Recent Results from the Daya Bay Reactor Neutrino Experiment

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On behalf of Daya Bay Collaboration

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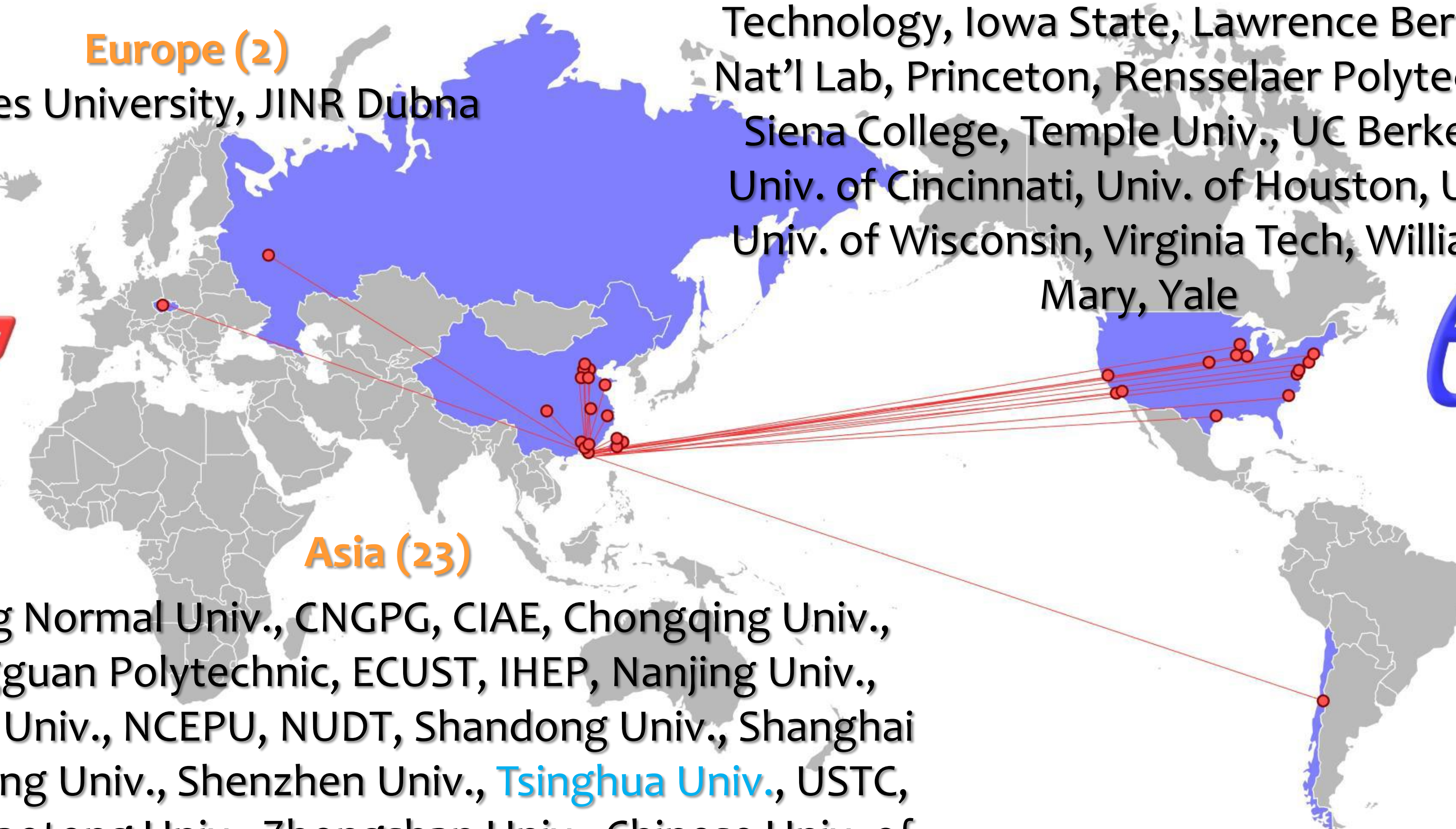
Daya Bay Collaboration

256 collaborators from 42 institutions:



Europe (2)

Charles University, JINR Dubna

North America (16)

Brookhaven Nat'l Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Nat'l Lab, Princeton, Rensselaer Polytechnic, Siena College, Temple Univ., UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

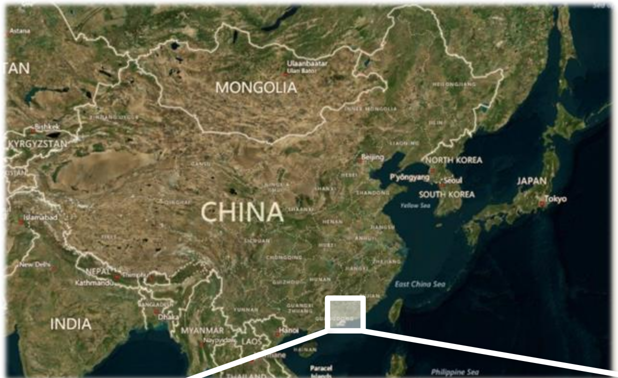
Asia (23)

Beijing Normal Univ., CNGPG, CIAE, Chongqing Univ., Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

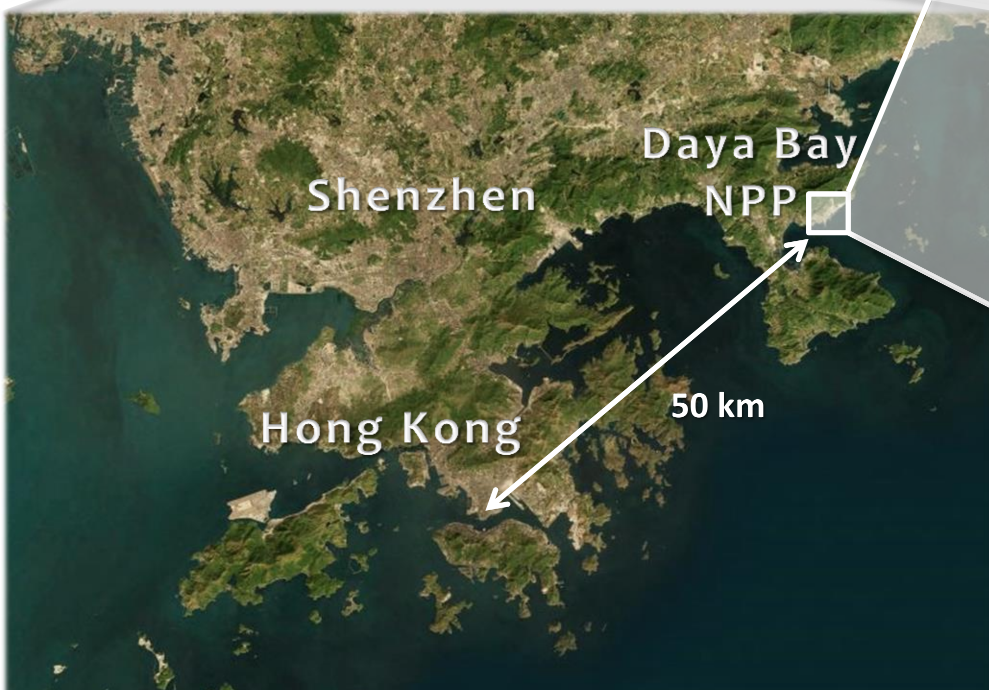
South America (1)

Catholic Univ. of Chile

Where is Daya Bay



Daya Bay Nuclear Power Plant is located in Shenzhen, southern China.



It’s about 50 km to the Victoria Harbour of Hong Kong.

Neutrino oscillation

The 3-generation neutrino oscillation framework:

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i \qquad \begin{array}{ll} \alpha = e, \mu, \tau & \text{Flavor eigenstates} \\ i = 1, 2, 3 & \text{Mass eigenstates} \end{array}$$

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

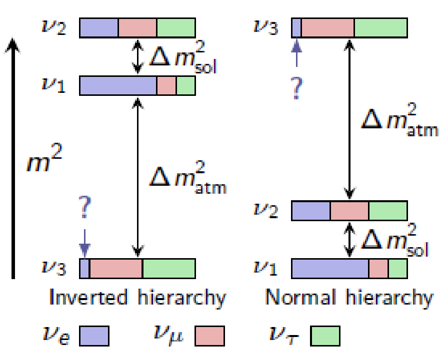
Parameters: 1 CP phase, 2 mass squared difference, 3 mixing angles

$$\delta \qquad \Delta m^2_{12}, \Delta m^2_{23} \qquad \theta_{12}, \theta_{23}, \theta_{13}$$

Remaining unknowns:

1) mass hierarchy

2) CP phase



Magnitude of θ_{13} is the signpost to the determination of these unknowns!

