Recent results from Daya Bay

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Feb. 20, 2015

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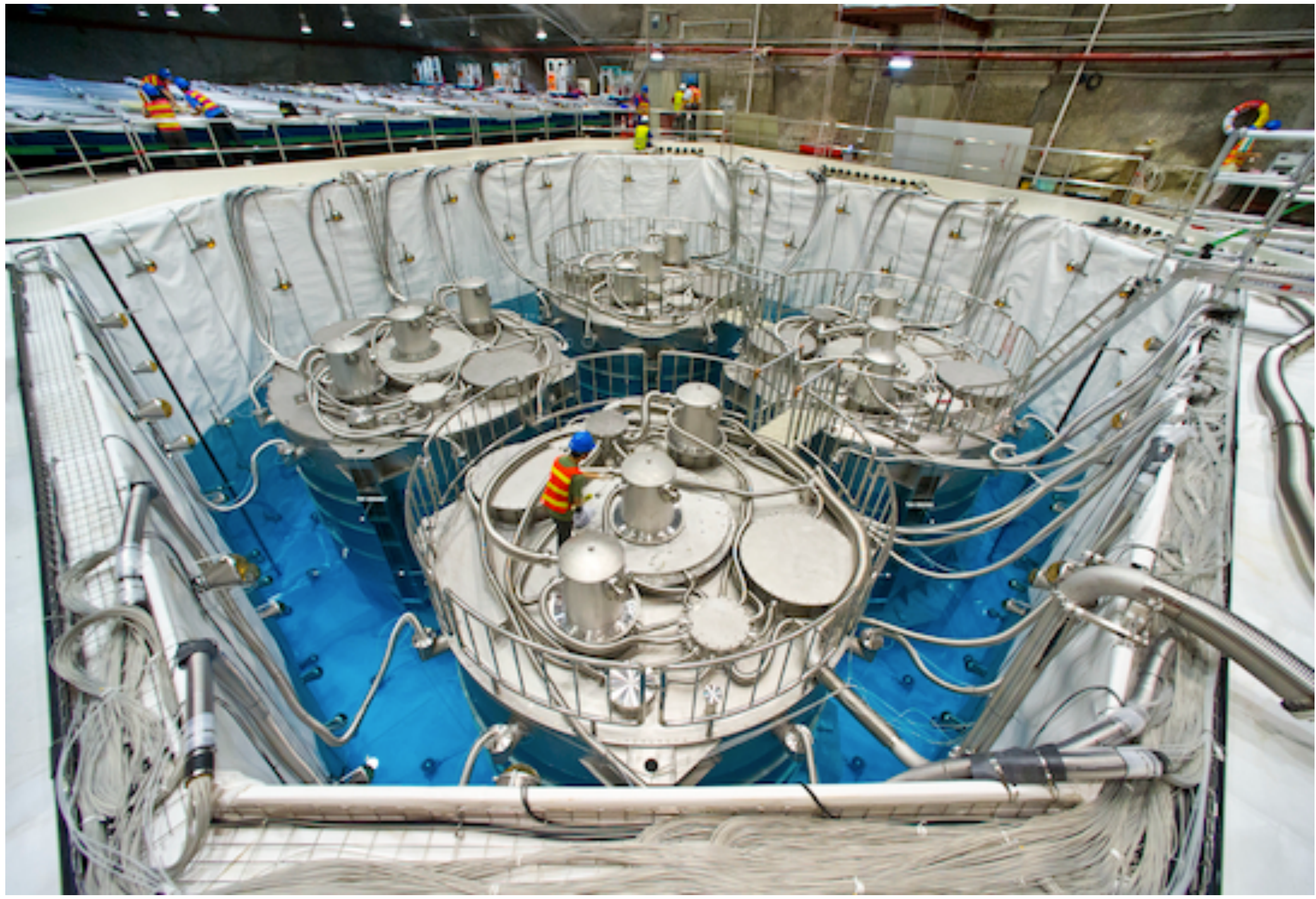
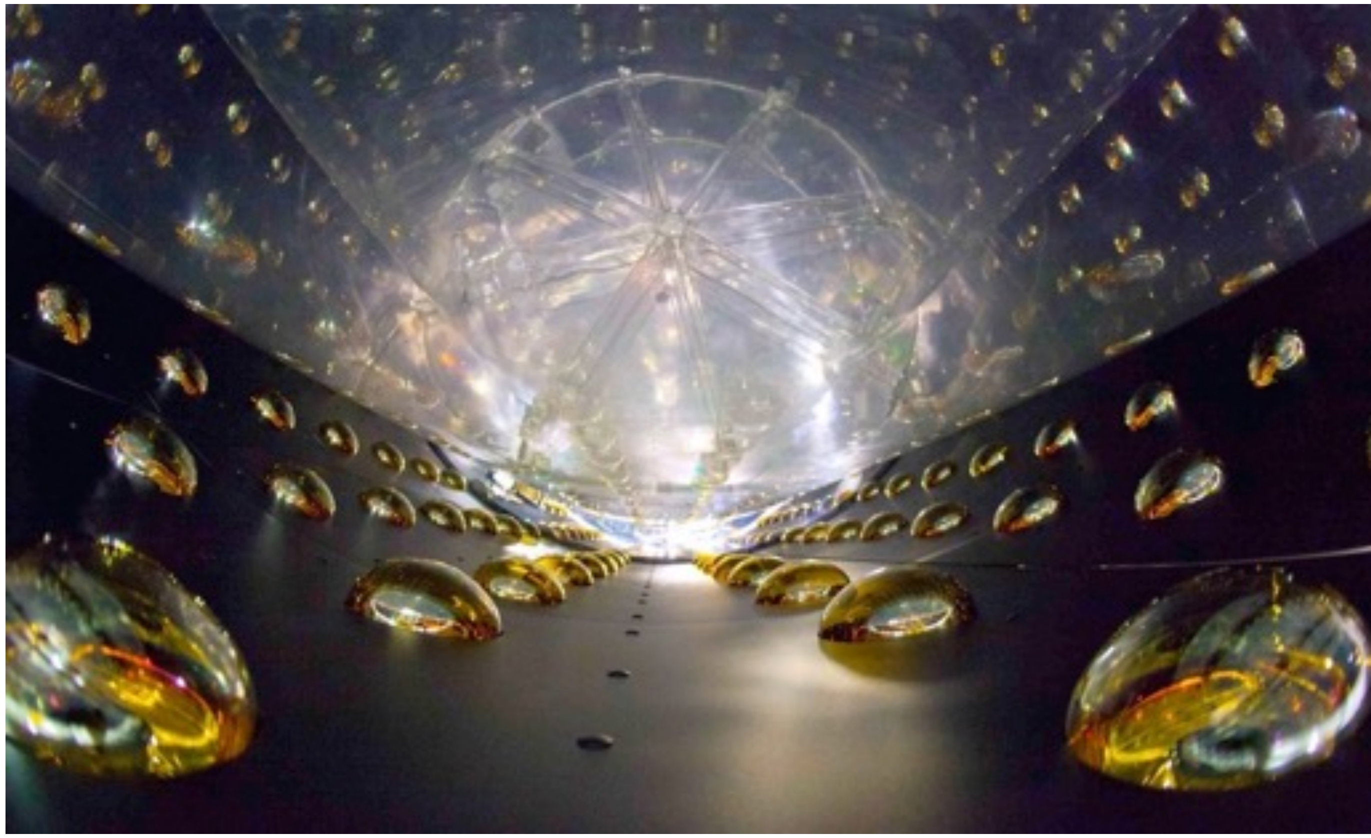
Outline

- Daya Bay experiment
- Detector performance and the data set
- Recent results:
  - Measurement of neutrino oscillation parameters
  - Measurement absolute reactor antineutrino flux
  - Search for sterile neutrinos

