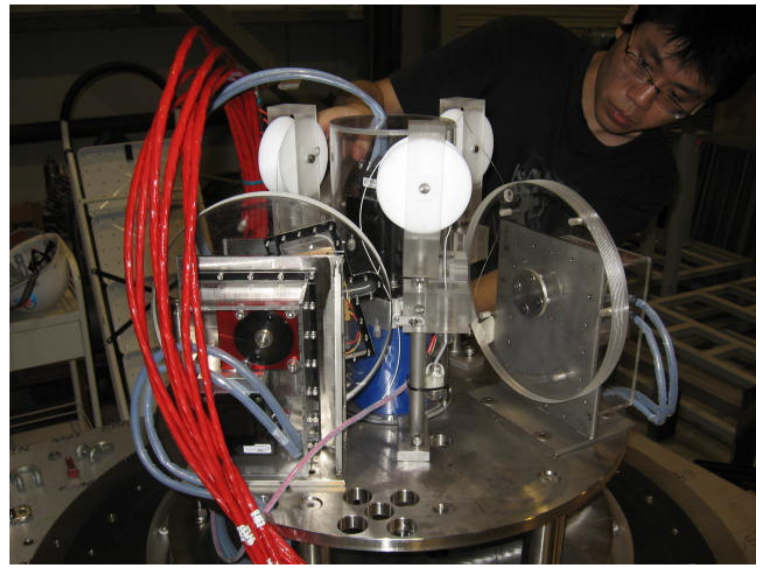




Calibration System of ADs

3 Automatic Calibration Units (ACUs) on each detector





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

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

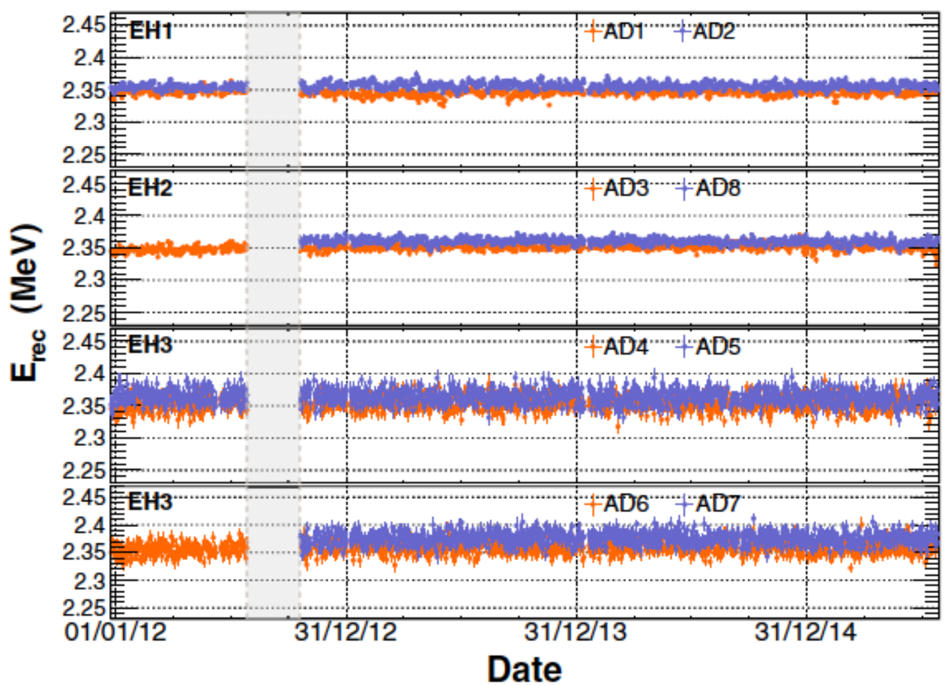
- ^{68}Ge (2×0.511 MeV γ's; 10 Hz)
- ^{241}Am-^{13}C neutron source (3.5 MeV n without γ; 0.7 Hz)
  ^{60}Co (1.173+1.332 MeV γ's; 100 Hz)
- LED diffuser ball (500 Hz)

Stability of Calibration

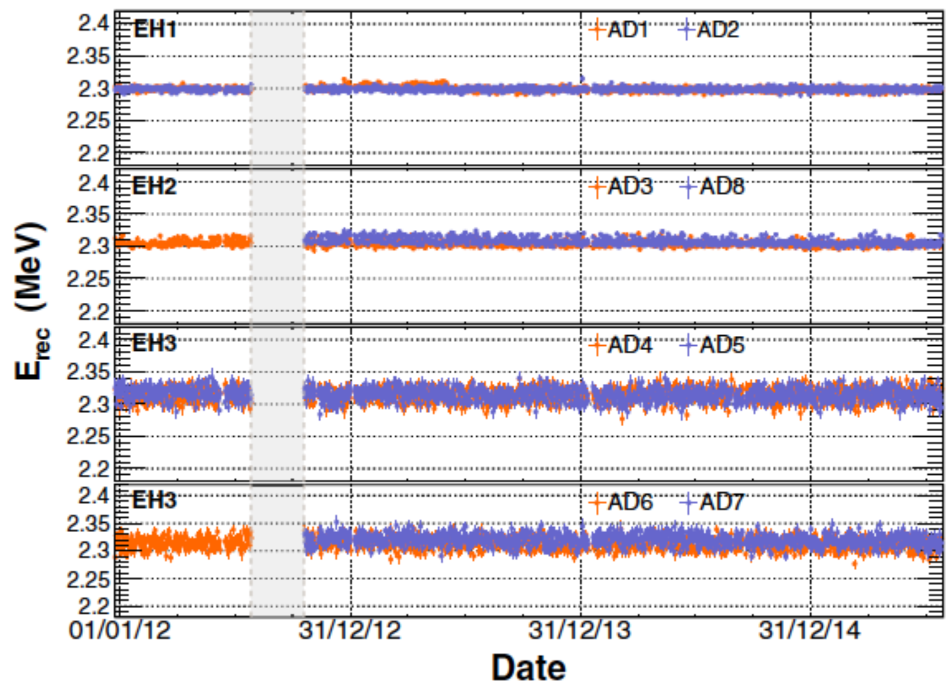
Method A: base on weekly deployed ^{60}Co and Am-C sources in ACUs

Method B: use spallation neutrons daily

Method A

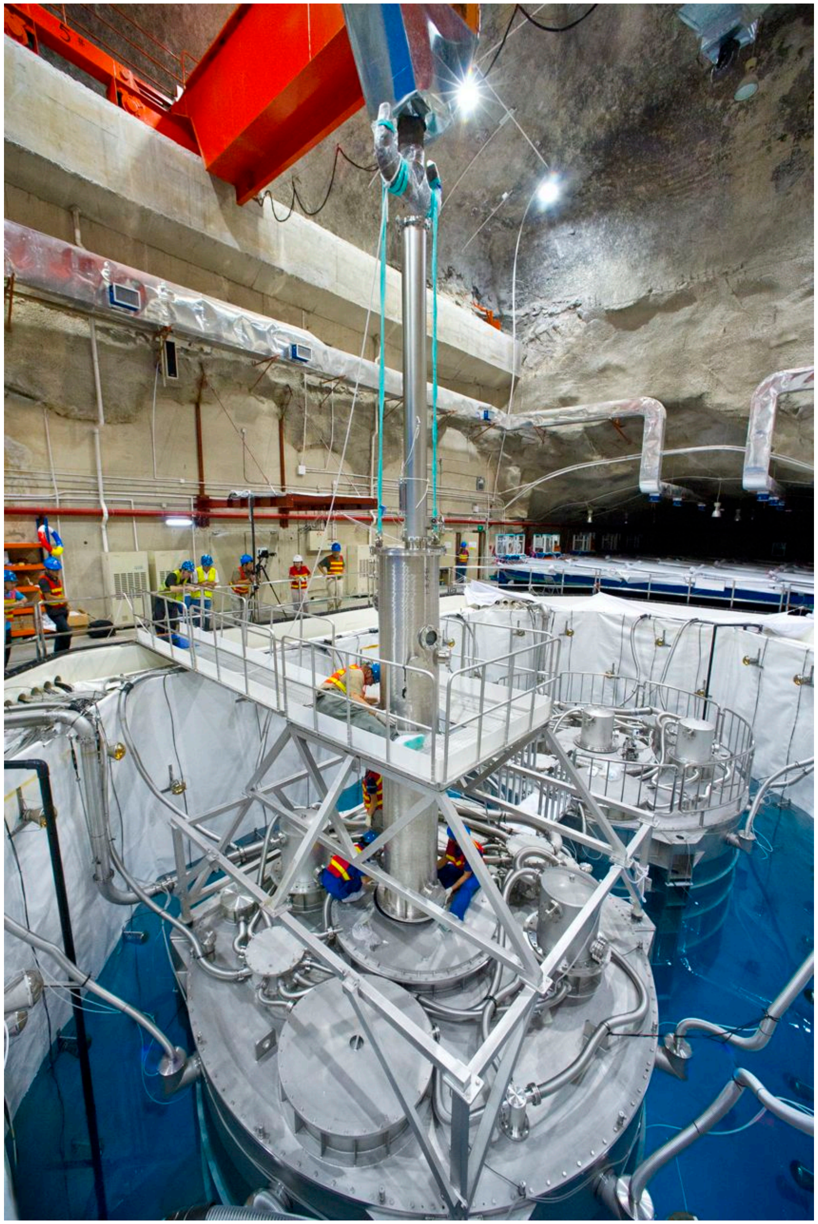


Method B

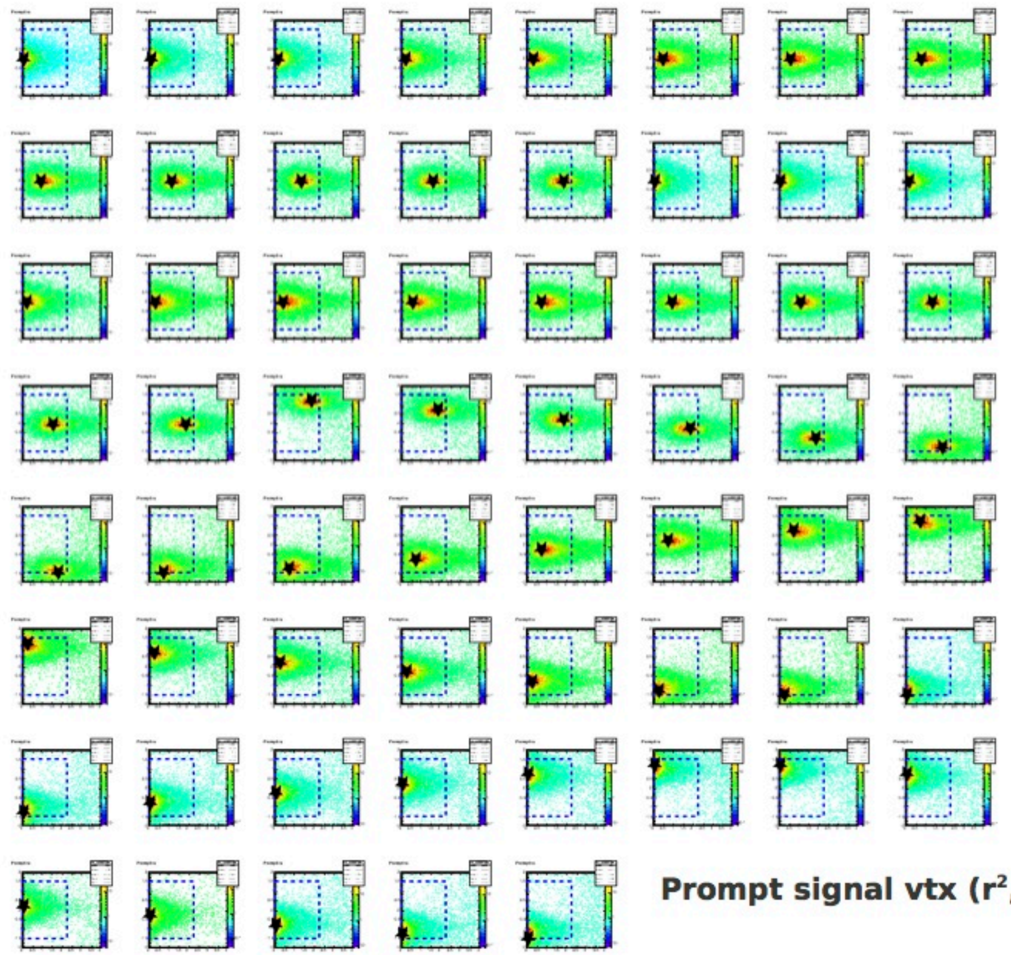


Reconstructed energy of IBD n-Gd capture is stable to better than 0.2 %

Improving Non-uniformity Correction

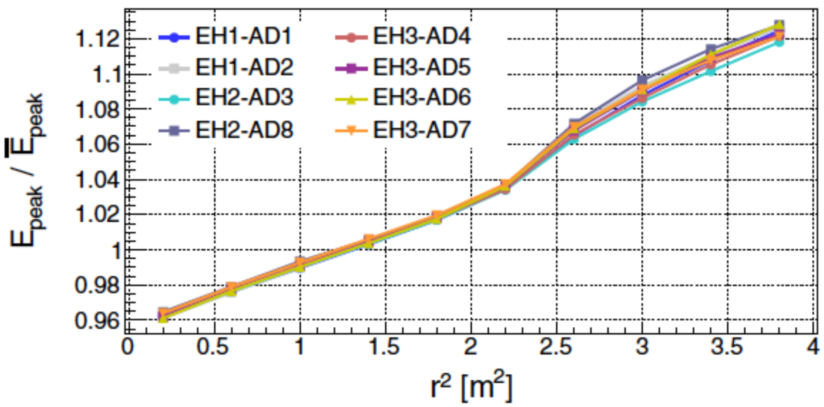


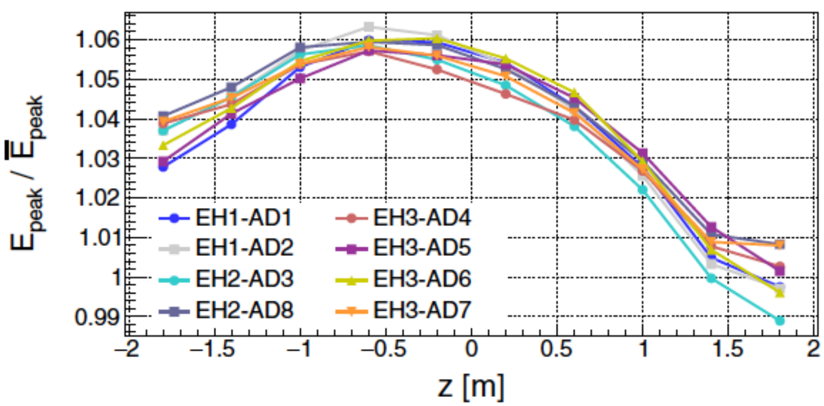
- Use the Manual Calibration Unit with a Pu-C/^{60}Co source deployed in AD1 to map out the response throughout the fudicial volume in (r, φ, z).