θ_{13} measurement with reactor

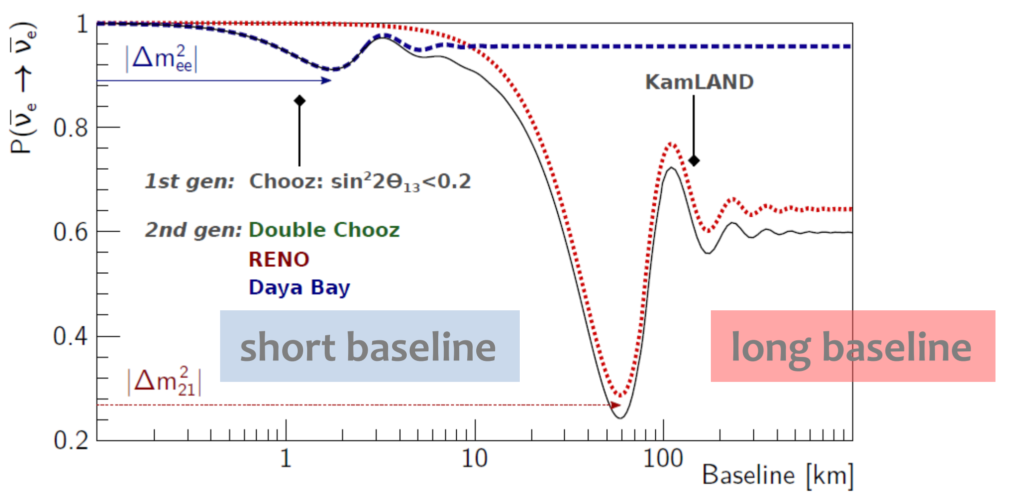
Reactor anti-neutrino survival probability

short baseline — long baseline

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

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

Reactor neutrino oscillation



θ_{13} can be revealed by deficit of reactor anti-neutrinos at ~ 2 km

Measurement method

Detection of electron antineutrino by Inverse Beta Decay (IBD)

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

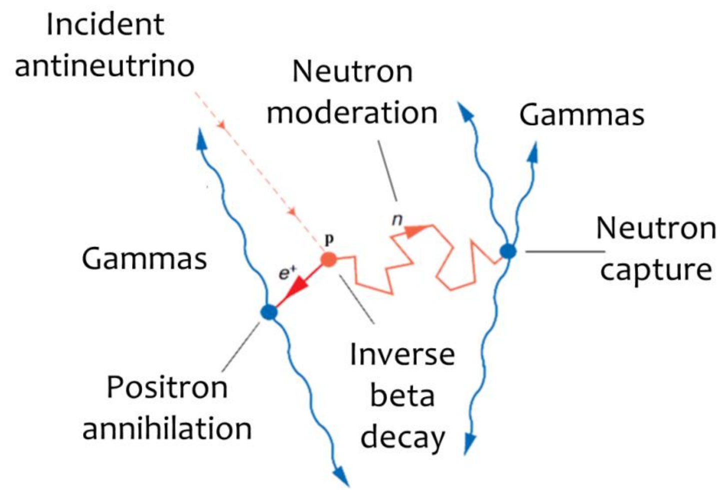
IBD

Prompt signal $e^+ + e^- \rightarrow \gamma s$

Delayed signal

$$n + p \rightarrow D + \gamma$$ 2.2 MeV 200 μs

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s$$ 8/8.5 MeV 30 μs



Extract θ_{13} from reactor antineutrino deficit

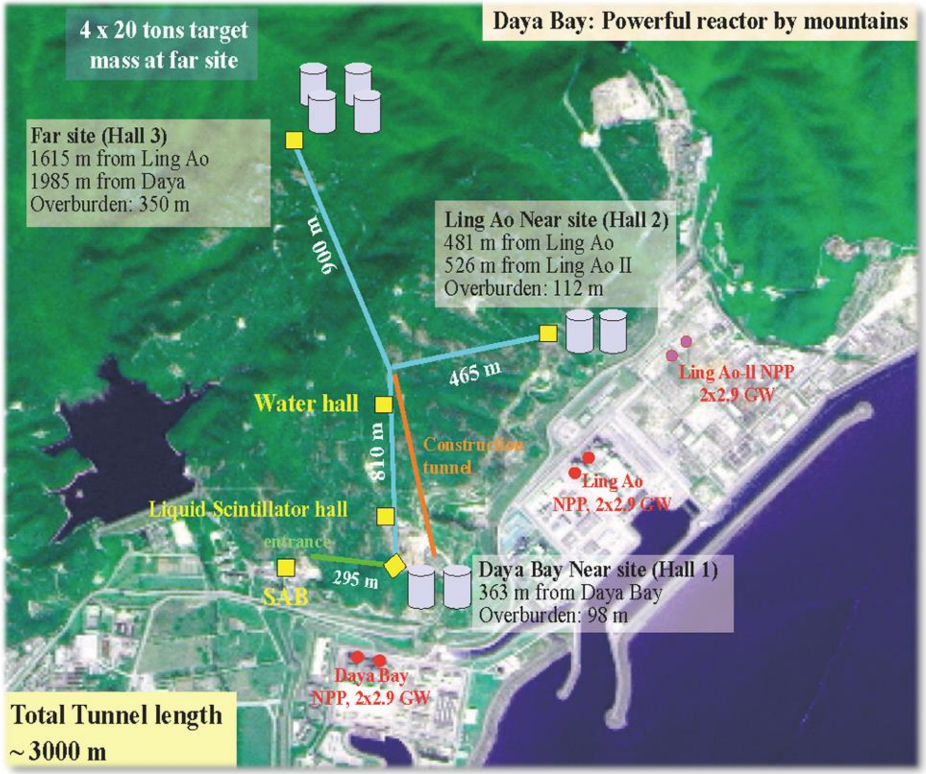
- ✓ Far/Near IBD events ratio
- ✓ IBD spectra distortion of the Far and Near sites

$$\frac{N_{\text{Far}}}{N_{\text{Near}}} = \left(\frac{N_{\text{target,Far}}}{N_{\text{target,Near}}}\right)\left(\frac{L_{\text{Near}}}{L_{\text{Far}}}\right)^2\left(\frac{\varepsilon_{\text{Far}}}{\varepsilon_{\text{Near}}}\right)\left[\frac{P_{\text{survival}}(E, L_{\text{Far}})}{P_{\text{survival}}(E, L_{\text{Near}})}\right]$$

Daya Bay experiment

High precision measurement ability with Daya Bay

- **Optimized baseline:**
  360 ~ 2000 m
- **High statistics with powerful reactor**
  6 reactor cores, 17.4 GW_{th} total power (4^{th} largest in the world)
- **Low cosmogenic background with good shielding**
  - ~250 m.w.e @ near sites
  - 860 m.w.e @ far site
- **Small reactor flux uncertainty by relative measurement**
  - 2 near sites, 1 far site
- **Small detector uncertainty with multiple identical detectors**
  - 6ADs to 8ADs since 2012 summer



Anti-neutrino Detector (AD)

Detector tanks	Inner acrylic tank (Φ3m) + Outer acrylic tank (Φ4m) + steel tank (Φ5m)
Detector liquids	20t GdLS + 22t LS + 36t MO
Photon collection	192 8" PMTs + top and bottom reflectors
Calibration system	3 Auto Calibration Units (ACU) at 3 axes with LED/AmC-Co/Ge

