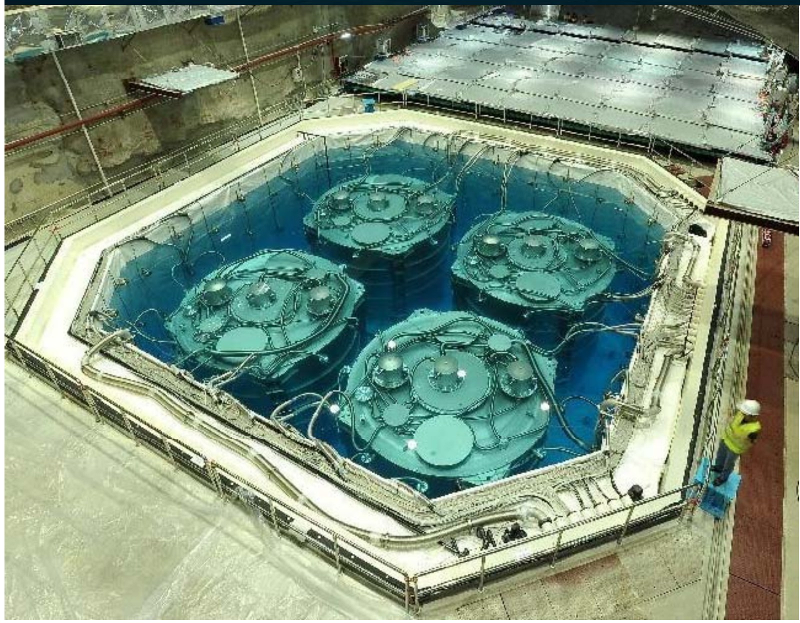
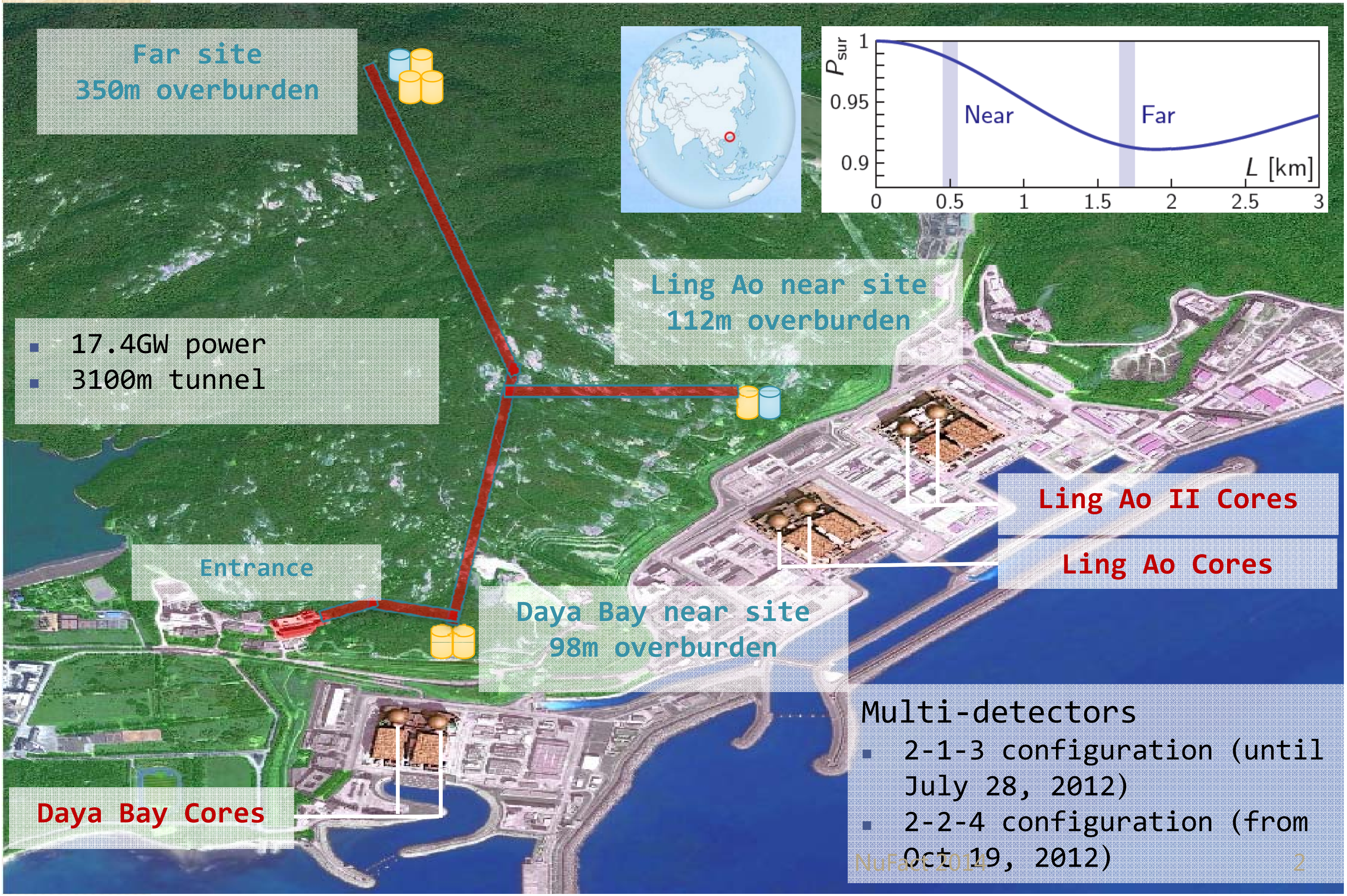
Recent oscillation analysis results from Daya Bay



Jie Zhao
(Institute of High Energy Physics)
On behalf of the Daya Bay collaboration

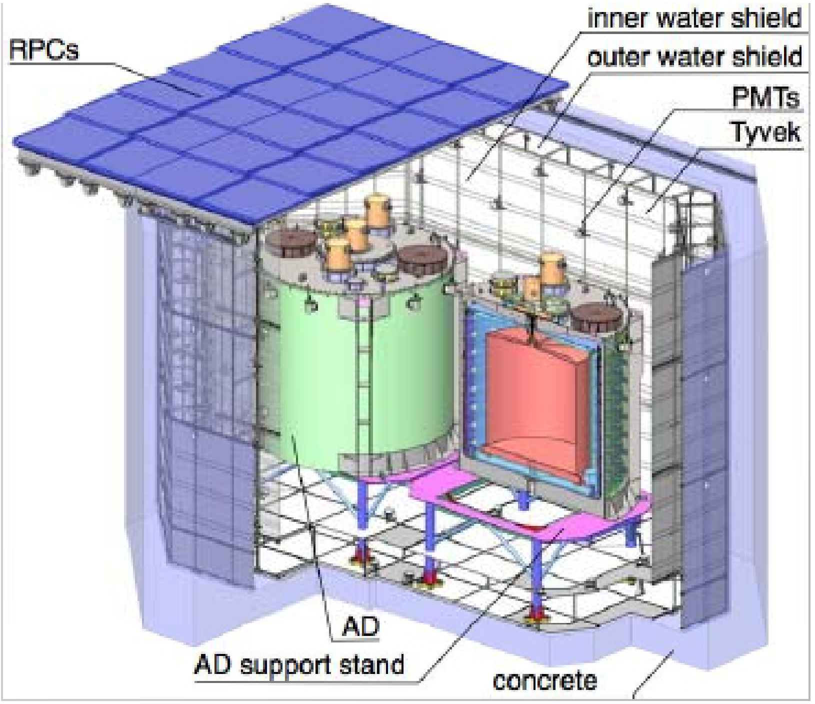
NuFact 2014, Glasgow Scotland
August 29, 2014