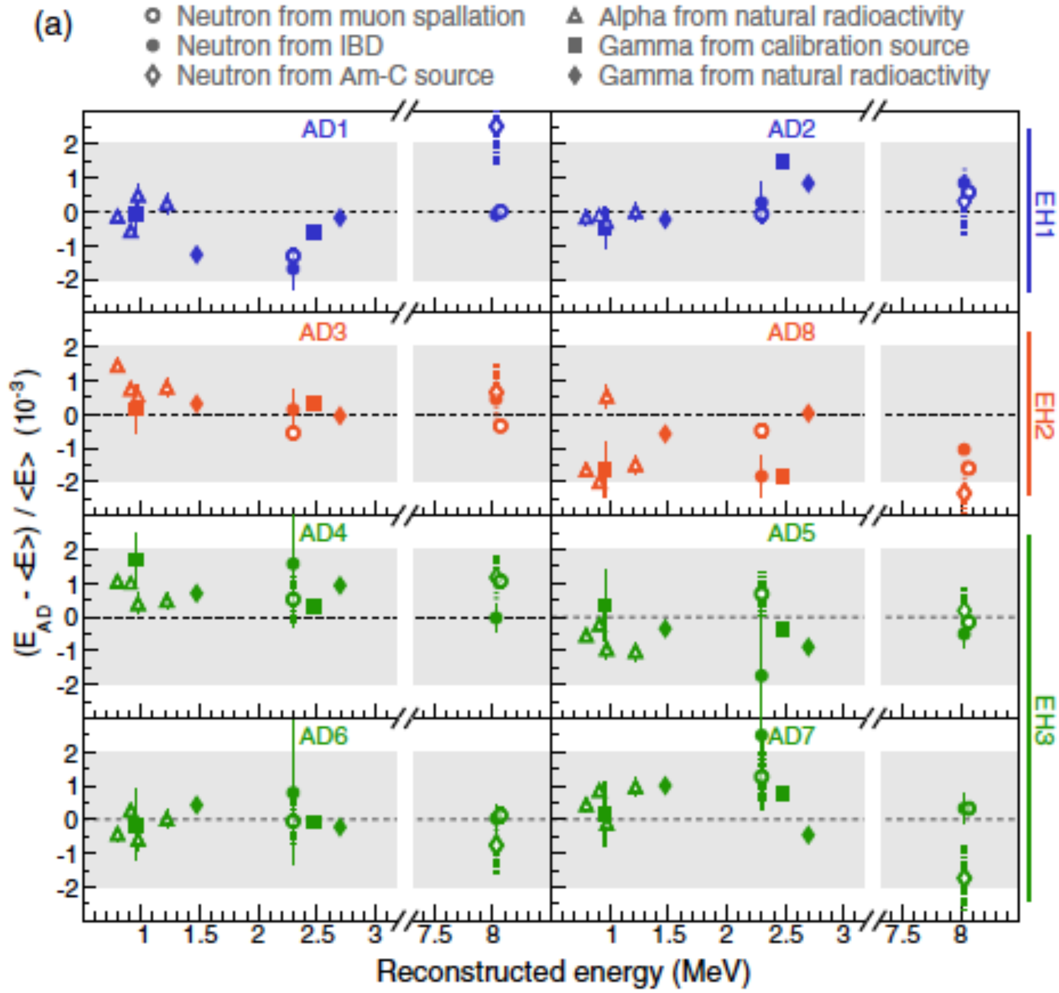


Prompt signal vtx (r^2, z)

Energy Calibration



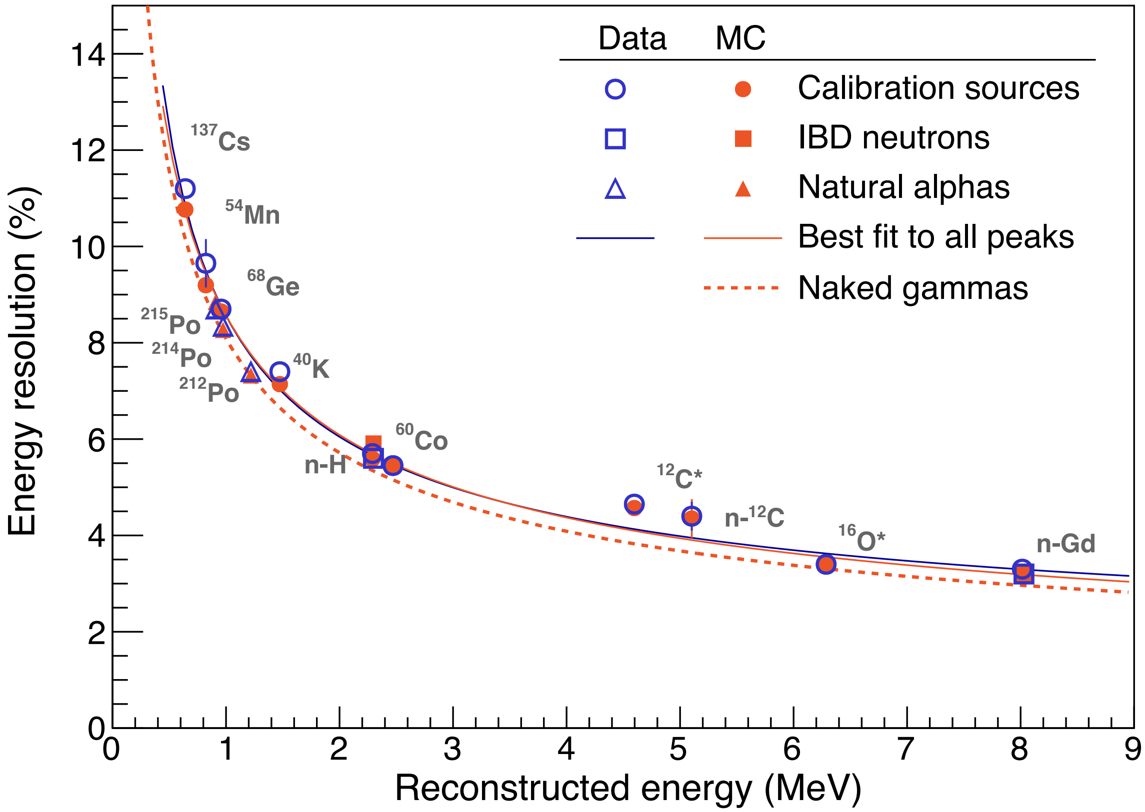




Position non-uniformity has been corrected for.

Relative uncertainty of <0.2% between detectors.

Energy Resolution



- Calibrated primarily using γ sources

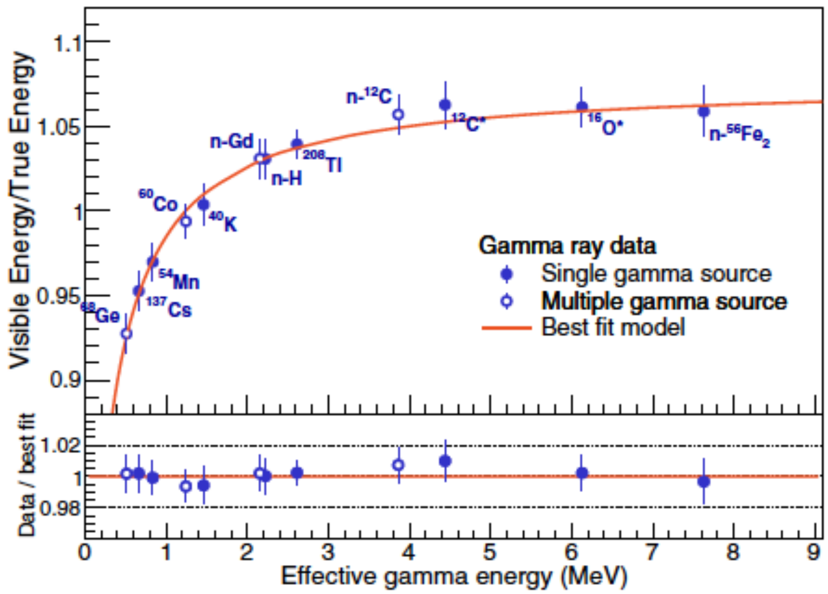
Parametrization:

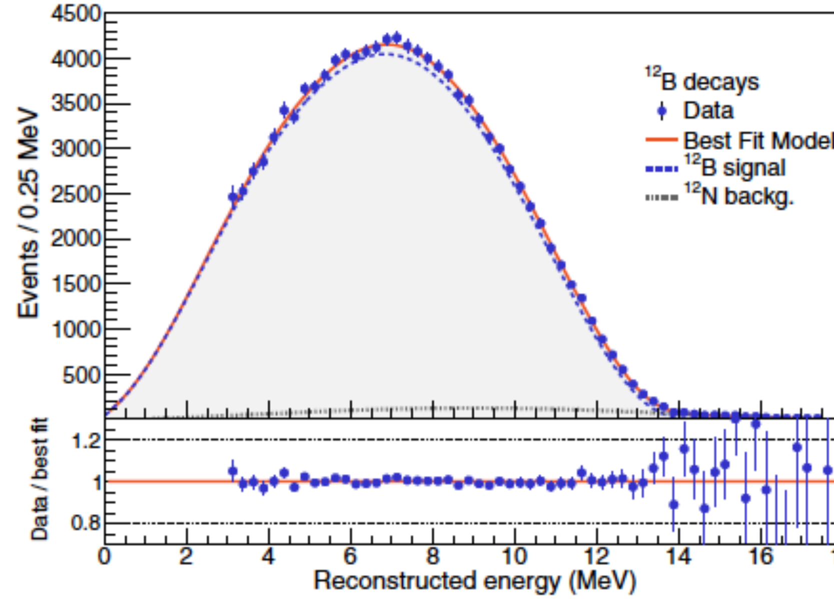
$$\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

where
a : Spatial/temp. resolution
b : Photon statistics
c : Dark noise (constant)

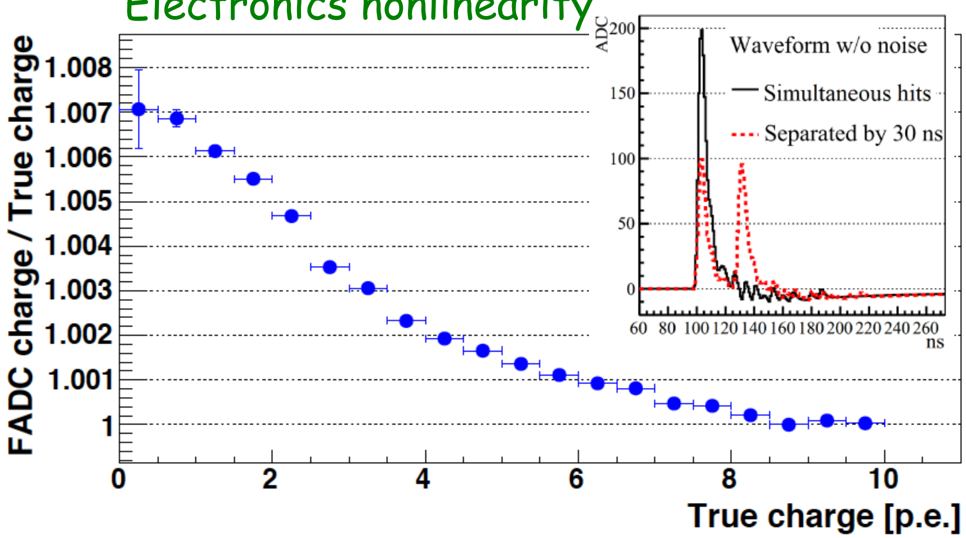
- Radioactive sources placed at the detector center
- Additional data from IBD and spallation neutrons, uniformly distributed in LS
- Alpha particles used as cross-check
  - Larger uncertainties due to different response from electronics

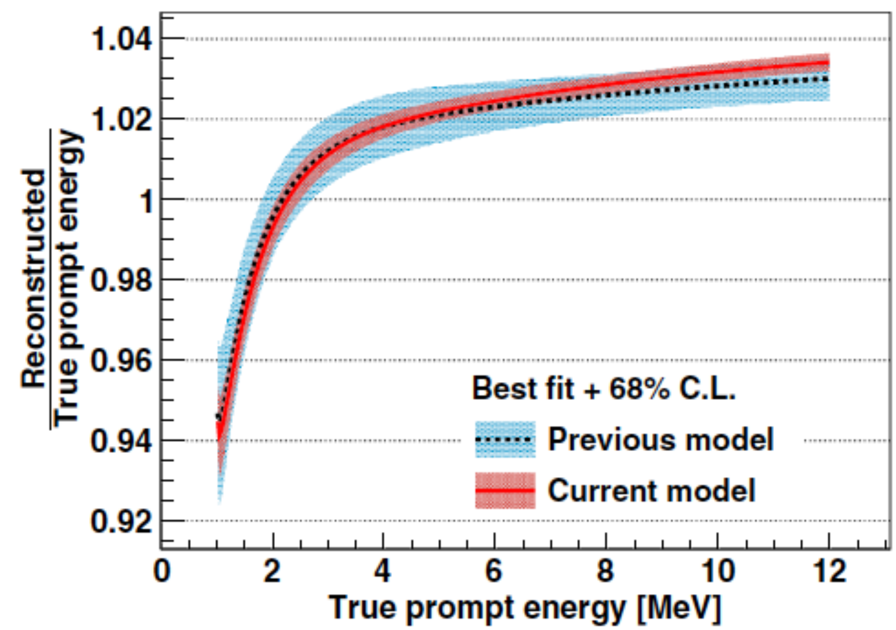
Energy Nonlinearity





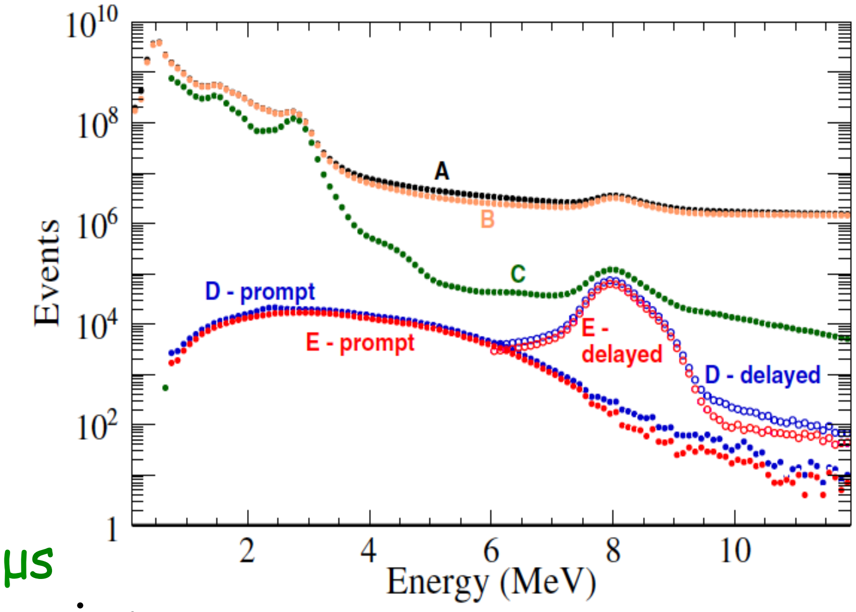
Electronics nonlinearity



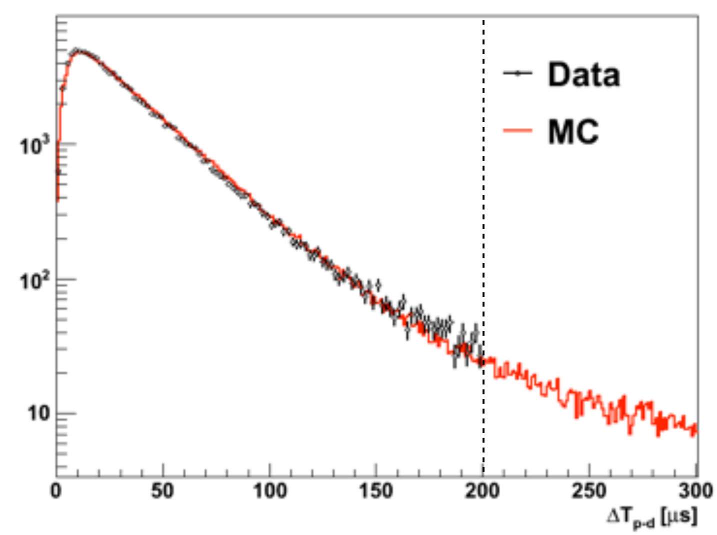


IBD Selection with n-Capture on Gd

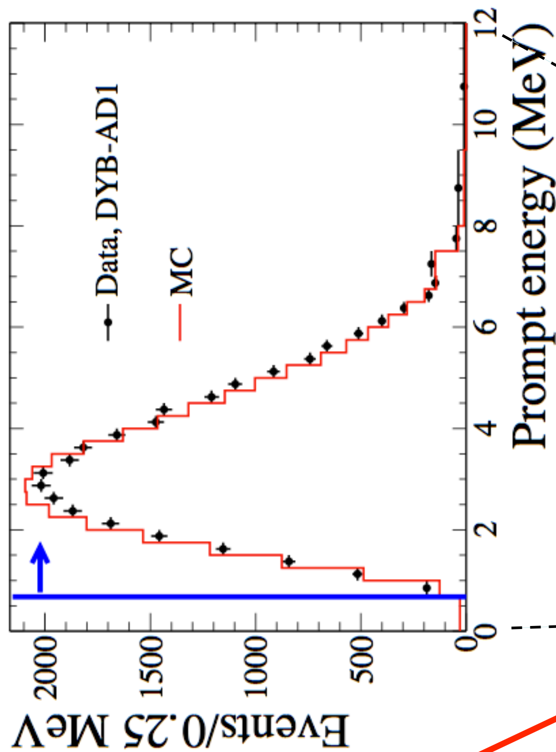
- Reject flashing PMTs
- Veto muons:
  - Pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD muon (>2.5 GeV): reject 1 s
- Prompt energy: 0.7 MeV < E_p < 12 MeV
- Delayed energy: 6 MeV < E_d < 12 MeV
- Neutron capture time : 1 μs < Δt < 200 μs
- Multiplicity cut: select isolated energy-pairs