Automated calibration system

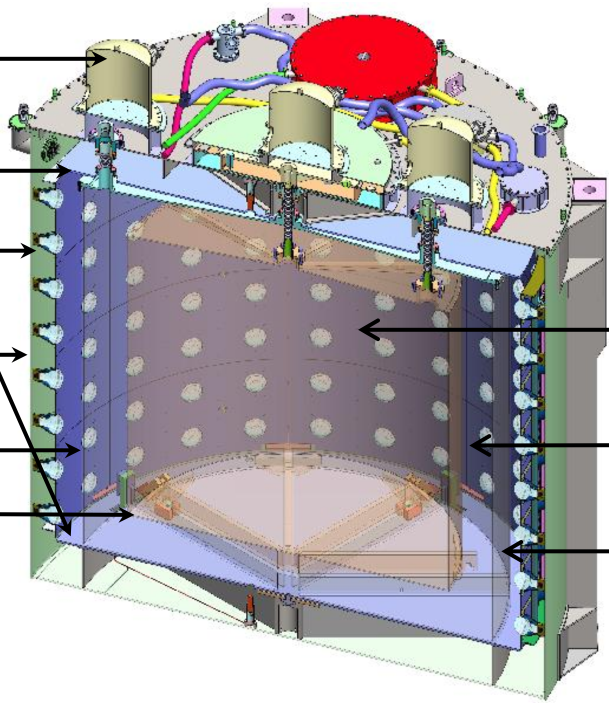
Reflectors at top/bottom of cylinder

Photomultipliers

Steel tank

Outer acrylic tank

Inner acrylic tank



target: Gd-loaded scintillator (GdLS), 20t

γ-catcher: normal scintillator (LS), 22t

buffer shielding: mineral oil (MO), 36t

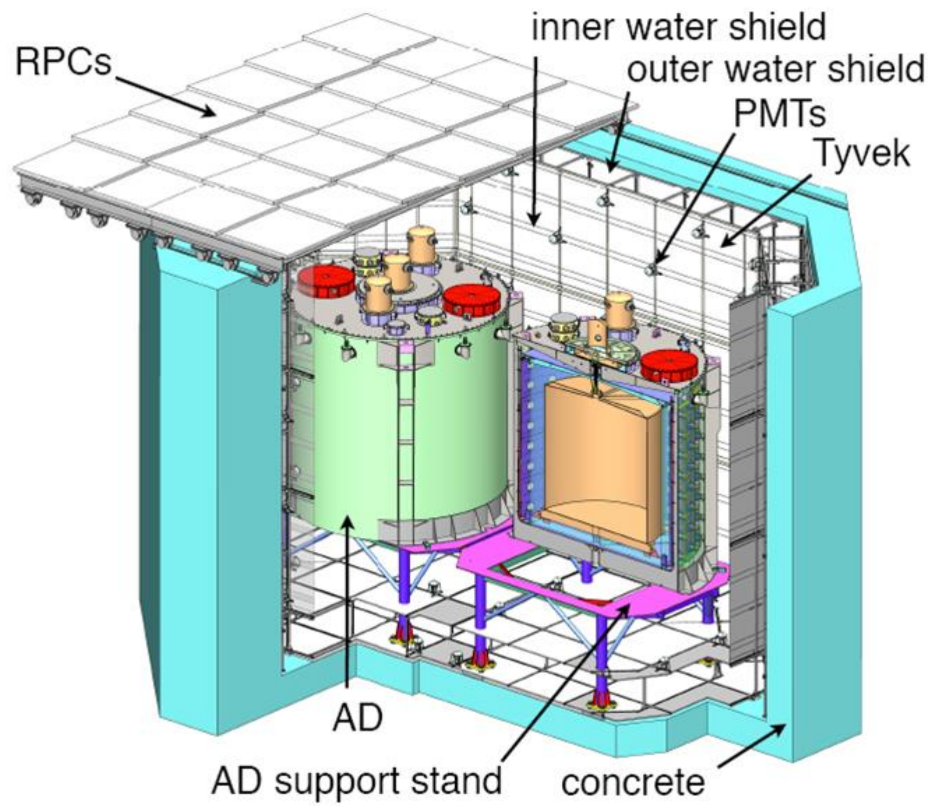
Muon Veto Detector

1. RPCs

- 4 layers/module
- 54 modules/near hall
  81 modules/far hall
- 2 telescope modules/hall

2. Water Cerenkov detector

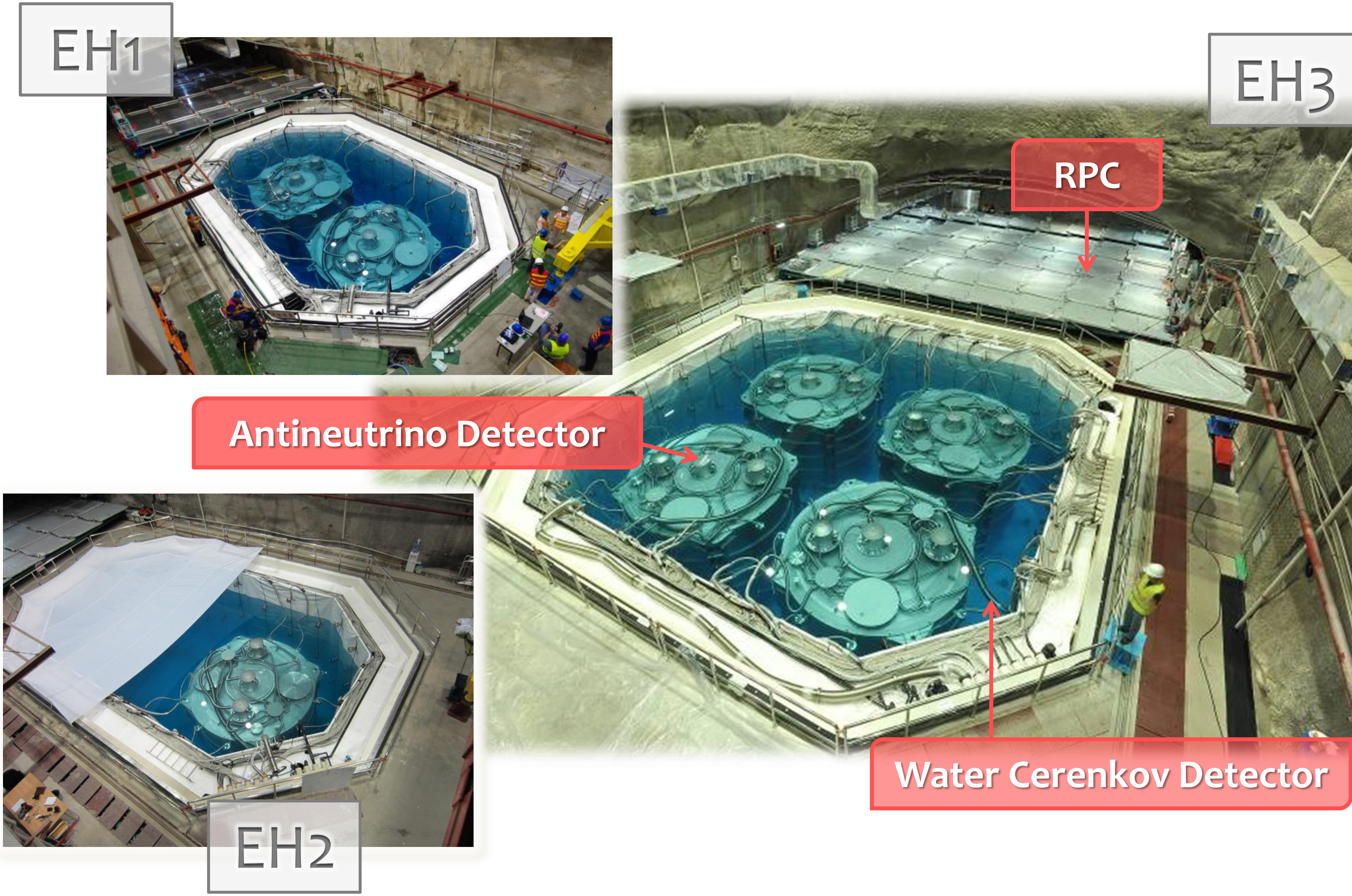
- Two layers, separated by Tyvek/PE/Tyvek film
- 288 8" PMTs for near halls
- 384 8" PMTs for the far hall



