Results from Daya Bay

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(on behalf of the Daya Bay Collaboration)
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Outline

- Introduction to Daya Bay experiment
- Detector performance
- Recent results
- Measurement of neutrino oscillation parameters
- Measurement of reactor antineutrino rate and spectrum
- Search for sterile neutrinos

The Daya Bay Experiment

Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden

Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden

Tunnels

Shenzhen 45 km

Hongkong 55 km

3 Underground
Experimental Halls

Entrance

Ling Ao II Cores

Ling Ao I Cores

Daya Bay Near Hall
363 m from Daya Bay
98 m overburden

Daya Bay Cores

- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

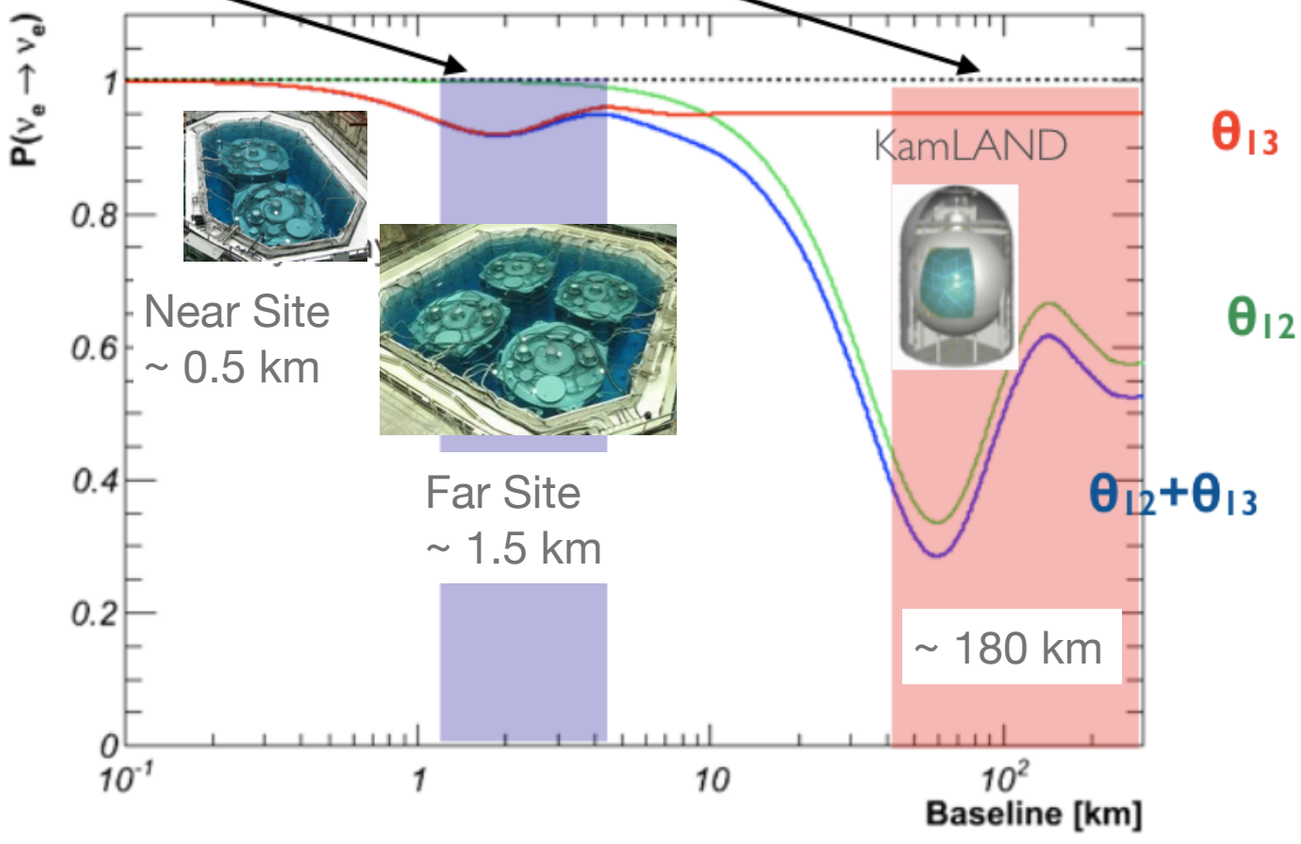
Reactor Antineutrino Oscillation

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

Survival Probability
- oscillation amplitude ↔ mixing angles
- oscillation frequency (in L/E) ↔ Δm^2

Relative Measurement
- minimize systematic uncertainties

Effective mass-squared difference
- $\Delta m^2_{ee} \sim \Delta m^2_{13} \sim \Delta m^2_{23}$
- insensitive for Daya Bay



Antineutrino Detector (AD)

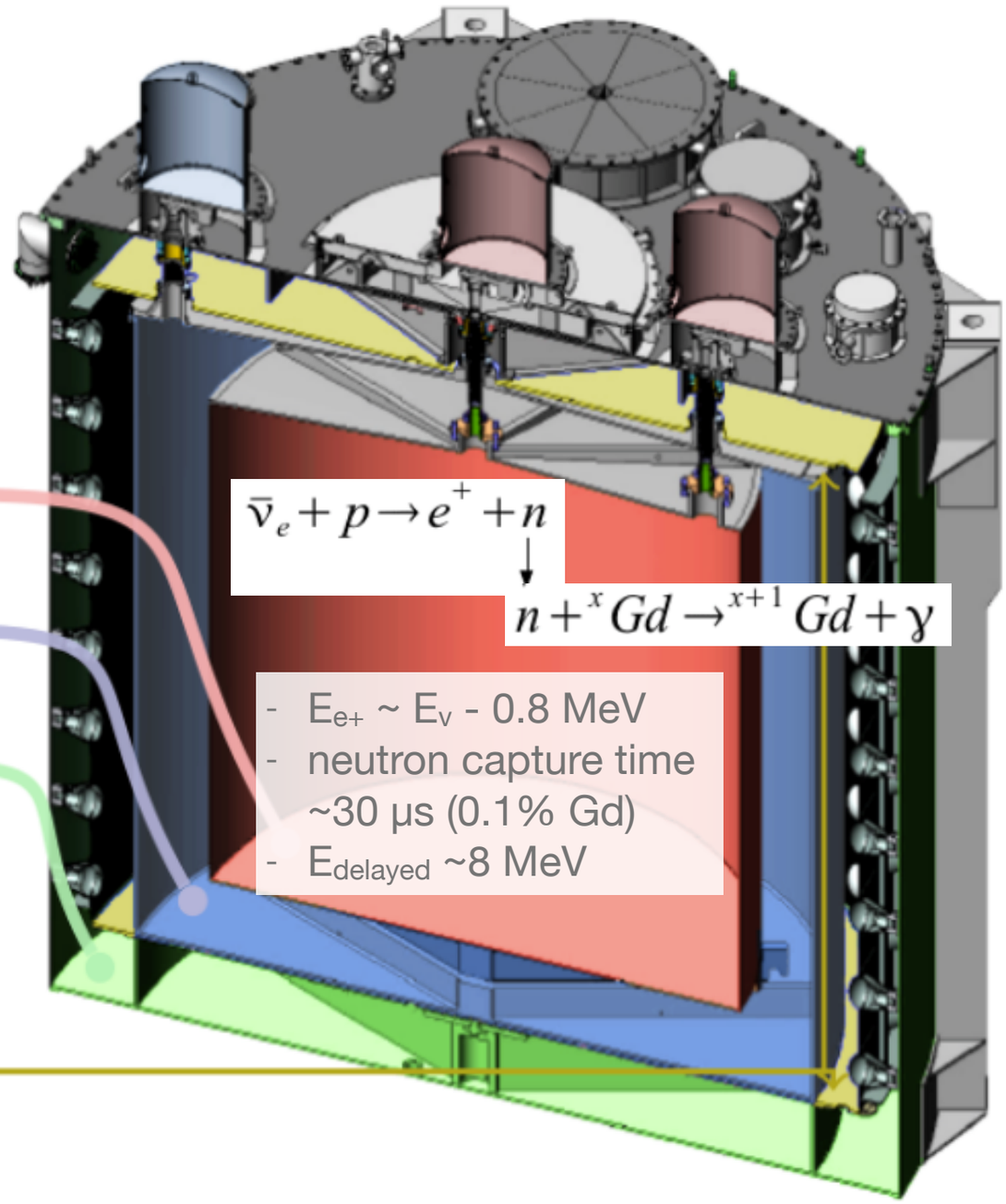
8 functionally identical detectors
reduce systematic uncertainties

3 zone cylindrical vessels

Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



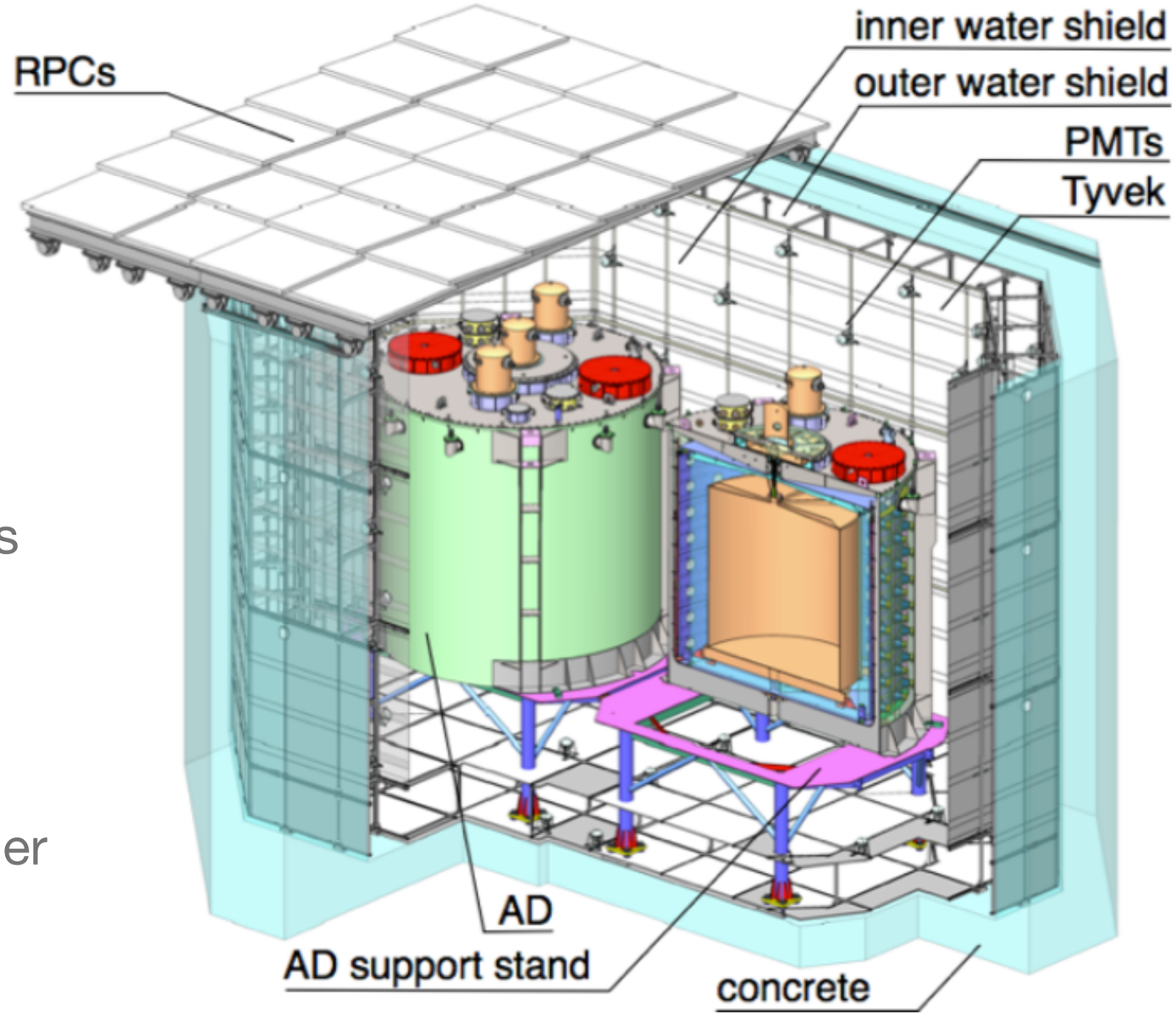
Muon Tagging System

2.5 meter thick two-section water Cherenkov detector

- tagging cosmic muons
- shielding of gammas and neutrons from surrounding materials