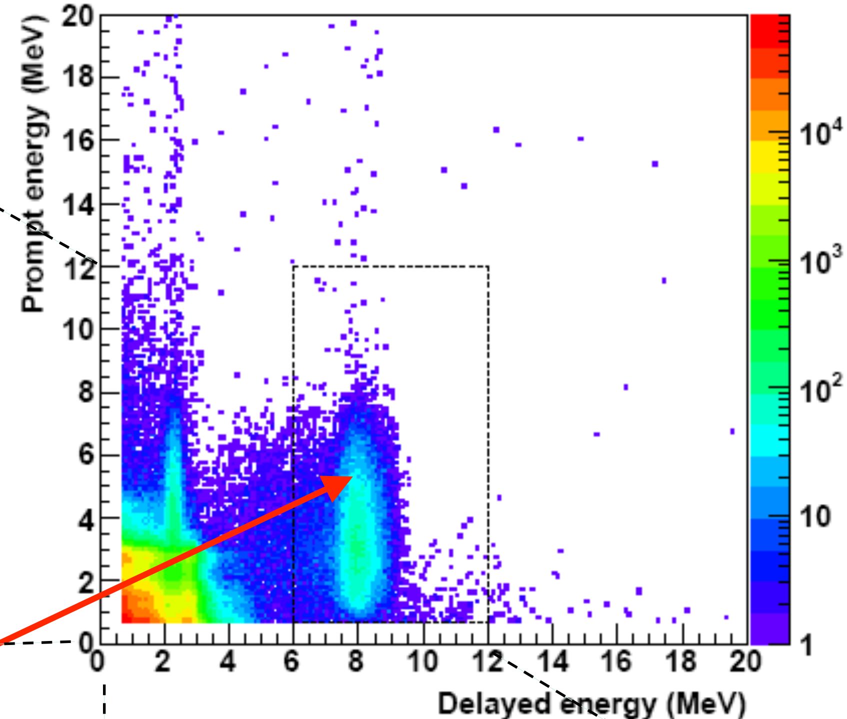


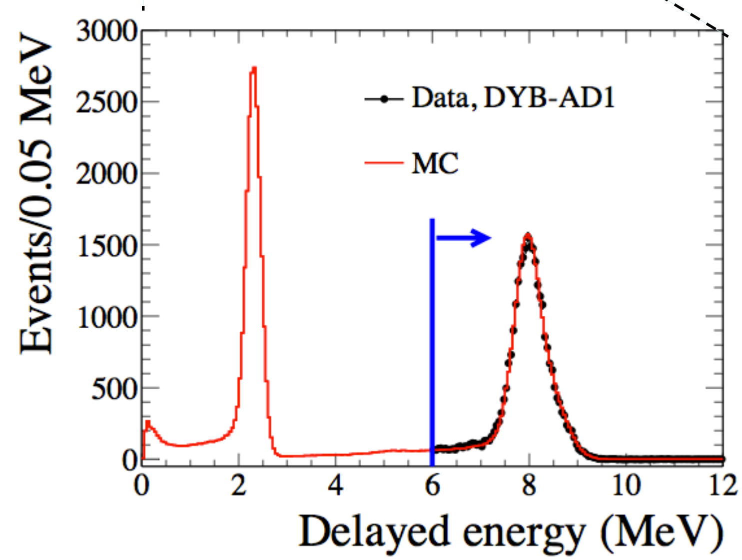
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%



Prompt/Delayed Energy

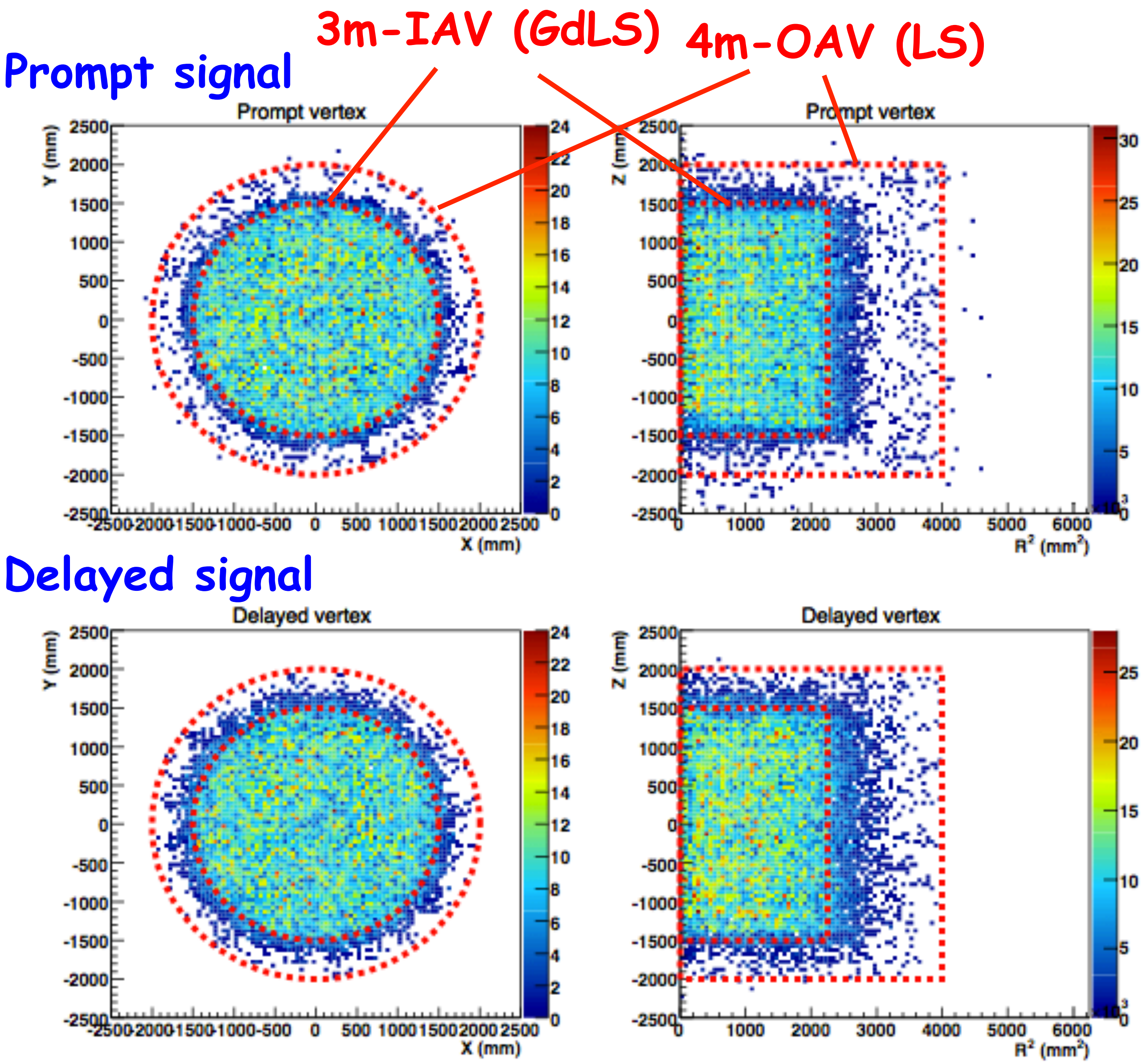






Clear separation of antineutrino events from most other signals

Spatial Distributions of IBD candidates

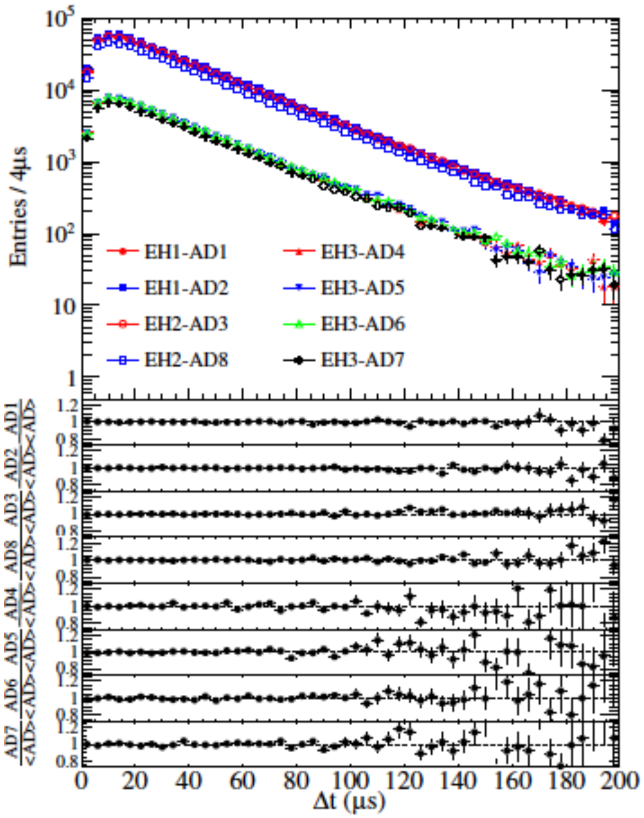


Real data
EH1-AD1

- After applying all IBD selection cuts.
- Vertices from IBD candidates are uniformly distributed within 3m-IAV.