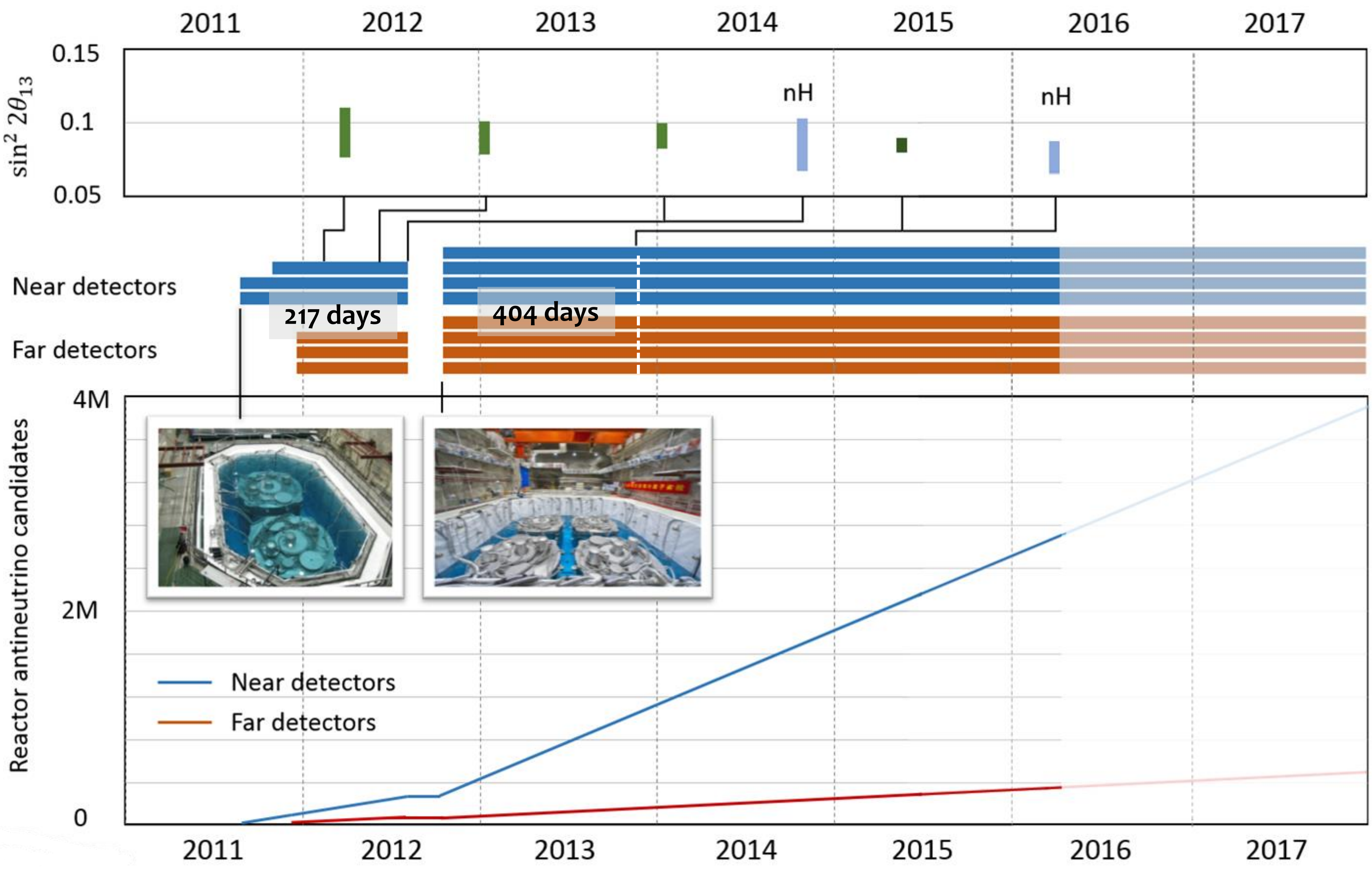
Cosmic-ray detecting efficiency

- ➢ RPC muon tracker efficiency > 88%
- ➢ Water Cerenkov detector efficiency >99.7% (long track muon)

Underground Experimental Halls

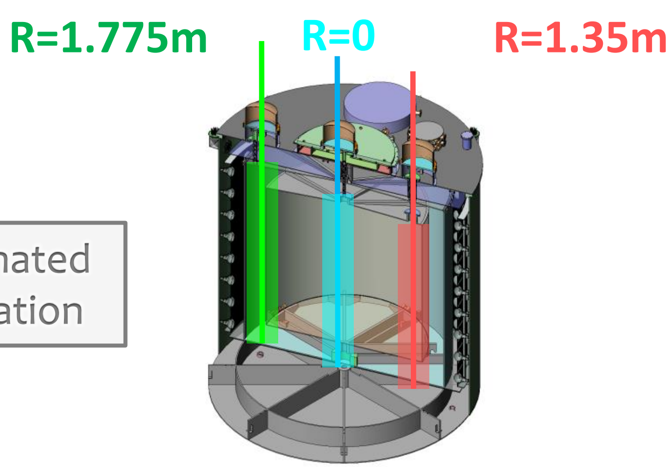


Data Collection

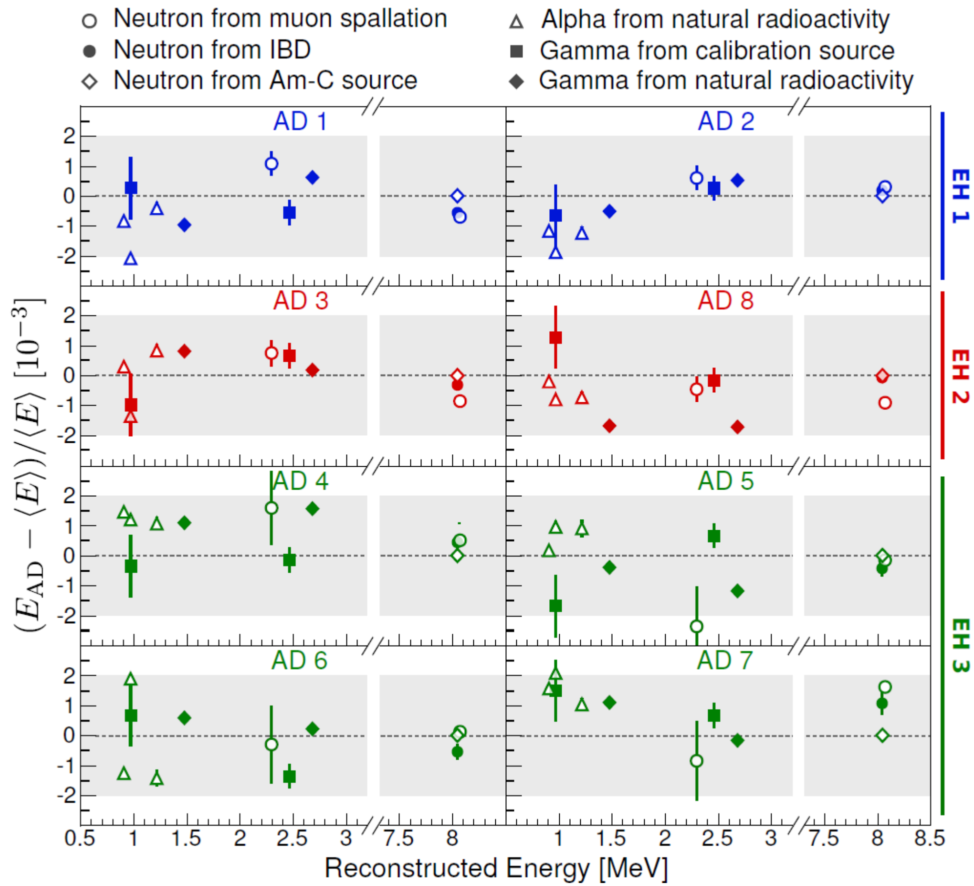


Energy calibration

- **PMT gain:**
  Single electrons from photocathode
- **Absolute energy scale:**
  Am-C at detector center
- **Time variation:**
  ^{60}Co at detector center
- **Non-uniformity:**
  ^{60}Co at different positions
- **Alternative calibration:**
  nGd events from muon spallation



Automated calibration



Relative energy scale uncertainty for nGd study: 0.2%

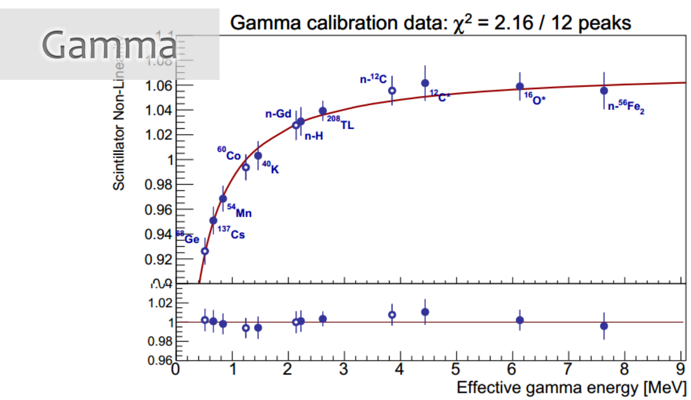
Energy non-linearity calibration

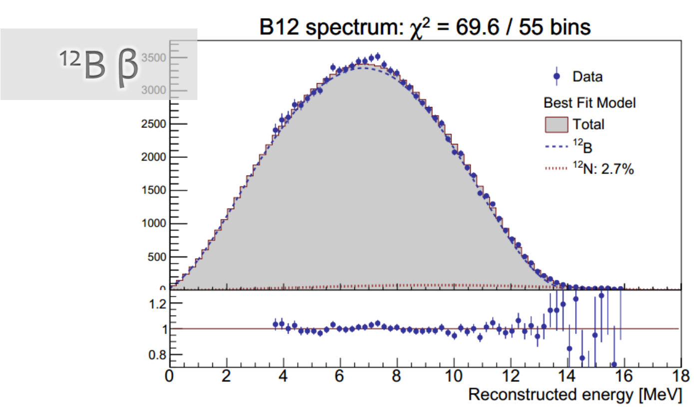
Physics driven semi-empirical non-linearity model