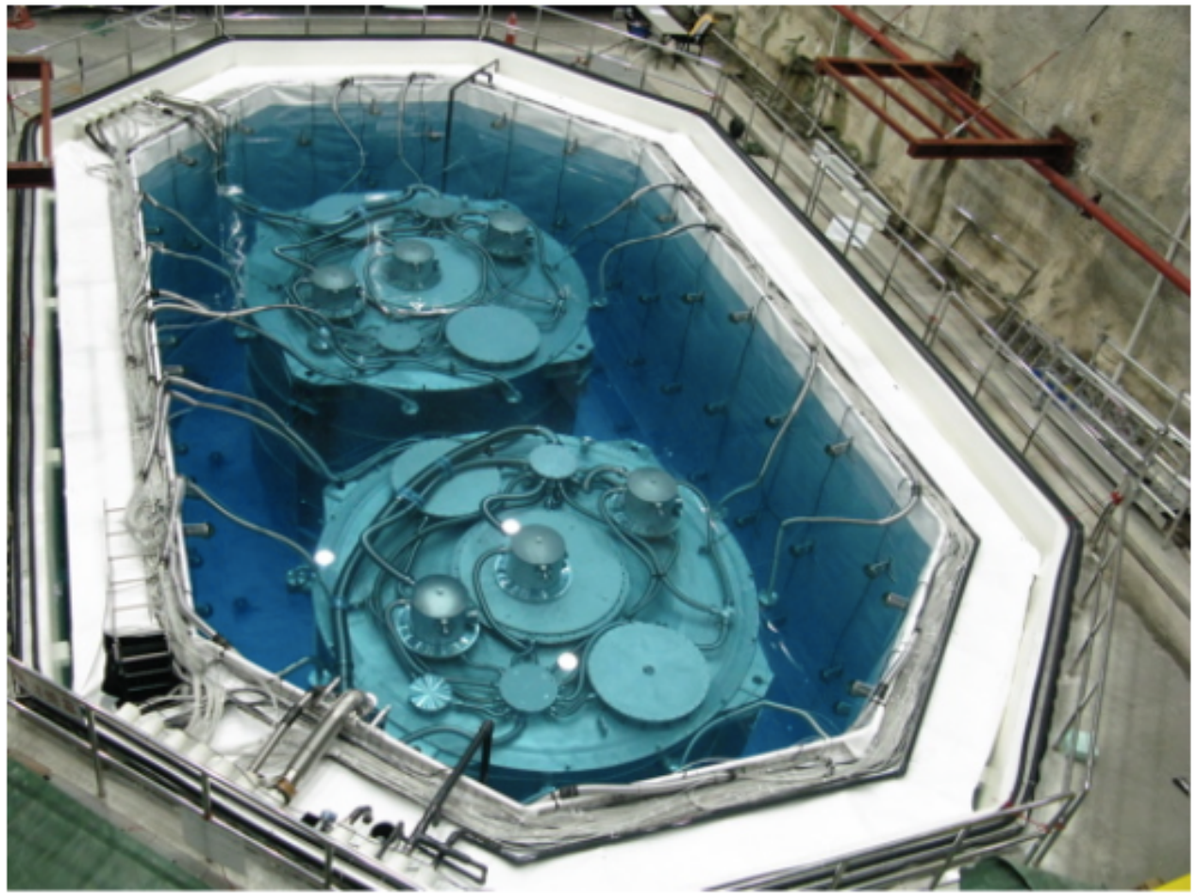
RPC

- covers water pool to provide further muon tagging

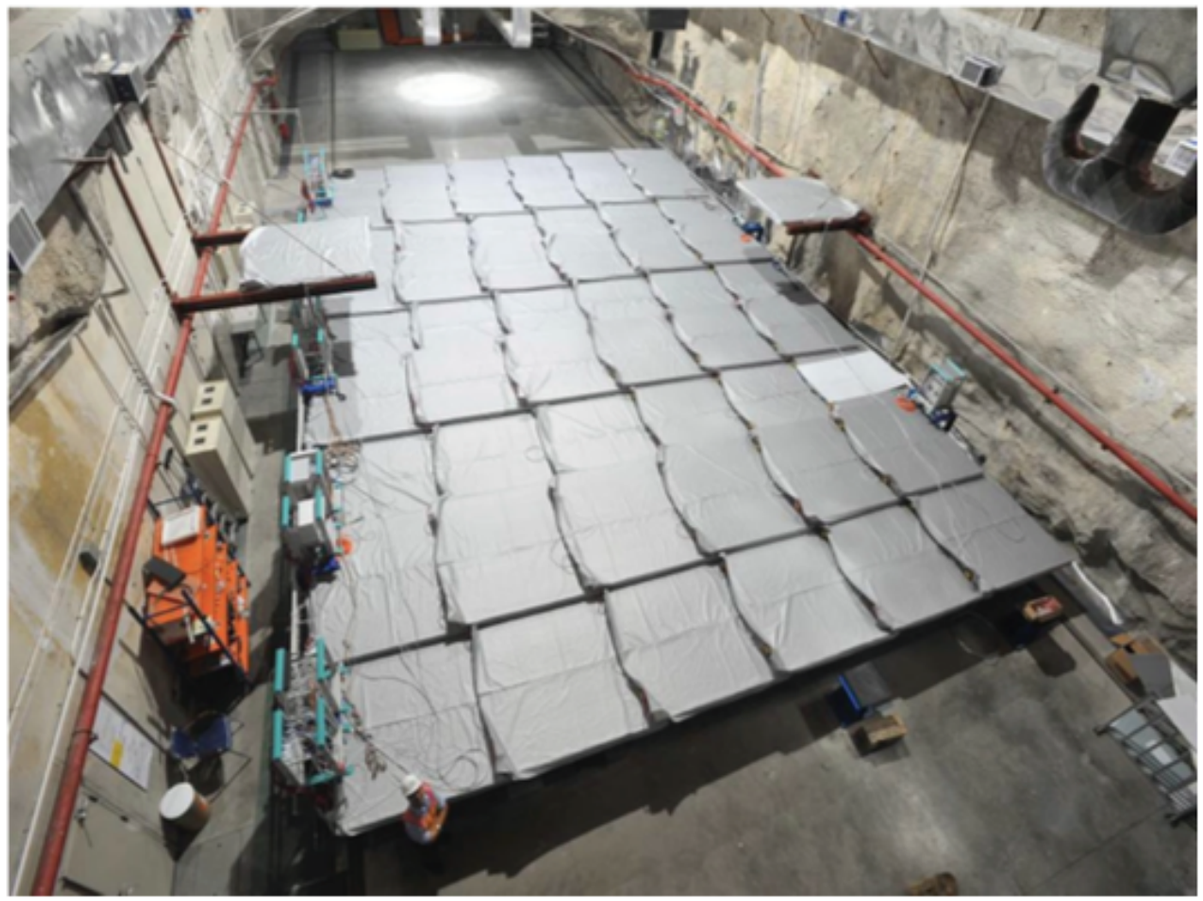


Daya Bay Experimental Hall

Detectors Inside Water Pool

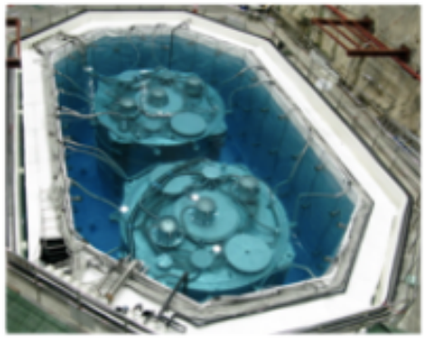


Water Pool Covered by RPC

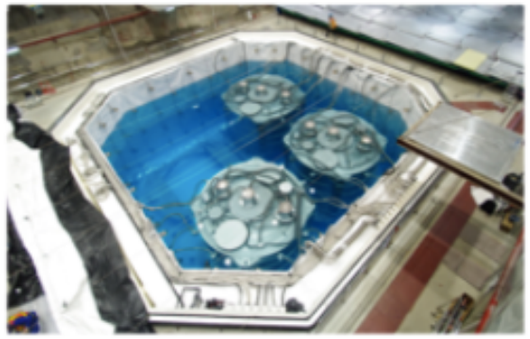


Timeline of Daya Bay Experiment

EH1



EH3



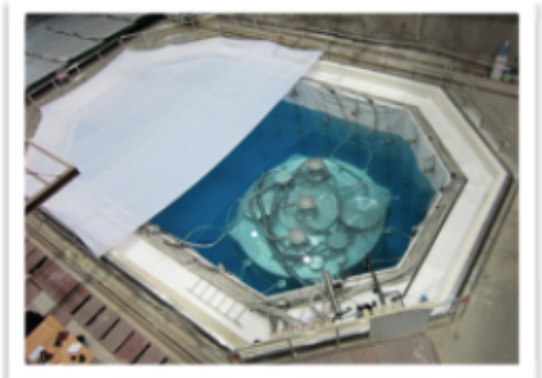