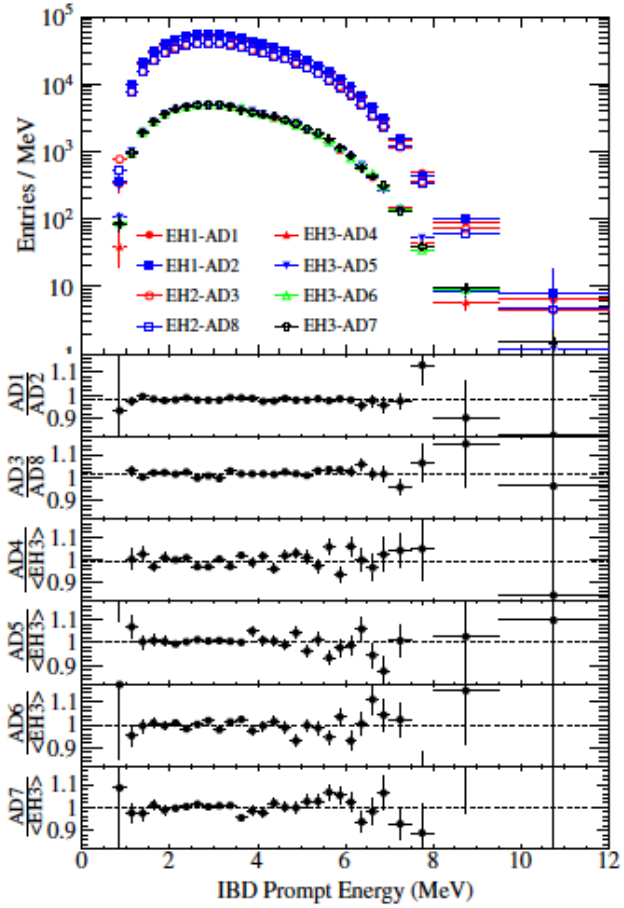
Relative Performance of ADs

IBD capture time

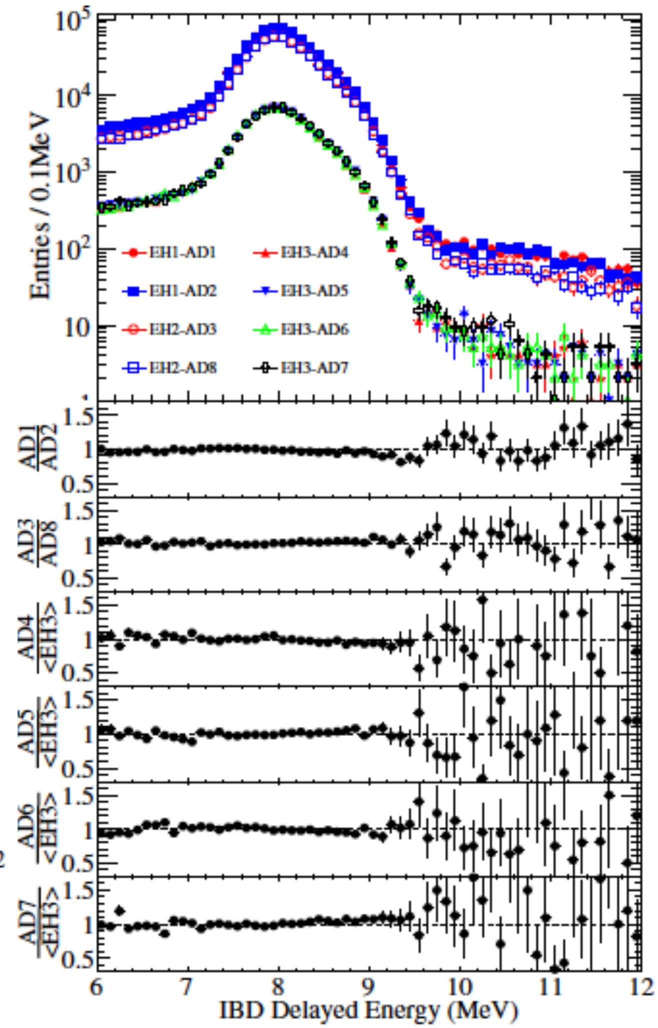


τ_{cap} ~ 29 µs

Prompt-energy spectra



Delayed-energy spectra



Remaining Background

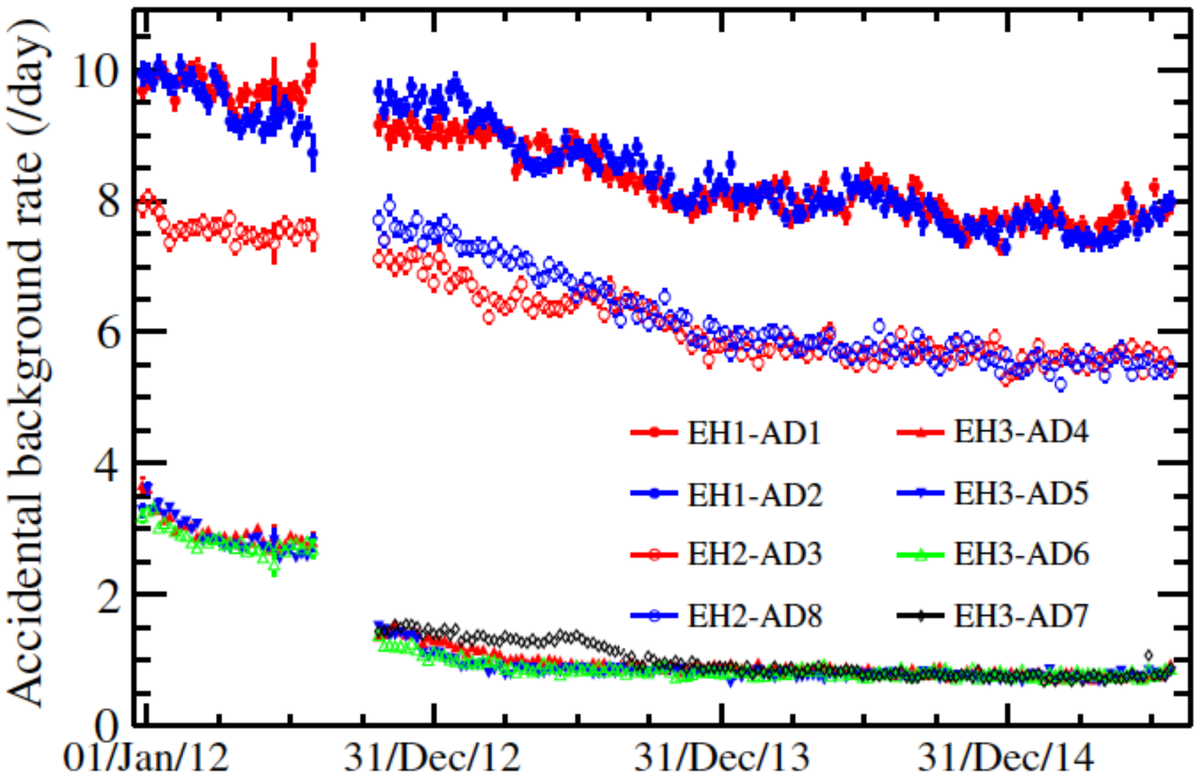
- Uncorrelated background
  - Accidentals: two uncorrelated events 'accidentally' pass the cuts and mimic IBD event.

- Correlated background
  - Muon spallation products
    - Fast neutron
    - $^{9}Li/^{8}He$
  - Correlated signals from ^{241}Am-^{13}C source
  - $^{13}C(\alpha,n)^{16}O$

Background: Accidentals

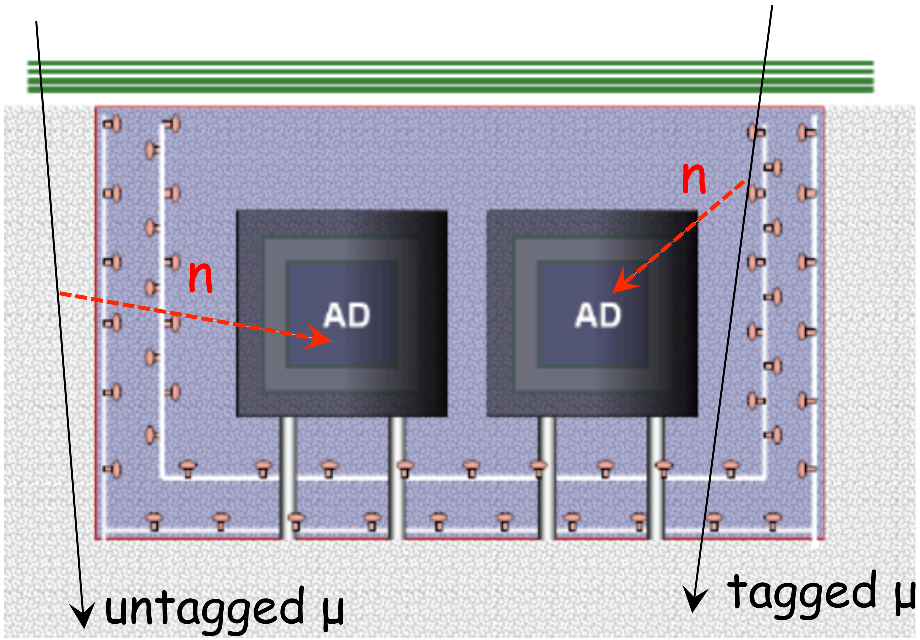
Two uncorrelated single signals mimic an antineutrino signal

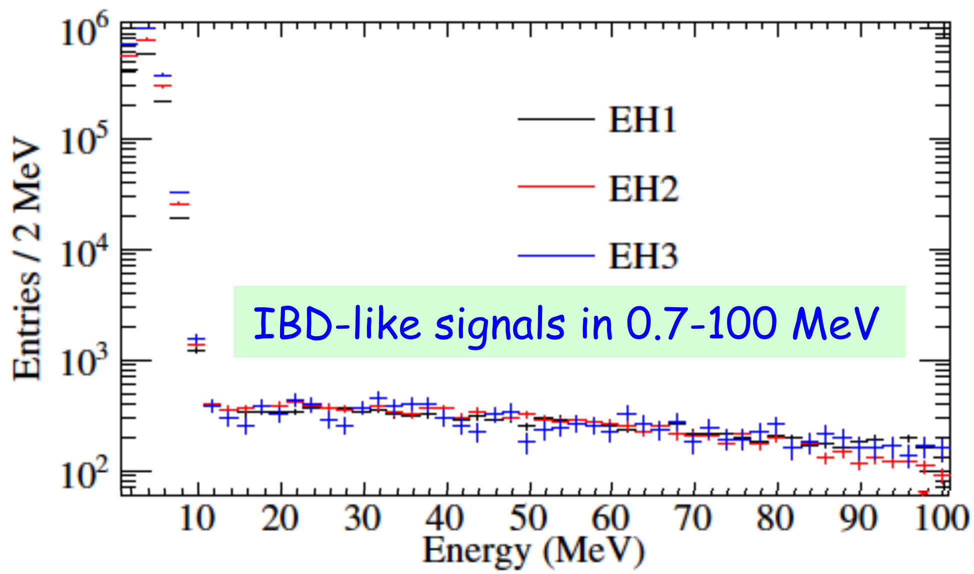
Rate and spectrum can be accurately predicted from singles data.



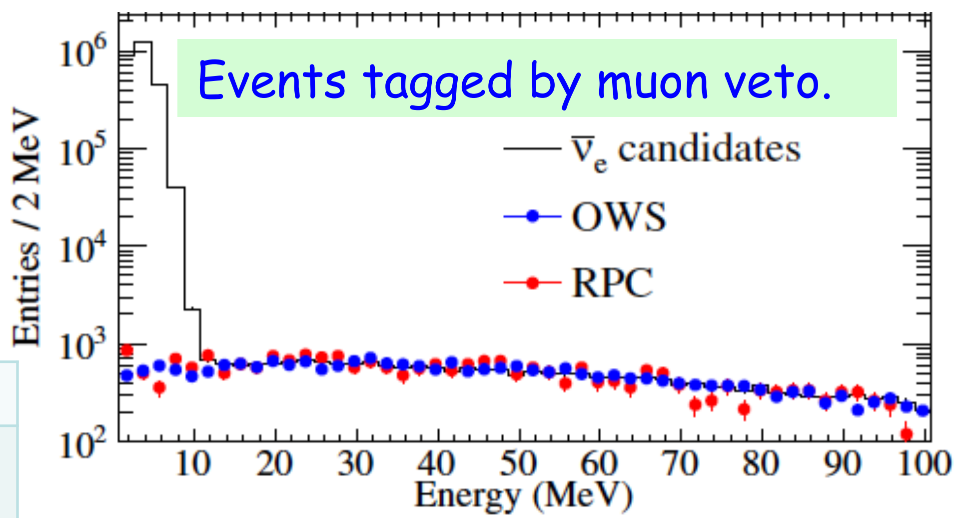
	EH1-AD1	EH1-AD2	EH2-AD3	EH2-AD8	EH3-AD4	EH3-AD5	EH3-AD6	EH3-AD7
Accidental rate(/day)	8.46±0.09	8.46±0.09	6.29±0.06	6.18±0.06	1.27±0.01	1.19±0.01	1.20±0.01	0.98±0.01

Background: Fast Neutrons





Can mimic the IBD signal:
- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd



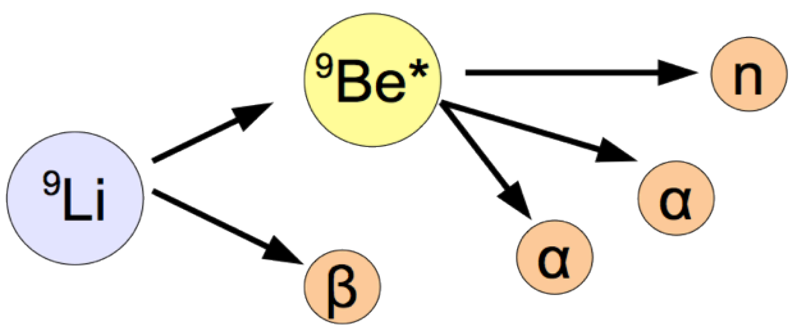
	EH1	EH2	EH3
Fast-n (/AD/day)	0.79±0.10	0.57±0.07	0.05±0.01

Background: ^{9}Li/^{8}He β-n Decays

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

β-n decay:

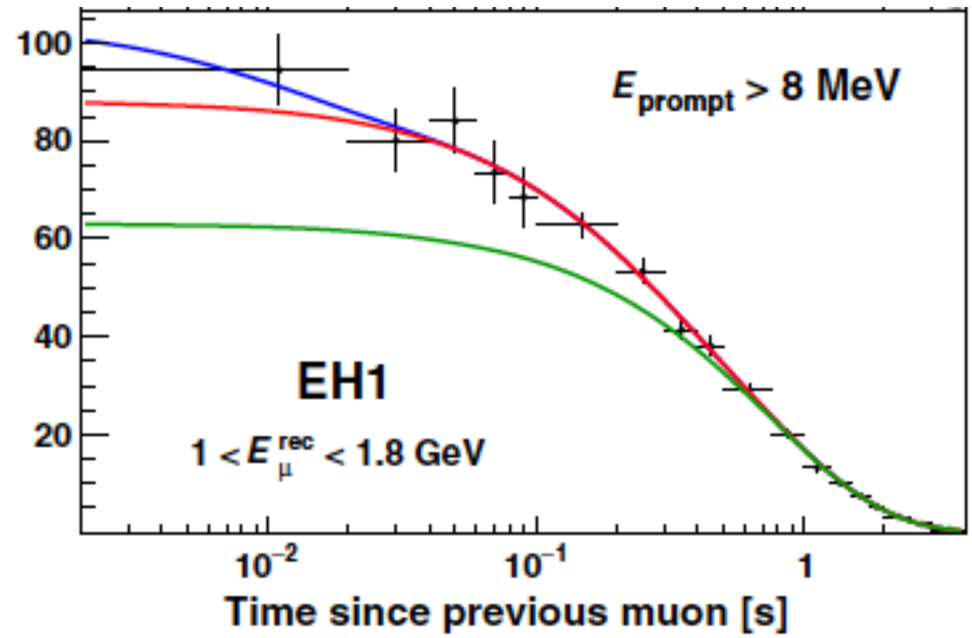
- Prompt: β-decay
- Delayed: neutron capture

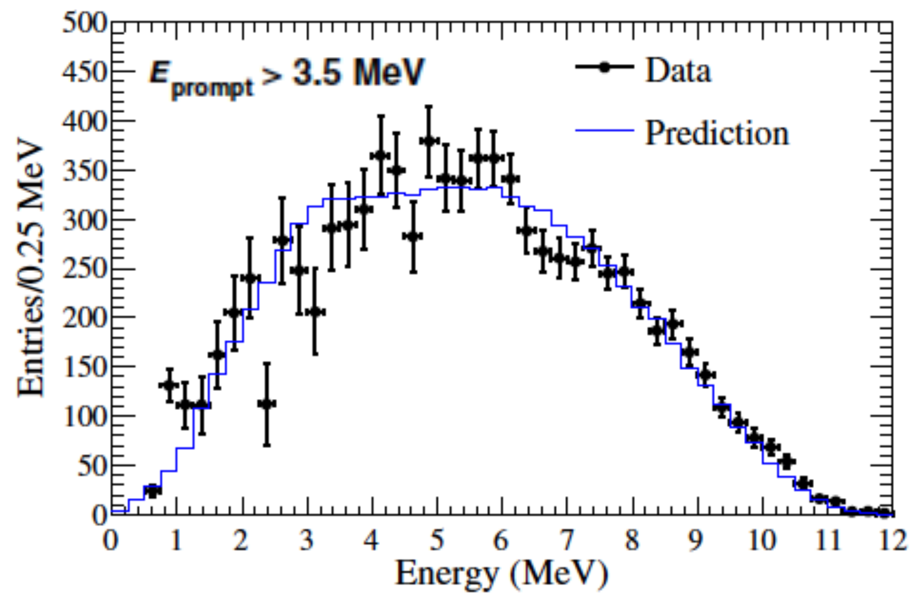


^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV

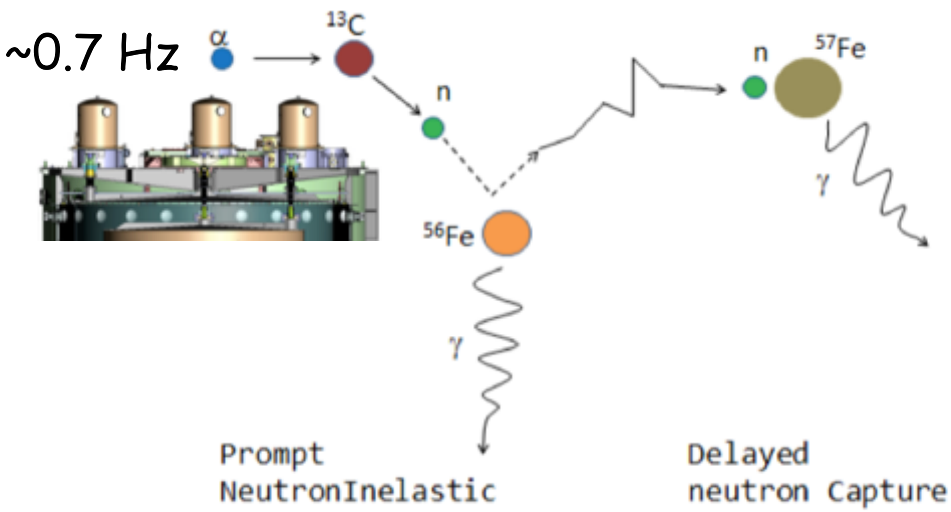
^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