Scintillator nonlinearity : model based on Birks' law and Cherenkov fraction from MC
Electronics nonlinearity: model based on MC and single channel FADC measurement

Fit with data

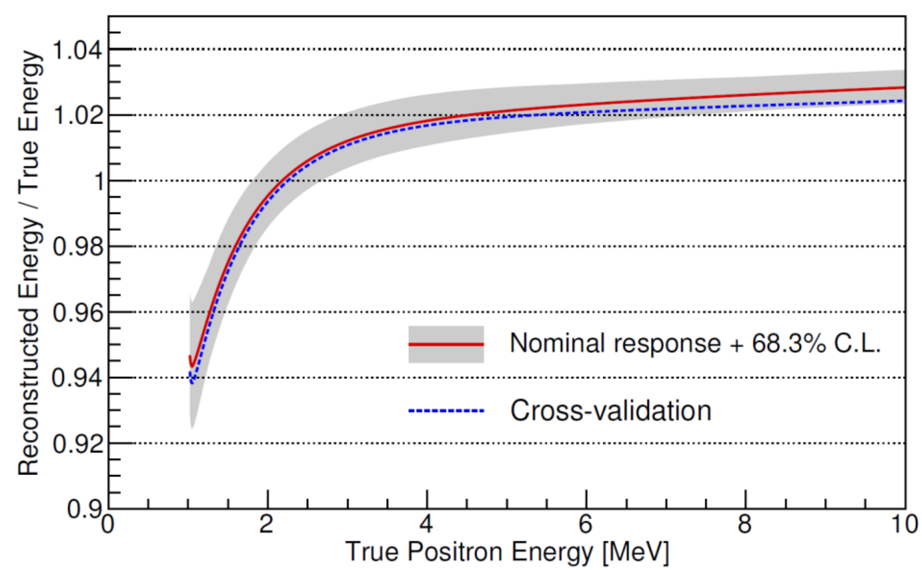
Uncertainty **<1%** above 2MeV





Nominal model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum

Cross-validation model: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron



Antineutrino candidates selection

	nGd	nH
Pool muon veto [μs]	600	400
AD muon (>20MeV) veto [μs]	1000	800
Shower muon (>2.5GeV) veto	1s	1s
Prompt Energy [MeV]	[0.7,12]	[1.5,12]
Delayed Energy [MeV]	[6,12]	peak±3σ
Capture time [μs]	[1,200]	[1,400]
Distance Cut [mm]	N/A	500

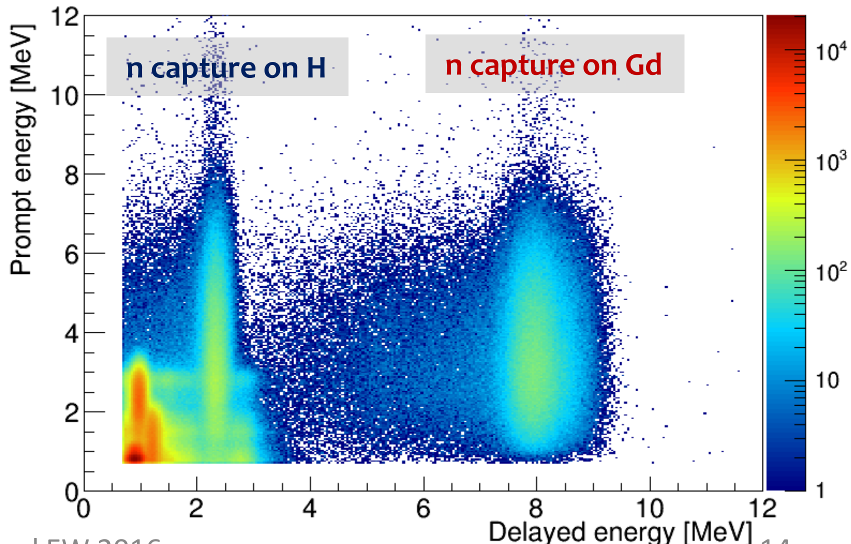
- **Reject PMT flashers firstly**
- **Muon veto**
- **Select double coincidence events with cuts**:

  Energy, Time, Distance (nH only)
- **Multiplicity cut (for nGd):**

  No other > 0.7 MeV trigger in (t_p-200 μs , t_d+200 μs)

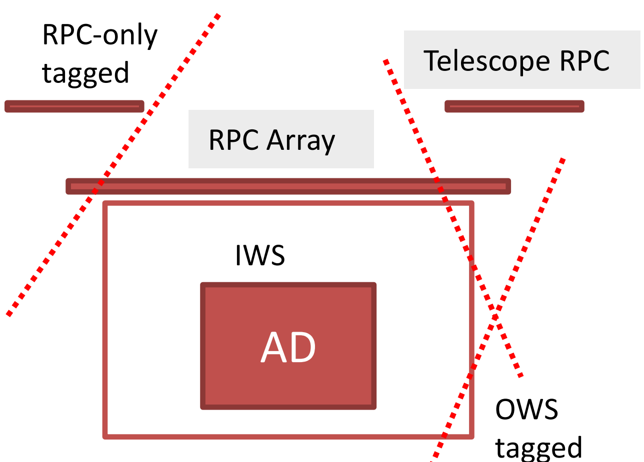
	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%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

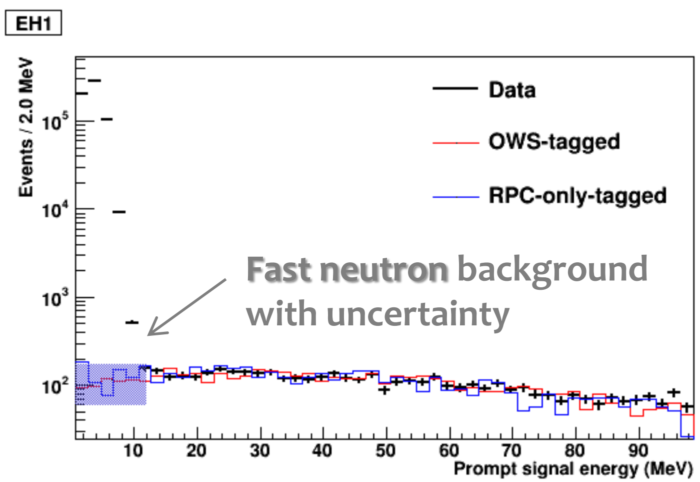
input in oscillation analysis



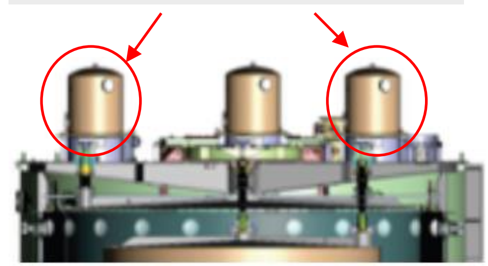
nGd signal Backgrounds

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	~1%	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	0.4%	0.4%	~50%	Measured with after-muon events	Extend to larger data set
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
Am-C source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong Am-C source	Two sources are taken out in Far site ADs
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics