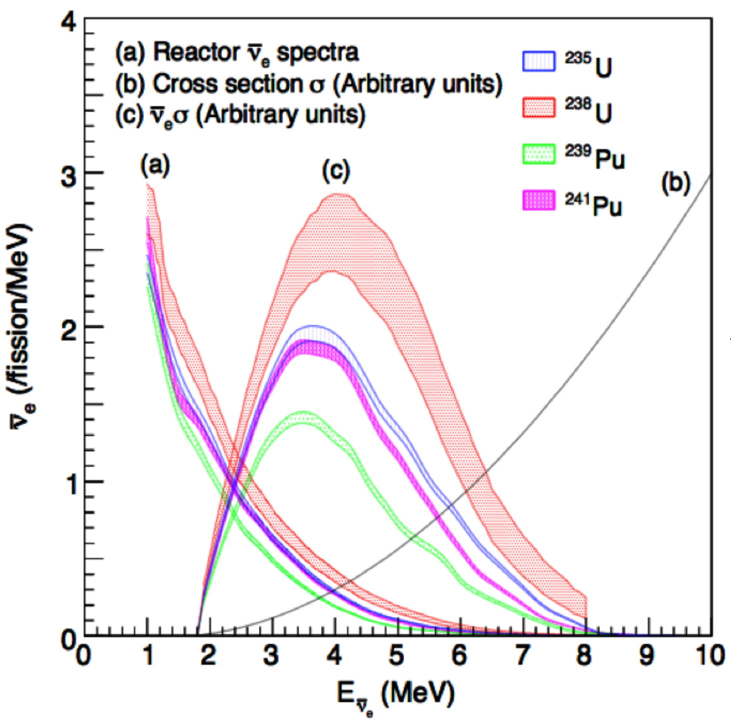




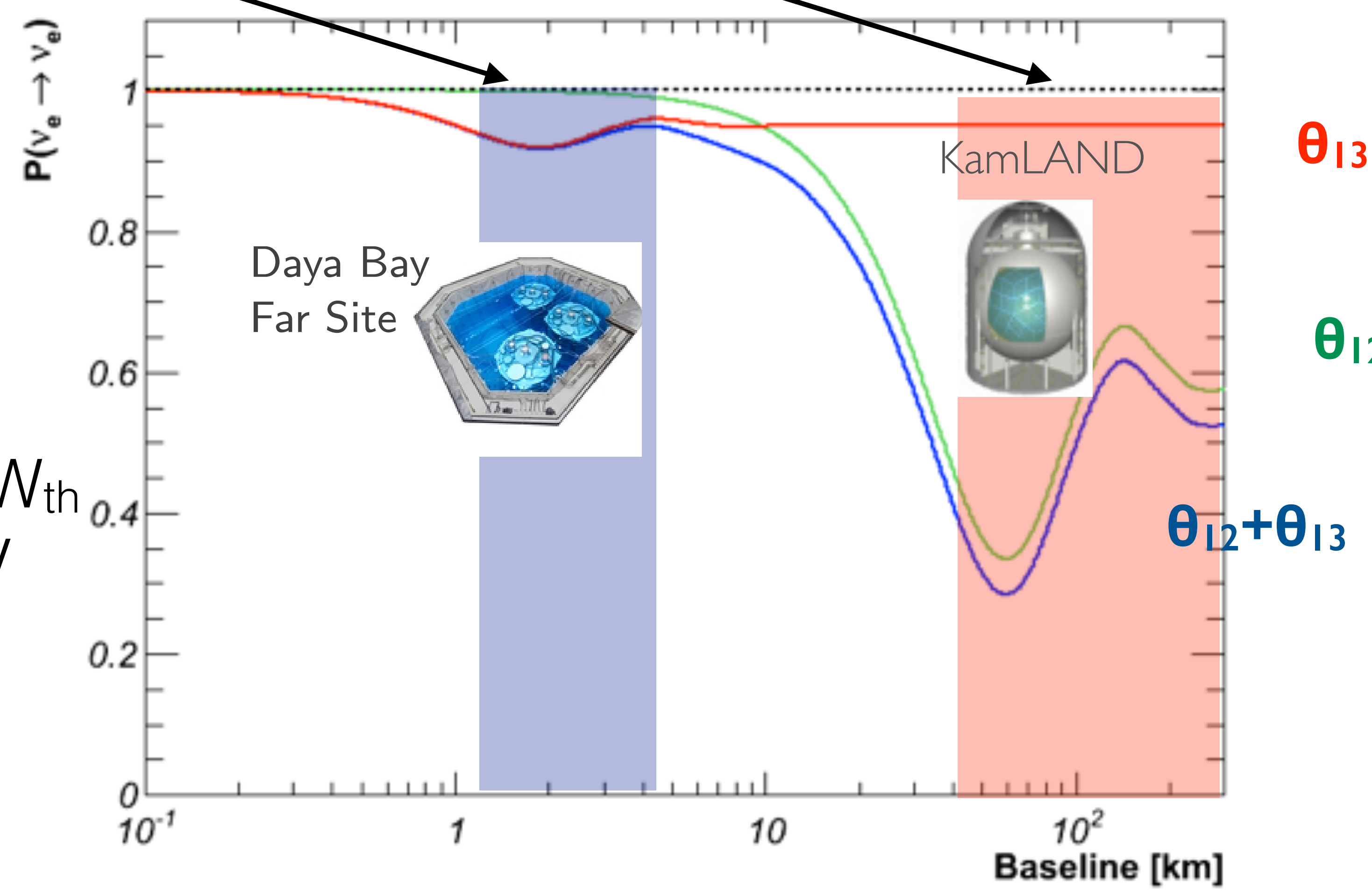
Reactor Antineutrino Oscillation

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

Reactor: The most powerful man-made source of antineutrinos

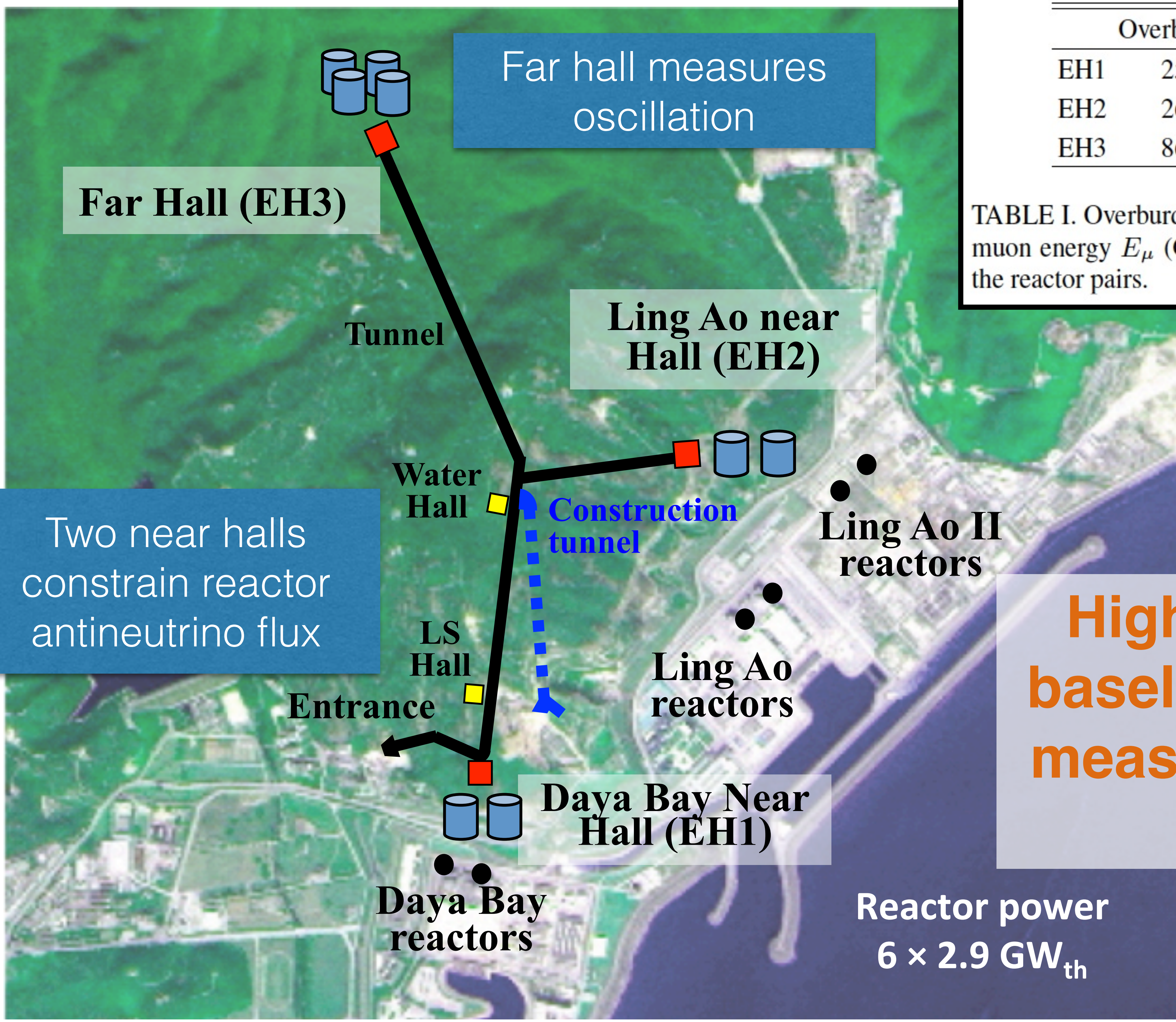


~2x10^{20} $\overline{\nu}_e$/GW$_{th}$
<E>~4MeV



- Goals of the Daya Bay experiment:
  - **Precise measurement of mixing parameters: θ_{13} and Δm^2_{ee} ($\sim\Delta m^2_{31}\sim\Delta m^2_{32}$)**
  - Precise measurement of reactor antineutrino flux and spectrum
  - Search for Physics beyond SM (sterile neutrino etc.)

Daya Bay Experiment



Far hall measures oscillation

Two near halls constrain reactor antineutrino flux

	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

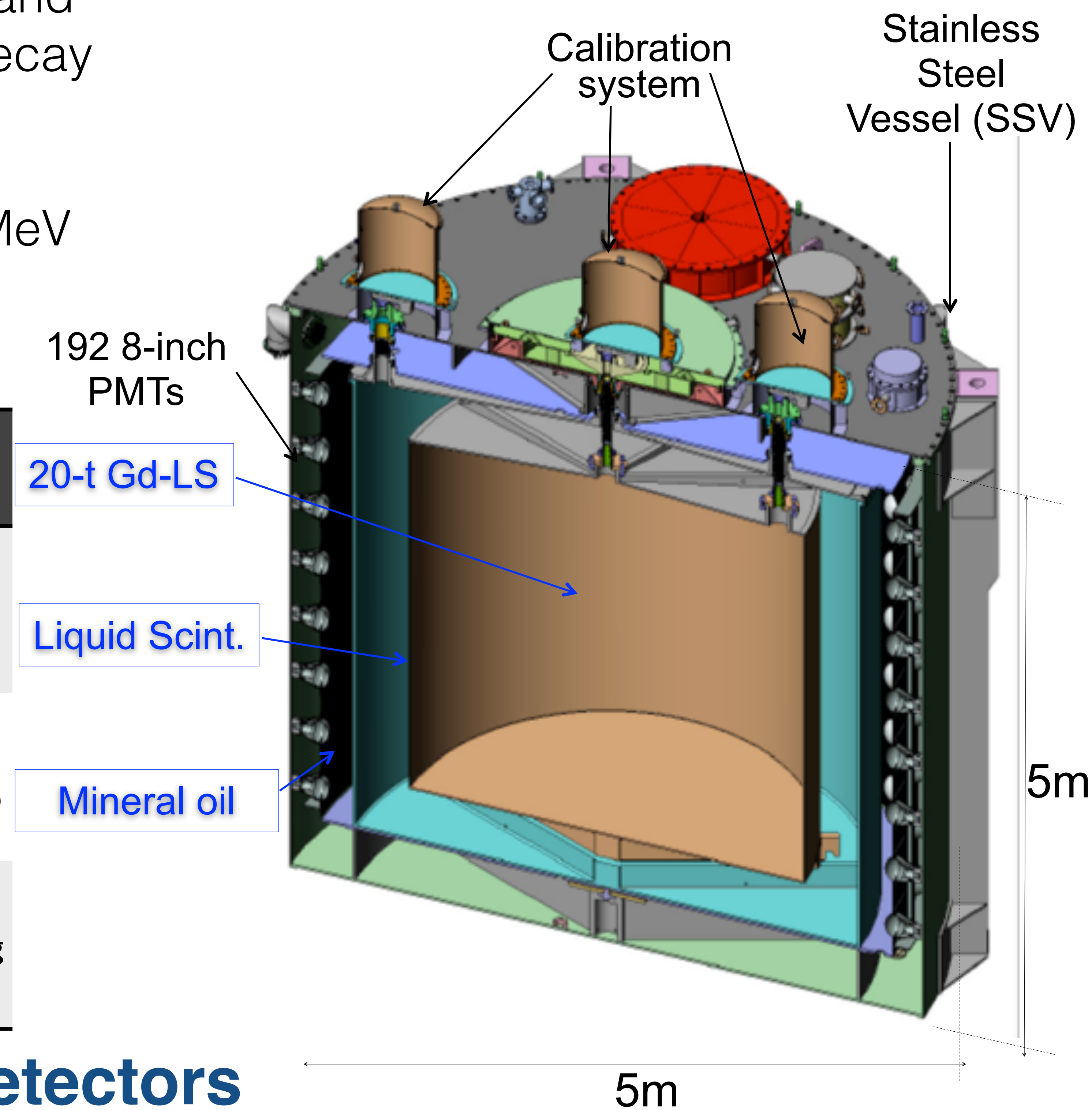
TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

High-statistics, multi-baseline (350m - 2000m) measurement of reactor antineutrinos

Antineutrino detector

- Designed to detect prompt positron and neutron-capture from Inverse beta decay (IBD) reaction
  - Neutron capture by Gd emits ~8MeV gammas
    Strong background suppression

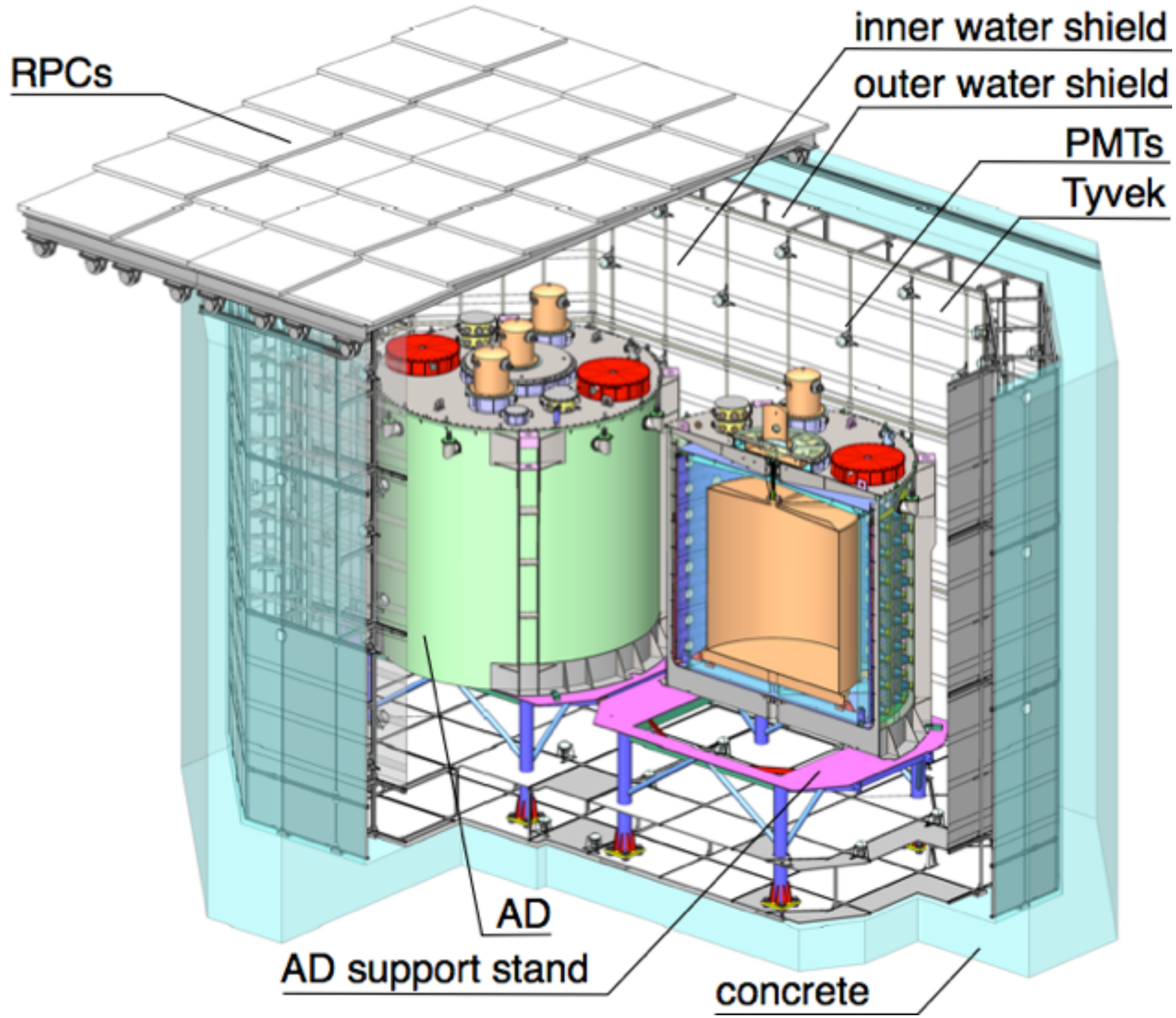
Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	22 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding



8 functionally identical detectors to reduce systematics

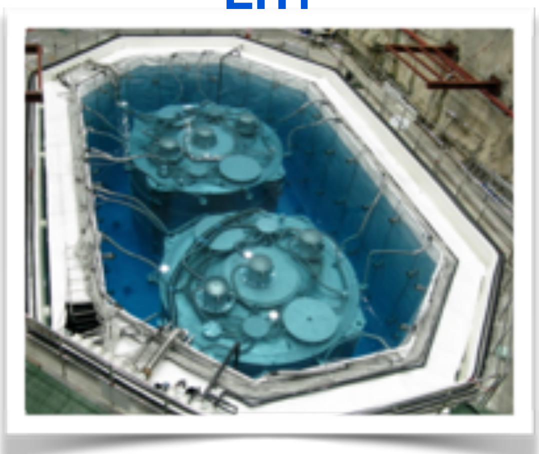
Muon Tagging System

- 2.5 meter thick two-section water shield
  - Cherenkov detector to tag cosmic ray muons.
  - Shield for neutrons and gammas from surrounding materials.
- RPC
  - Covers water pool to provide further muon tagging.