EH3

Aug. 2011 | Dec. 2011 | Aug. 2012

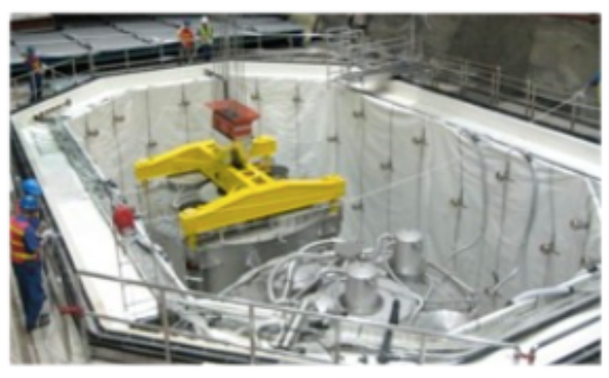
6-AD Data Taking | 8-AD Data Taking

2011/12 - 2012/07 | 2012/10 - now

Nov. 2011 | Aug. 2012

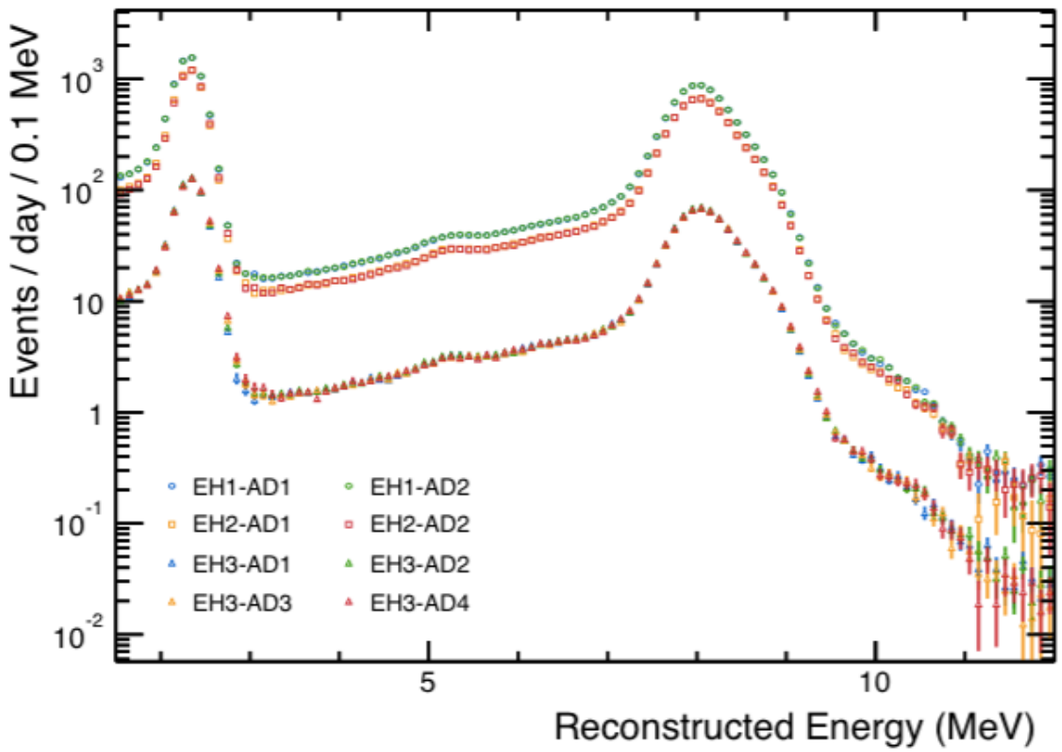


EH2

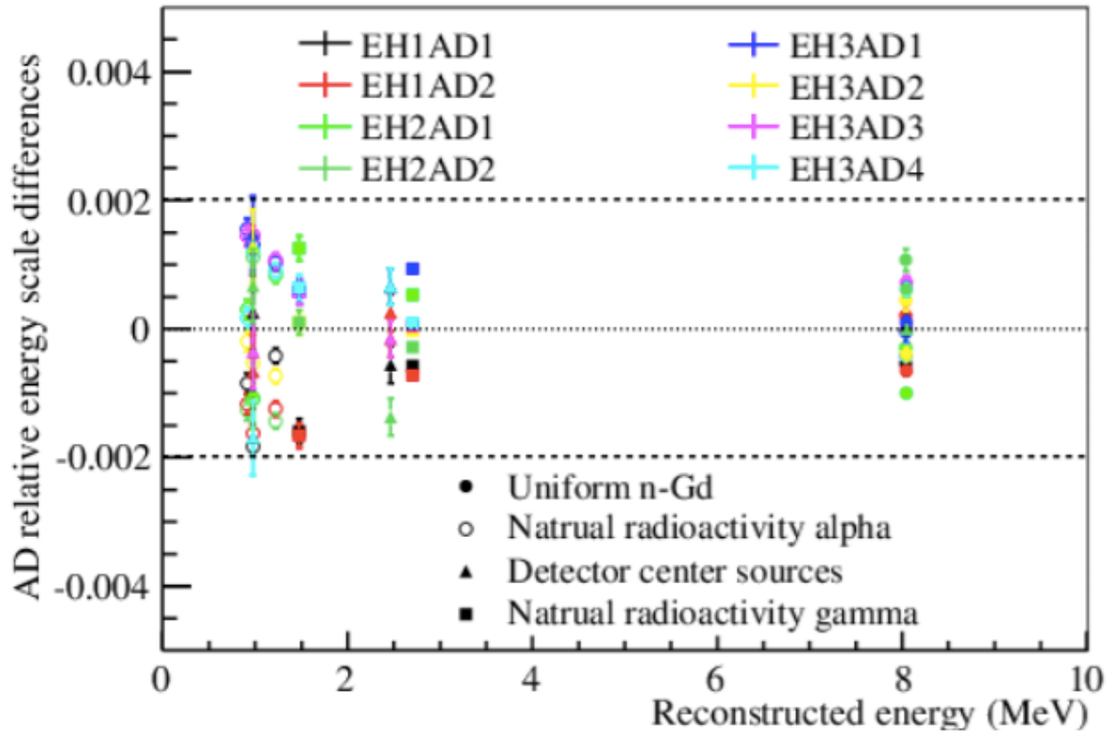


EH2

Relative Energy Scale



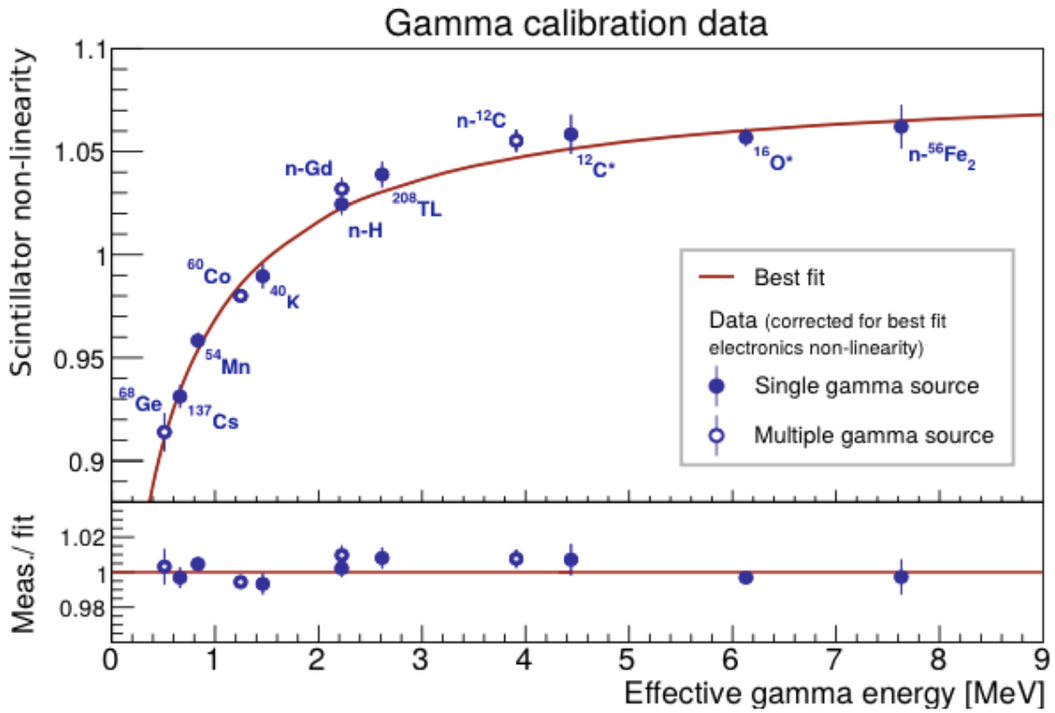
Spallation Neutrons (After Calibrations)