Two Am-C sources removed per far AD



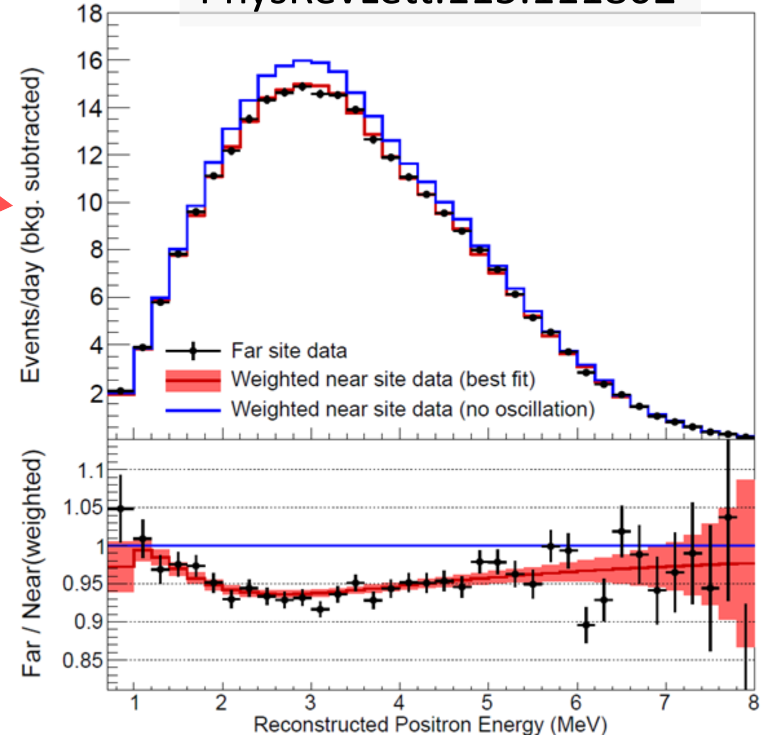
Updated nGd Oscillation Results

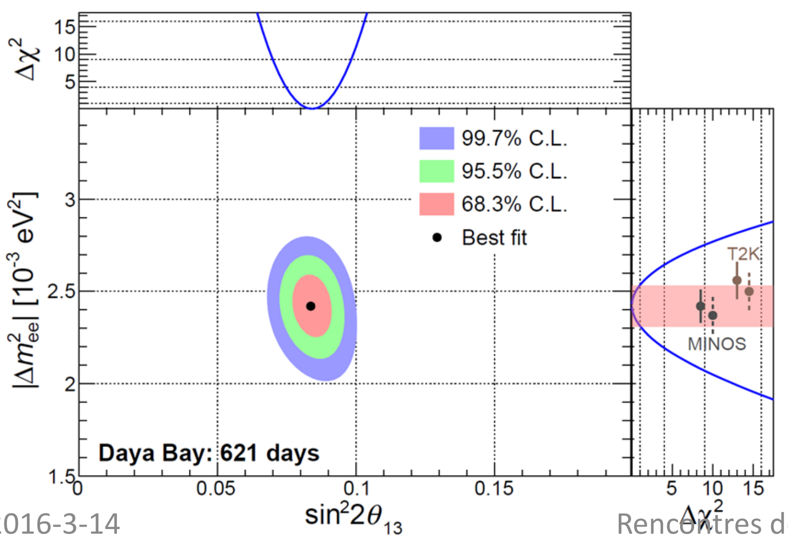
- 217 days x 6AD + 404 days x 8AD
- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: **6%**
- Precision of $|\Delta m^2_{ee}|$: **4%**

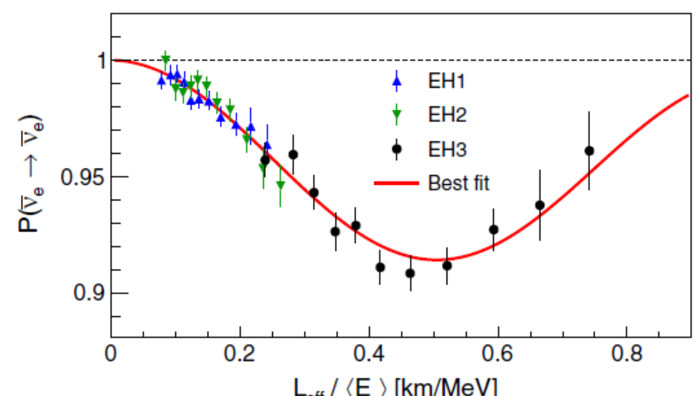
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$\left|\Delta m^2_{ee}\right| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$

PhysRevLett.115.111802



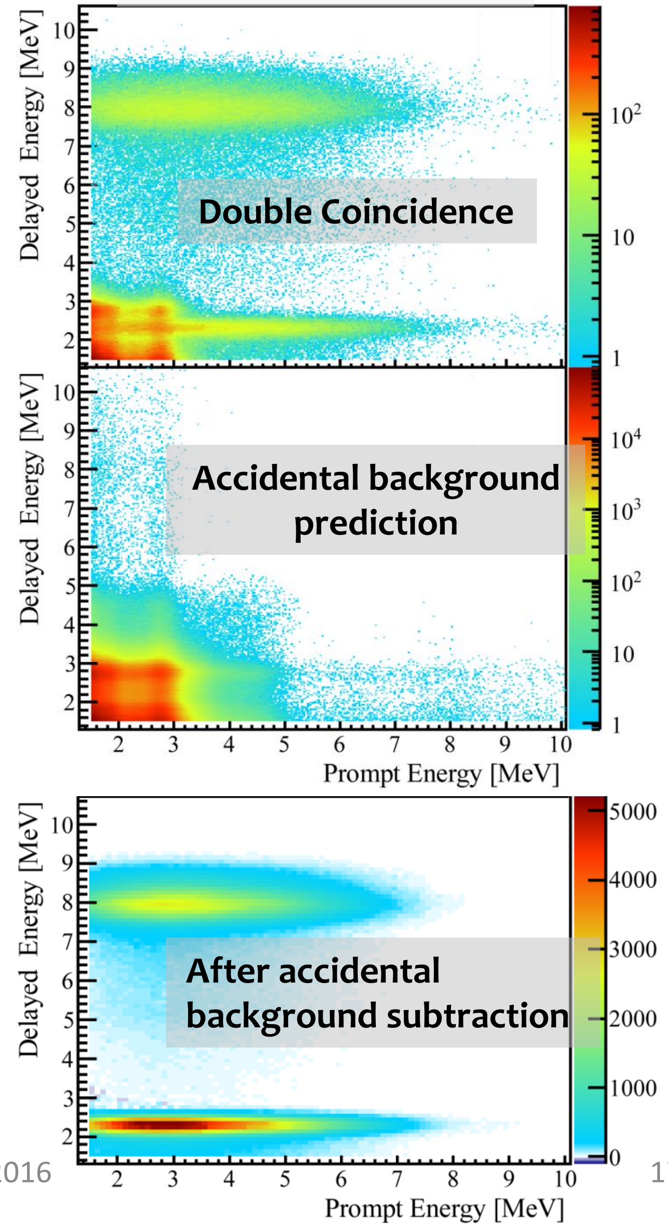




New result of independent θ_{13} with nH sample

New!

arXiv:1603.03549



Data sample:

217 days of 6AD data + 404 days of 8AD data
same as nGd analysis on last page

Key features:

- Independent statistics
- Different systematics

Challenges:

- **High accidental background** because of longer capture time and lower delayed energy
- **More energy leakage** at the edge of detector

Strategy: (data-driven analysis)

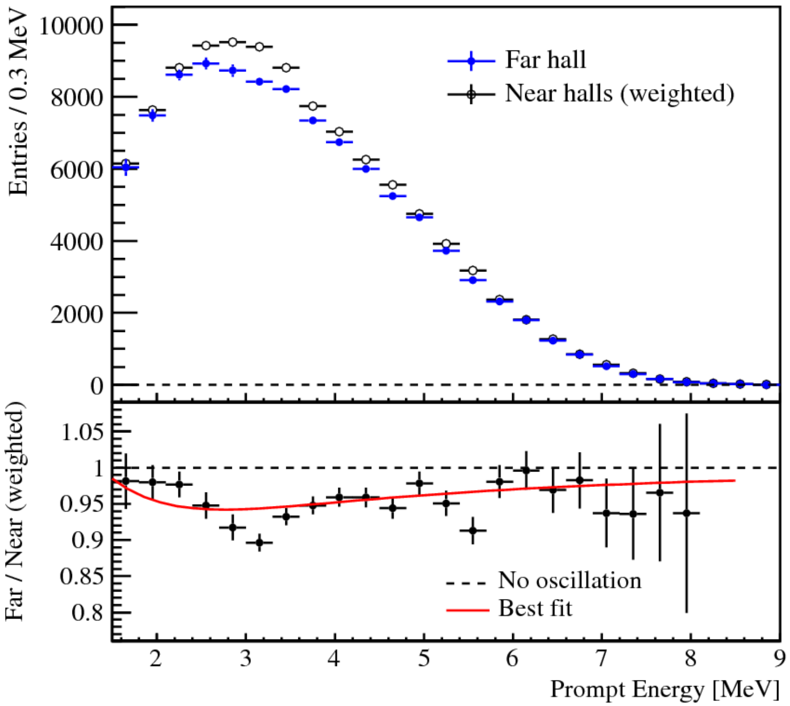
- Prompt energy cut (>1.5MeV)
- Delayed energy 3σ cut (about 1.9~2.7 MeV)
- Prompt-to-delayed distance cut (<0.5m)
- Precise accidental background subtraction (detail in backup)