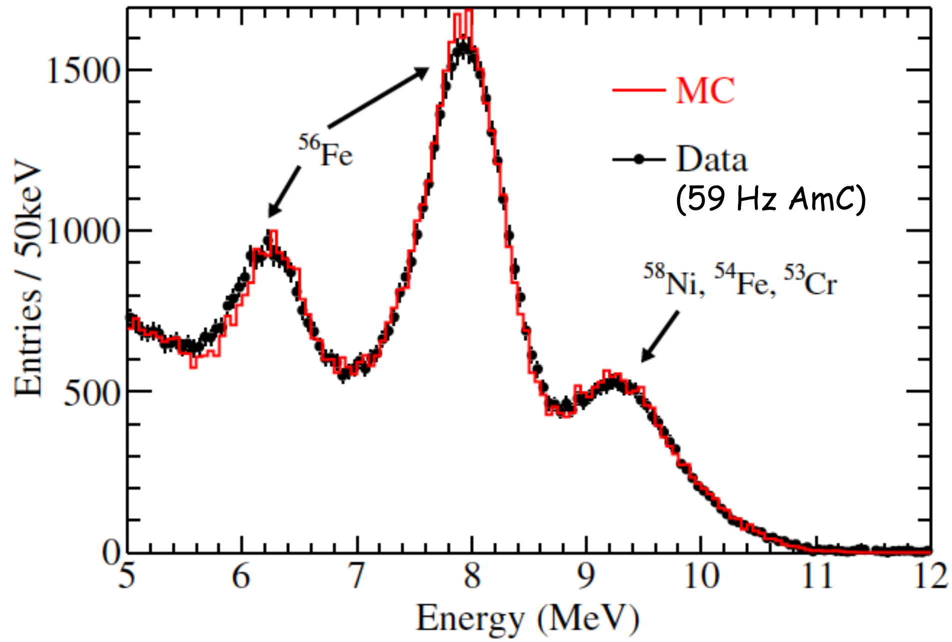
	EH1	EH2	EH3
^{9}Li/^{8}He (/AD/day)	2.38±0.66	1.59±0.49	0.19±0.08





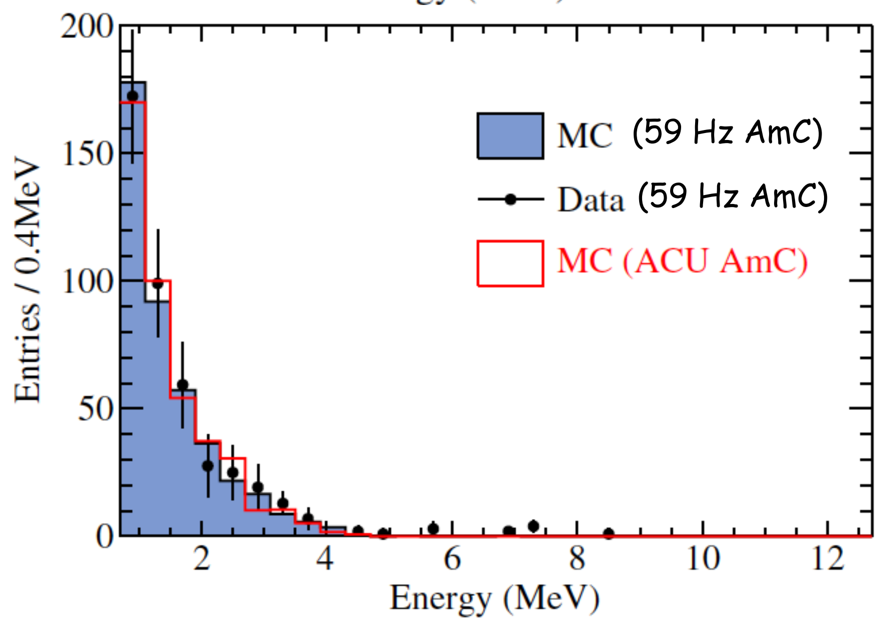
^{241}Am-^{13}C Source Background



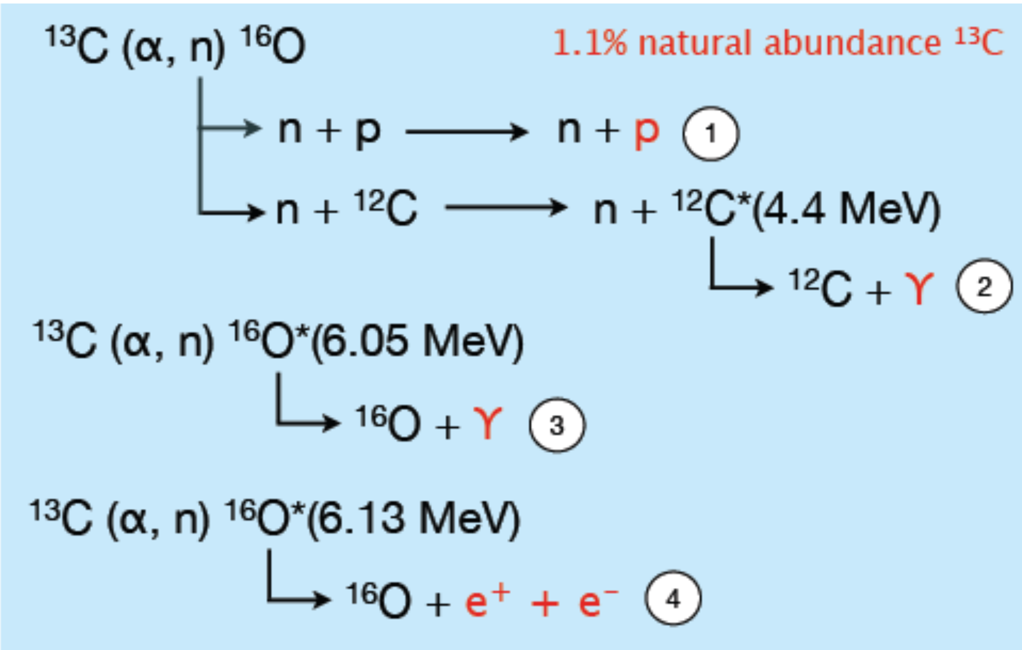


- Placed a ~59 Hz Am-C source on top of EH3 AD5 for 10 days in summer of 2012 to understand this background.

- Removed this source from ACU-B and ACU-C from all ADs in EH3 in summer of 2012.



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



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.

	EH1-AD1	EH1-AD2	EH2-AD3	EH2-AD8	EH3-AD4	EH3-AD5	EH3-AD6	EH3-AD7
$^{13}C(\alpha,n)^{16}O$ rate(/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.07±0.04	0.05±0.03	0.05±0.03	0.05±0.03	0.05±0.03

Summary of Signal and Background

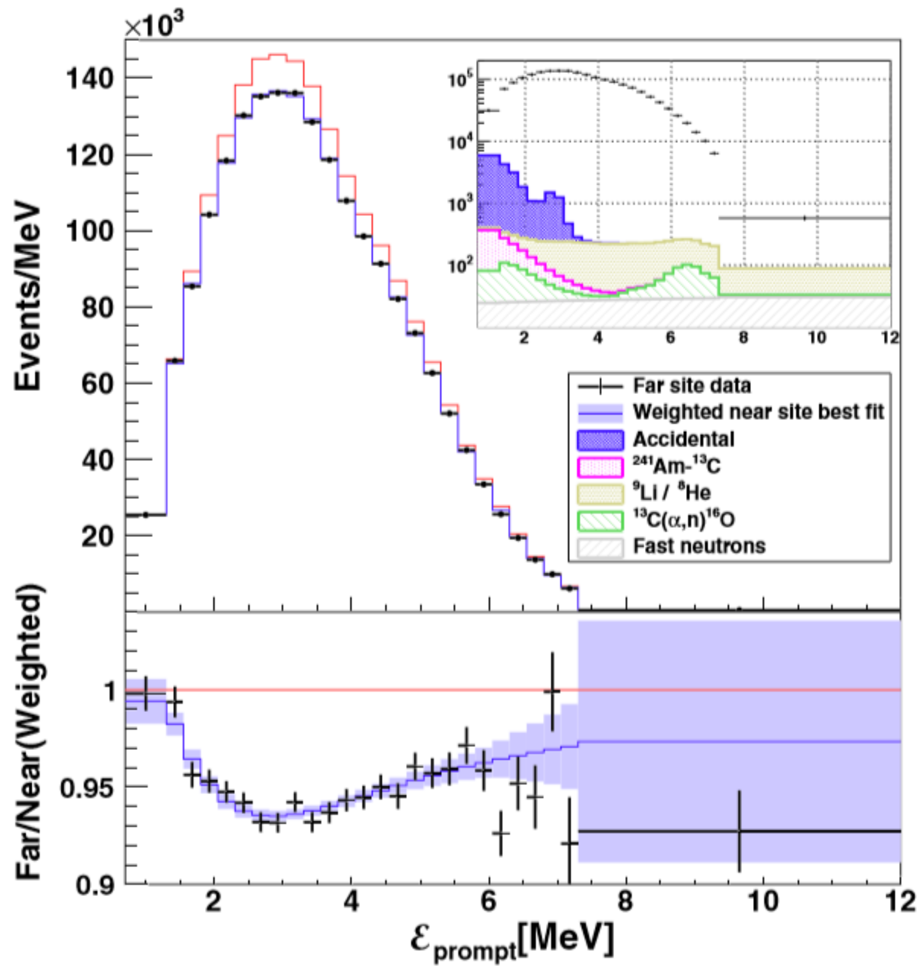
- Obtained ~4 x 10^6 IBD events in 1958 days with
  - 6 ADs (217 days)
  - 8 ADs (1524 days)
  - 7 ADs (217 days)

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	830 036	964 381	889 171	784 736	127 107	127 726	126 666	113 922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
$\varepsilon_\mu \times \varepsilon_m$	0.8050	0.8013	0.8369	0.8360	0.9596	0.9595	0.9592	0.9595
Accidentals (day^{-1})	8.27±0.08	8.12±0.08	6.00±0.06	5.86±0.06	1.06±0.01	1.00±0.01	1.03±0.01	0.86±0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated (day^{-1})	0.17±0.07	0.15±0.07	0.14±0.06	0.13±0.06	0.06±0.03	0.05±0.02	0.05±0.02	0.04±0.02
^{13}C (α, n) ^{16}O (day^{-1})	0.08±0.04	0.06±0.03	0.04±0.02	0.06±0.03	0.04±0.02	0.04±0.02	0.04±0.02	0.04±0.02
$\bar{\nu}_e$ rate (day^{-1})	659.36±1.00	681.09±0.98	601.83±0.82	595.82±0.85	74.75±0.23	75.19±0.23	74.56±0.23	75.33±0.24

- Consistent rates for side-by-side detectors

Prompt-energy Spectrum in 2018

- 3.5 millions inverse beta decay candidates (IBDs) were detected in the near halls.
- 0.5 million IBDs were observed in the far hall.
- Daily rate was ~2500 IBDs in the near halls and ~300 IBDs in the far hall.
- ≤ 2% backgrounds.

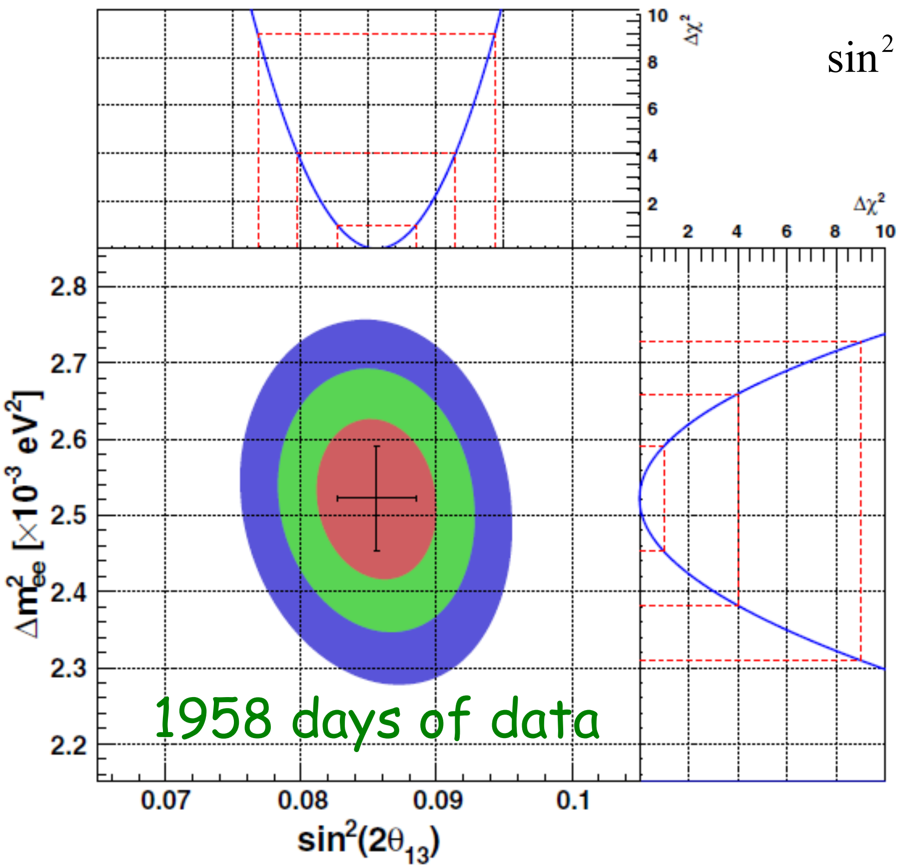


1958 days of data

Most Precise $\sin^2 2\theta_{13}$ & Δm^2_{ee}

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) \leftrightarrow \cos^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

$|\Delta m^2_{ee}| = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{32} = +(2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2$ (NH)

$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2$ (IH)

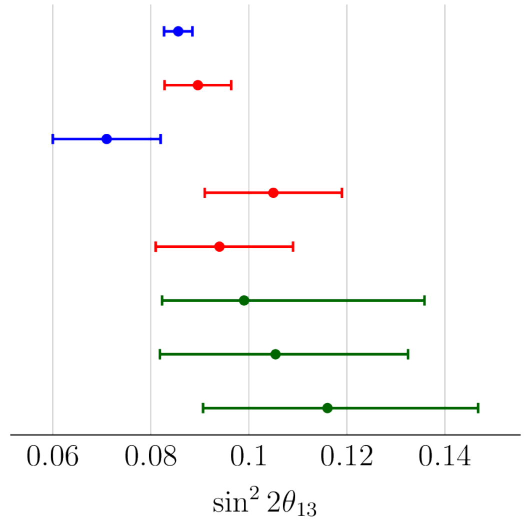
χ^2/NDF = 148/154

PRL **121** (2018) 241805

$\sin^2 2\theta_{13}$ & Δm^2_{32} : Global Landscape

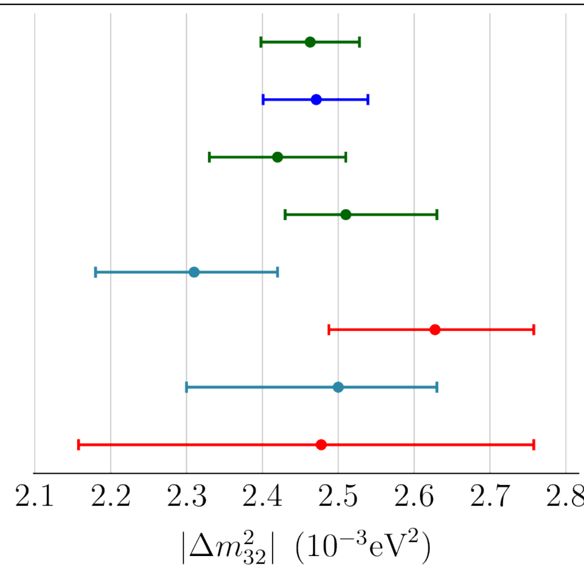
$\sin^2 2\theta_{13}$

Experiment		Value
Daya Bay	nGd	0.0856 ± 0.0029
RENO	nGd	0.0896 ± 0.0068
Daya Bay	nH	0.071 ± 0.011
D-CHOOZ	nGd+nH	0.105 ± 0.014
RENO	nH	$0.094^{+0.015}_{-0.013}$
	bayessian	$0.099^{+0.037}_{-0.017}$
T2K	NH	$0.105^{+0.027}_{-0.024}$
	IH	$0.116^{+0.031}_{-0.025}$