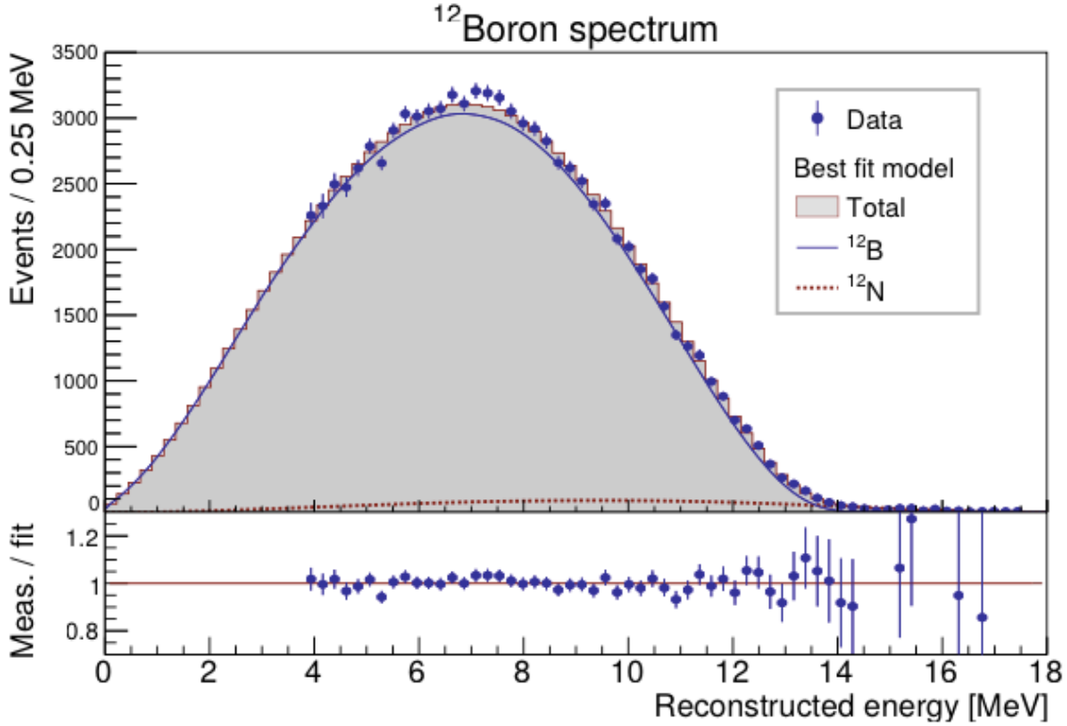


ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po

< 0.2% variation in reconstructed energy between ADs

Energy Model





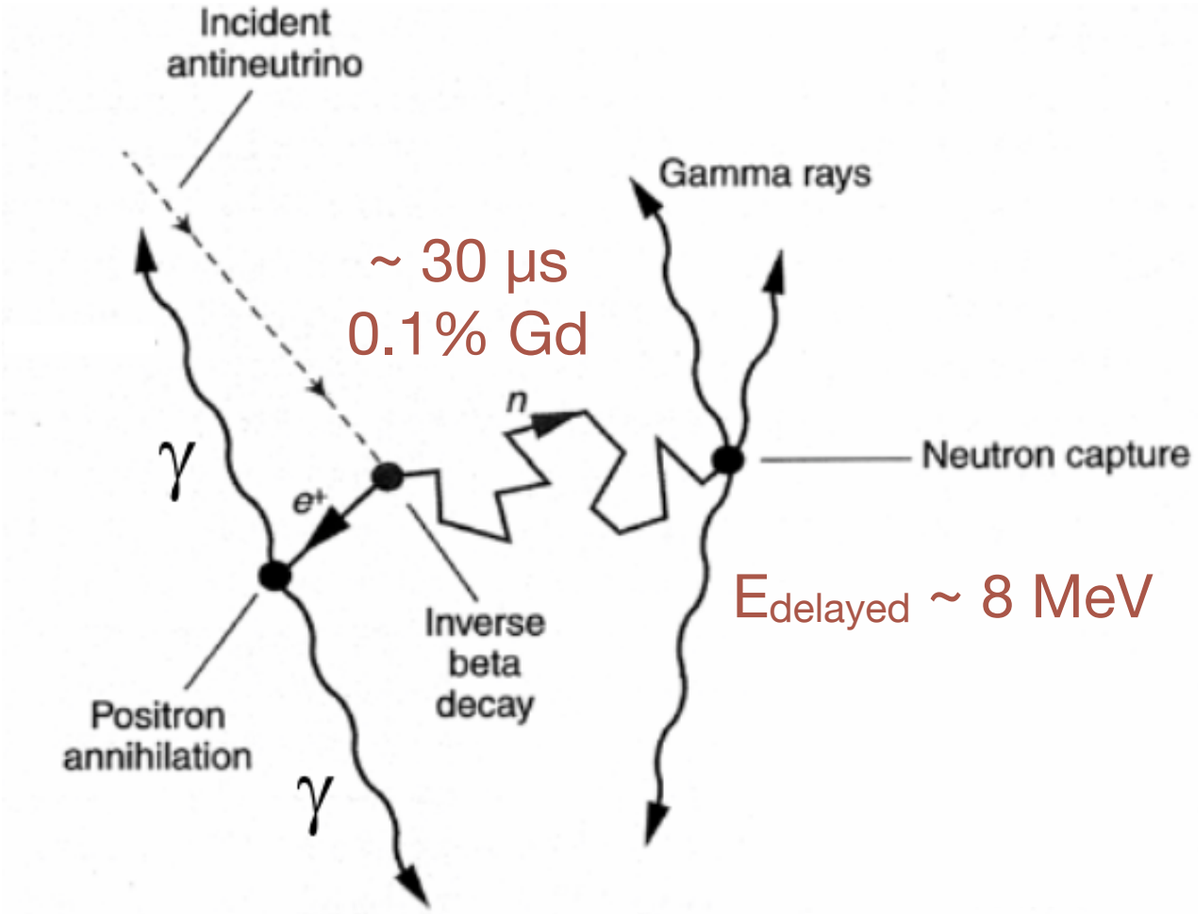
Two major sources of non-linearity

- **scintillator response:** modeled with Birks formula and Cherenkov fraction
- **electronics:** modeled with MC and single channel FADC measurement

Combined fit with mono-energetic gamma peaks and ^{12}B beta-decay spectrum.

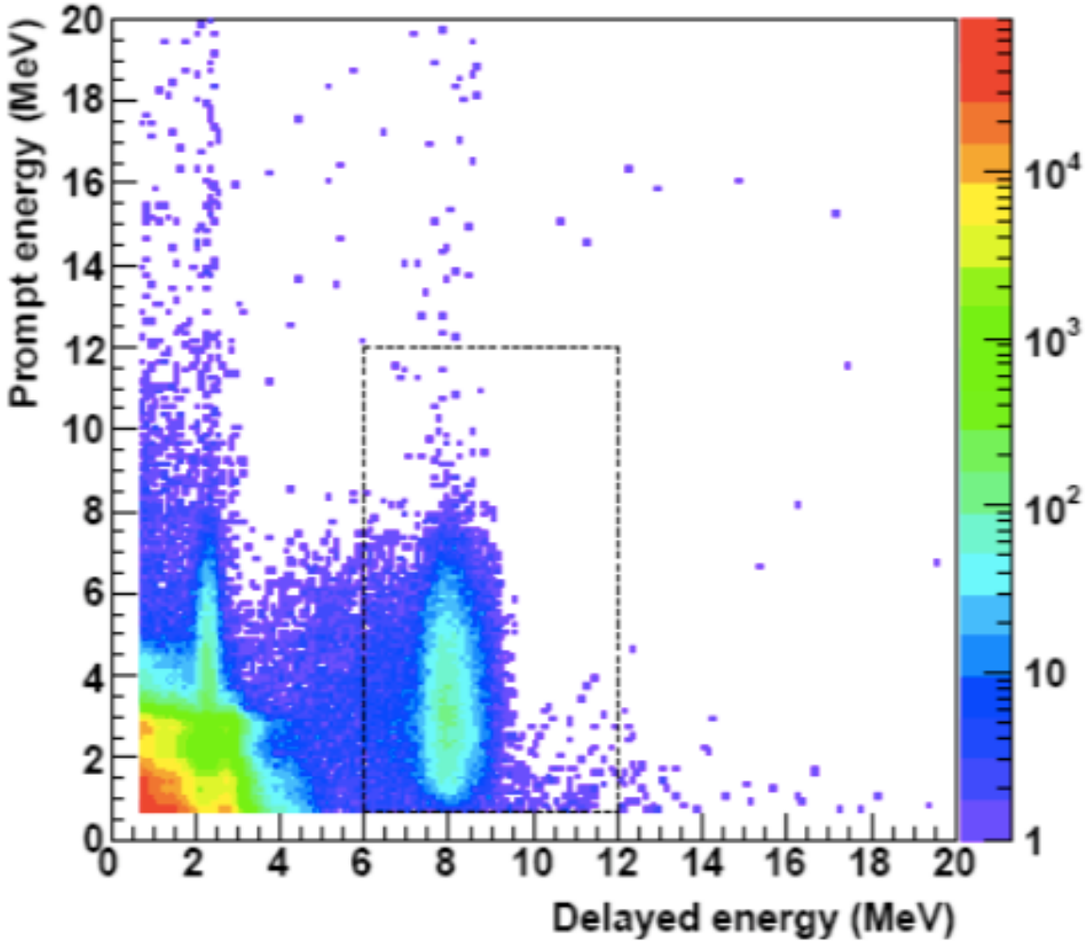
Cross-validated with ^{214}Bi, ^{208}Tl beta-decay spectrum, Michel electron spectrum and standalone bench-top Compton scattering measurement.