The Daya Bay experiment



- 17.4GW power
- 3100m tunnel

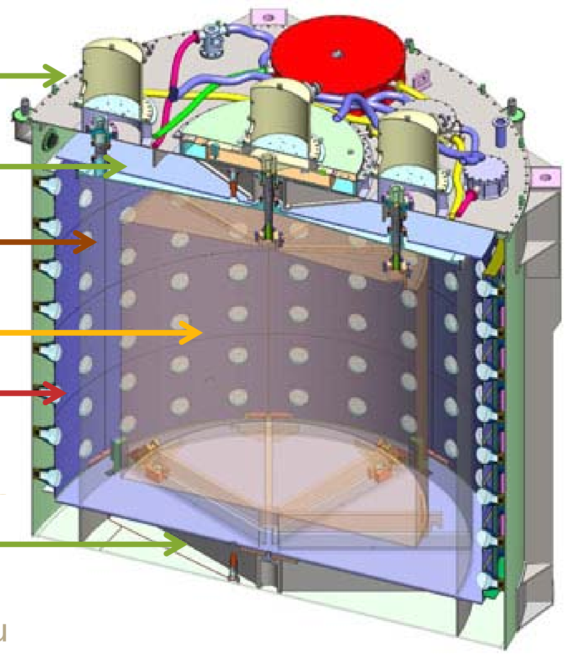
Multi-detectors
- 2-1-3 configuration (until July 28, 2012)
- 2-2-4 configuration (from Oct 19, 2012)



Layout of the detectors

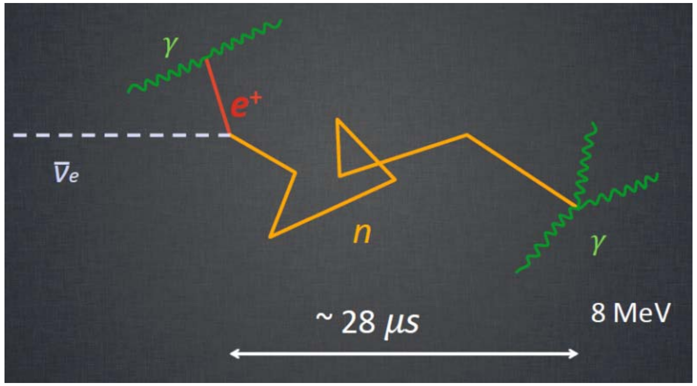
- Far-near relative measurement
- Eight identical antineutrino detectors (ADs)
- Multiple muon tagging system (RPC+IWS+OWS)

* Calibration unit
* 20t LS
* 20t Gd-LS
* 37t Mineral Oil
* Reflector



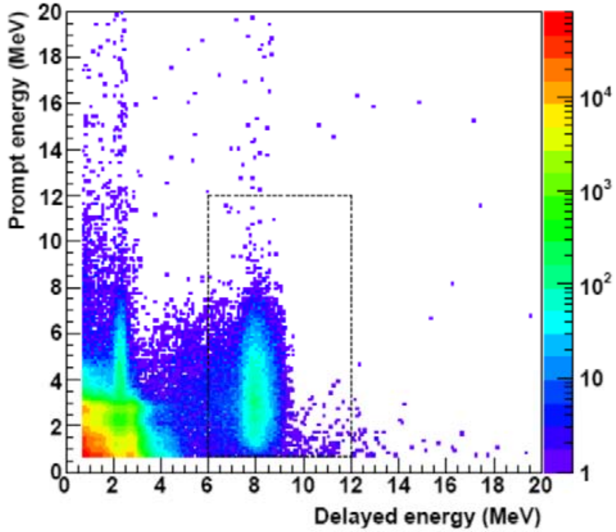
Antineutrino candidates selection(IBD)

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



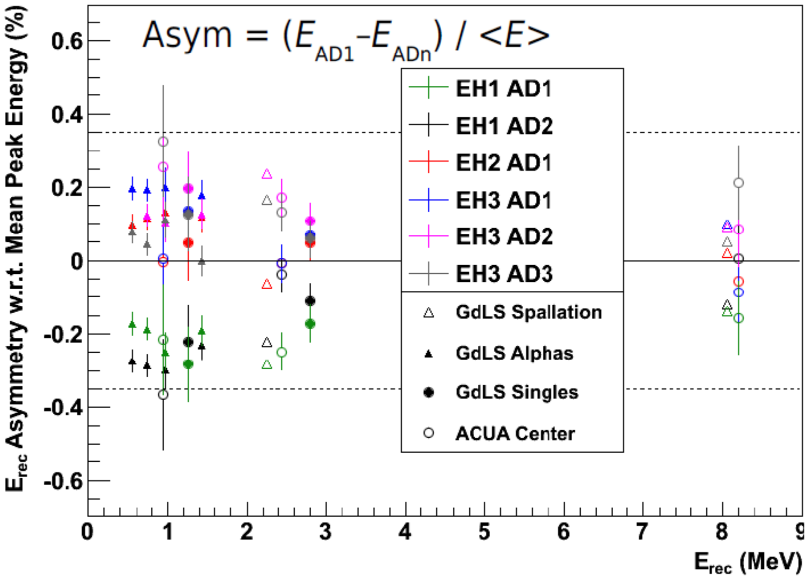
- Reject PMT flashers
- Muon veto:
  - Water pool Muon: reject 0.6ms
  - AD Muon (>20MeV): reject 1ms
  - AD shower Muon (>2.5GeV): reject 1s
- Prompt positron energy: 0.7MeV<Ep<12MeV
- Delayed neutron energy: 6MeV<Ed<12MeV
- Neutron capture time: 1us<Δt<200us
- Multiplicity cut:
  - only select isolated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

	Efficiency	Uncertainty Correlated	Uncertainty 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%