Timeline of Detector Installation

EH1



EH3

EH3

Aug, 2011

Dec, 2011

Aug, 2012

6-AD Data Taking

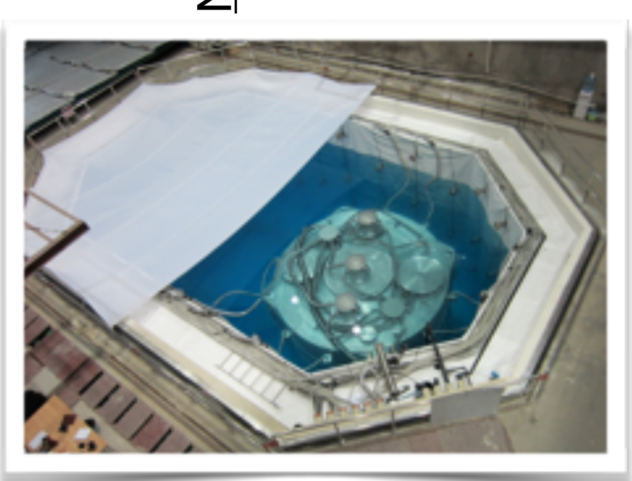
8-AD Data Taking

Nov, 2011

2011/12 - 2012/07

Aug, 2012

2012/10 - now

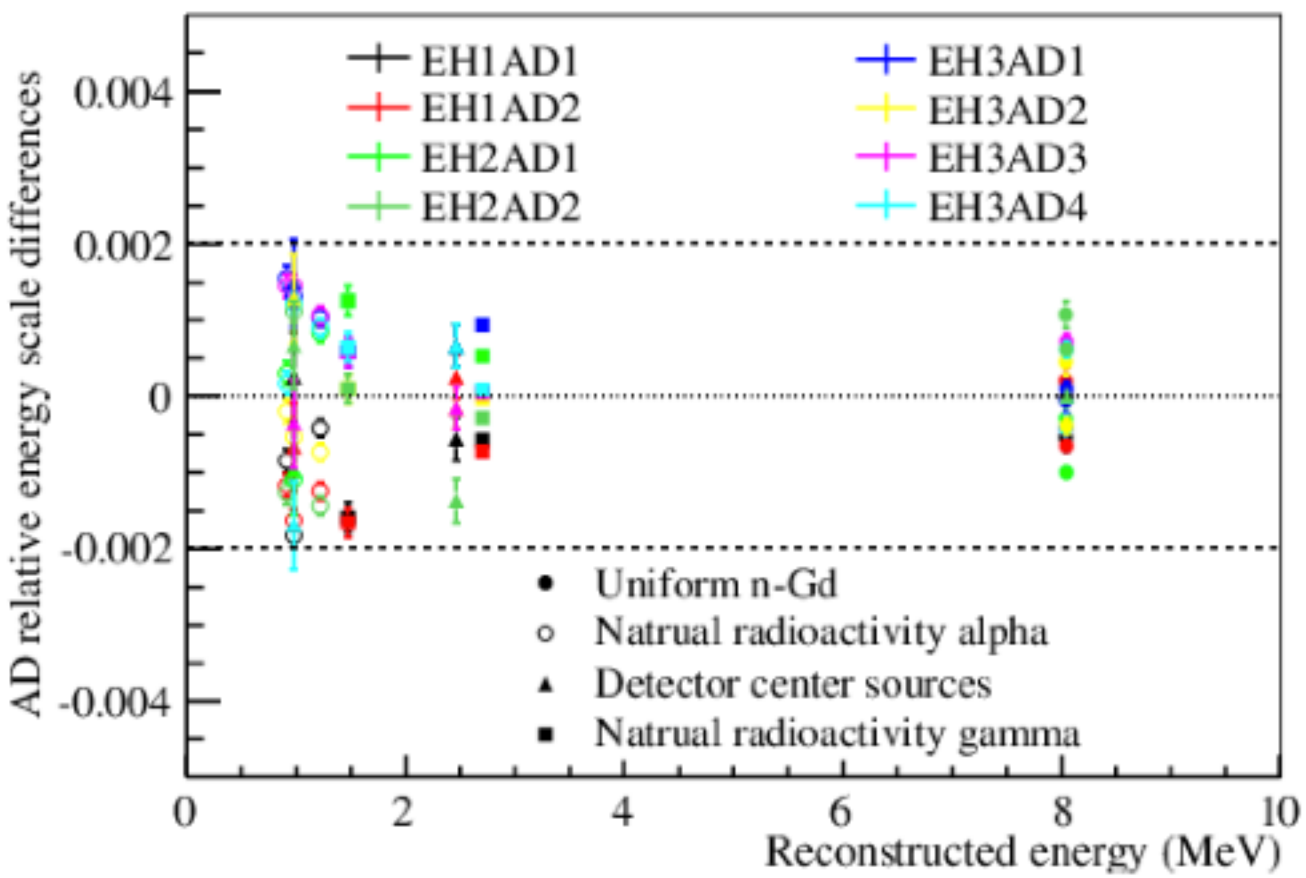


EH2

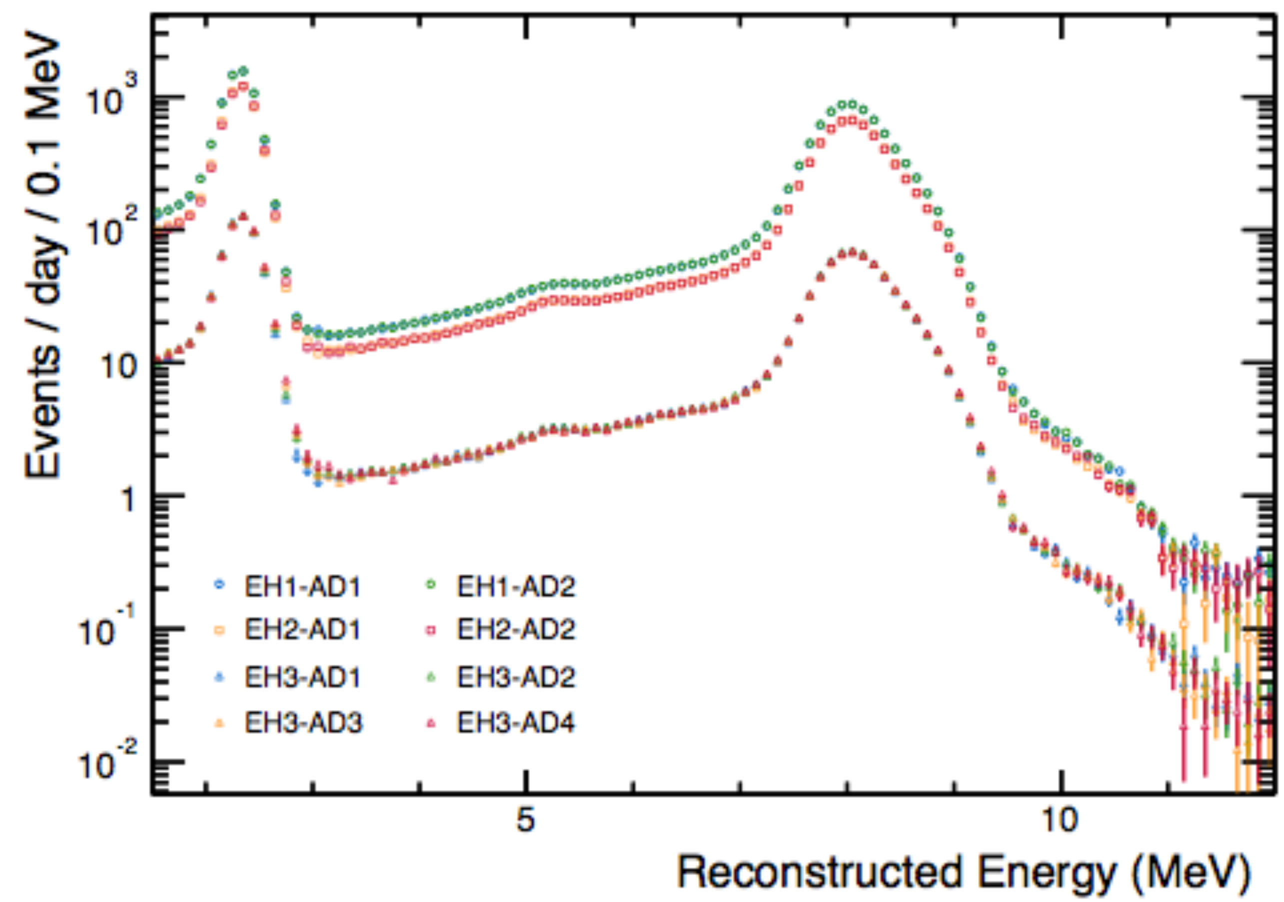
EH2

Energy calibration

ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po

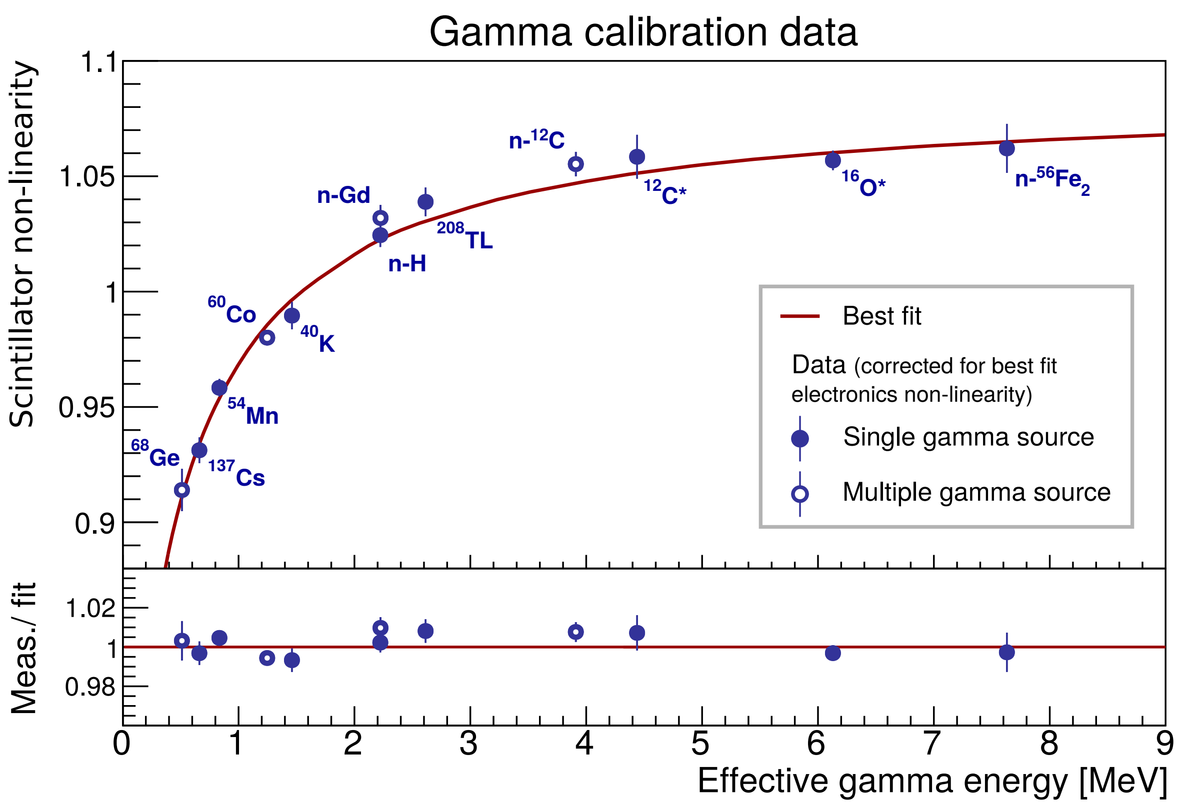


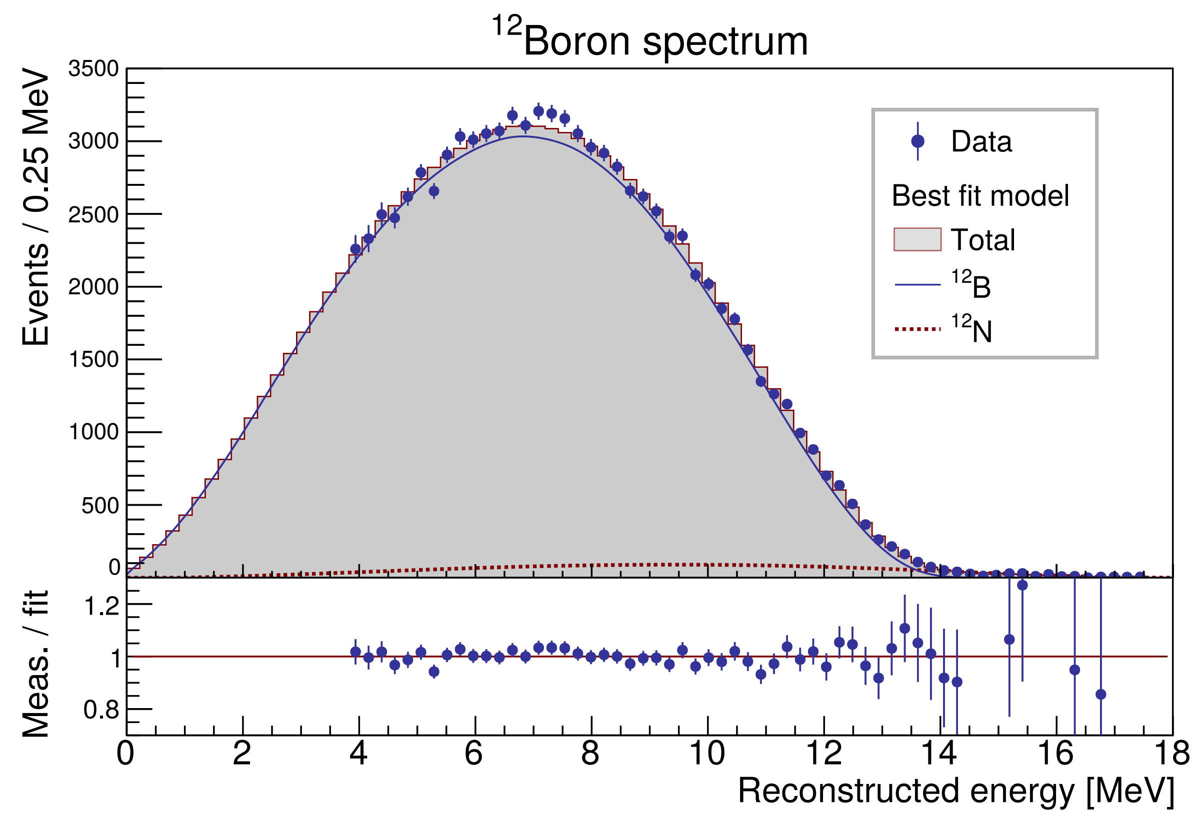
spallation neutron capture spectrum



Less than 0.2% variation in reconstructed energy between detectors

Energy non-linearity





Full detector calibration data

1. Monoenergetic gamma lines from various sources
   - Radioactive calibration sources, employed regularly: ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C and during special calibration periods: ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am-^{9}Be, Pu-^{13}C
   - Singles and correlated spectra in regular physics runs (^{40}K, ^{208}Tl, n capture on H)
2. Continuous spectrum from ^{12}B produced by muon spallation inside the scintillator