Event Selection



$E_{delayed}$ ~ 8 MeV

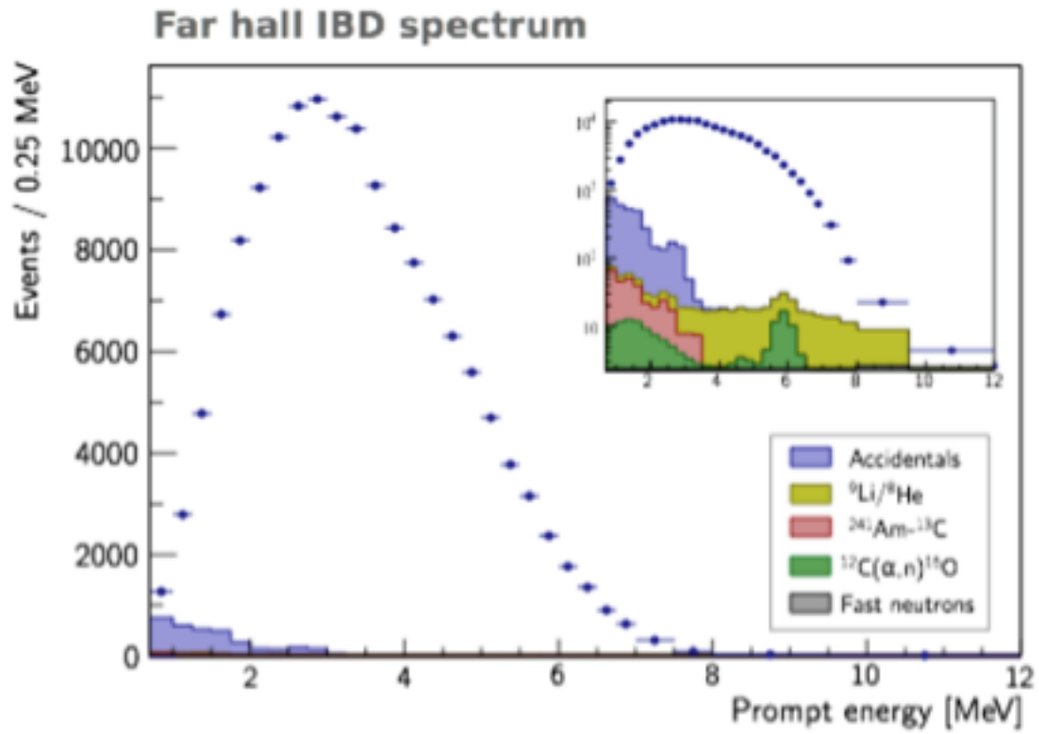
$E_{e+} \sim E_{\nu} - 0.8$ MeV



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

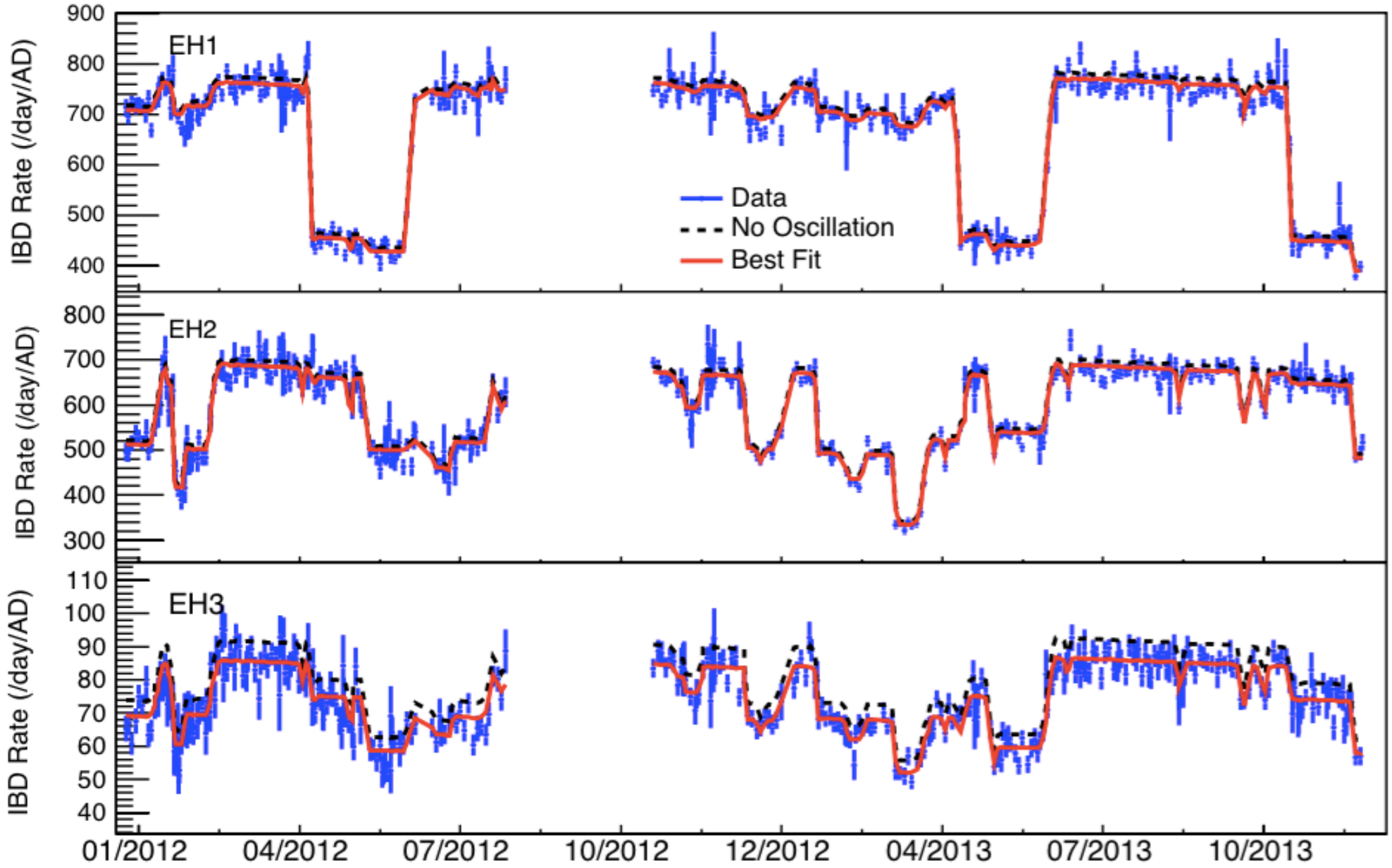
- Reject spontaneous PMT light emission
- Select only isolated pairs
- Veto after muon events to suppress cosmogenic backgrounds

Low Background Measurement



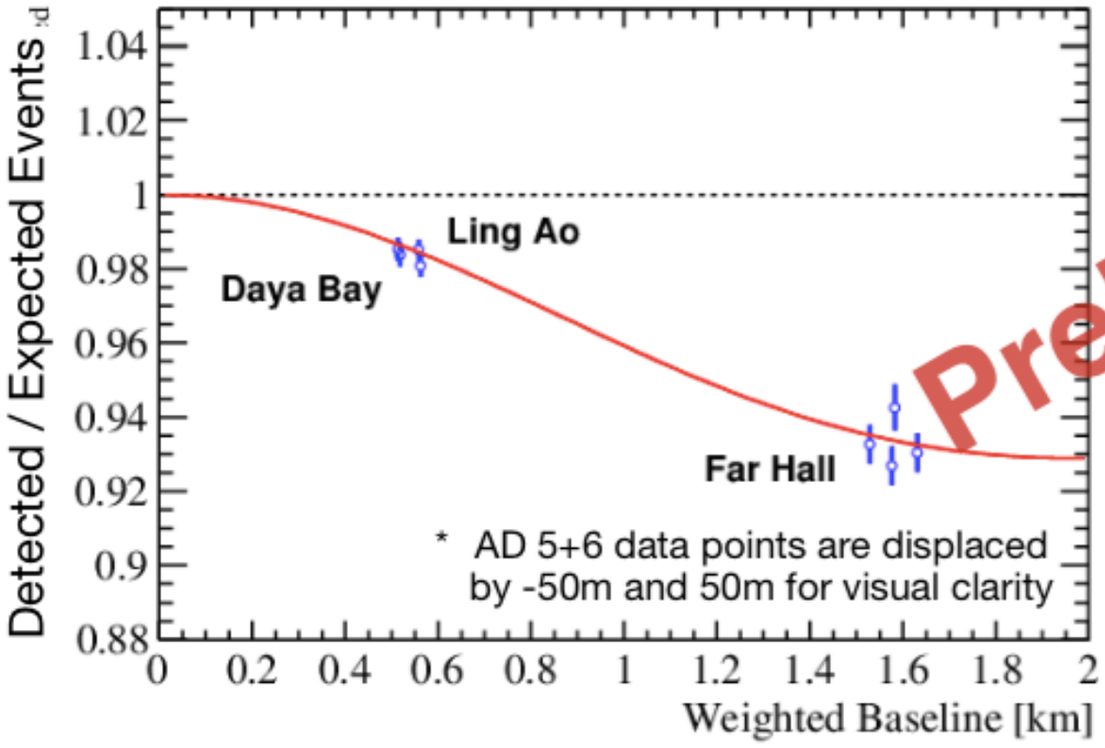
Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
^{9}Li/^{8}He	0.4%	0.4%	50%	measured with after-muon events
^{241}Am-^{13}C	0.03%	0.2%	50%	MC benchmarked with single gamma and strong AmC source
Fast neutrons	0.1%	0.1%	30%	measured from AD/water/RPC tagged muon events
$^{12}C(\alpha, n)^{16}C$	0.01%	0.1%	50%	calculated from measured radioactivity

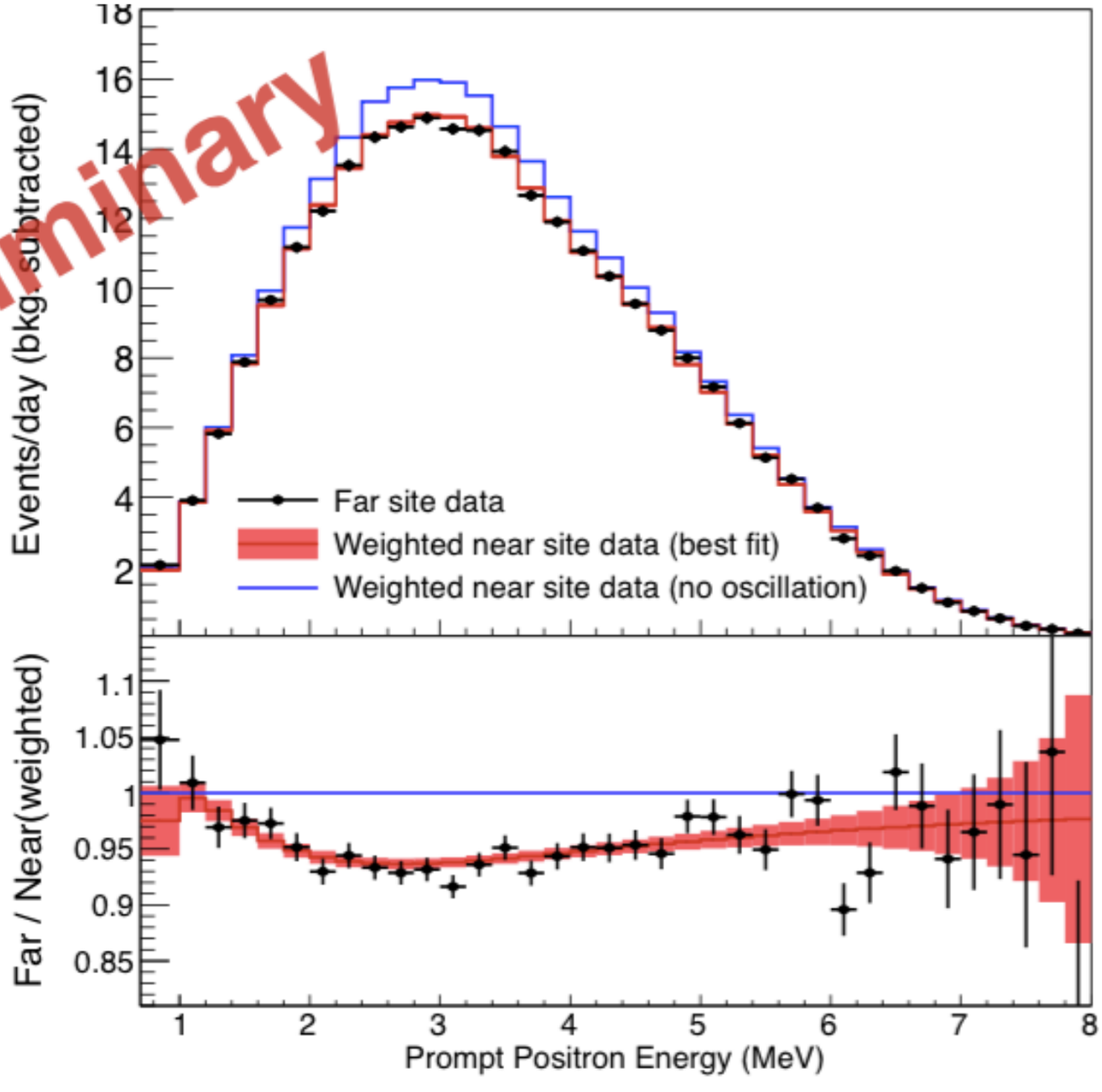
Over 1 million antineutrino interactions !



Strongly correlated with reactor operation conditions.