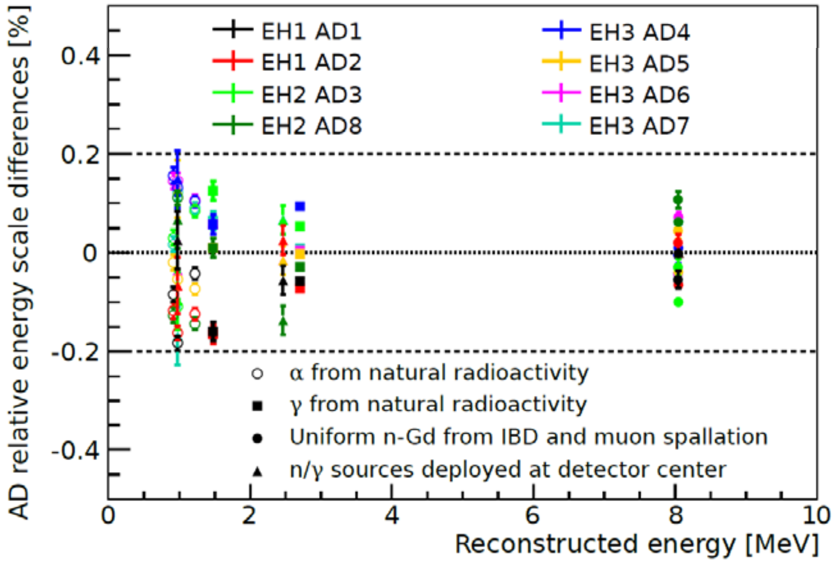


Relative energy scale

6AD



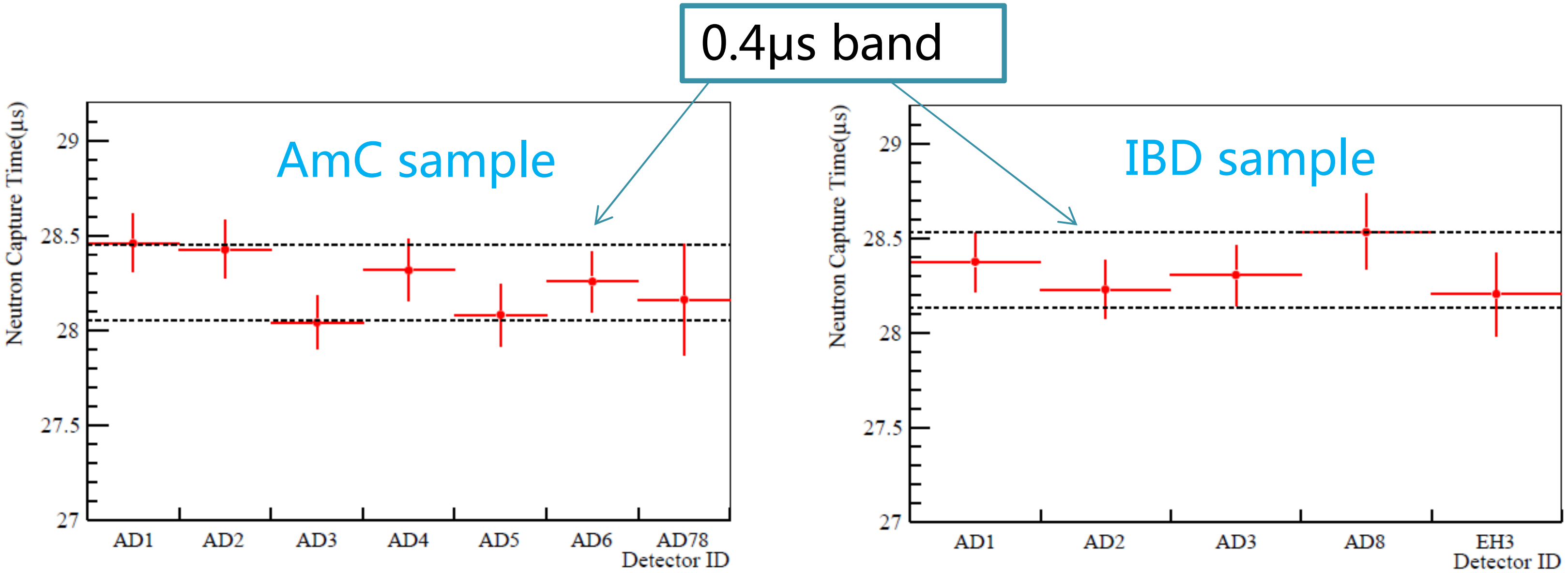
6+8AD



ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{216}Po

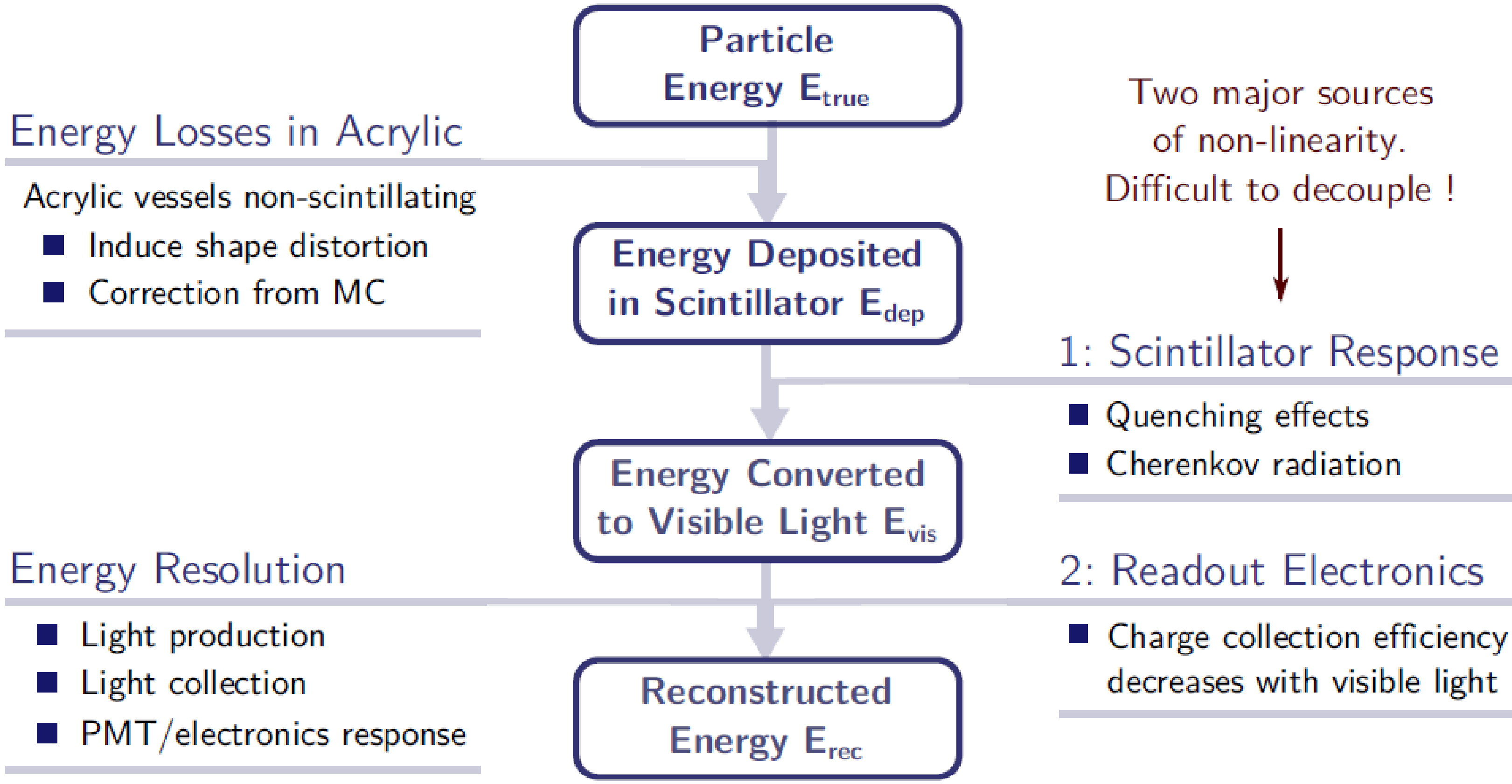
- < 0.2% variation in reconstructed energy between ADs
- Improved from 0.35% in 2013 which was between 6 detectors.

Gd capture fraction



- <0.2μs variation in time interval for both IBD and AmC between ADs
- 0.2μs variation will lead to 0.1% uncertainty of Gd capture fraction.

Overview of the energy response model



- Model maps reconstructed energy E_{rec} to true kinetic energy E_{true}
  - Minimal impact on oscillation measurement
  - Crucial for measurement of reactor spectra

Overview of the energy response model

Total effective non-linearity f

$$f = \frac{E_{\text{rec}}}{E_{\text{true}}} = \frac{E_{\text{vis}}}{E_{\text{true}}} \times \frac{E_{\text{rec}}}{E_{\text{vis}}} = f_{\text{scint}}(E_{\text{true}}) \times f_{\text{elec}}(E_{\text{vis}})$$

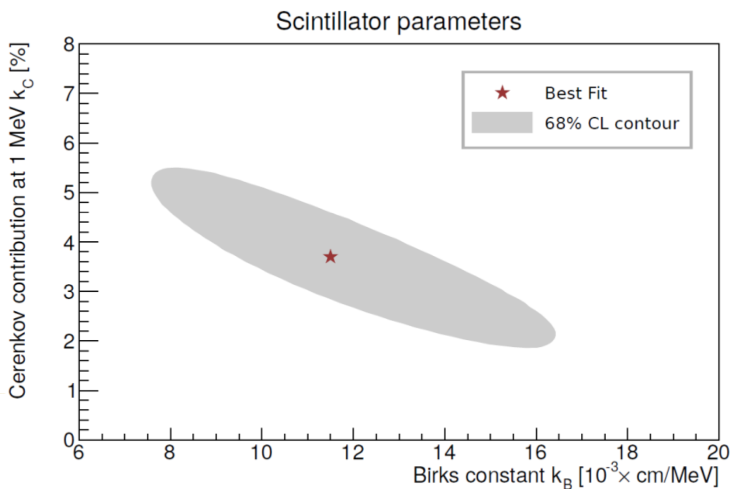
1 Scintillator non-linearity ($E_{\text{vis}}/E_{\text{true}}$)

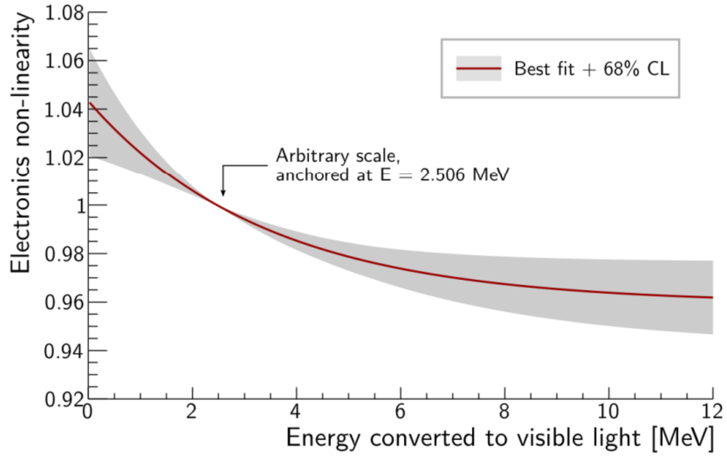
2 Electronics non-linearity ($E_{\text{rec}}/E_{\text{vis}}$)