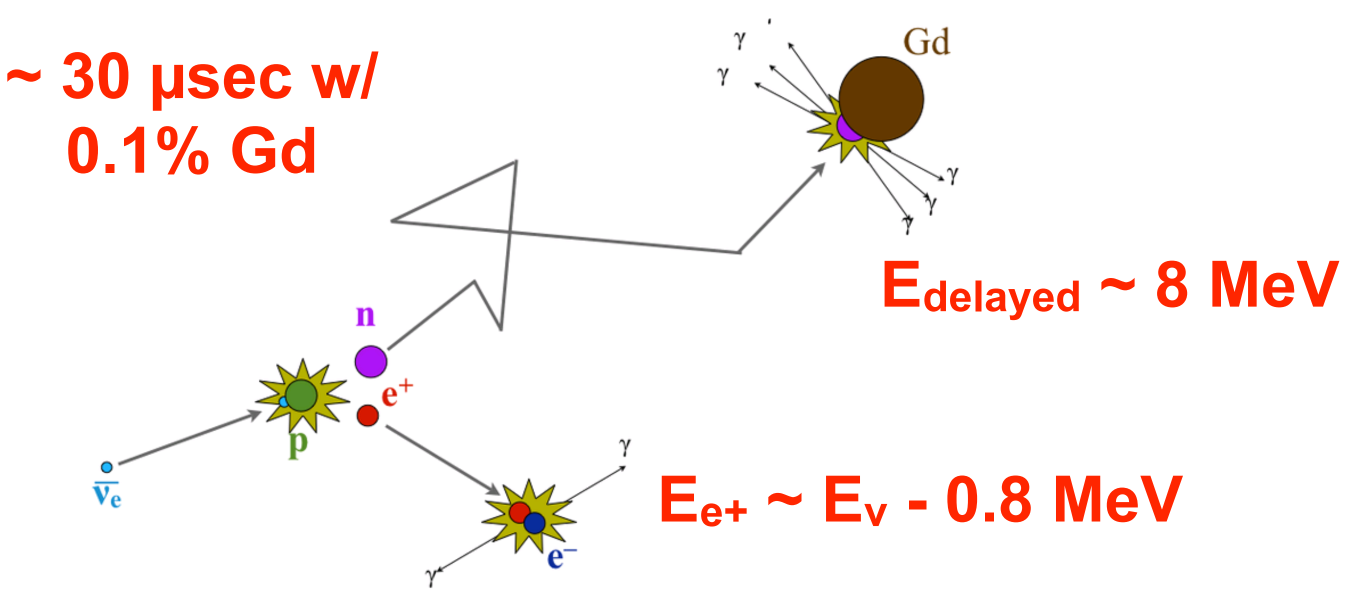
Standalone measurements

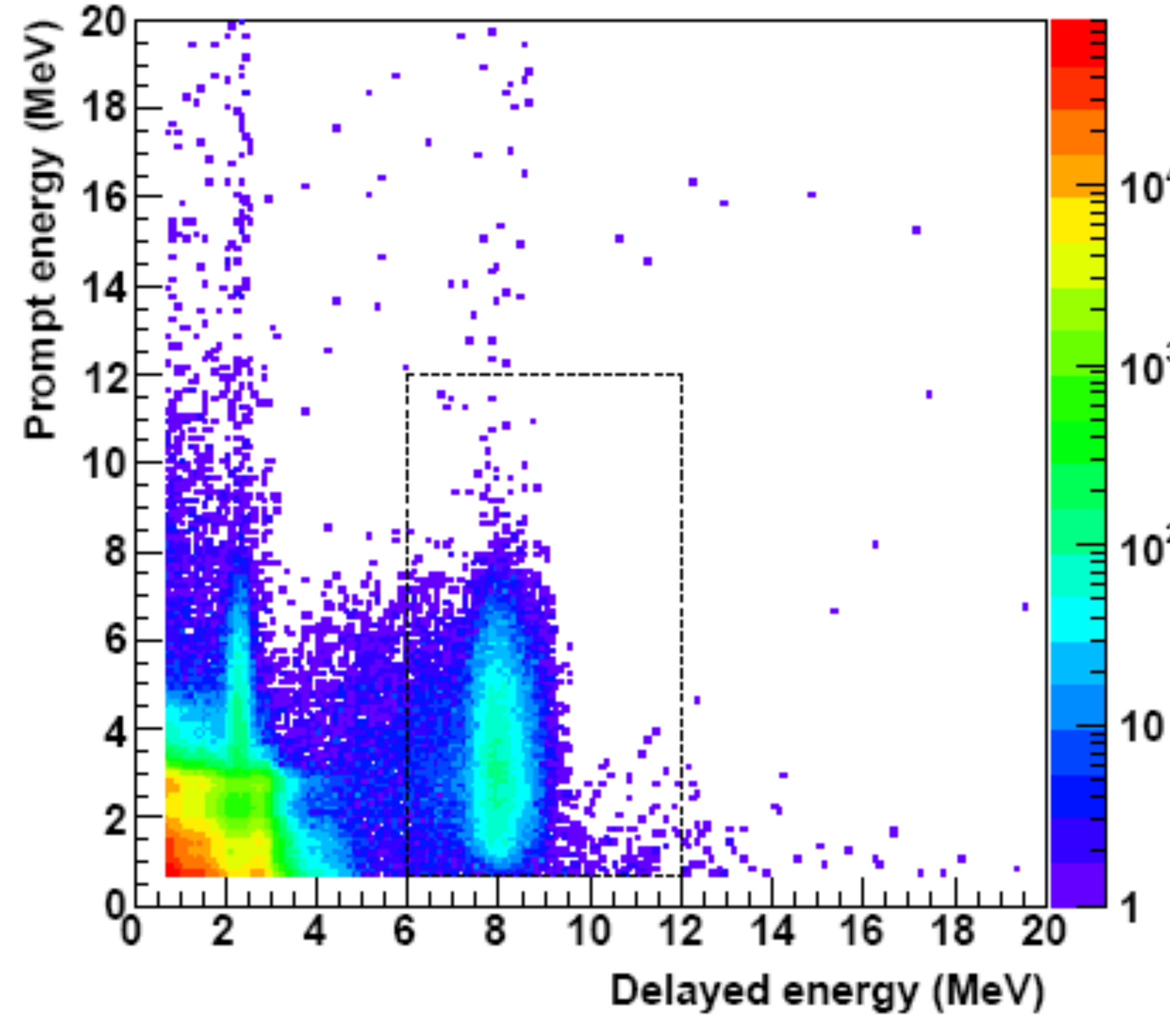
- Scintillator quenching measurements using neutron beams and Compton e$^-$
- Calibration of readout electronics with flash ADC

Antineutrino Selection

Positron+neutron coincidence from inverse beta decay reaction:

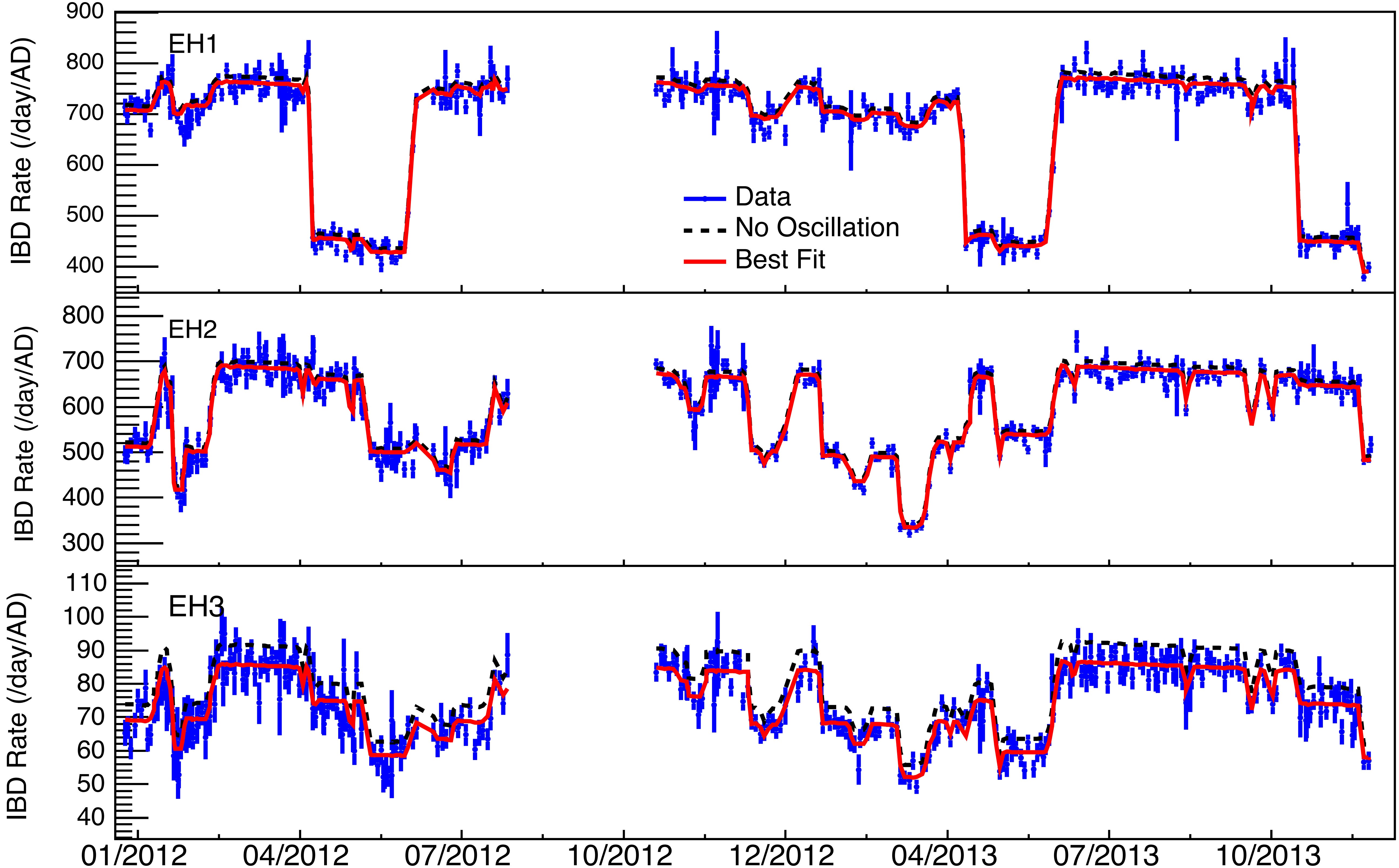
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$





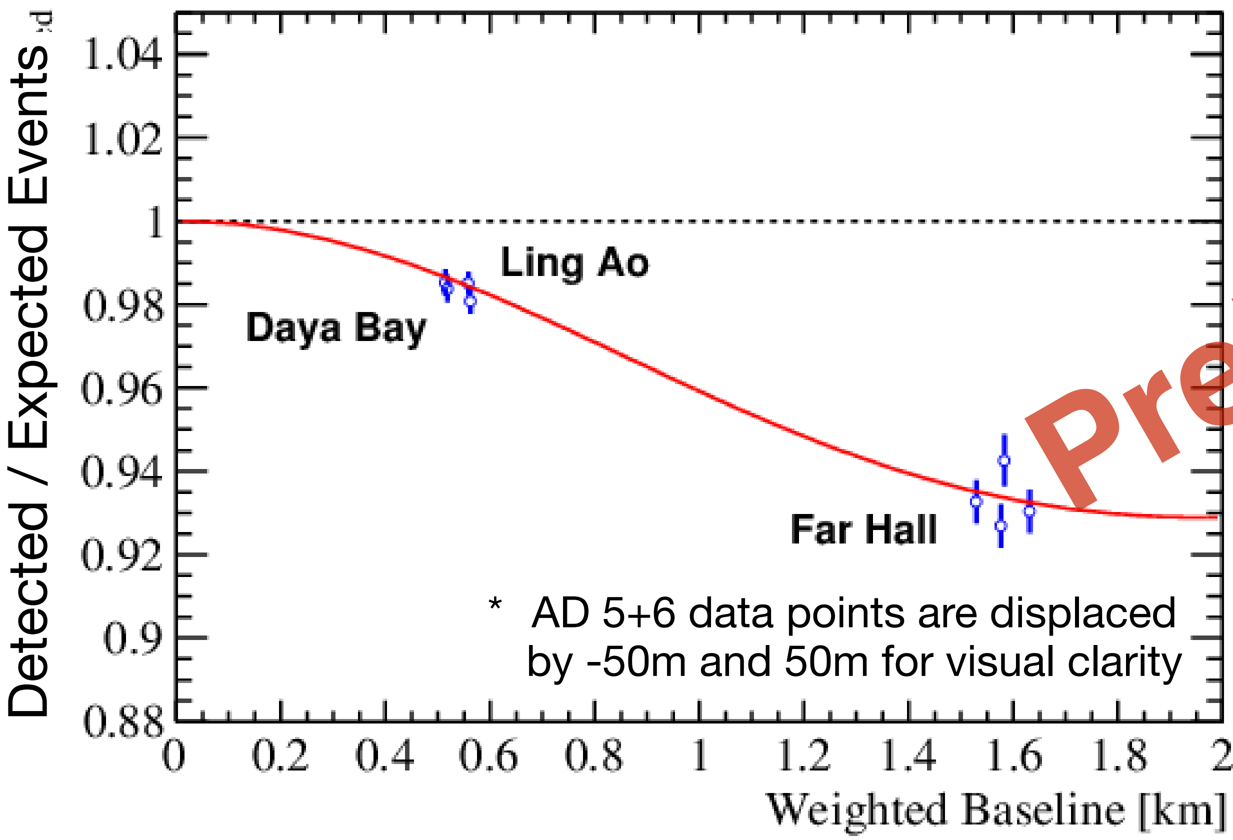
- Prompt positron energy: 0.7 < Ep < 12 MeV
- Delayed neutron energy: 6 < Ed < 12 MeV
- Neutron capture time: 1 < Δt < 200 μsec