Near v.s Far Comparison





621 days of data

The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation

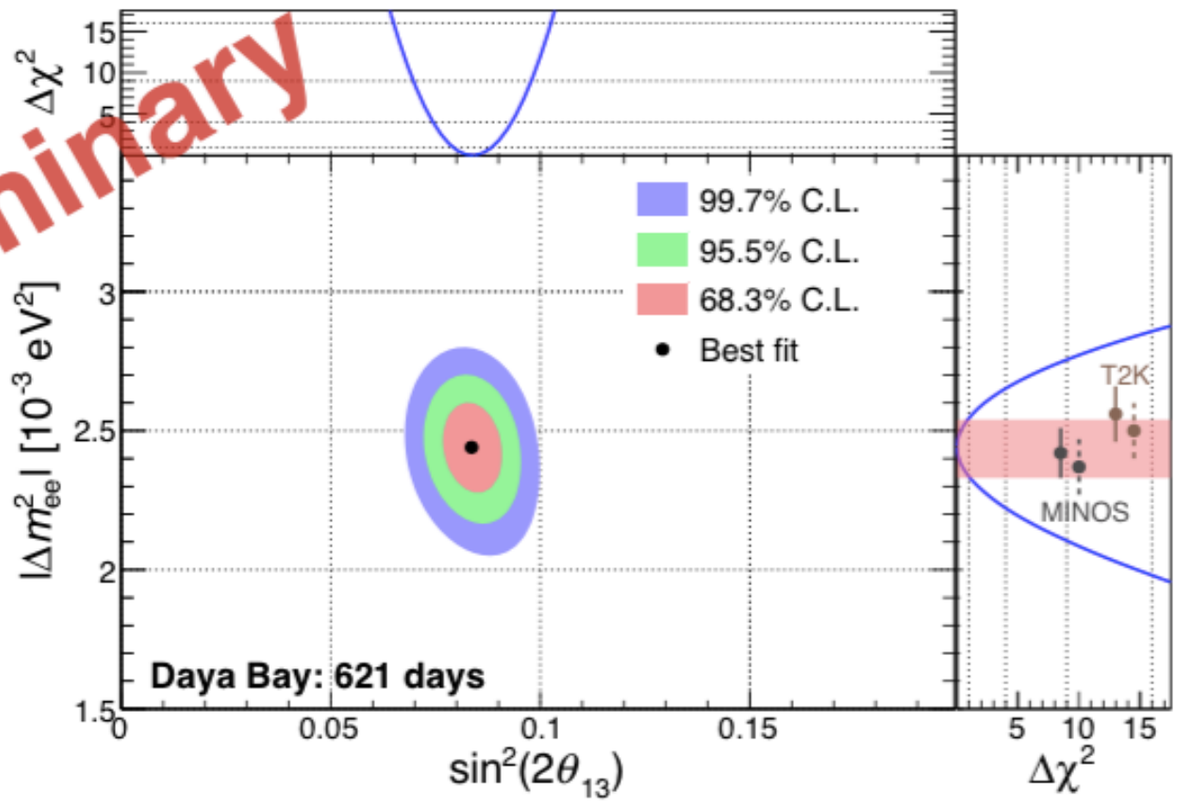
Results of Oscillation Parameters

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

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

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

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)

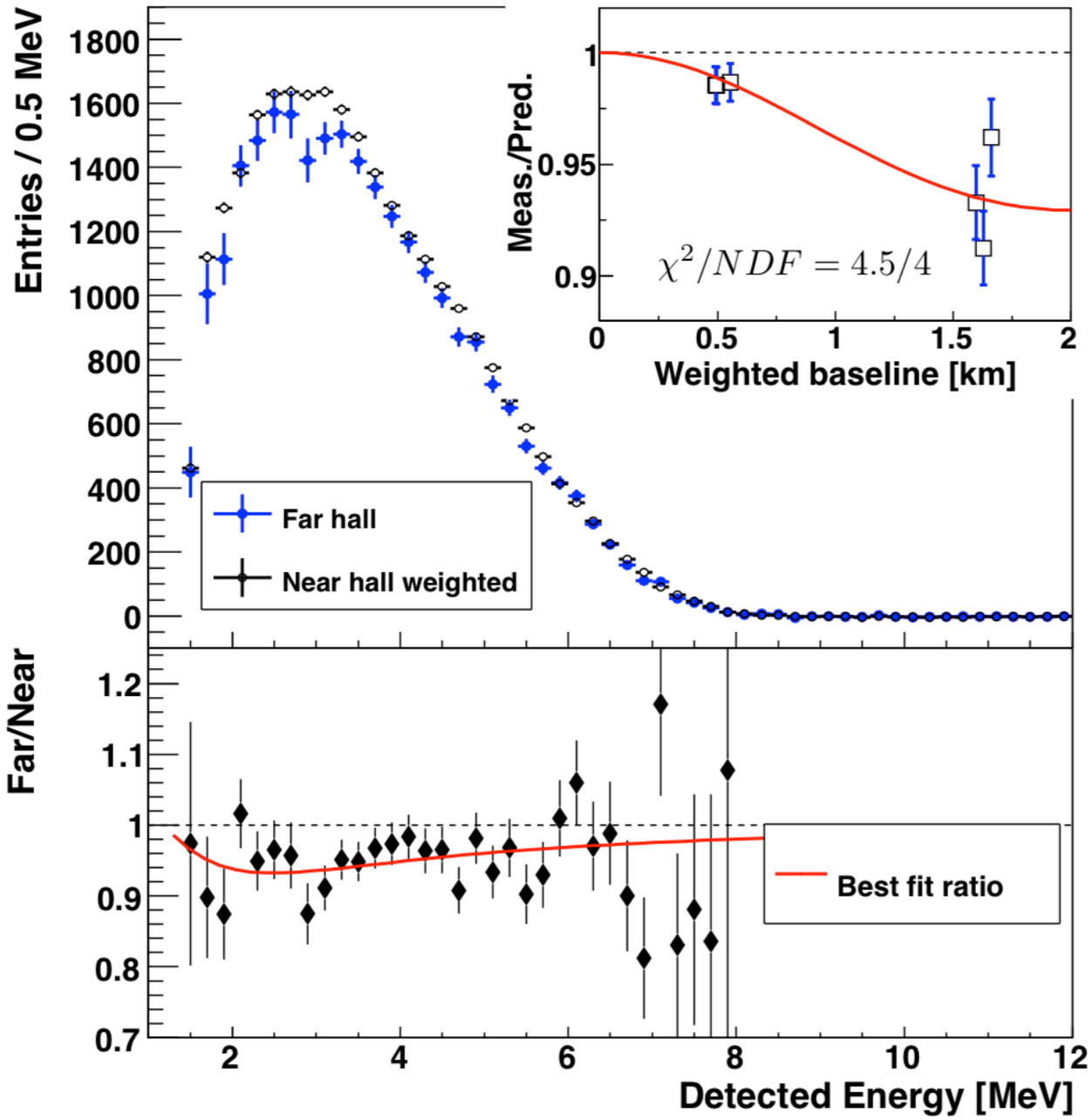
Publication in preparation

Results of nH Analysis

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

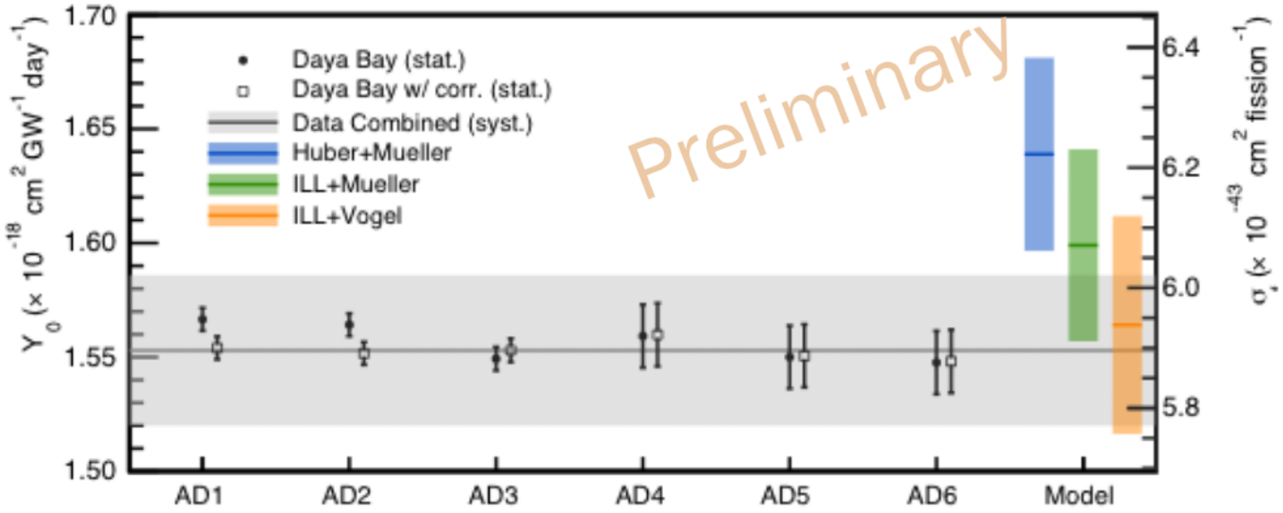
$+H \rightarrow D + \gamma$	2.2 MeV	200 μs
$+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's$	8MeV	30 μs

- 217 days of data (6 detectors)
- rate deficit at far site gives
  - $\sin^2 2\theta_{13} = 0.083 \pm 0.018$
- independent and consistent result with nGd analysis
- spectrum distortion is consistent with oscillation interpretation
- spectral analysis in progress …



Reactor Antineutrinos Measurements

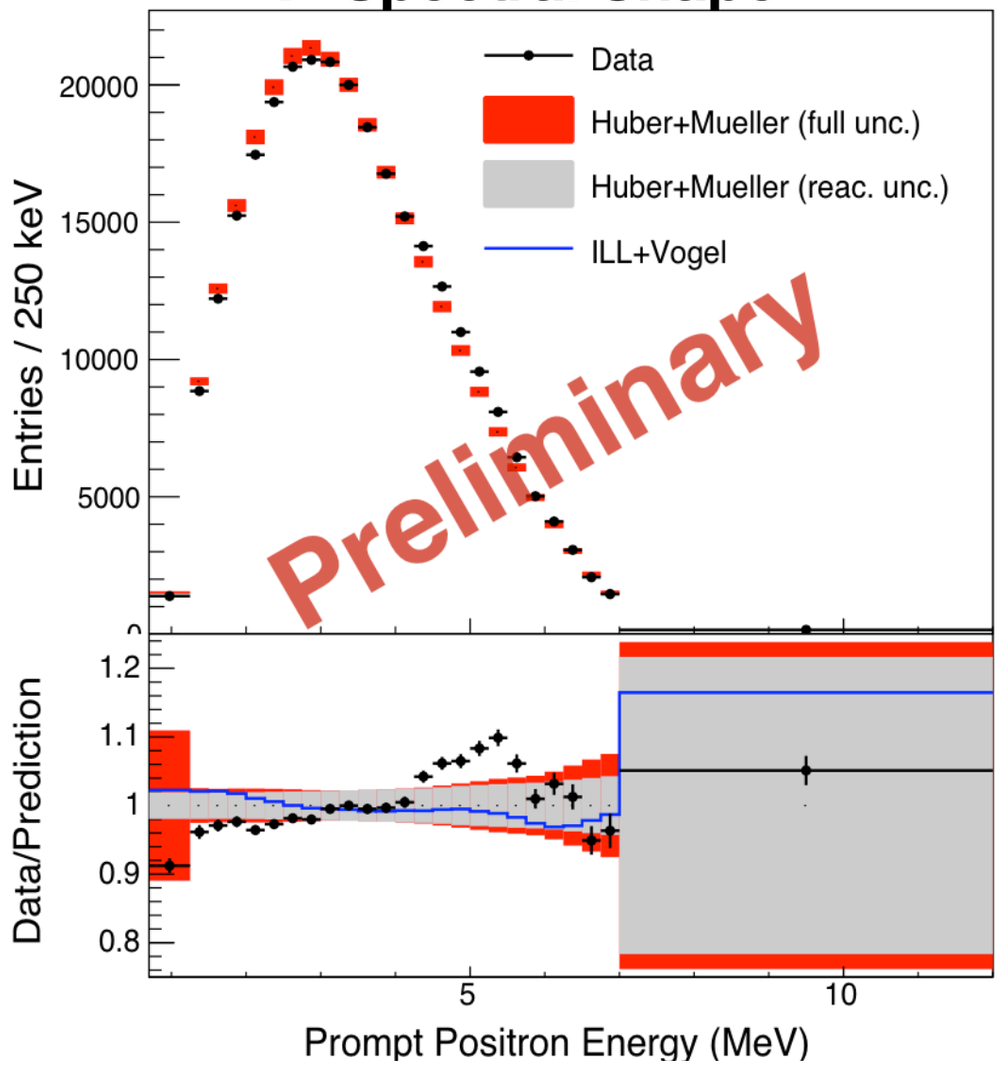
Absolute Rate



- Measured rate from reactor antineutrinos is consistent with previous short baseline experiments
- Measured Rate / Prediction
  - 0.947 ± 0.022 (Huber + Muller)
  - 0.992 ± 0.023 (ILL + Vogel)