- Non-linear response from liquid scintillators
  - Semi-empirical electron response model based on Birks law

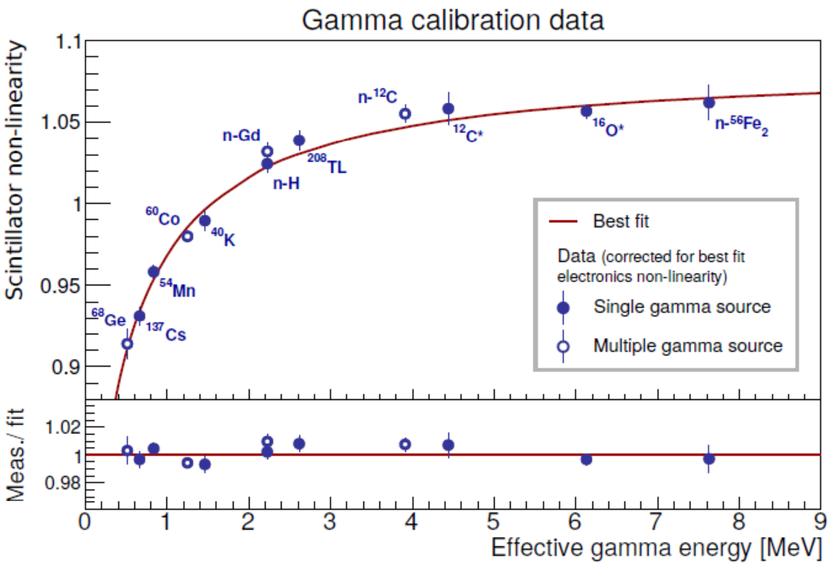
$$\frac{E_{\text{vis}}}{E_{\text{true}}} = f_{\text{q}}(E_{\text{true}}, k_B) + k_C \cdot f_c(E_{\text{true}})$$

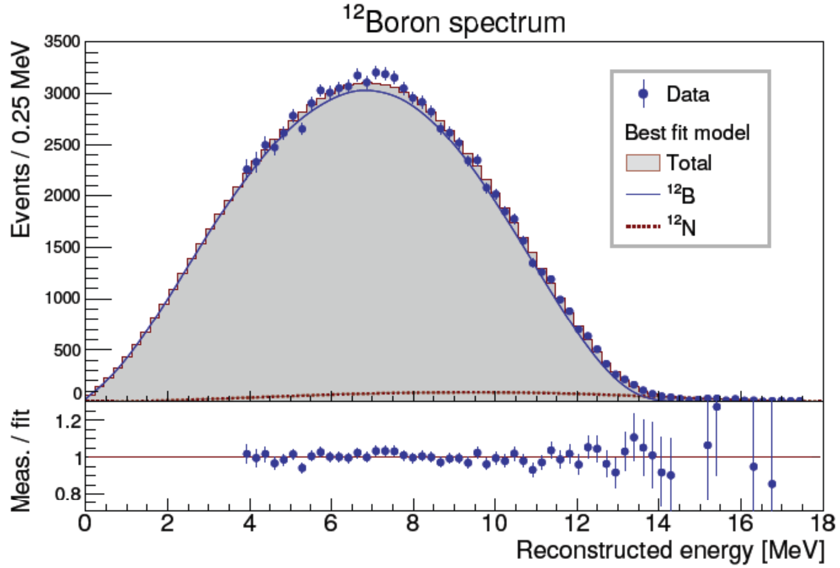
- Non-linear response from PMT readout electronics
  - Use effective exponential model as a function of total visible energy
  - Two parameters: size and decay constant





Constraining the Non-Linearity Parameters

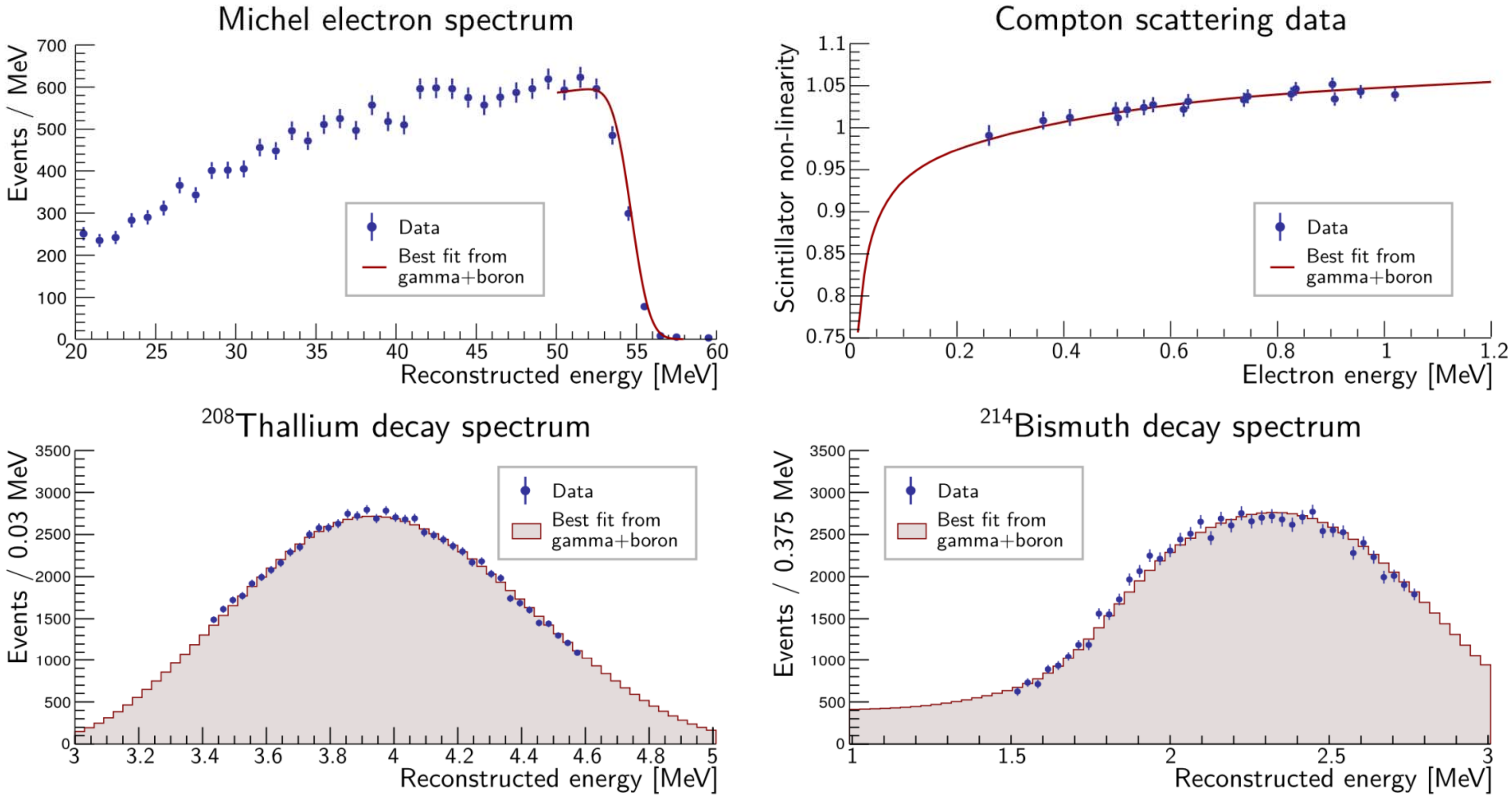




- Unconstrained 5-parameter fit to γ+^{12}B data
  - Absolute energy scale
  - Birks constant, relative contribution from Cherenkov light
  - Size and decay constant from readout electronics
- Gammas are connected to electron scintillator model through MC

$$E^{\gamma}_{\mathrm{vis}} = \int E^{e^-}_{\mathrm{vis}}\left(E^{e^-}_{\mathrm{true}}\right) \cdot \frac{dN}{dE}\left(E^{e^-}_{\mathrm{true}}\right) dE^{e^-}_{\mathrm{true}}$$