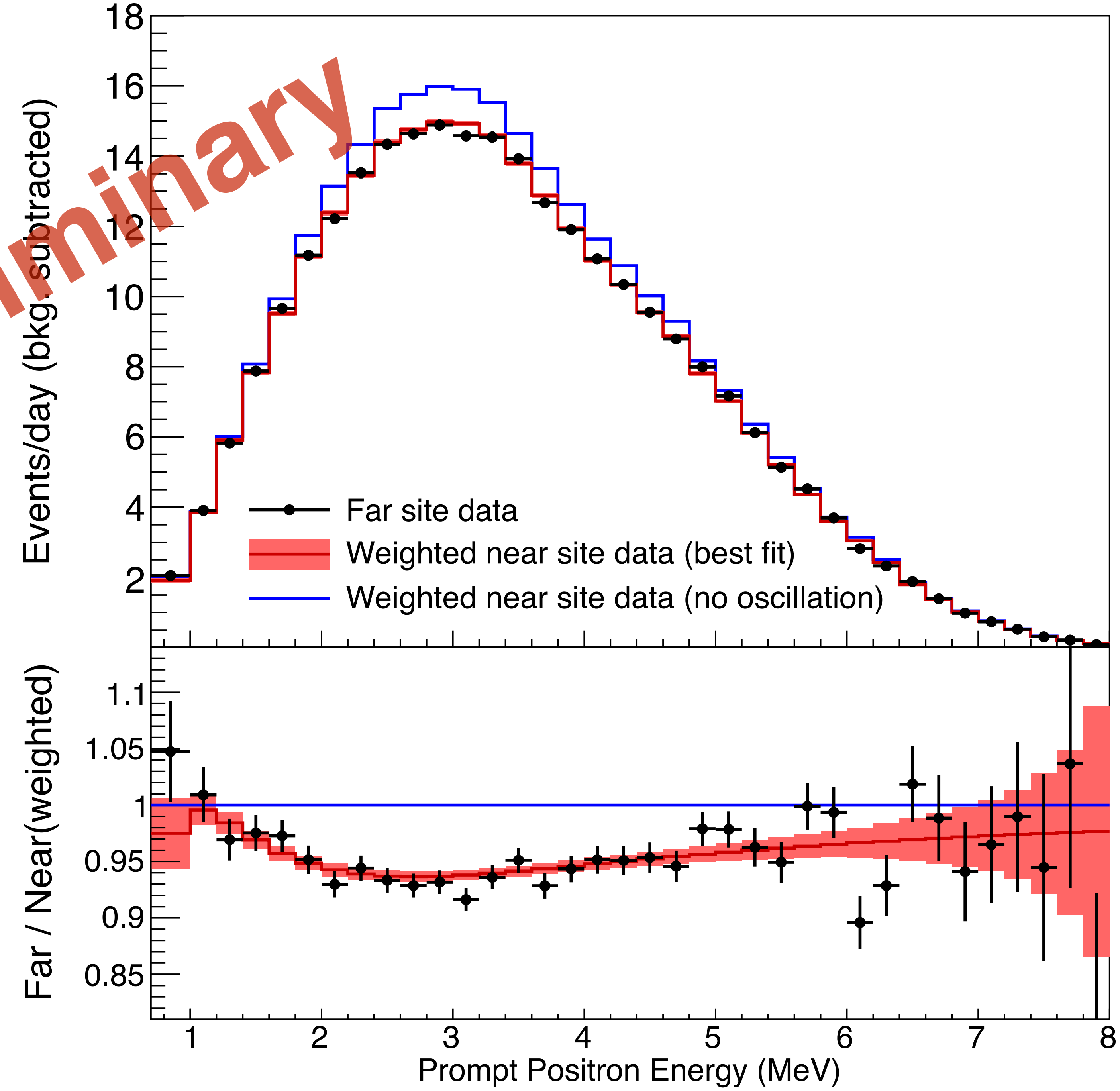
- Reject spontaneous PMT light emission (“flashers”)
- Muon vetos to suppress cosmogenic backgrounds
- Multiplicity cut to select only isolated pairs



Detected rate strongly correlated with reactor flux

Oscillation parameter measurement





- Relative comparison of near and far site data
- 621 days of data used for this analysis
- Observed data highly consistent with oscillation interpretation

Oscillation parameter measurement

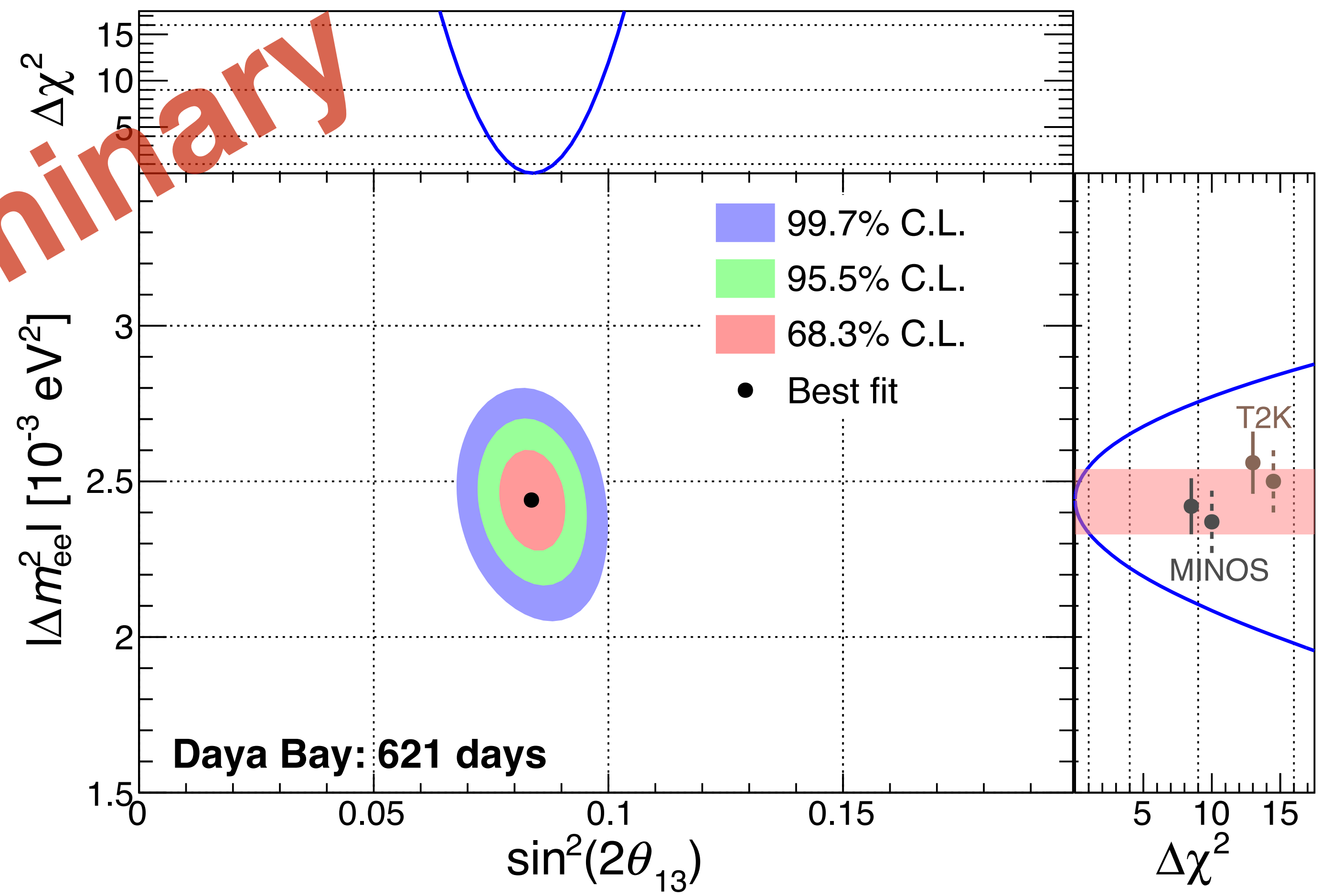
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

Preliminary

- The most precise measurement of $\sin^2 2\theta_{13}$
  - Precision better than 6%
- The most precise measurement of Δm^2_{ee} in electron antineutrino disappearance channel
  - Consistent with muon neutrino disappearance results
  - Comparable precision.

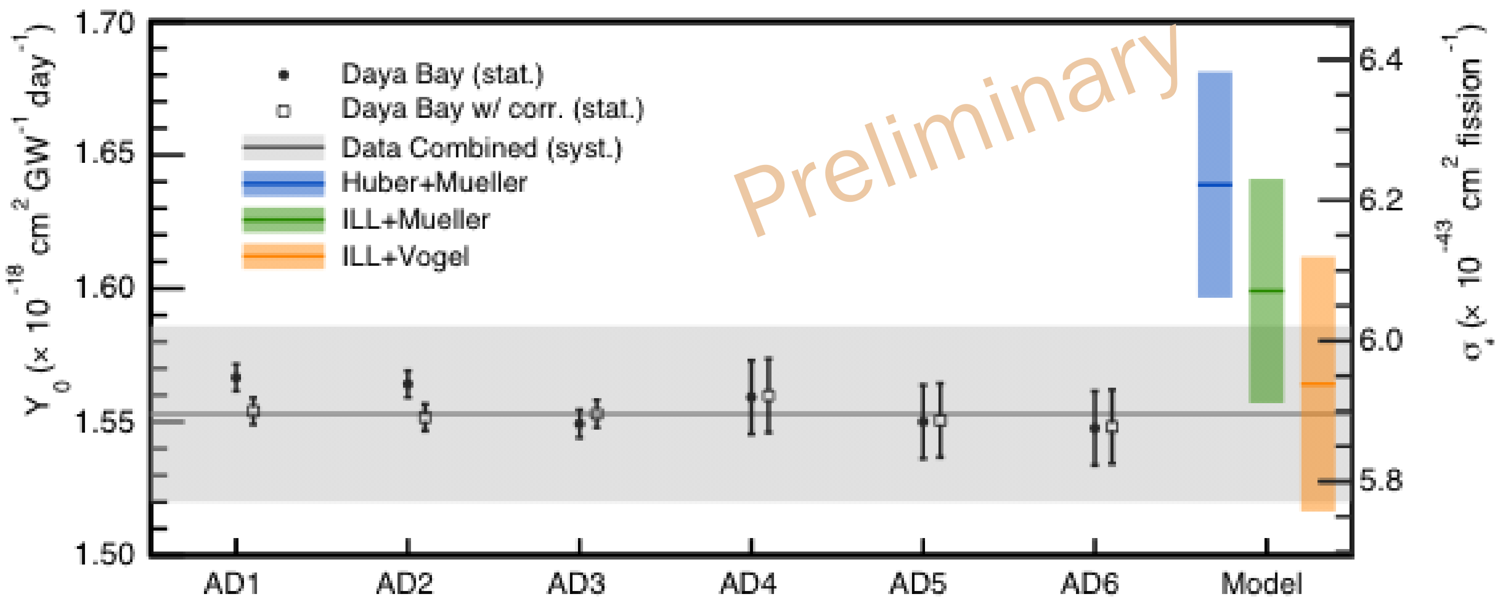


MINOS: Phys.Rev.Lett. 112, 191801 (2014)
T2K: Phys.Rev.Lett. 112, 181801 (2014)

Publication in preparation

Absolute flux and shape

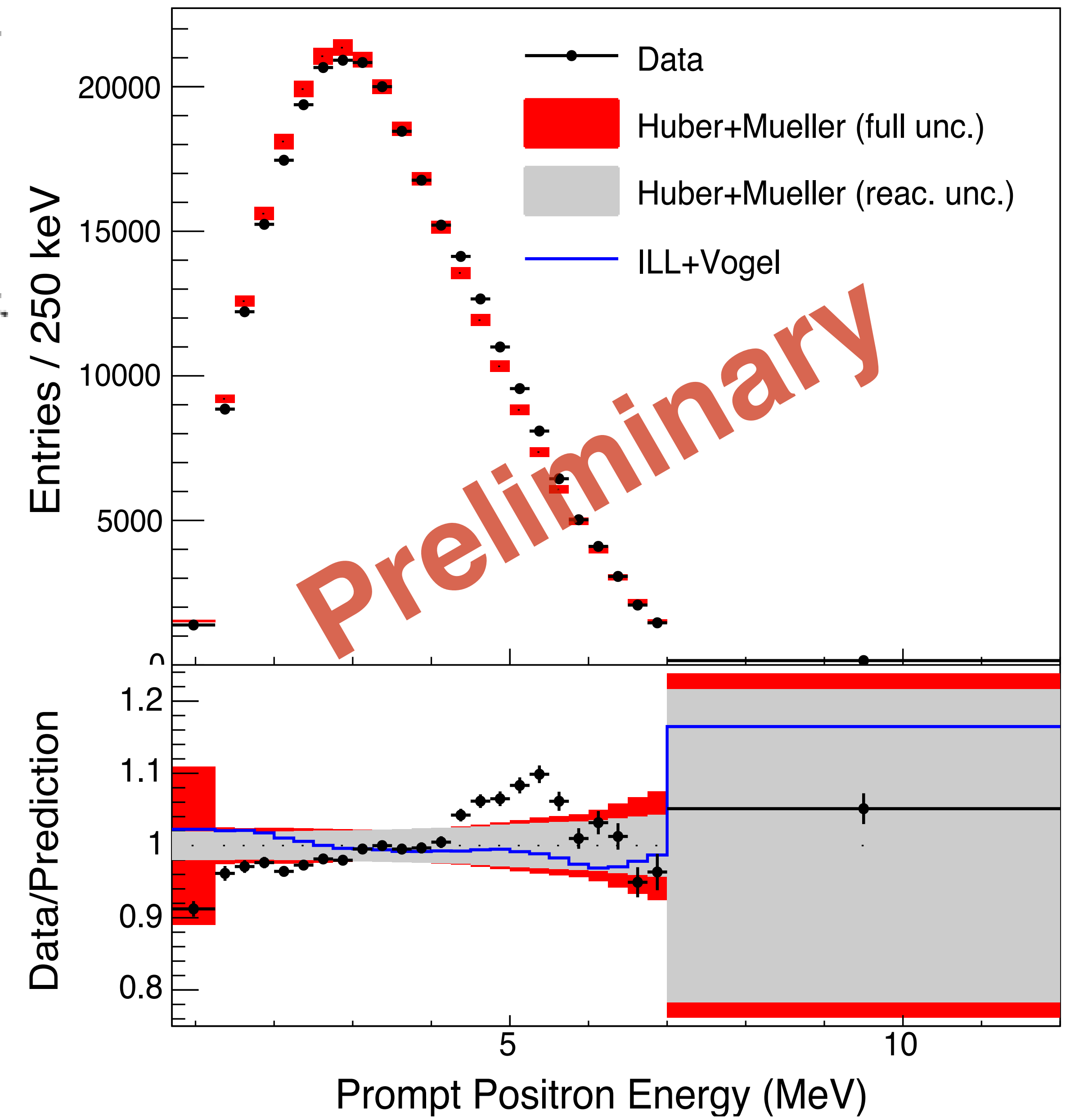
Absolute rate



- Measured IBD rate / predicted:
  - 0.947 ± 0.022 (Huber+Mueller)
  - 0.992 ± 0.023 (ILL+Vogel)
- Consistent with previous short baseline experiments