Publication in preparation

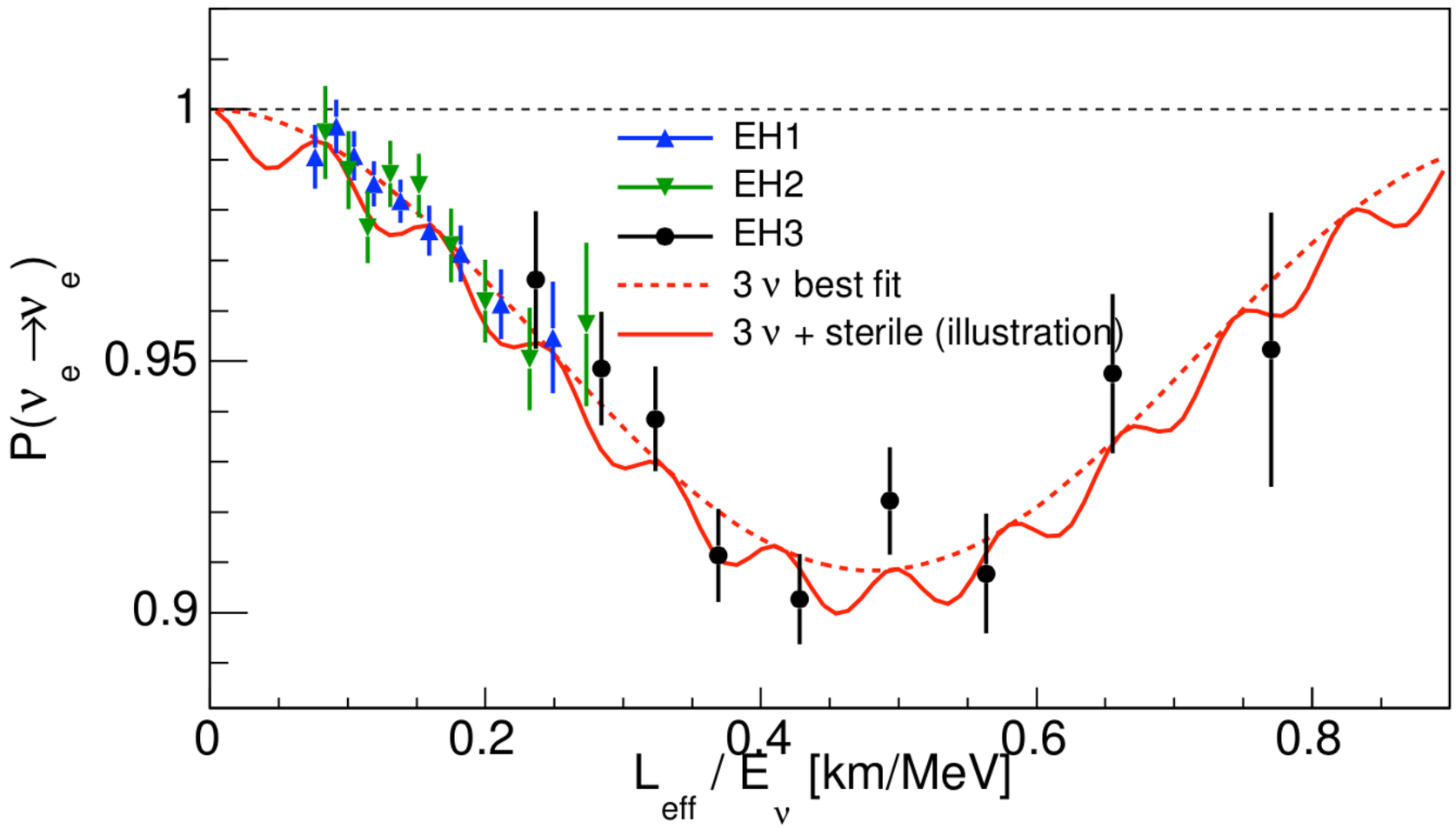
Spectral Shape

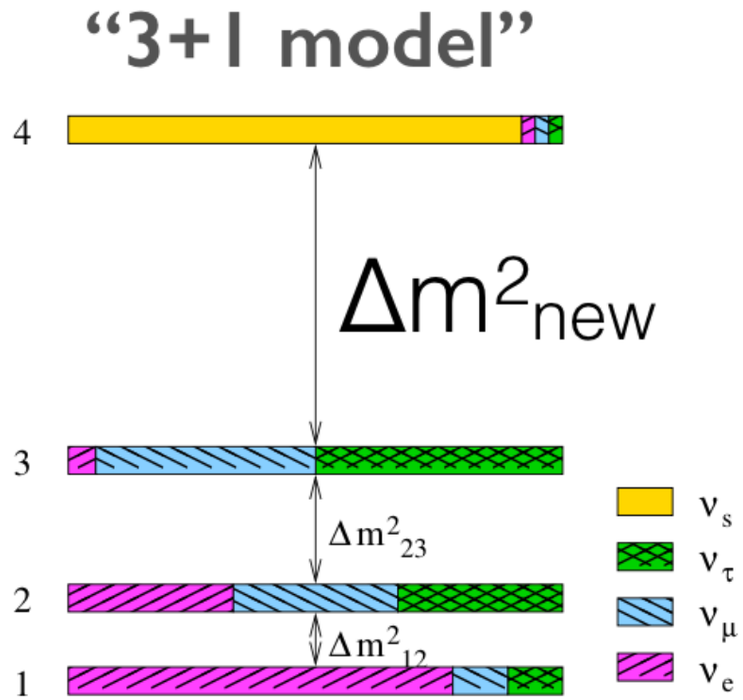


$E_{prompt} \sim E_\nu - 0.8$ MeV

- Observed antineutrino spectrum is inconsistent with traditional predictions.