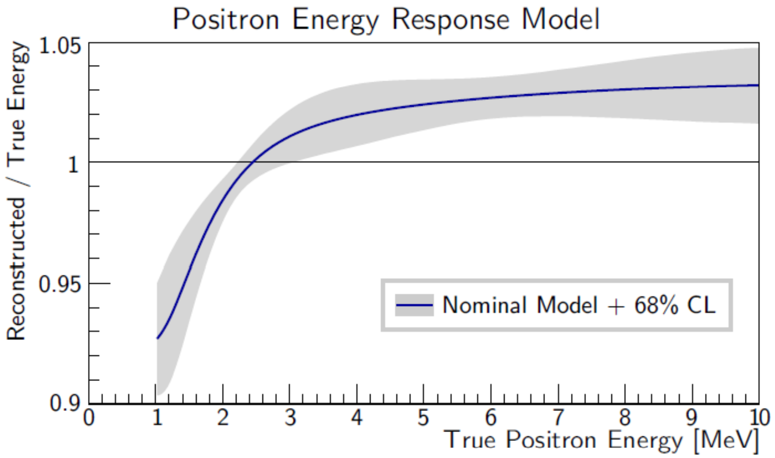
Validation with additional calibration data



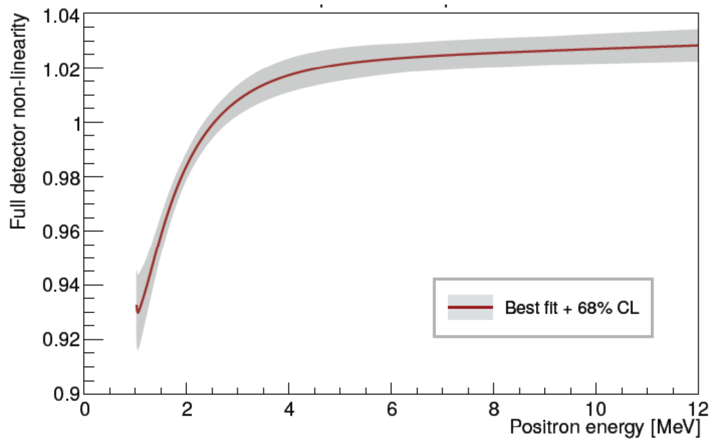
- 53MeV cutoff in michel electron spectrum from muon decays
- Continuous beta+gamma spectra from ^{214}Bi and ^{208}Th
- Benchtop scintillator response measurement using compton electrons
- Calibration of readout electronics response using flash ADC

Improvement on non-linearity

Old model



New model



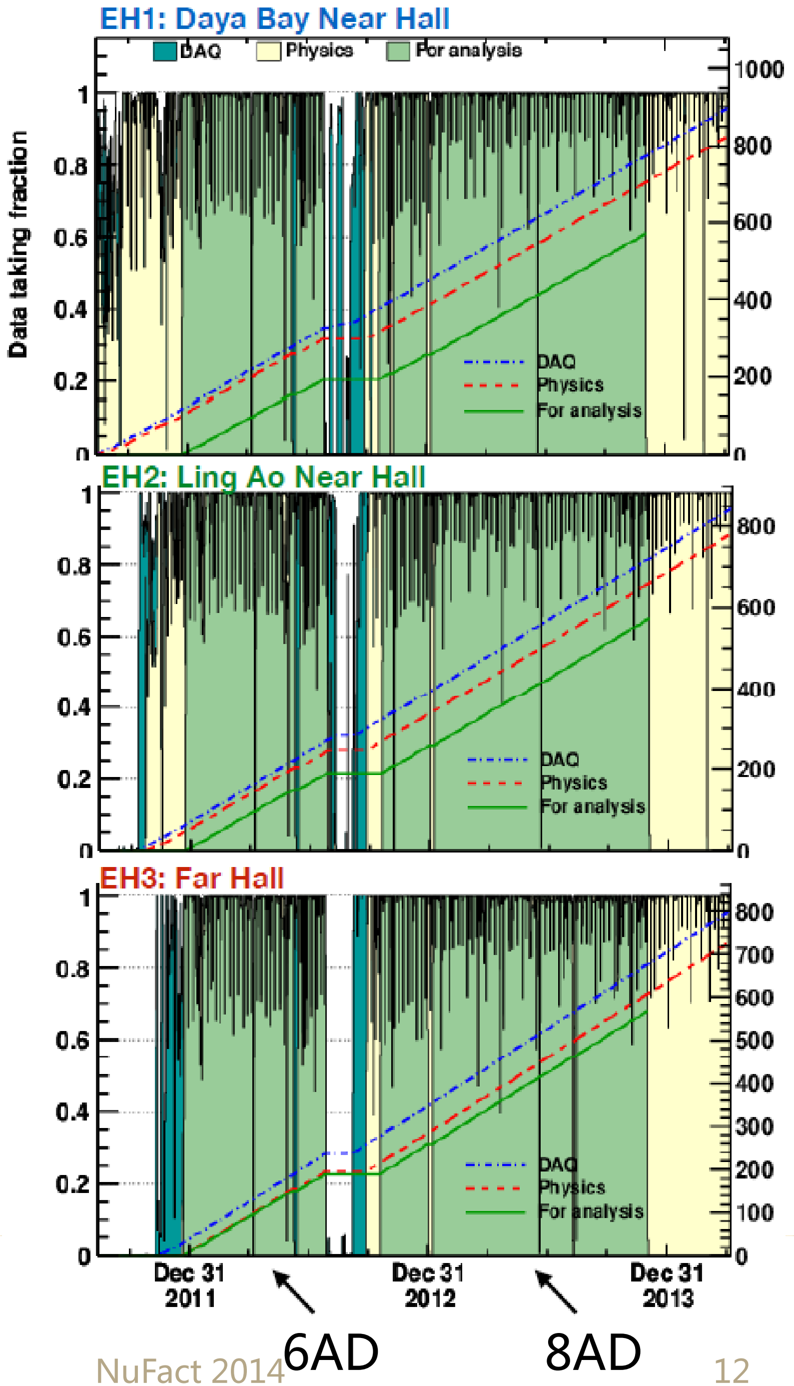
$$E_{\mathrm{vis}}^{e^+} = E_{\mathrm{vis}}^{e^-} + 2 \cdot E_{\mathrm{vis}}^{\gamma}(0.511\,\mathrm{MeV})$$

- Old model
  - Combination of 5 models to conservatively estimate uncertainty
- New model
  - A new combined model is used as the nominal model, which is constrained by all the calibration data.