Publication in preparation

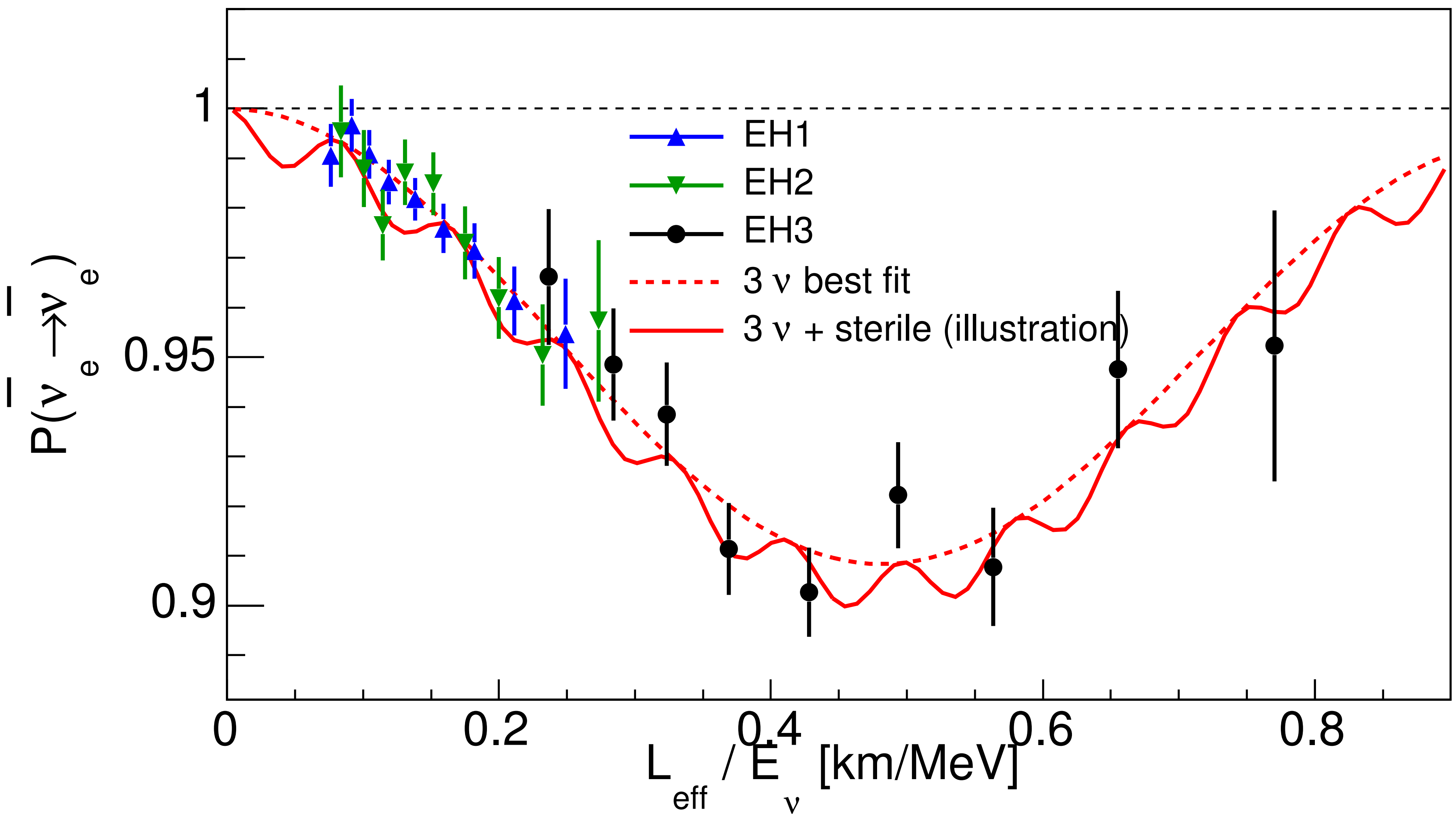
Spectral shape



Observed absolute antineutrino spectrum is inconsistent with the conventional predictions

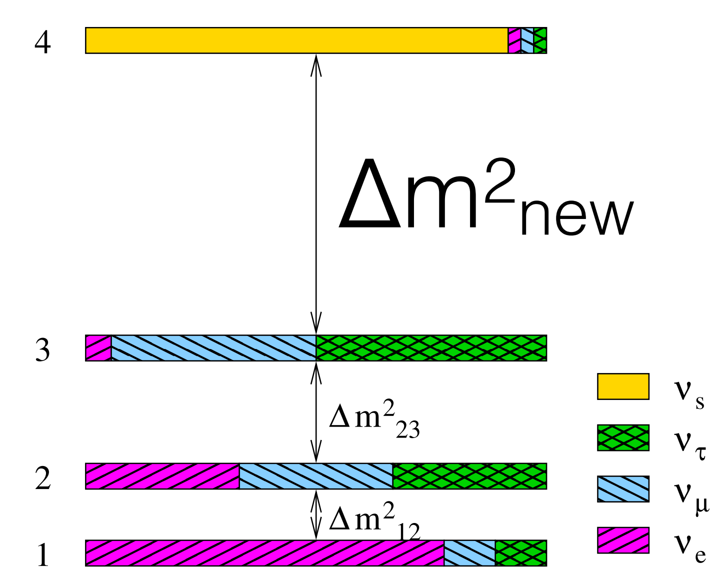
Search for light sterile neutrino

- Light sterile neutrinos could introduce additional mode of oscillation

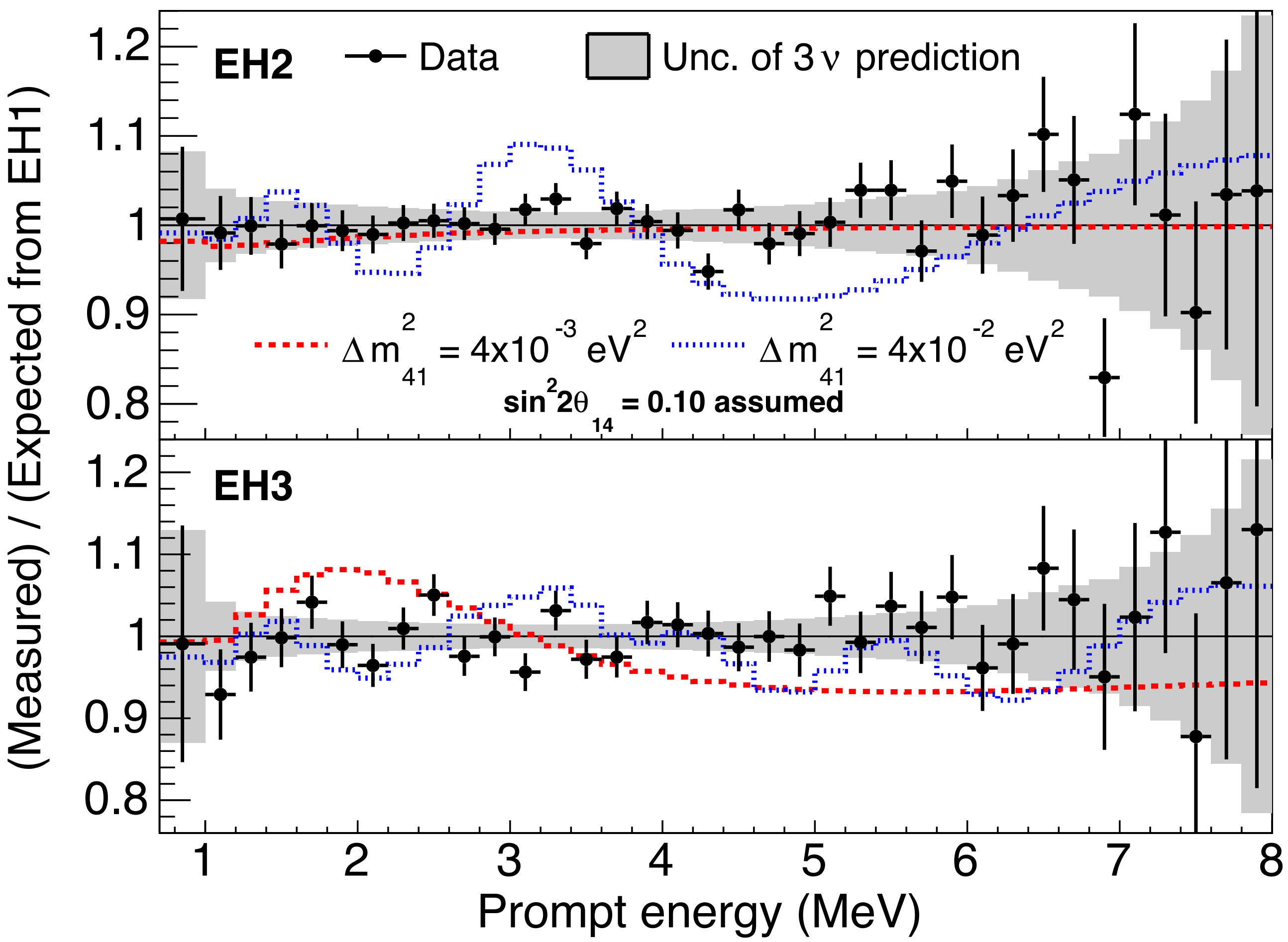


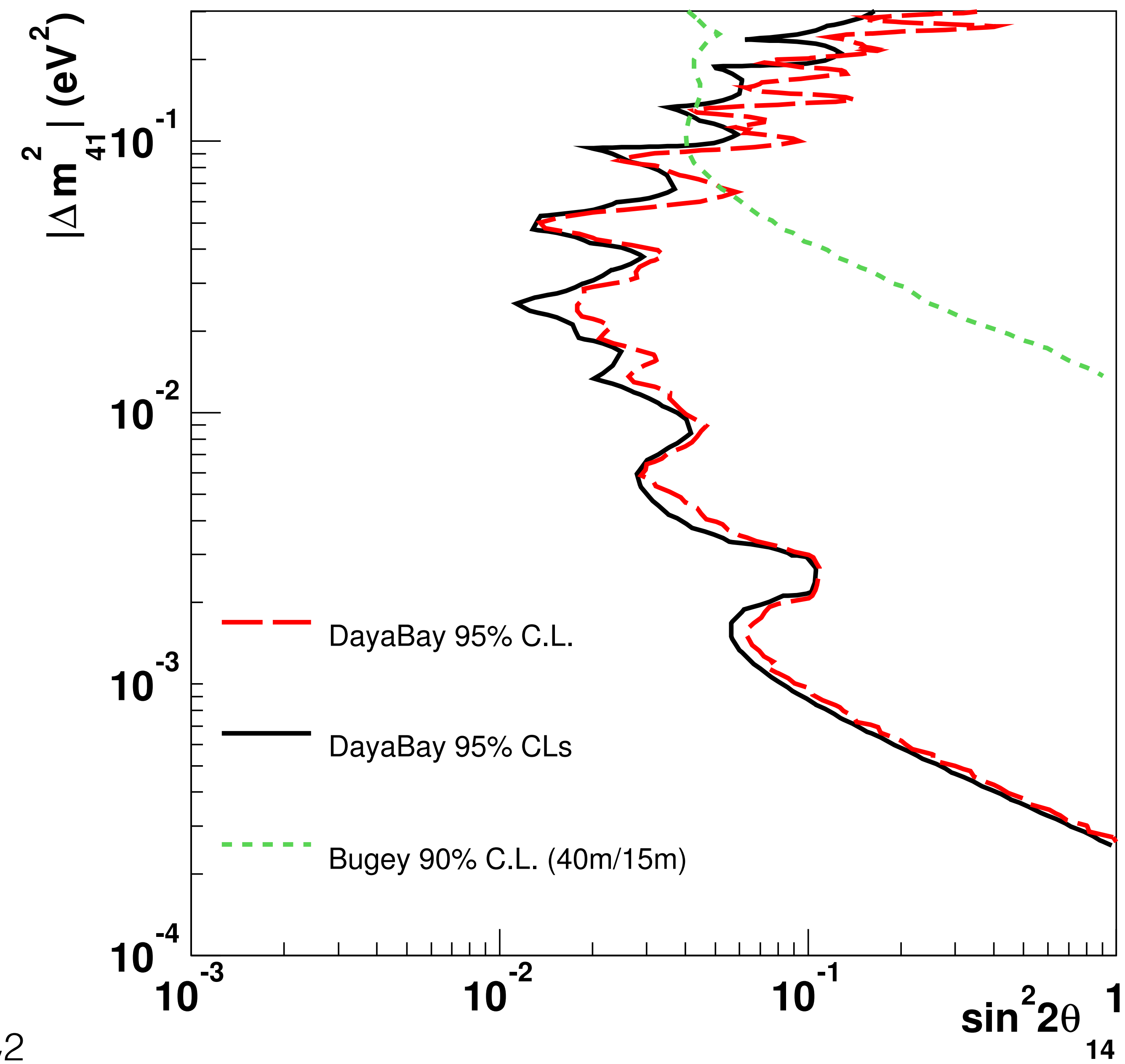
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right)$$
$$-\sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