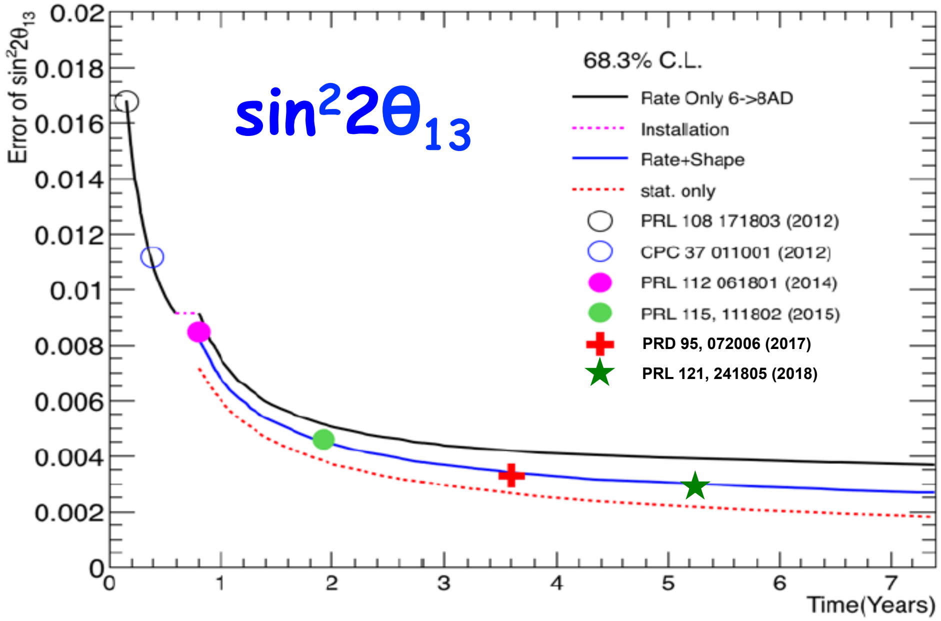
Δm^2_{32}
Normal mass hierarchy

Experiment	Value (10^{-3} eV^2)
T2K	2.463 ± 0.065
Daya Bay	$2.471^{+0.068}_{-0.070}$
MINOS	2.42 ± 0.09
NOvA	$2.51^{+0.12}_{-0.08}$
IceCube	$2.31^{+0.11}_{-0.13}$
RENO (nGd)	$2.63^{+0.13}_{-0.14}$
Super-K	$2.50^{+0.13}_{-0.20}$
RENO (nH)	$2.48^{+0.28}_{-0.32}$

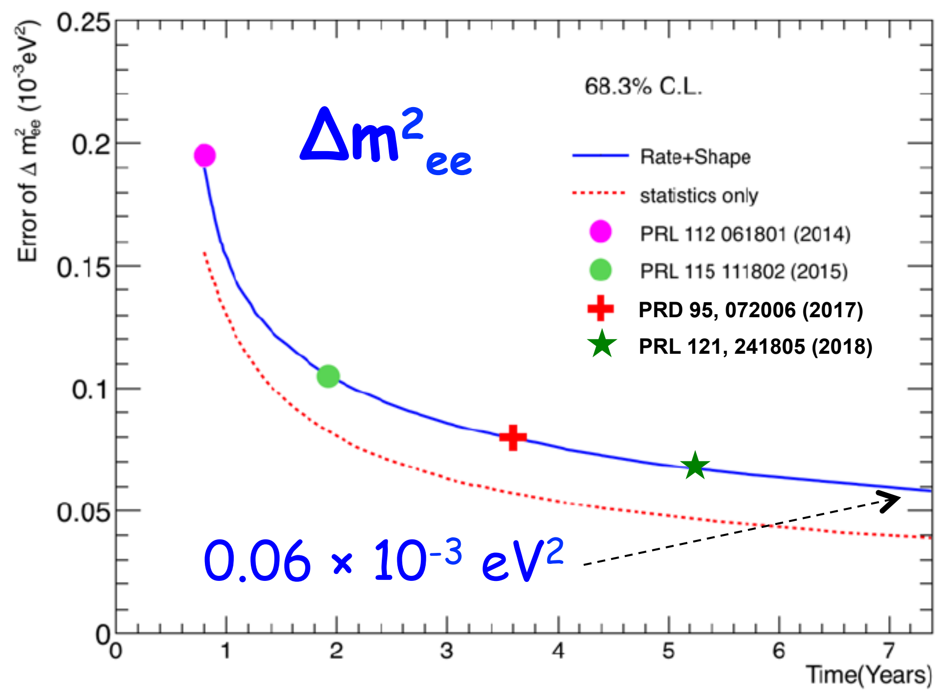


$|\Delta m^2_{32}|$ obtained with ν_e & ν_μ agree, supporting 3-flavor paradigm

Outlook of $\sin^2 2\theta_{13}$ & Δm^2_{ee}



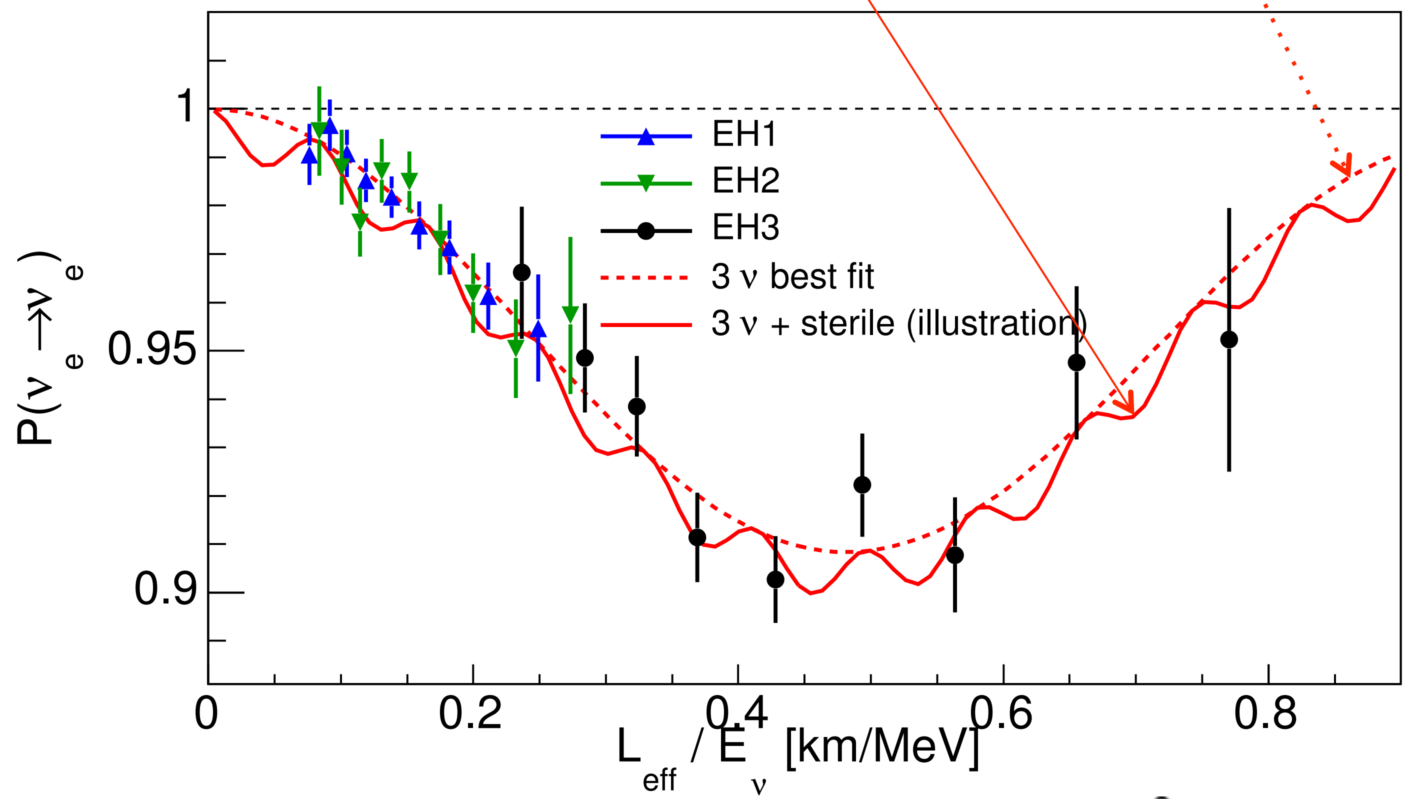
0.0025



Sterile-active Neutrino Oscillation

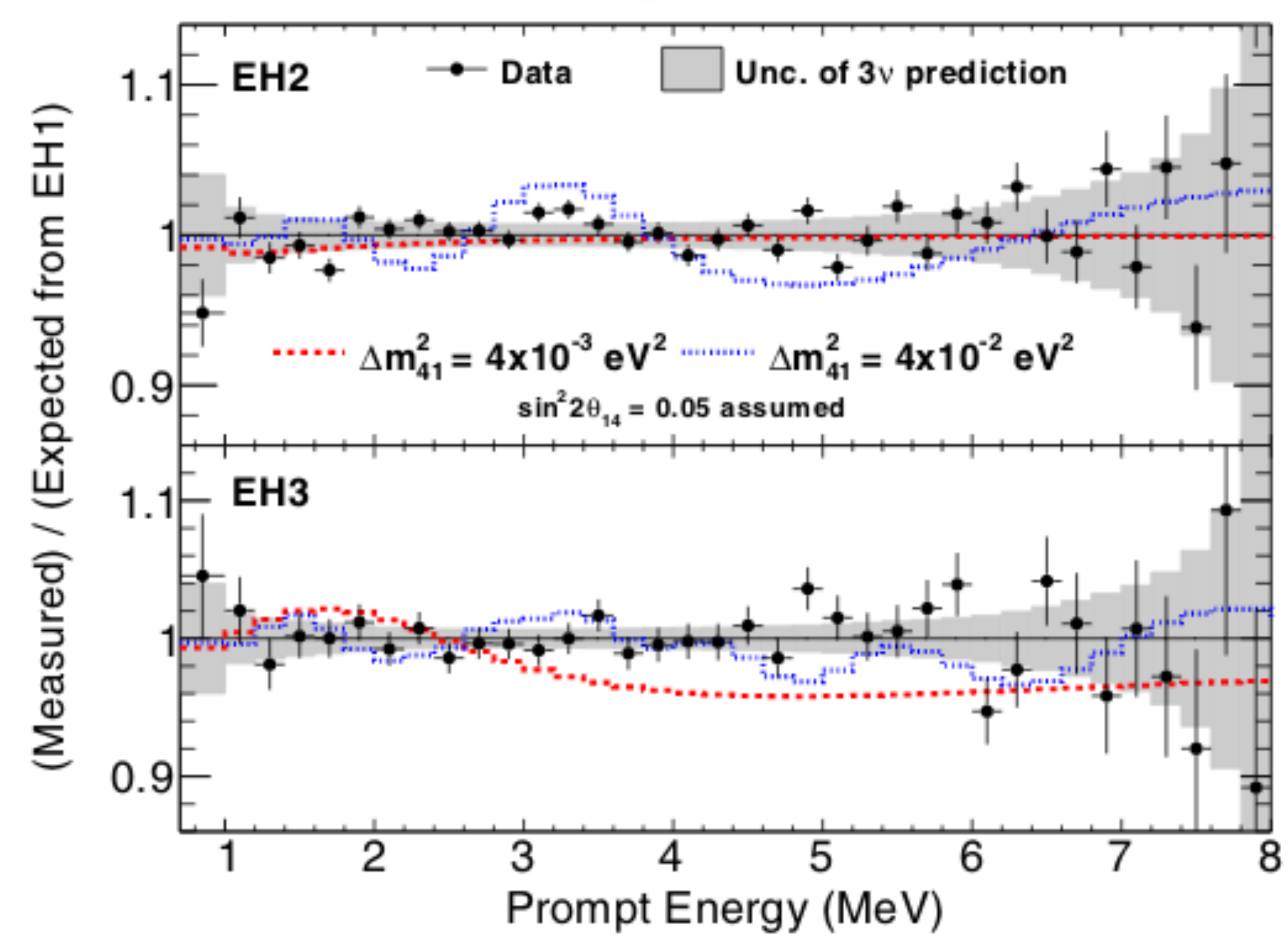
- Assume mixing of 3 favours of active neutrinos with 1 sterile neutrino.
- Survival probability of reactor antineutrino is modified:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right)$$



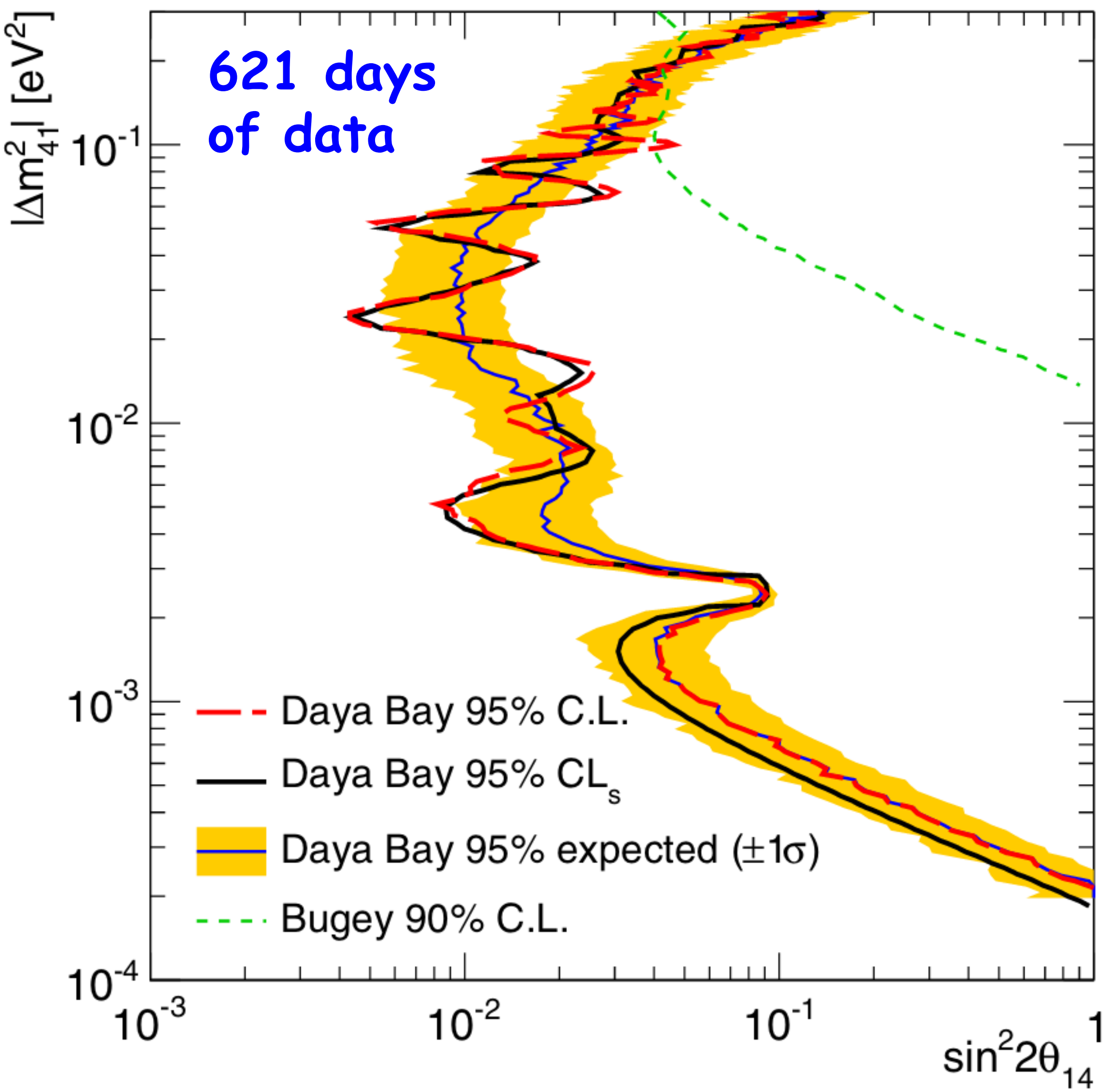
Look For Additional Spectral Distortion

- Multiple baselines and detectors
  - cover a broad mass range to search for sterile neutrino
  - relative measurement of energy spectra reduces systematic errors