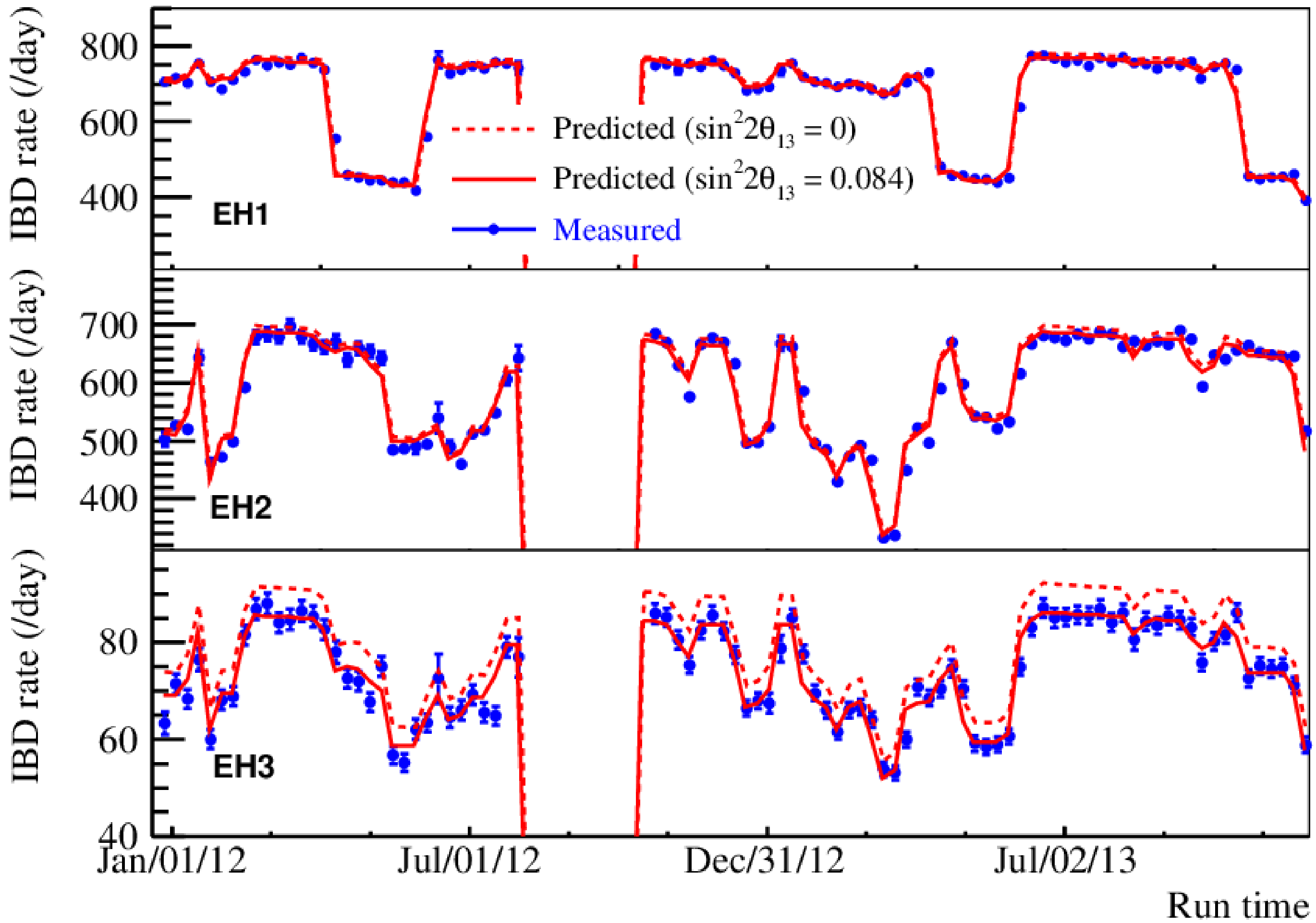
Analysis data set

- 6-AD data set :
  - Dec/24/2011 – July/28/2012 (217 days)
- 8-AD data set :
  - Oct/19/2012 – Nov/27/2013 (404 days)

- Latest analysis :
  - 6+8 AD combined nGd θ_{13} spectru analysis
  - 6AD nH θ_{13} rate analysis
  - 6AD absolute reactor flux measurement
  - 6AD light sterile neutrino search



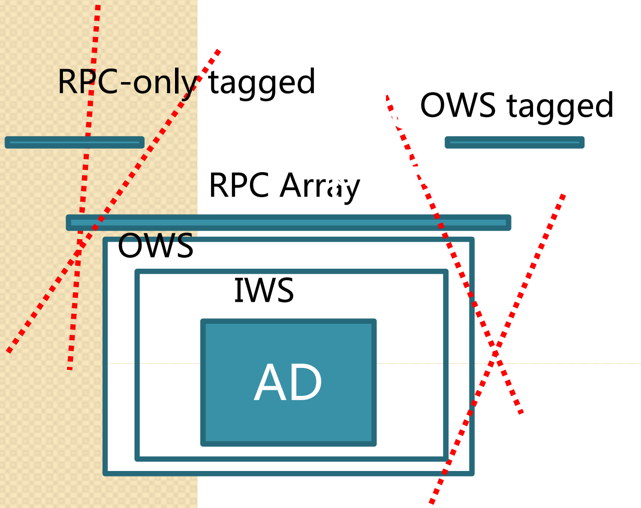
Detected IBD rate vs. time

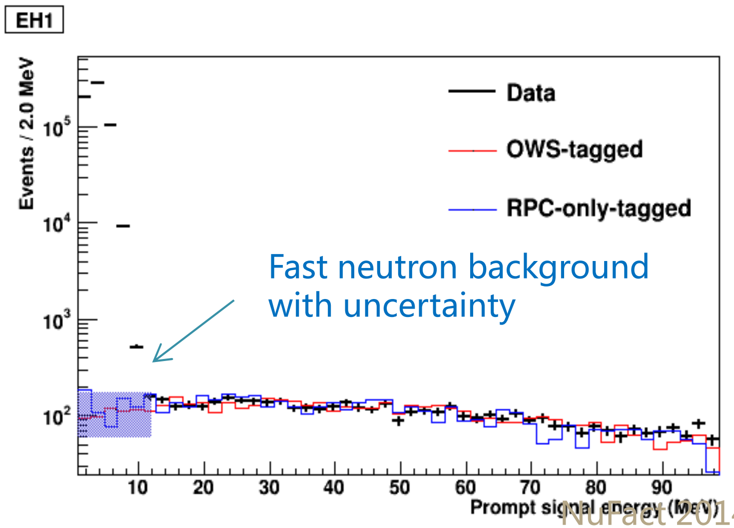


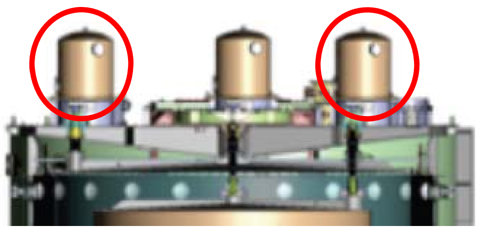
- Detected rate strongly correlated with reactor flux

Background budget

Background	Near	Far	Uncertainty	Method	Comment
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Same as before
9Li/8He	0.4%	0.4%	~50%	Measured with after-muon events	Same as before
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Same as before







Data summary

Preliminary

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 ± 0.10	0.21 ± 0.10	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 ± 0.03
$^{13}C(\alpha, n)^{16}O$(/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					

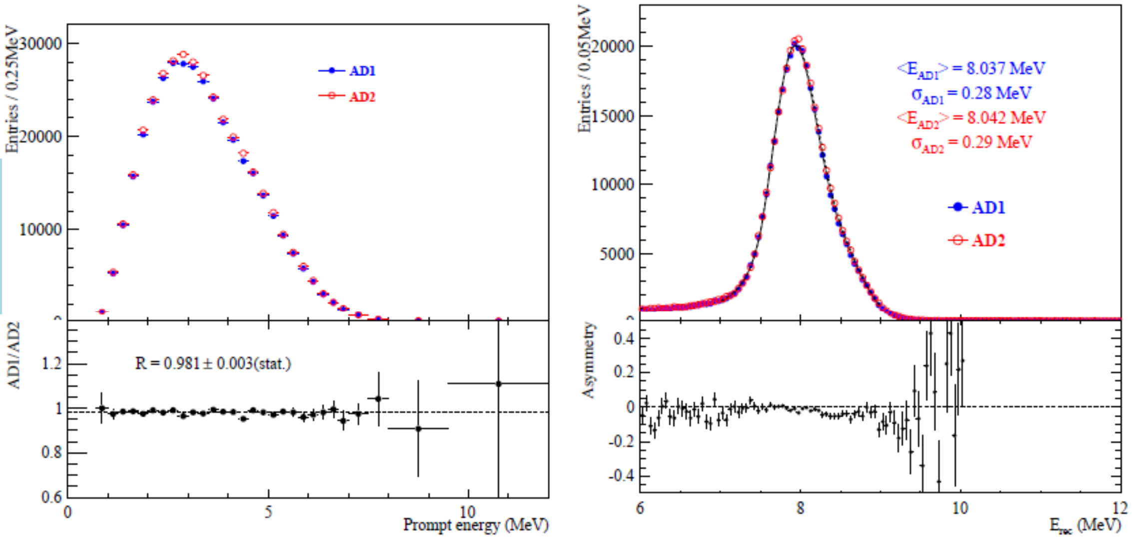
- Consistent rate for side-by-side detectors