"3+1 model"



Sterile neutrino search results





- Result from 217 days of data
- No significant signal observed
- Set most stringent limit at $\Delta m^2_{41} < 0.1$ eV^2

Phys. Rev. Lett. 113, 141802 (2014)

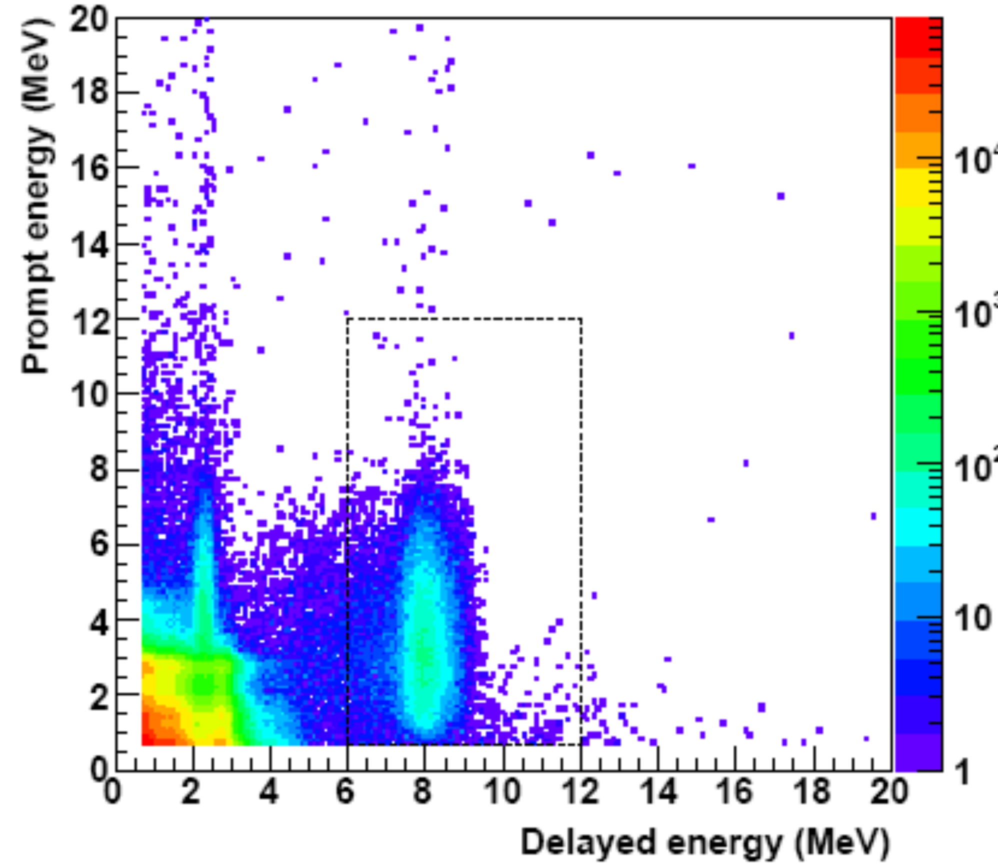
Summary

- Daya Bay: High precision measurement of reactor antineutrino at O(100m) - O(1000 m) baseline.
- Many results recently released:
  - **The most precise measurement of θ_{13} and Δm^2_{ee}.**
  - Oscillation analysis using H-capture sample (not talked today)
  - Absolute reactor antineutrino flux and spectrum
  - Search for light sterile neutrinos
- Many more coming in the future
- Stay tuned for future results from Daya Bay!

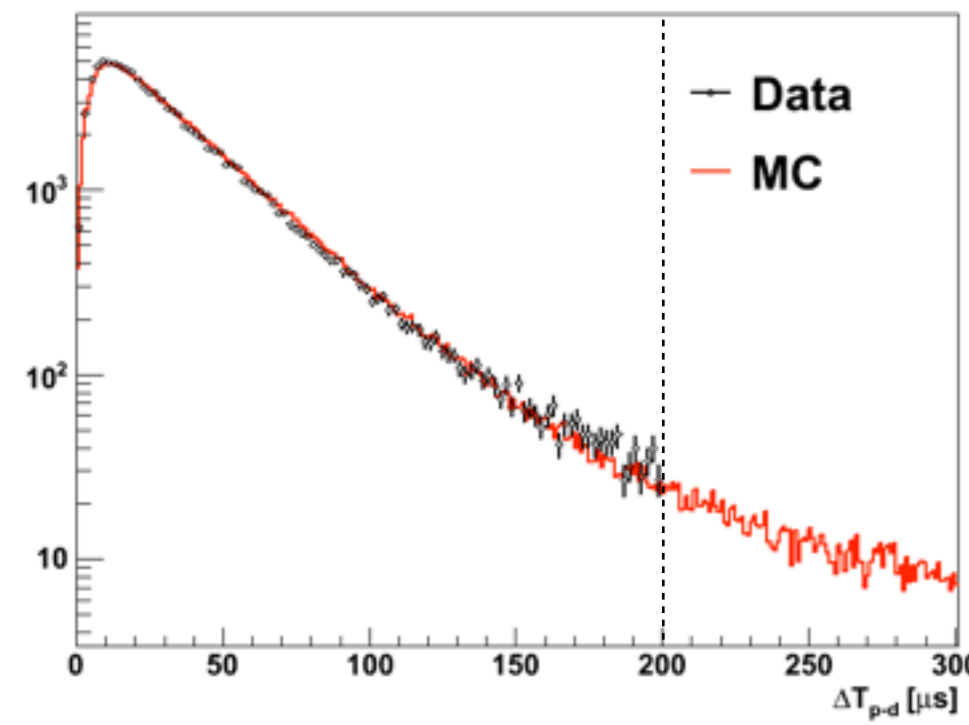
Backup slides

Antineutrino Candidate Selection

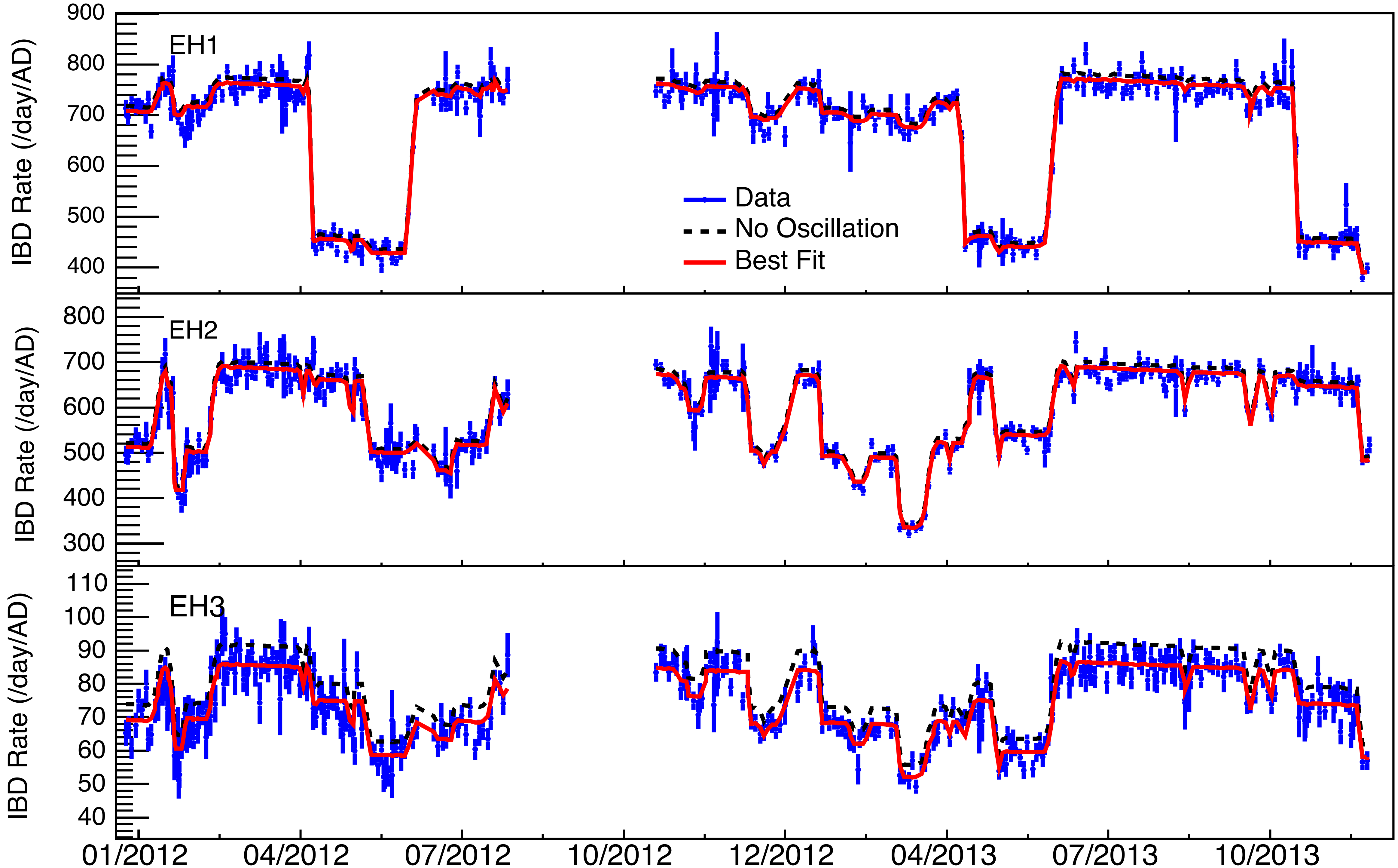
- Reject PMT flashers
- Muon veto:
  - Water pool Muon: reject 0.6ms
  - AD Muon (>20 MeV): reject 1 ms
  - AD Shower Muon (>2.5 GeV): reject 1s
- Prompt positron Energy: 0.7 MeV < Ep < 12 MeV
- Delayed neutron Energy: 6 MeV < Ed < 12 MeV
- Neutron Capture time: 1 us < Δt < 200 us
- Multiplicity cut: only select isolated candidate pairs



	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

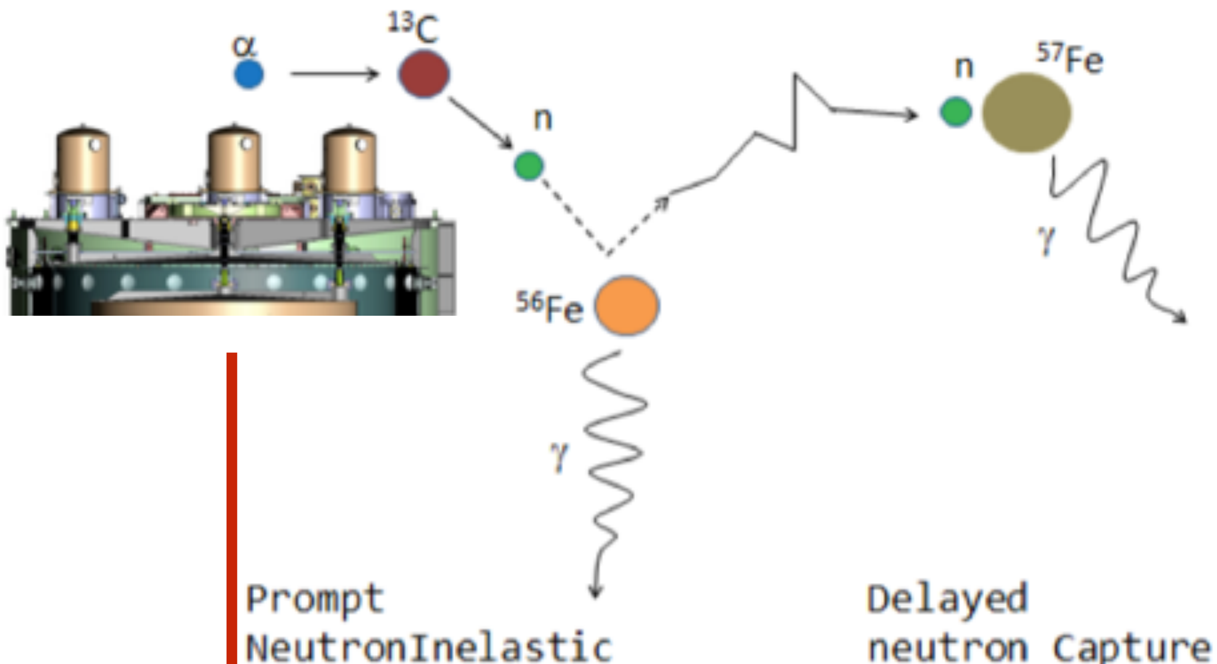


Over 1 million antineutrino interactions!!
(150k at the far site)