621 days of data

Limit on A Light Sterile Neutrino

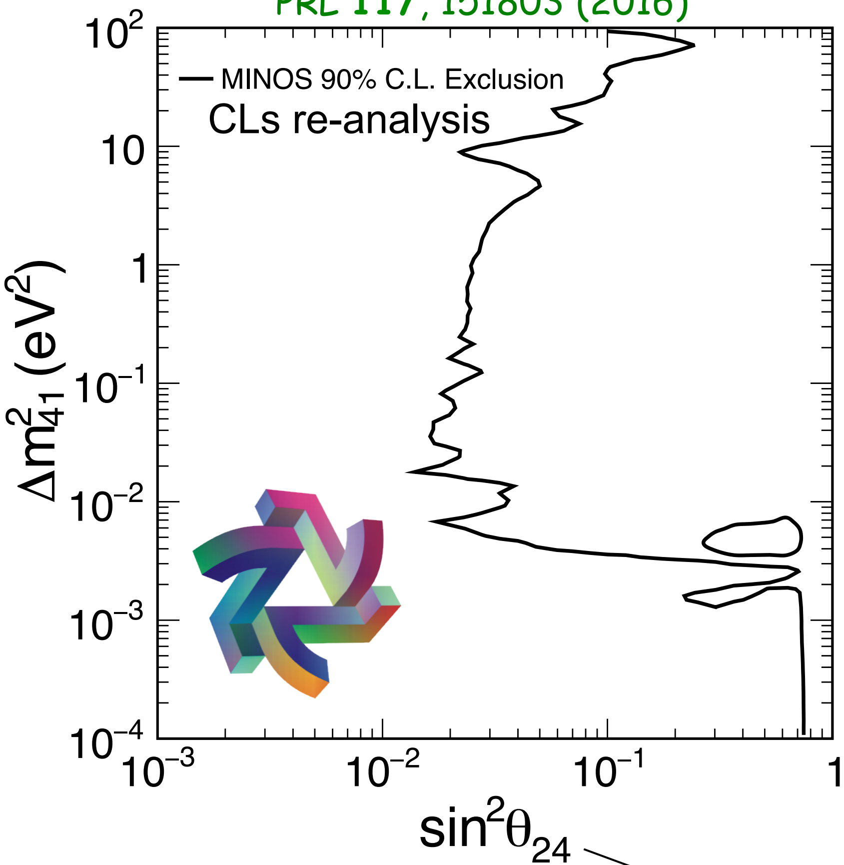


- Two analyses yield consistent results
- Results are insensitive to combinations of mass hierarchies for active and sterile neutrinos
- Provide the best limit in the $|\Delta m^2_{41}| < 0.1$ eV^2 region
- Region of $|\Delta m^2_{41}| <$ 0.3eV^2 is insensitive to the reactor antineutrino flux model

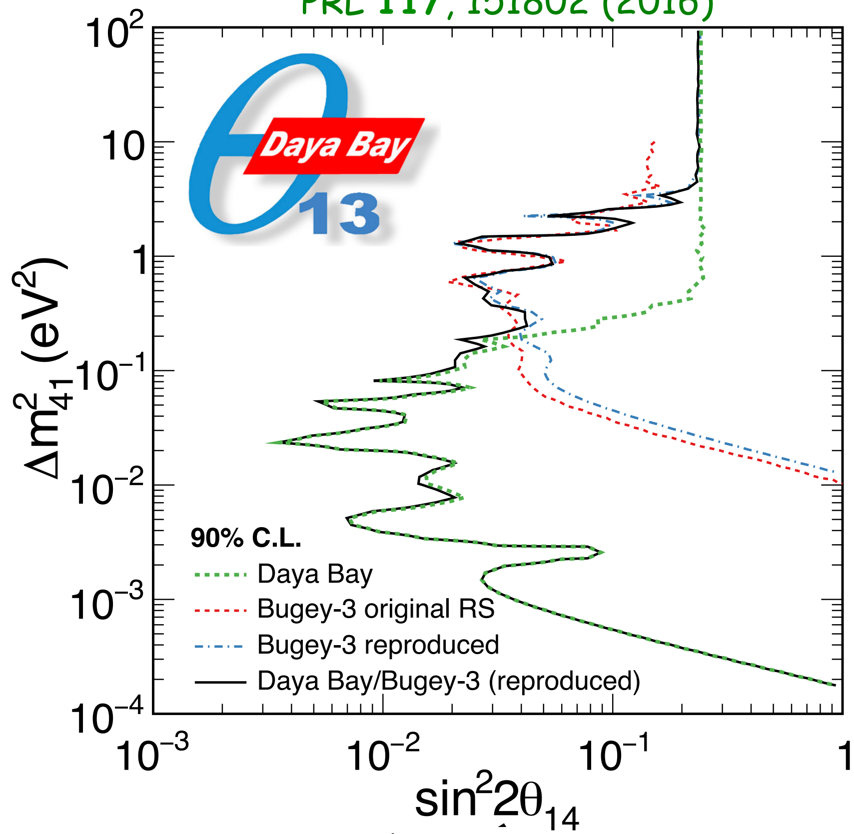
Sterile Neutrinos: MINOS+Daya Bay+Bugey-3

- ν_μ to ν_e appearance results from LSND and MiniBooNE hinted $\sin^2 2\theta_{\mu e} > 0$.

PRL **117**, 151803 (2016)

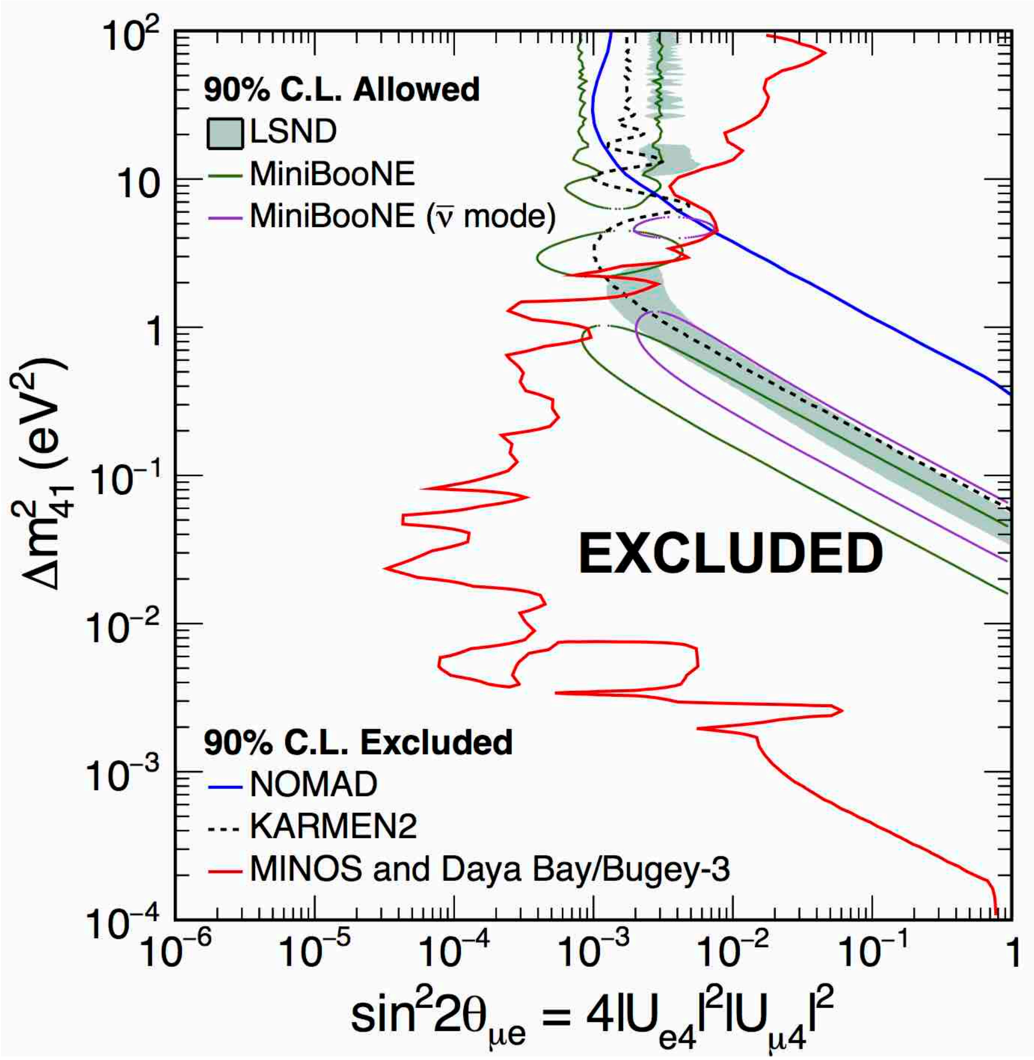


PRL **117**, 151802 (2016)



$$4\left|U_{\mu 4}\right|^2 \left|U_{e4}\right|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

Sterile Neutrinos: MINOS+Daya Bay+Bugey-3

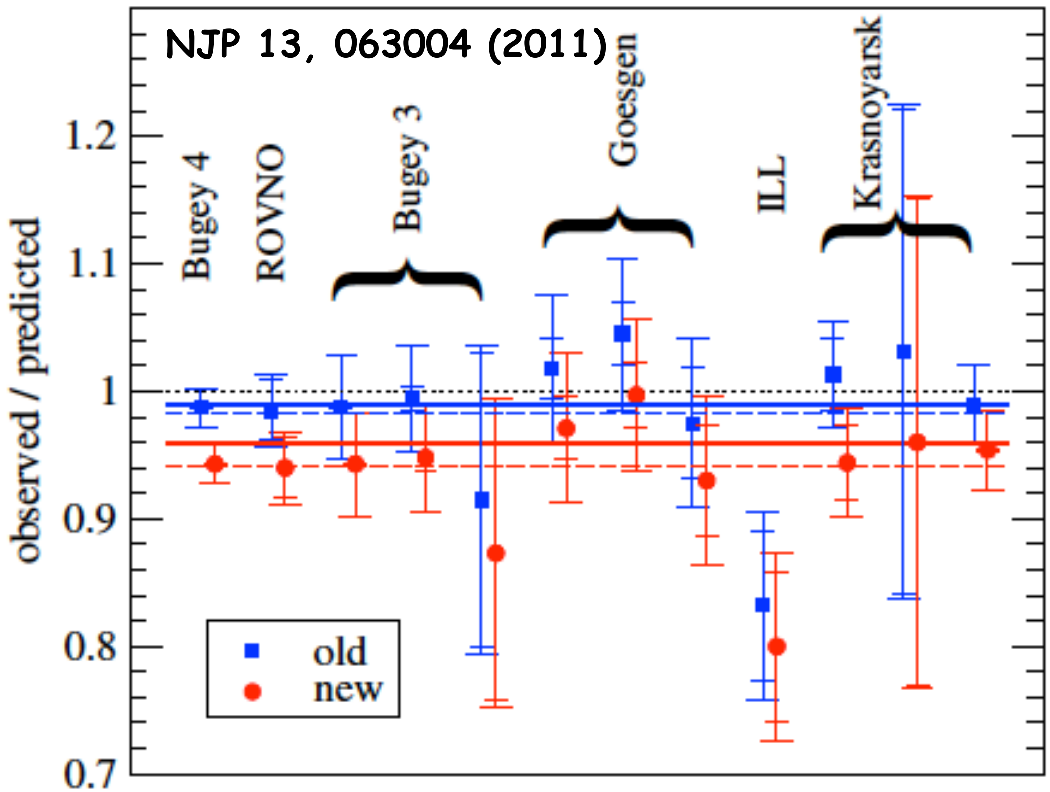


PRL **117**, 151801 (2016)

- Allowed region of LSND and MiniBooNE is excluded for $\Delta m^2_{41} < 0.8$ eV^2 (95% c.l.)

Reactor Antineutrino Anomaly

- Reactor antineutrino flux at short distance is ~6% smaller
  - New calculations yielded 3% more flux
    - Mention etal., PRD **83**, 054615 (2011) and update (2012)
    - Huber PRC **84**, 024617 (2011)
  - Included contributions from long-lived isotopes
  - Measured neutron lifetime has decreased, leading to larger σ(IBD).

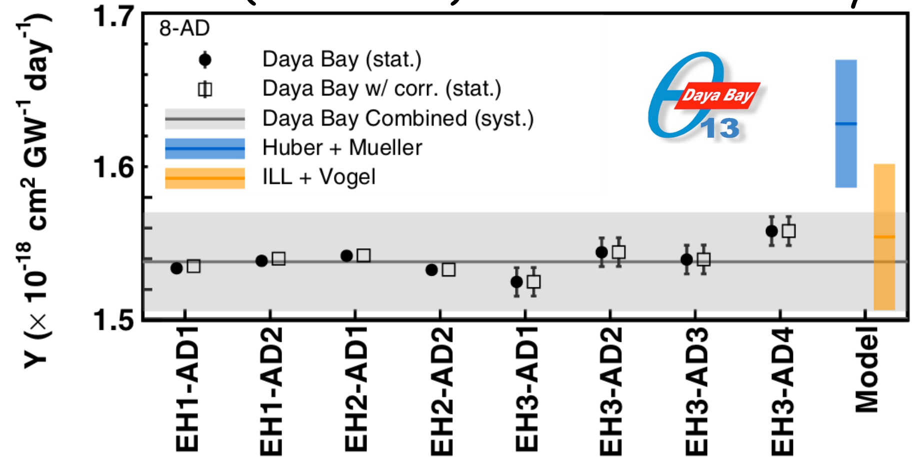


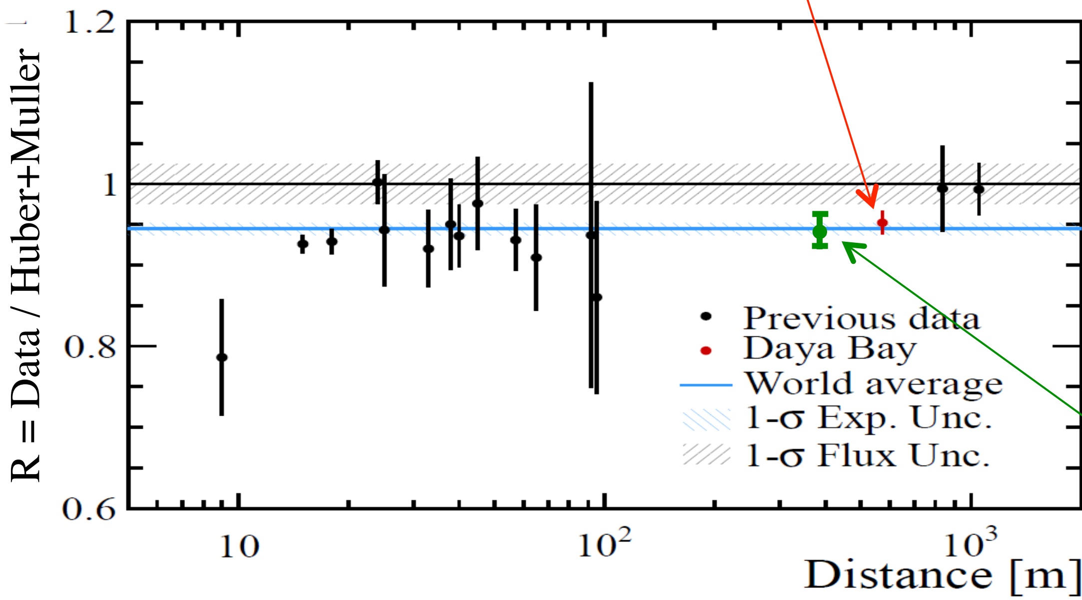
Reactor $\overline{\nu}_e$: Absolute Flux