New result of independent θ_{13} with nH sample

arXiv:1603.03549

Improvement compared with 6AD period result (PRD 90, 071101)

- The dominant **statistical uncertainty** was reduced by **49%**
- **The systematic uncertainty** was reduced by **26%** by intensive study of:
  1. cosmogenic muon-induced background (^{9}Li and fast neutron)
  2. neutron capture energy selection efficiency



Oscillation analysis based on rate information

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

nH and nGd combined result

arXiv:1603.03549

Correlations between the two analyses were estimated for **efficiencies, backgrounds,** and **reactor-related quantities.**

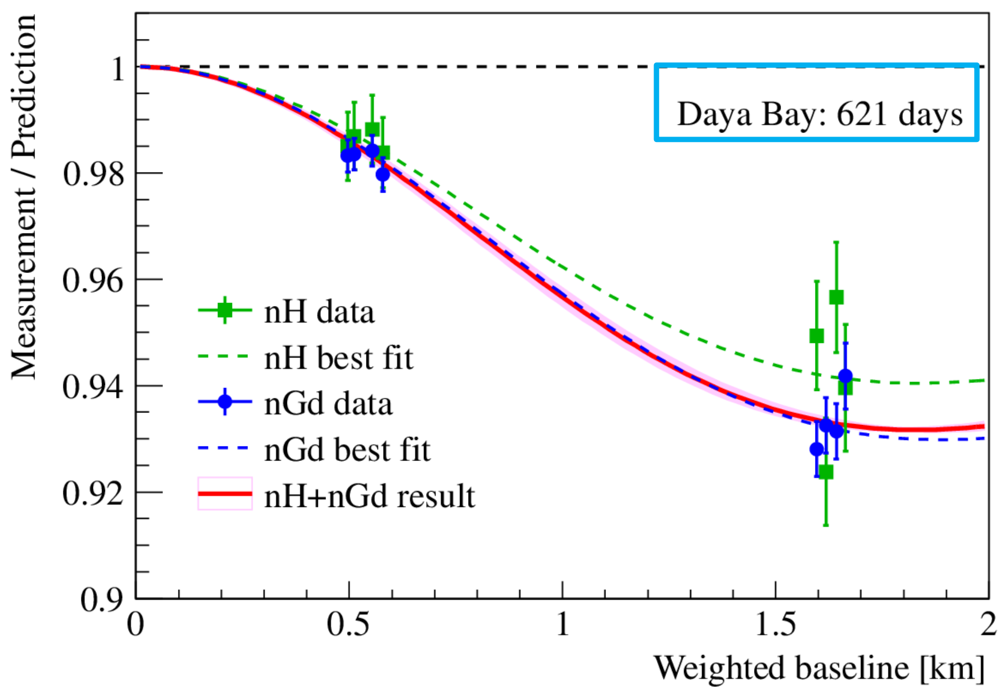
An overall correlation coefficient of **0.02** indicates the independence of the two analyses (detail in backup)

Combine the nGd result with nH

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011 \quad \text{(nH)}$$

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005 \quad \text{(nGd)}$$

$$\sin^2 2\theta_{13} = 0.082 \pm 0.004 \quad \text{(Combined)}$$



Absolute Reactor Flux Measurement

Using nGd sample

PhysRevLett.116.061801

Absolute flux and spectrum are measured with the absolute detection efficiency and energy scale. Correlated uncertainties are used, **different from θ_{13} study**

3-AD (near sites) measurement with 217 days of data

IBD yield

$$Y = (1.55 \pm 0.04) \times 10^{-18} cm^2 / GW / day$$

$$\sigma_f = (5.92 \pm 0.14) \times 10^{-43} cm^2 / \ fission$$

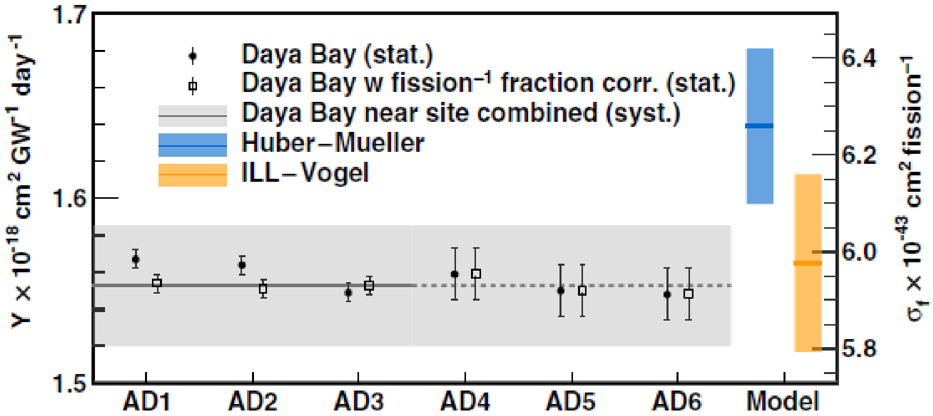
Compare to flux models

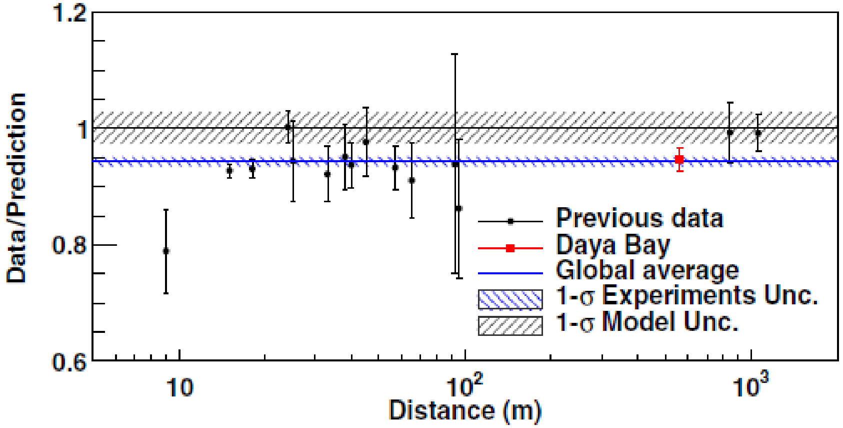
- Data/Prediction (Huber+Mueller)

  0.946 ± 0.022

- Data/Prediction (ILL+Vogel)

  0.991 ± 0.023





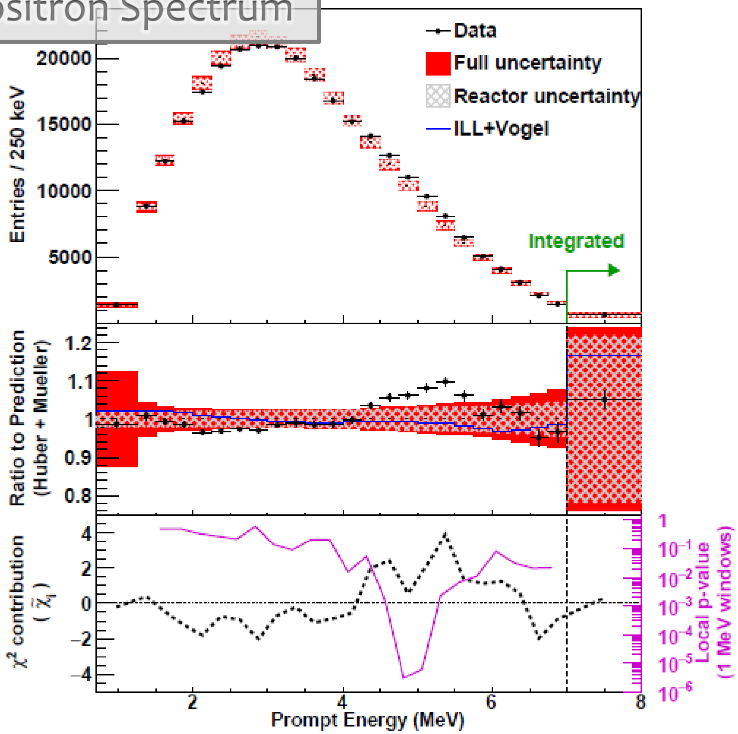
Measurement consistent with previous short baseline experiments