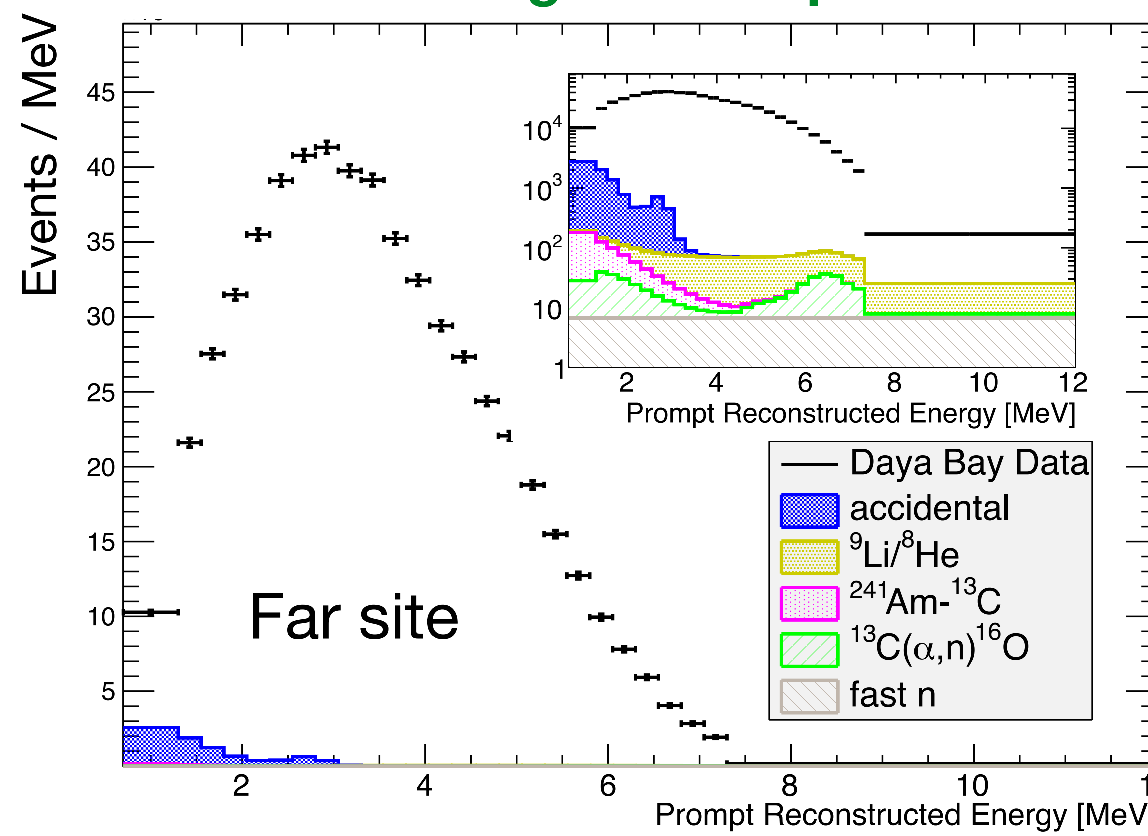


Detected rate strongly correlated with reactor flux

Background Budget



a low background experiment



Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source
Li-9 / He-8	0.4%	0.4%	~50%	measured with after-muon events
Fast neutron	0.1%	0.1%	~30%	measured from AD/water/RPC tagged muon events
Alpha-n	0.01%	0.1%	~50%	calculated from measured radioactivity

Data Summary

6-AD Period

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	101998	103137	93742	13889	13814	13645
DAQ live time(day)	190.989		189.623	189.766		
ε_μ	0.8234	0.8207	0.8576	0.9811	0.9811	0.9808
ε_m	0.9741	0.9745	0.9757	0.9744	0.9742	0.974
Accidentals(/day)	9.53 ± 0.10	9.29 ± 0.10	7.40 ± 0.08	2.93 ± 0.03	2.87 ± 0.03	2.81 ± 0.03
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19	0.05 ± 0.01		
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9	0.27 ± 0.14		
AmC correlated(/day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12	0.22 ± 0.1	0.21 ± 0.1	0.21 ± 0.09
$^{13}C(\alpha,n)^{16}O$(/day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(/day)	652.38 ± 2.58	662.02 ± 2.59	580.84 ± 2.14	73.04 ± 0.67	72.71 ± 0.67	71.88 ± 0.67
side-by-side ibd rate ratio	0.985 ± 0.005					

8-AD Period

	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	202461	206217	193356	190046	27067	27389	27032	27419
DAQ live time(day)	374.447		378.407		372.685			
ε_μ	0.8255	0.8223	0.8574	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9746	0.9749	0.9759	0.9756	0.9762	0.976	0.9757	0.9758
Accidentals(/day)	8.62 ± 0.09	8.76 ± 0.09	6.43 ± 0.07	6.86 ± 0.07	1.07 ± 0.01	0.94 ± 0.01	0.94 ± 0.01	1.26 ± 0.01
Fast neutron(/day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
9Li/8He(/day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
AmC correlated(/day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.02
$^{13}C(\alpha,n)^{16}O$(/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
IBD rate(/day)	659.58 ± 2.12	674.36 ± 2.14	601.77 ± 1.67	590.81 ± 1.66	74.33 ± 0.48	75.40 ± 0.49	74.44 ± 0.48	75.15 ± 0.49
side-by-side ibd rate ratio	0.978 ± 0.004		1.019 ± 0.004					

Expected: AD1/AD2 = 0.982; AD3/AD8 = 1.012

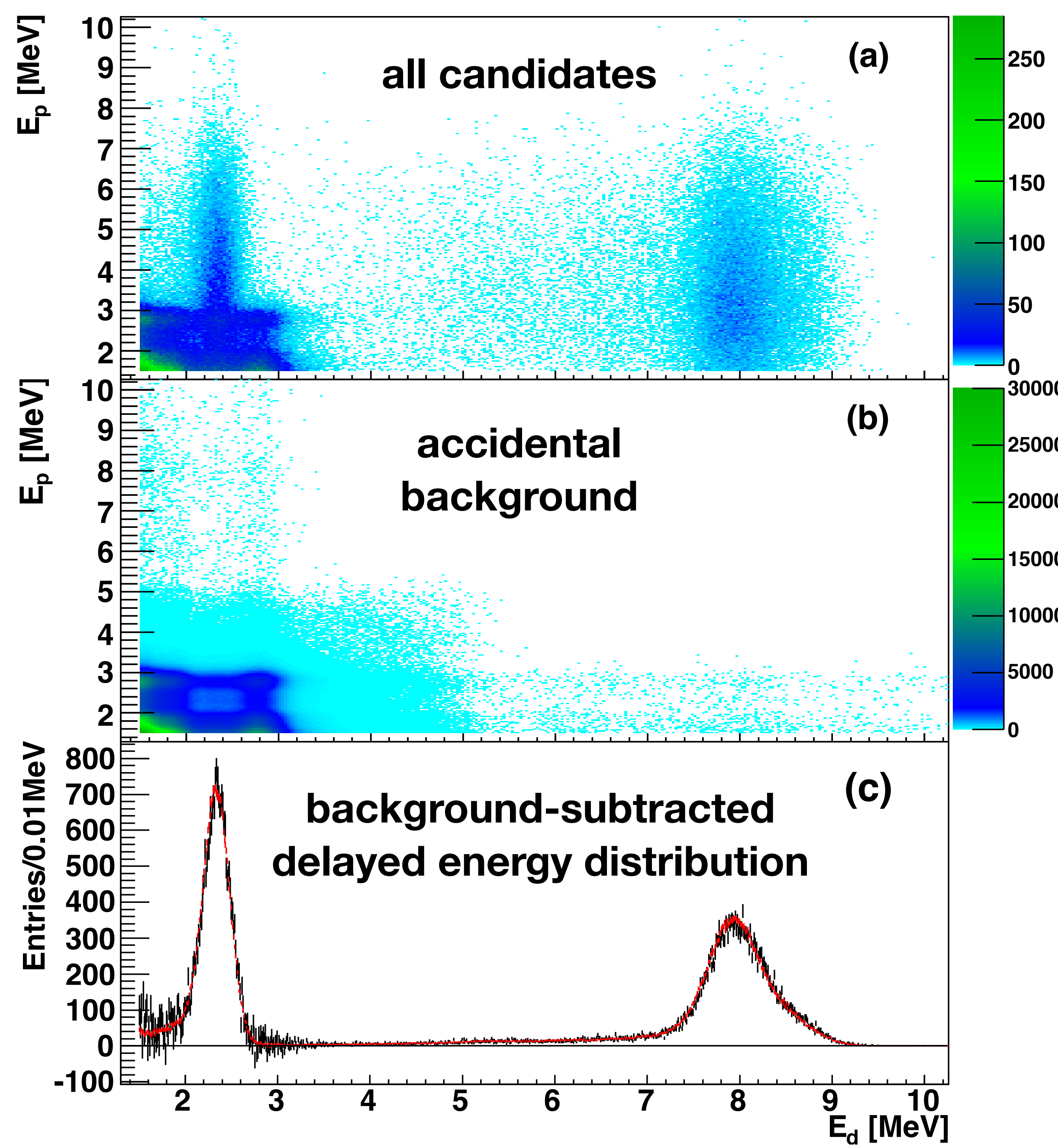
consistent rate for side-by-side detectors

Independent $\sin^2 2\theta_{13}$ measurement through nH

- Advantage
  - High statistics (15% capture in the 20-ton Gd-LS region and 100% in the 20-ton LS region)
  - Different systematic uncertainties from nGd analysis
- Challenge
  - High accidental background
    - longer capture time
    - lower delayed energy
- Strategy
  - Raise prompt energy cut Ep > 1.5 MeV
  - Require prompt to delayed distance ΔR < 0.5 m
  - Relative measurement to reduce systematics

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

$+H \rightarrow D + \gamma$	2.2 MeV	200 μs
$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma ' s$	8MeV	30 μs

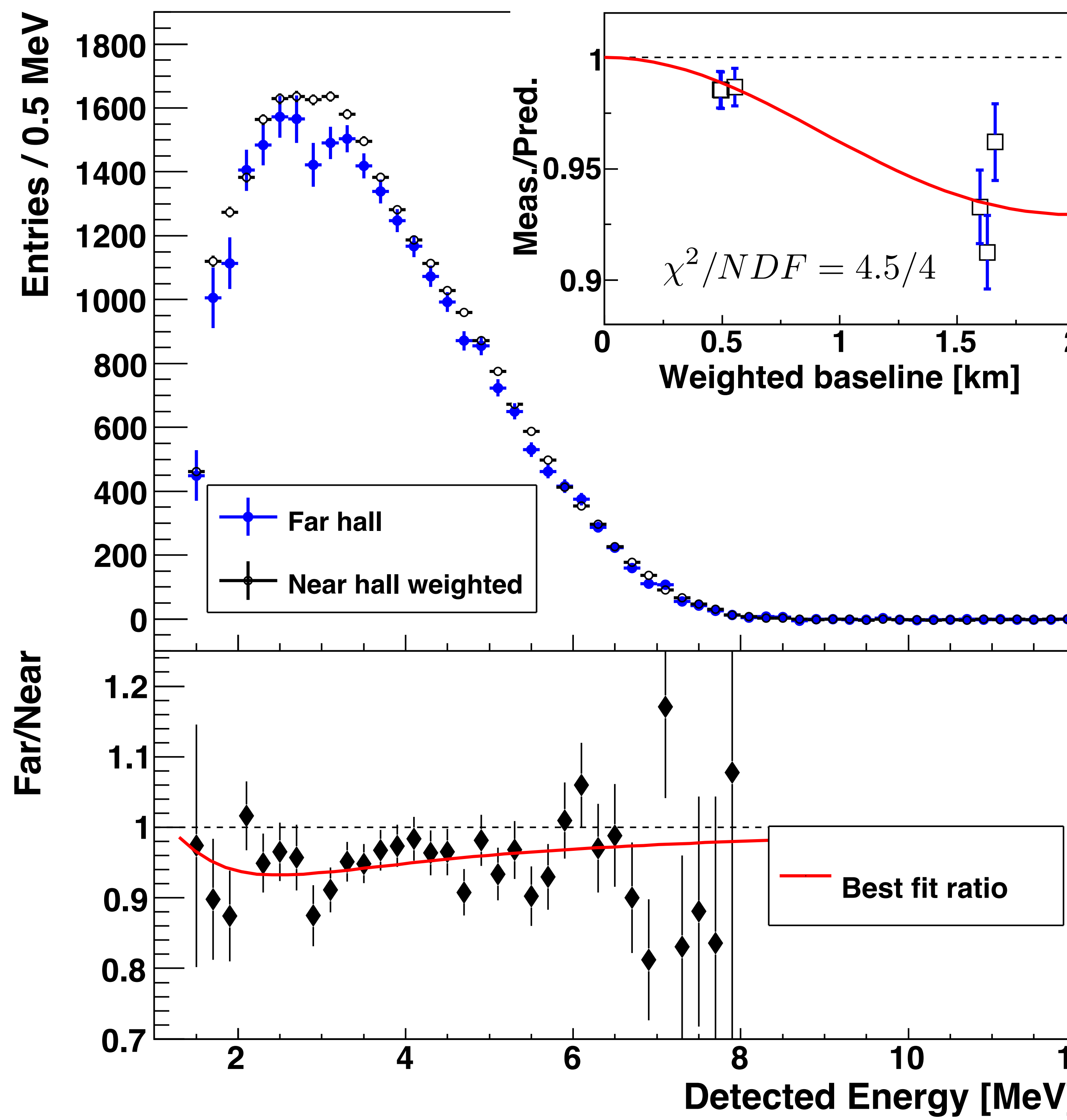


nH Analysis Results

- All 217 days of 6-AD period
- Observed significant rate deficit at far site, rate analysis measures:

  $\sin^2 2\theta_{13} = 0.083$ +- 0.018

  - an independent and consistent result with nGd analysis
  - another precise measurement of $\sin^2 2\theta_{13}$



- Spectrum distortion is consistent with oscillation explanation
  - spectral analysis in progress