Daya Bay (1230 days) :
R = 0.952 ± 0.014 ± 0.023

arXiv: 1808.10836

$Y = (1.55 \pm 0.03) \times 10^{-18}$ cm²/GW/day





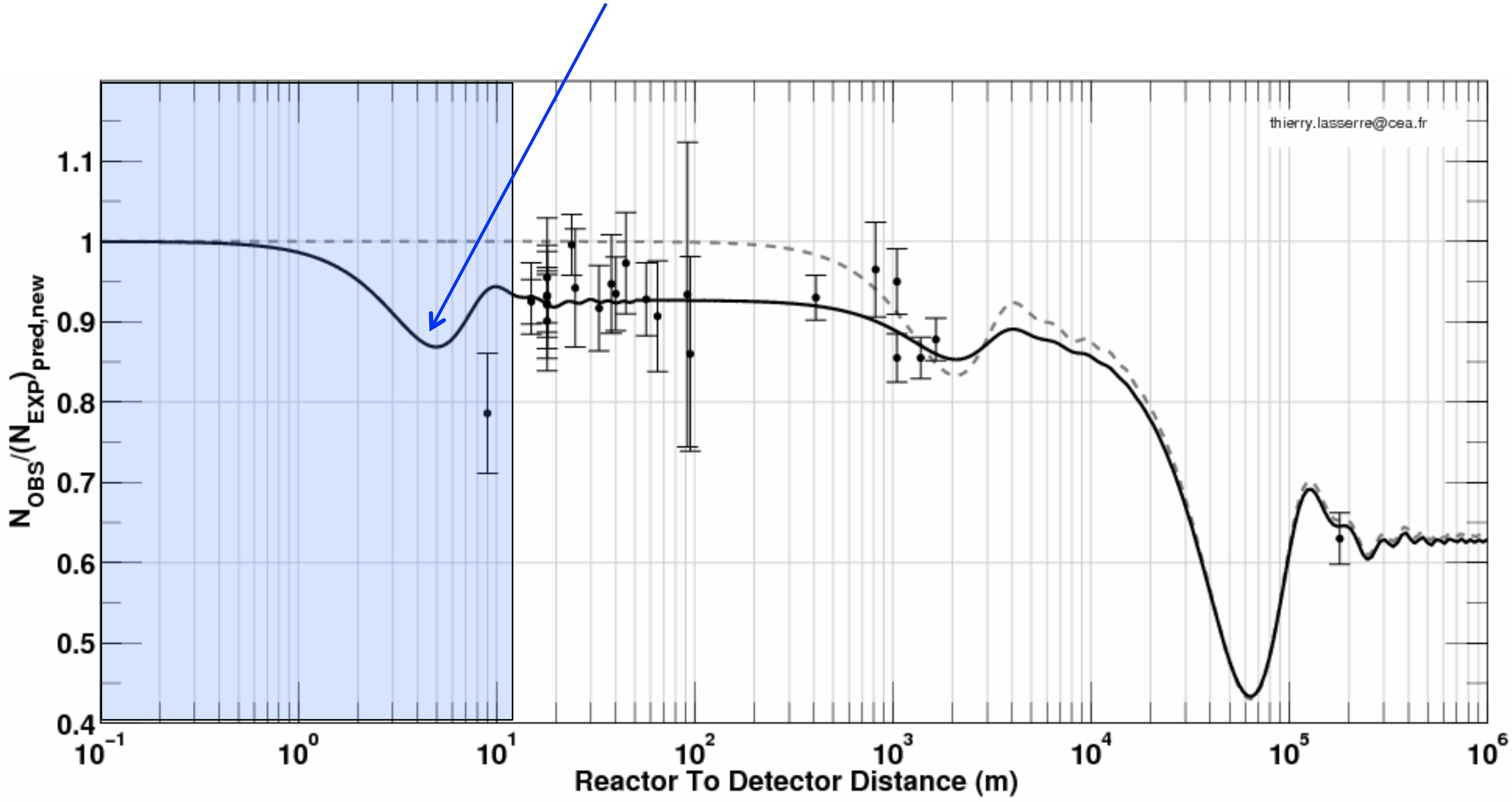
Previous average:
R = 0.942 ± 0.009 (exp)
± 0.025 (model)

RENO (500 days) :
R = 0.946 ± 0.021 (prelim.)

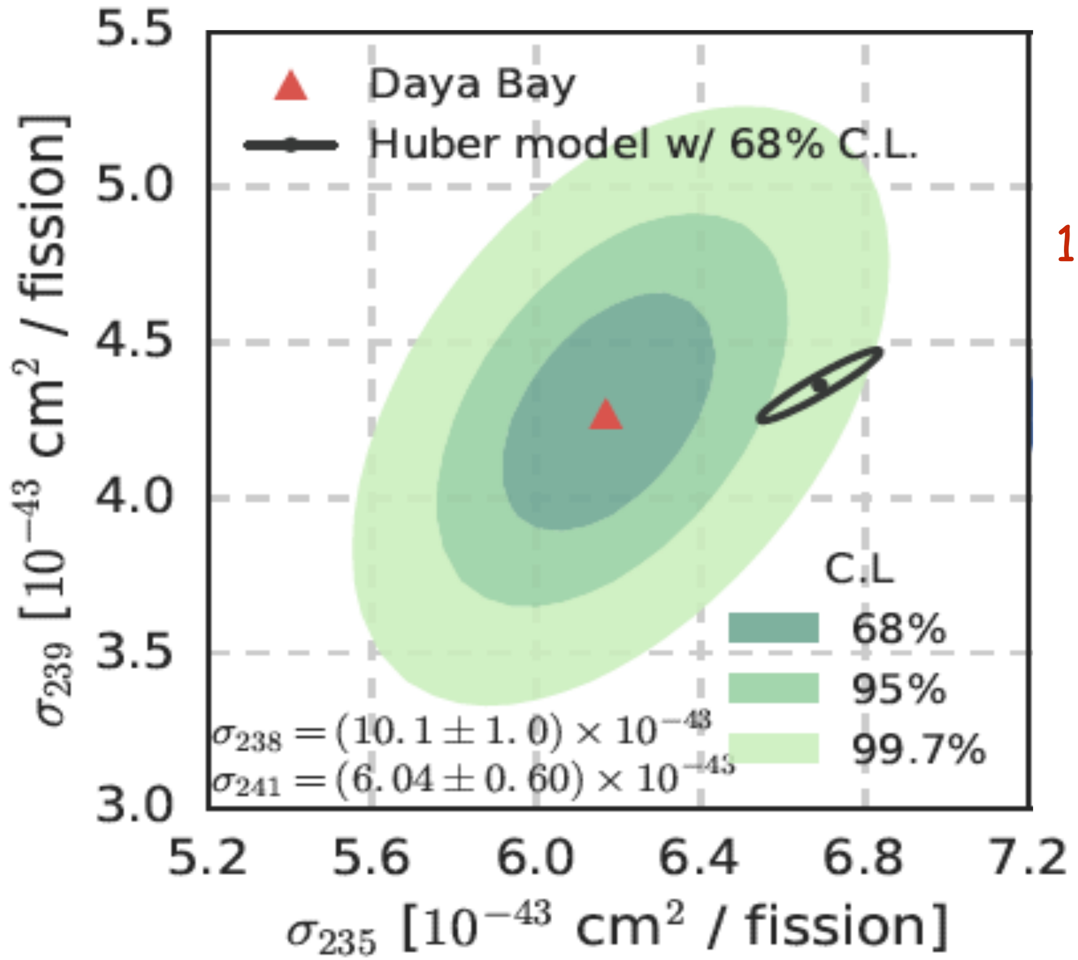
- Reactor $\overline{\nu}_e$ anomaly due to
  - new physics ?
  - incomplete theoretical understanding ? [see Huber's Neutrino 2016 talk]

Sterile Neutrino As A Solution

Reactor anti-neutrino anomaly may be due to sterile-active neutrino oscillation with $\Delta m^2 \sim 1\ eV^2$:



IBD Yields Per Fission



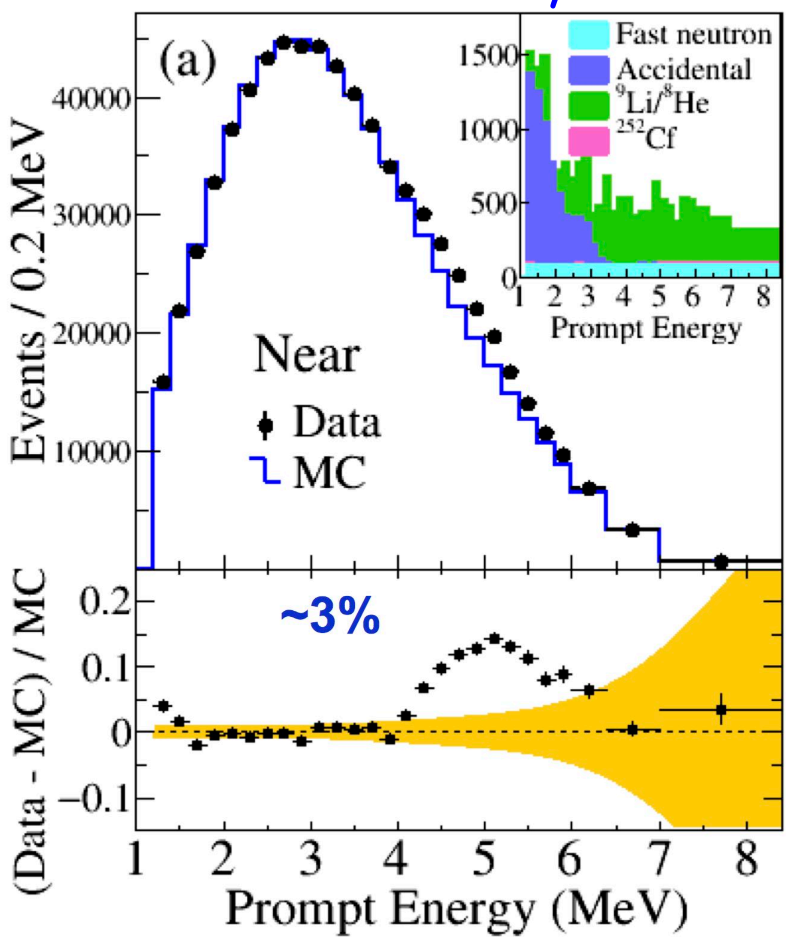
1230 days, near detectors
PRL **118** (2017) 251801

- 7.8% overestimation of predicted anti-neutrino flux from ^{235}U
- ^{235}U could be the key source of the reactor anti-neutrino anomaly.

Excess Near 5 MeV in Spectrum

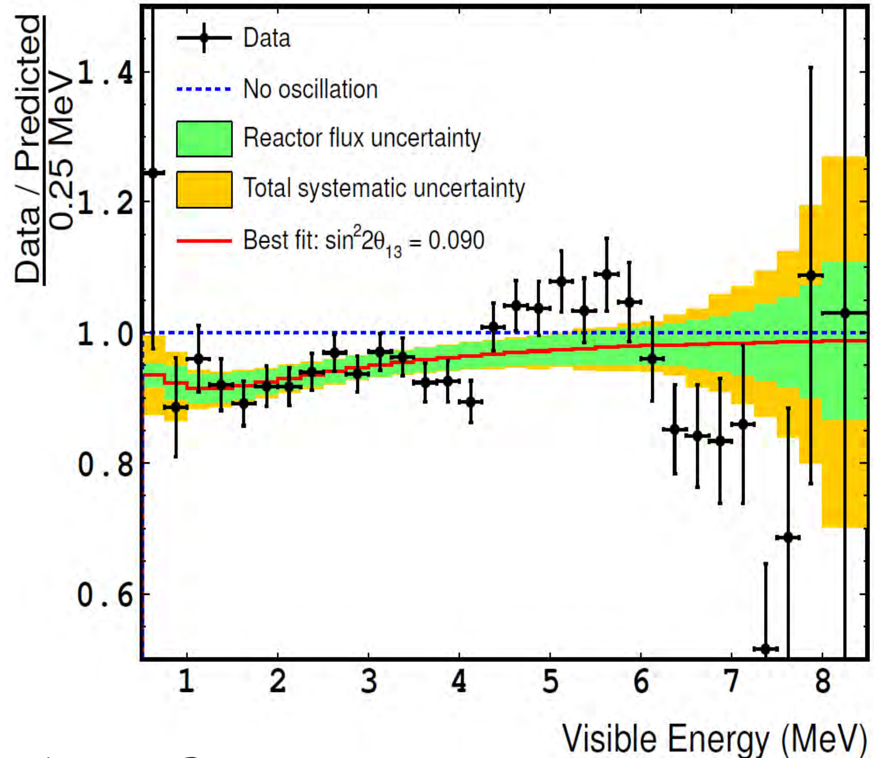
Prediction: Huber+Mueller

RENO Preliminary

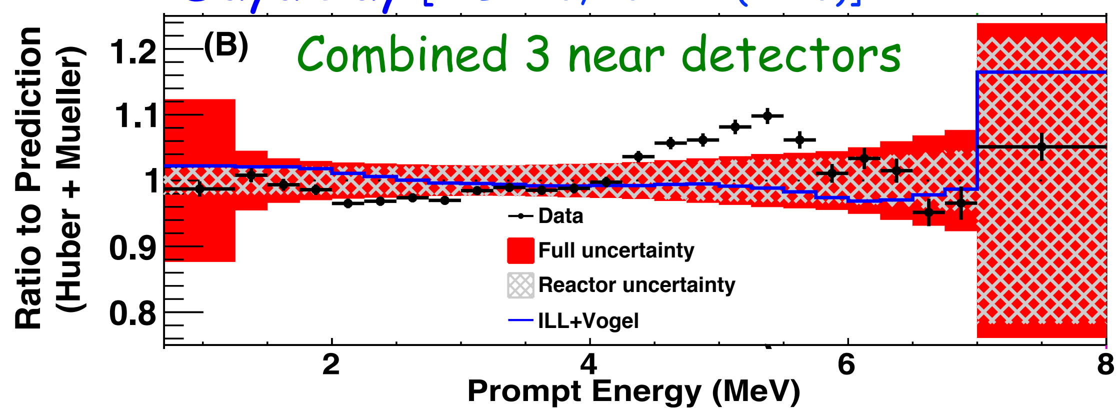


Excess tracks reactor power.

Double Chooz [JHEP **10**, 086(2014)]



Daya Bay [PRL **116**, 061801 (2016)]



Summary

- Daya Bay continues to be the leading reactor-based neutrino experiment that
  - has acquired the largest sample of reactor antineutrinos
  - provides the most precise measurement of
    - $\sin^2 2\theta_{13}$ and Δm^2_{ee}
    - absolute reactor antineutrino spectrum
  - has the best sensitivity of searching for a light sterile neutrino with ~10^{-3} eV^2 < mass < ~10^{-1} eV^2
  - yields interesting results on other topics.
- Daya Bay will stop data taking by the end of 2020
  - Precision in $\sin^2 2\theta_{13} \approx 0.0025$
    - Remains the most precise in the foreseeable future
  - Precision in $\Delta m^2_{ee} \approx 0.06 \times 10^{-3}$ eV^2

Thank You