Search for Light Sterile Neutrinos

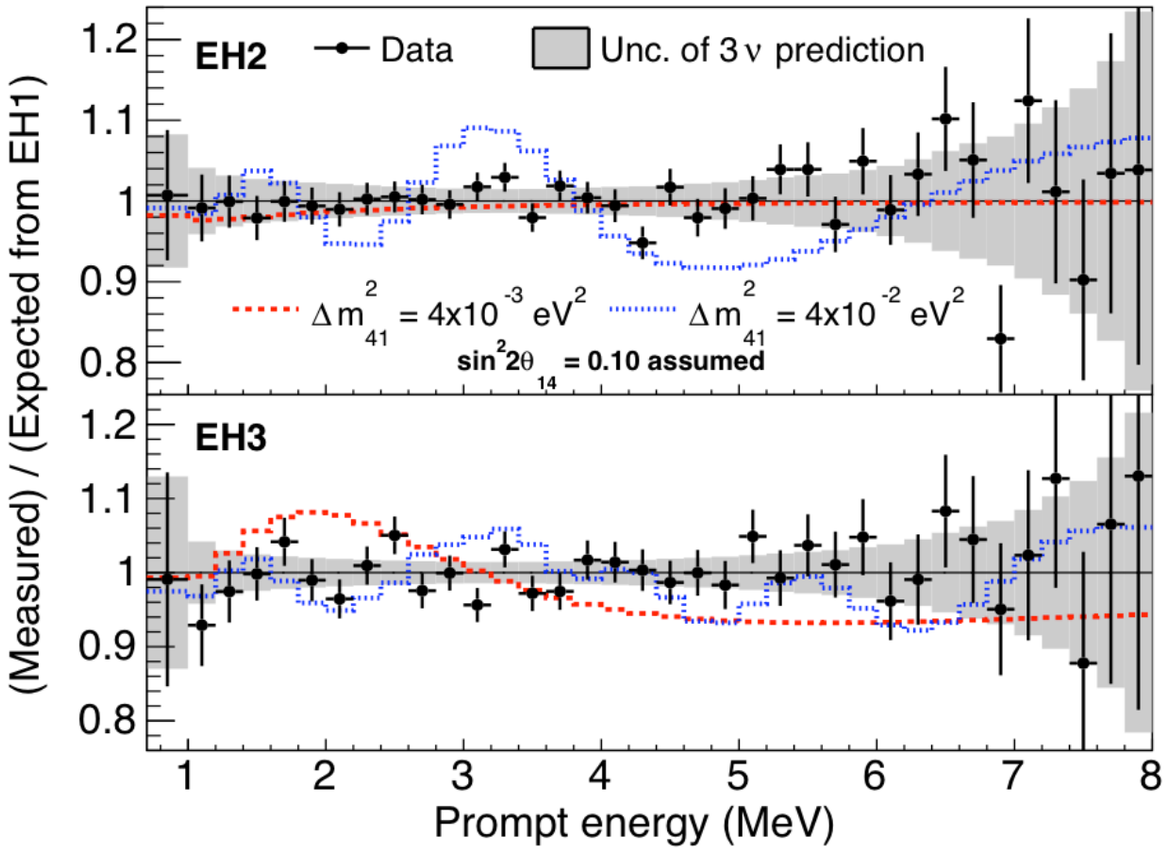


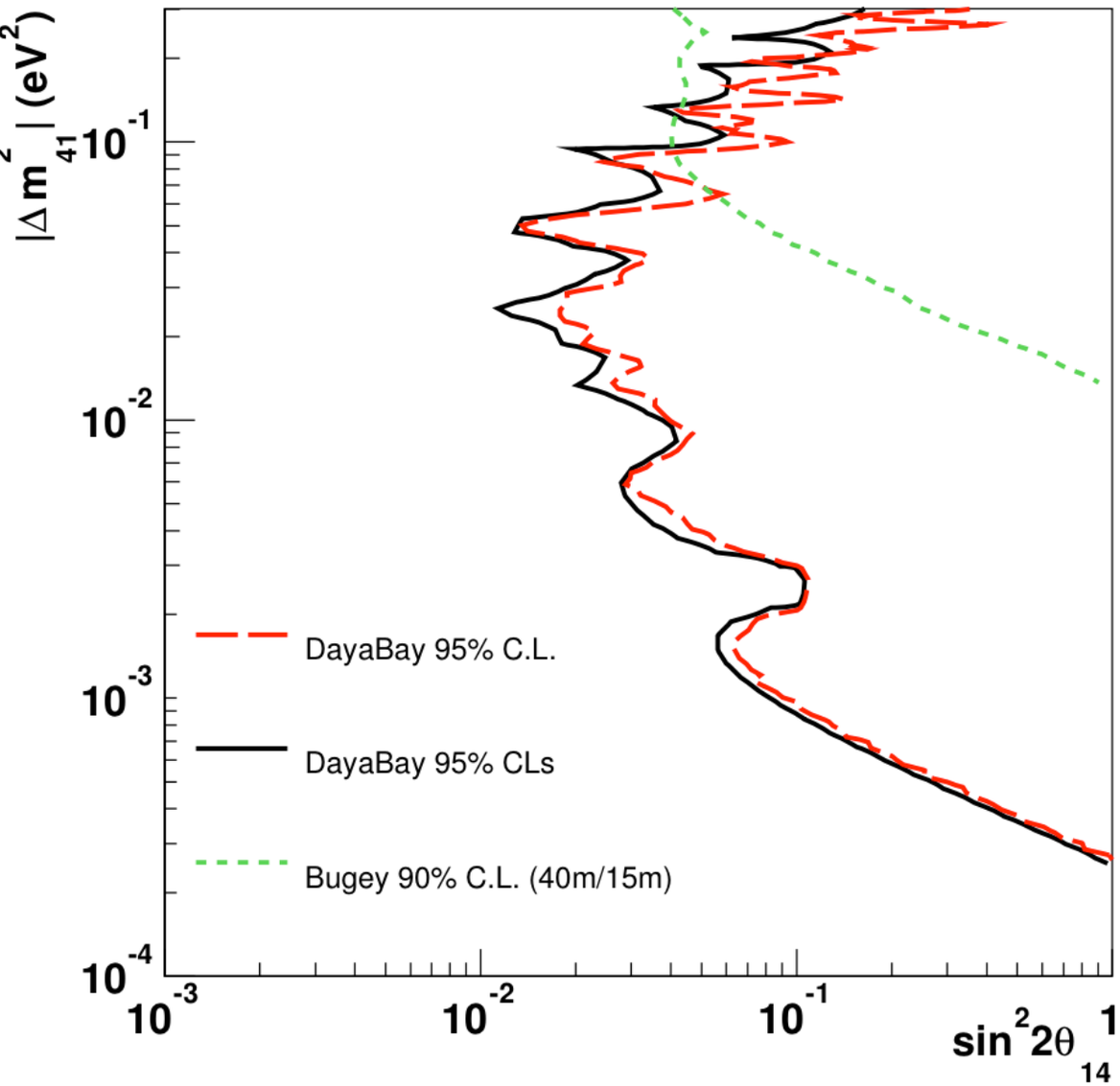


New oscillation mode from a fourth (sterile) neutrino

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

Results of Sterile Neutrino Search





- 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 of Daya Bay Results

- the most precise measurement of $\sin^2 2\theta_{13}$ and Δm^2_{ee}
- independent measurement of $\sin^2 2\theta_{13}$ with nH capture
- absolute measurement of reactor antineutrino flux
  - consistent with previous measurements
  - inconsistent with model predictions
- measured reactor antineutrino spectrum
  - inconsistent with traditional model predictions

More results are coming, stay tuned.

Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

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

Europe (2)

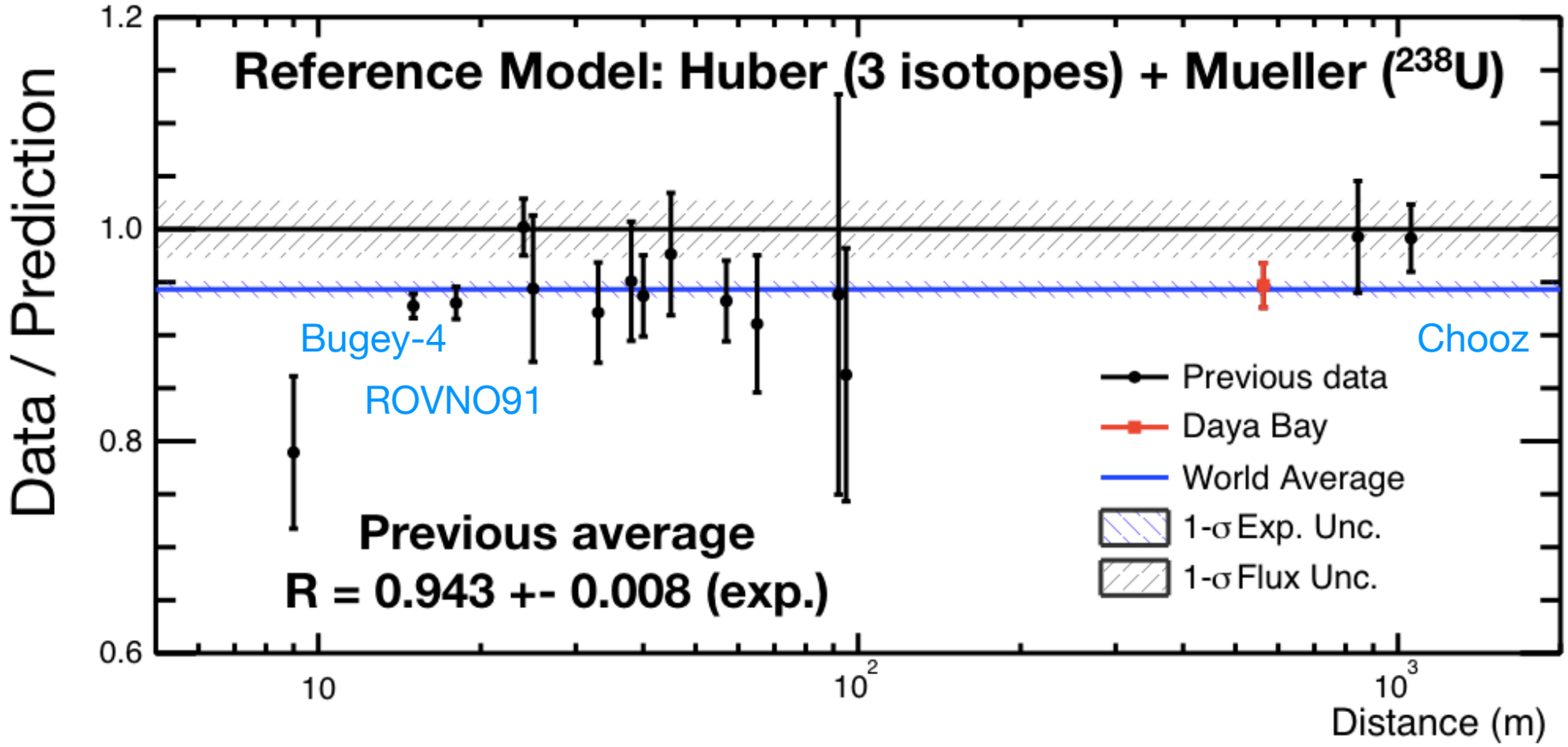
JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

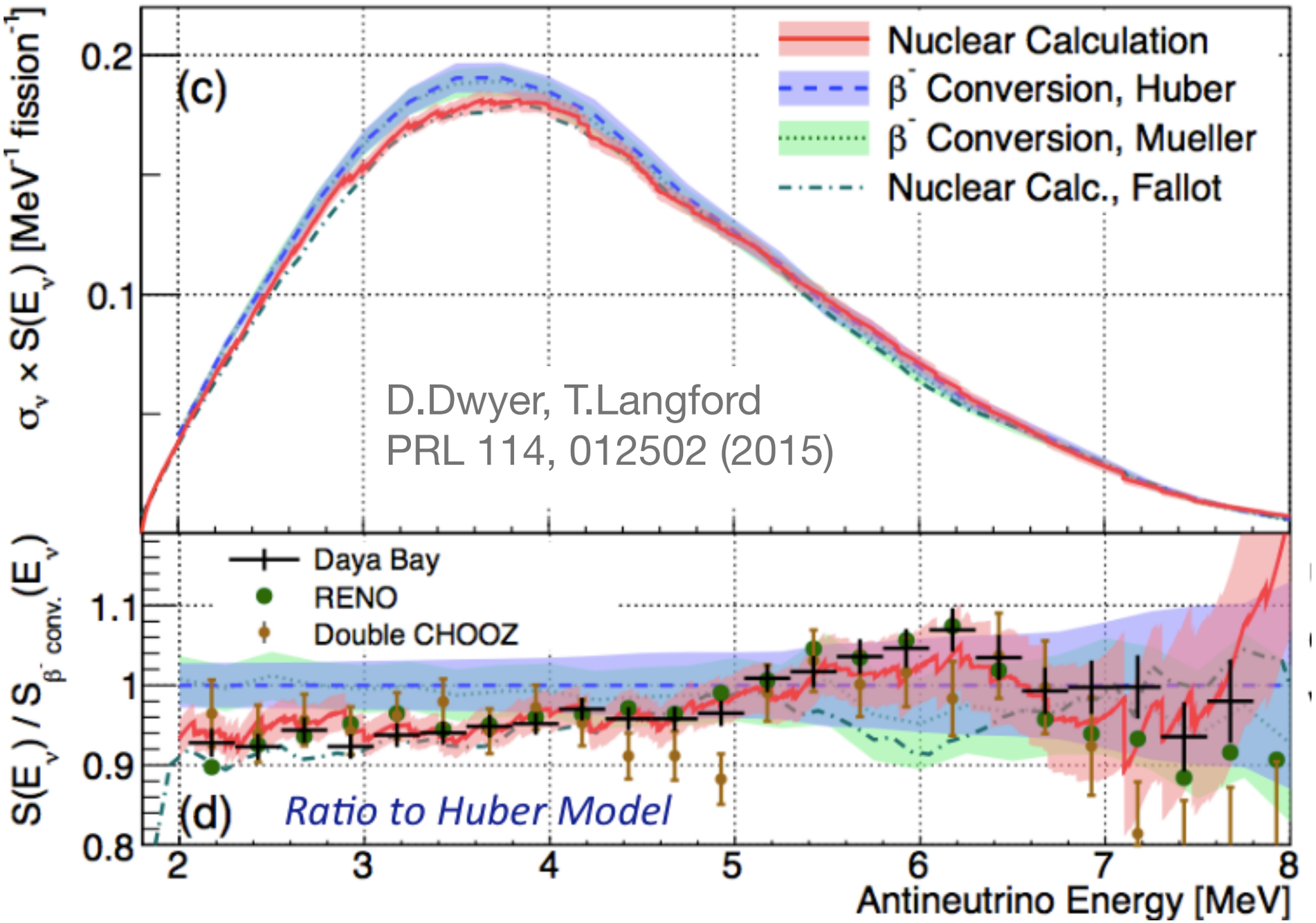
Catholic Univ. of Chile

Thank you!

Backup
Previous Reactor Antineutrino Measurements



Backup
Recent Reactor Antineutrino Model Prediction



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