Consistent spectrum for side-by-side detectors

Positron spectrum   Neutron capture spectrum

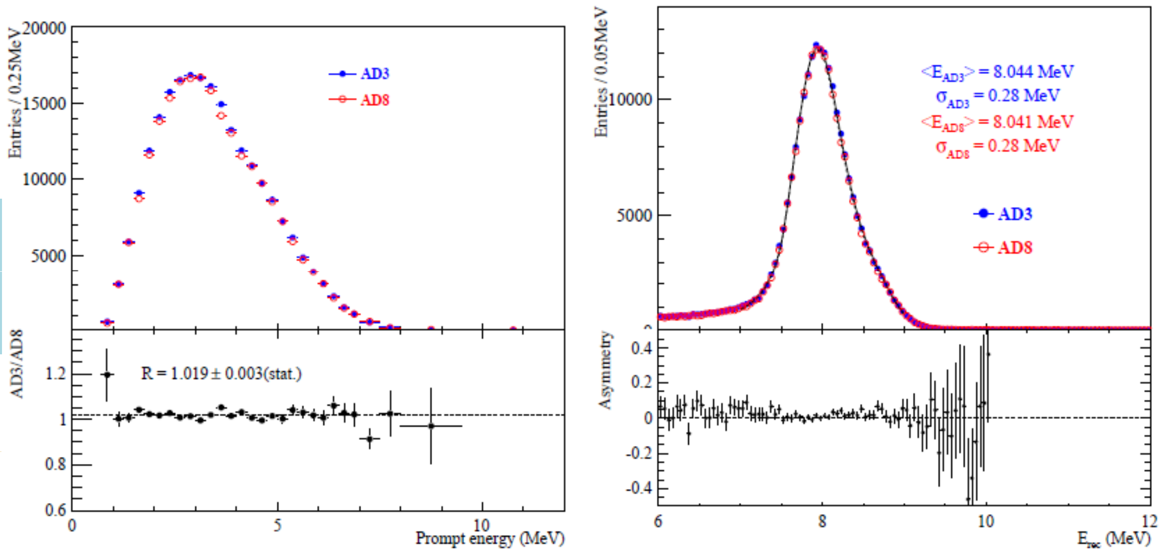
AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981±0.004

EH1

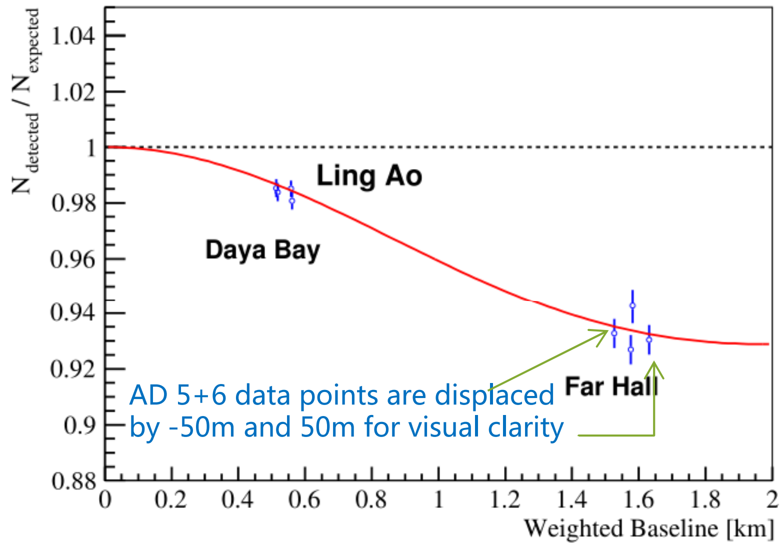


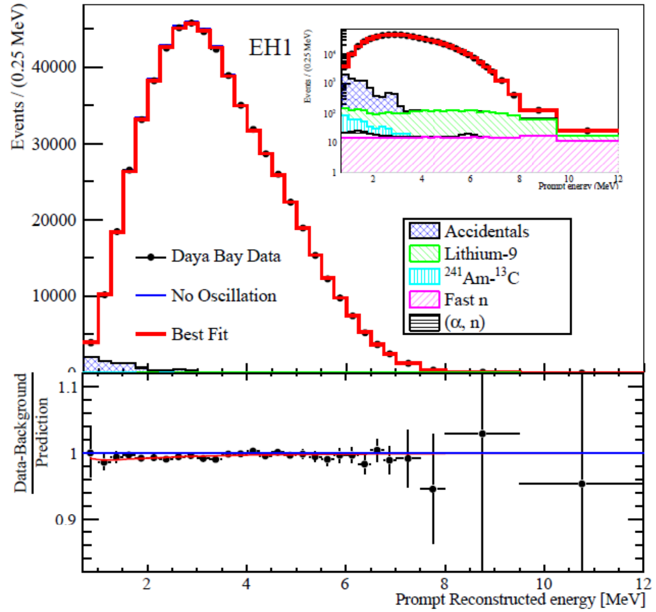
AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019±0.004