Reactor Antineutrino Spectrum Measurement

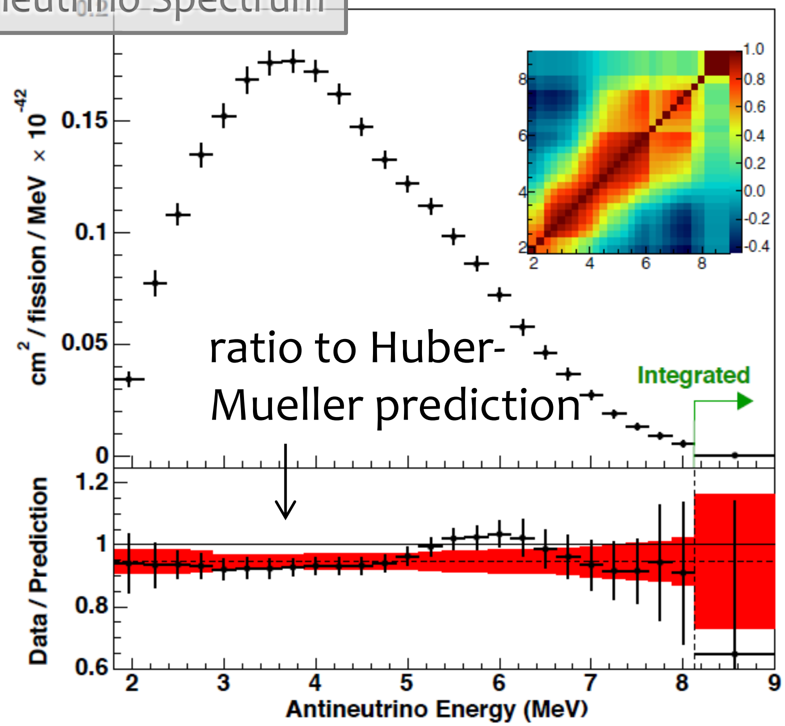
Using nGd sample

PhysRevLett.116.061801

Positron Spectrum



Antineutrino Spectrum



Absolute positron spectral shape is **NOT consistent** with the prediction.
Discrepancy in 4-6 MeV region reached ~**4σ** deviation

Extract antineutrino spectrum by applying detector response model unfolding.
Can be **directly used** as a reference spectrum for other reactor experiments and the theorists

Summary

Updated reactor antineutrino oscillation results using nGd sample with full experimental configuration (8 ADs), 621 days' data

$\sin^2 2\theta_{13}$ precision 6% $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

$|\Delta m^2_{ee}|$ precision 4% $\left|\Delta m^2_{ee}\right| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$

Independent oscillation measurement with nH sample, 621 days' data

New!

Oscillation analysis of rate $\sin^2 2\theta_{13} = 0.071 \pm 0.011$

Combination of the nGd and nH results with 621 days' data

$$\sin^2 2\theta_{13} = 0.082 \pm 0.004$$

Precise measurement of the reactor antineutrino flux and spectrum with nGd sample, 217 days' data

- Flux is consistent with previous short baseline experiments
- Spectrum is **NOT consistent** with prediction at **4σ** level in **4-6 MeV** (5-7 MeV) positron (antineutrino) energy region

Experiment will continue to operate until 2017

We expect to have more precise measurement of $\sin^2 2\theta_{13}$, $|\Delta m^2_{ee}|$ and antineutrino spectrum. Other results would come as well.

Thank you!

Backup

Non-linearity semi-empirical model

Non-linearity comes from scintillator (quenching + Cerenkov) and electronics

$$\frac{E_{rec}}{E_{true}} = \frac{E_{vis}}{E_{true}} \frac{E_{rec}}{E_{vis}} = A f_{scintillator} f_{electronics}$$

The model has 5 parameters in total

1. Absolute energy scale
2. Birks constant k_B and Cerenkov constribution at 1 MeV k_C

   $f_{\text{scintillator}} = f_q(E_{\text{true}}, k_B) + k_C \cdot f_C(E_{\text{true}})$
3. Size α and decay constant τ of electronics response

   $f_{\text{electronics}} = \alpha \cdot \exp(-E_{\text{vis}}/\tau) + 1$

$$f_q(E_{true}; k_B) = \frac{E_{quenched}}{E_{true}} = \frac{1}{E_{true}} \int_0^{E_{true}} \frac{1}{1 + k_B \cdot \frac{dE}{dx}} \cdot dE$$

$$f_C(E_{true}) \propto \frac{1}{E_{true}} \int_{\omega_1}^{\omega_2} \int_{E_{threshold}}^{E_{true}} \frac{\alpha}{\frac{dE}{dx}} \left(1 - \frac{1}{\beta^2(E_e) \cdot n^2(\omega)}\right) dE_e \, d\omega$$

Accidental background subtraction for nH sample

- Select single events (not passing coincidence selection)
- Make random pairs of single events (> 10 h separation) → $N_{\text{ABS-Total}}$
- Pass the same IBD cut → $N_{\text{ABS-cut}}$
- Accidental background rate and entries:

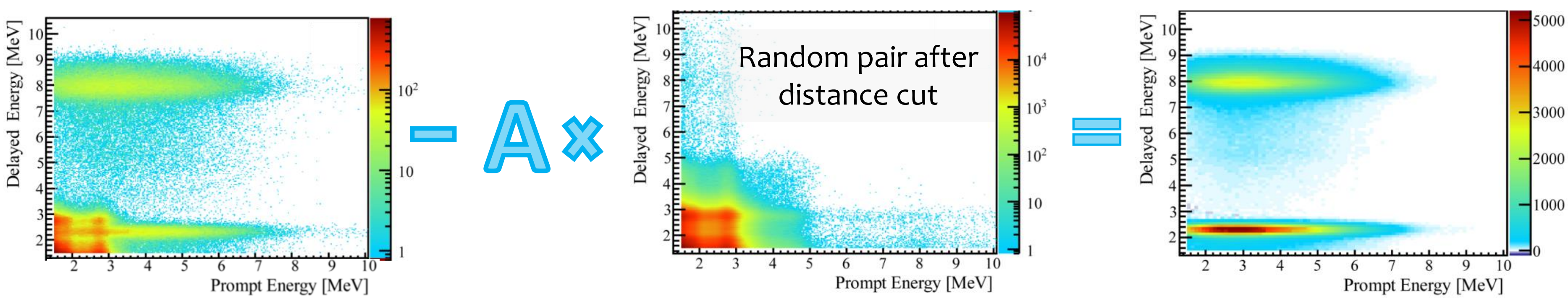
$$R_{AccBkg} \approx R_S e^{-R_S T_C} \cdot R_S T_C e^{-R_S T_C}$$

$$N_{AccBkg} = R_{AccBkg} T_{\text{livetime}} \varepsilon_{\text{muonveto}} \varepsilon_{\text{AccBkg-cut}}$$

$$A = R_{AccBkg} T_{\text{livetime}} \varepsilon_{\text{muonveto}} \varepsilon_{\text{AccBkg-distance}} \, / \, N_{\text{ABS-distance}}$$

Rs: genuine single rate
Rμ: muon rate
Tc: coincidence window

$$\varepsilon_{\text{AccBkg-cut}} = N_{\text{ABS-cut}} / N_{\text{ABS-Total}}$$



Rs is got from average event rate before and after removing coincidence events. Their differences induce **0.18%**, **0.16%** and **0.05%** uncertainty for EH1, 2 and 3 accidental background respectively.

nH and nGd result correlation

nH analysis uncertainty budget

	Uncertainty (%)	Correlation
Target protons ($N_{p,\mathrm{GdLS}}$)	0.03	1
Target protons ($N_{p,\mathrm{LS}}$)	0.13	0
Target protons ($N_{p,\mathrm{Acrylic}}$)	0.50	-
Prompt energy (ε_{E_p})	0.10	1
Coincidence time (ε_T)	0.14	1
Delayed energy (ε_{E_d})	0.35	0.07
Coincidence distance (ε_D)	0.40	0
Combined (N_ε)	0.57	0.07

Correlation with nGd events, used in the combination with nGd result

Correlation of nH and nGd analysis

	Uncertainty Fraction (%)	Correlation
Statistical	51.8	0
Detector	39.2	0.07
Reactor	4.2	1
^{9}Li/^{8}He	4.4	0
Accidental	0.4	0
Fast neutron	0.3	0
Am-C	0.1	0.7
Combined	100.4	0.02

An overall correlation coefficient of **0.02** indicates the independence of the two analyses

Search for light sterile neutrinos

PRL 113, 141802 (2014)

- **An unique opportunity for sterile neutrino searches**
  - Sterile neutrino would introduce additional oscillation mode.
  - Relative measurement at multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2(\Delta m^2_{41} \frac{L}{4E}) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E})$$

- **Oscillation analysis**
  - No significant signal observed, consistent with 3-flavor neutrino oscillation.
  - Set most stringent limit at $10^{-3}\text{eV}^2 < \left|\Delta m^2_{41}\right| < 0.1\text{eV}^2$