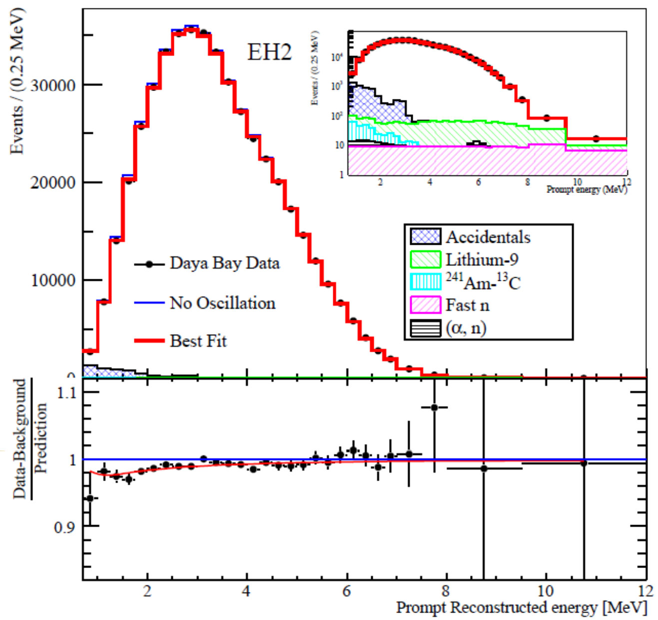
EH2

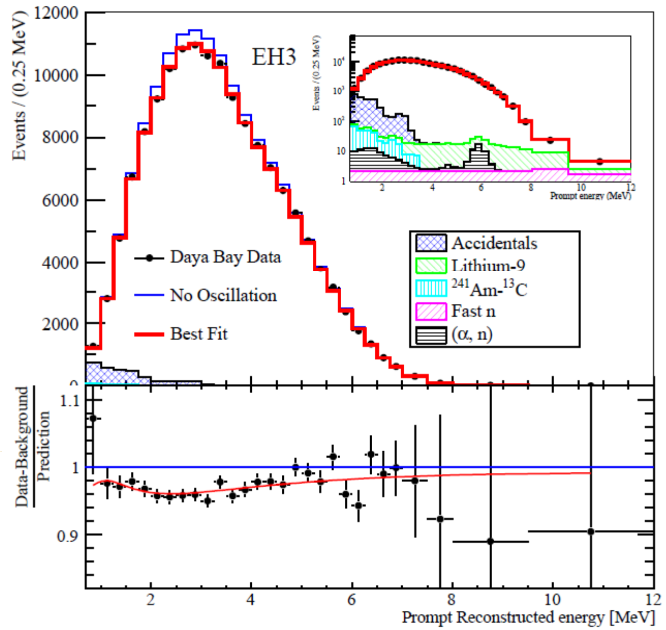


Rate and Spectrum distortion

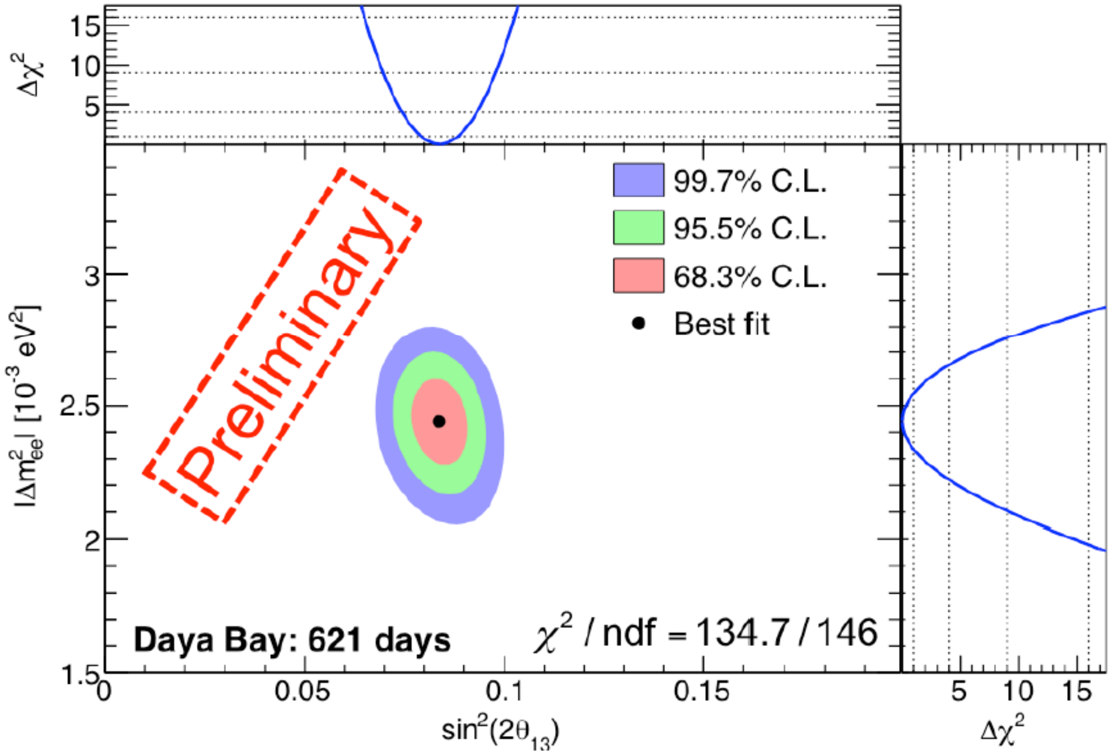








Latest oscillation results



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

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

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

- Most precise measurement of $\sin^2 2\theta_{13}$ (6%)
- Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel (4%)
  - Consistent with the muon neutrino disappearance experiments

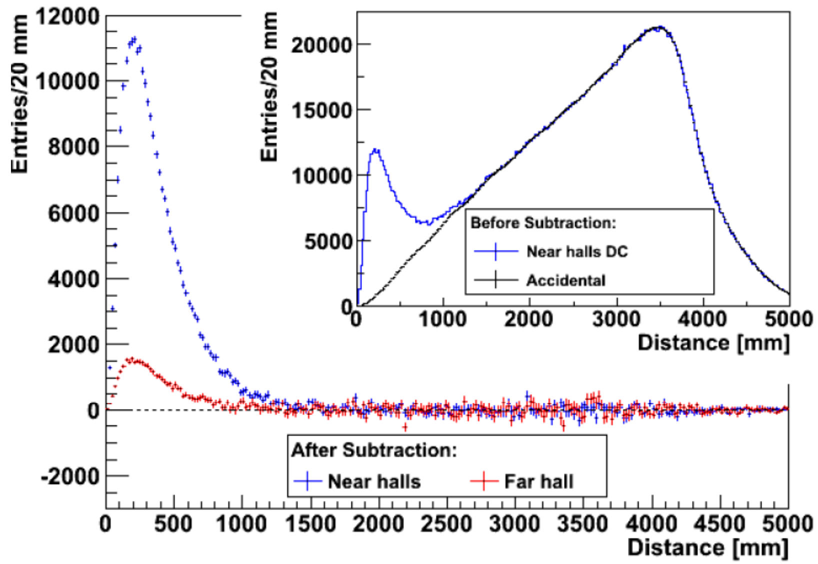
Independent θ_{13} oscillation analysis through nH

- Key feature
  - High statistics (additional 20 ton LS target)
  - Different systematic uncertainties from nGd analysis
- Challenges
  - High accidental background
    - Longer capture time
    - Lower delayed energy
- Strategy
  - Raise prompt energy cut (>1.5MeV)
  - Require prompt to delay distance cut (<0.5m)
  - Longer coincidence time (1~400μs)

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

$$+H \rightarrow D + \gamma \quad 2.2\text{ MeV} \quad 200\ \mu s$$

$$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's \quad 8\text{MeV} \quad 30\ \mu s$$

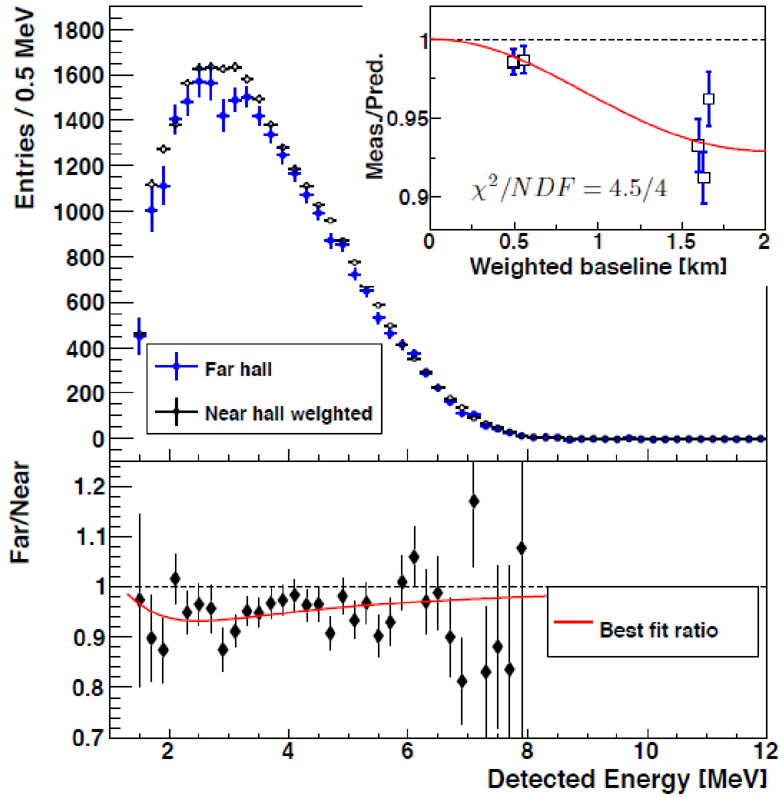


nH analysis result

- 217 days of 6AD period
- Rate analysis measures :

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

  - An independent and consistent result with nGd analysis
  - Another precise measurement of $\sin^2 2\theta_{13}$
- Spectrum distortion is consistent with oscillation explanation.



Summary and conclusion

- Daya Bay has measured
  - with 621 days of data.

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

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

- The precision is expected to be further improved by the end of 2017 to 3%.

- Consistent result from 6AD nH rate analysis.

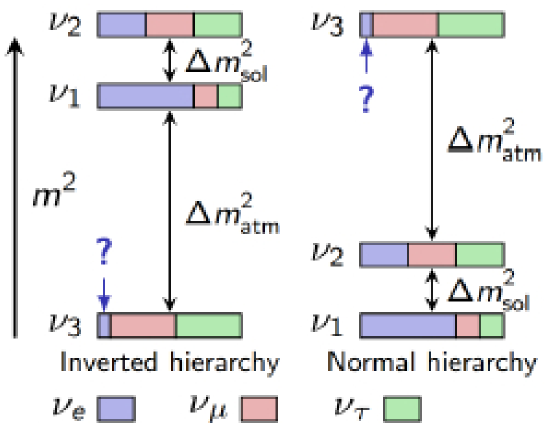
$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

Backup

Neutrino oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

- PMNS matrix
- Mass eigenstates
- Weak eigenstates



- Known : $\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{32}|$
- Unknown : CP phase, mass hierarchy, $m_1/m_2/m_3$, δ_1/δ_2

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23}~45° by atmospheric neutrinos (1998)	θ_{13}~9° by reactor and accelerator neutrinos (2012)	θ_{12}~34° by solar neutrinos (2001)	neutrino-less double beta decay