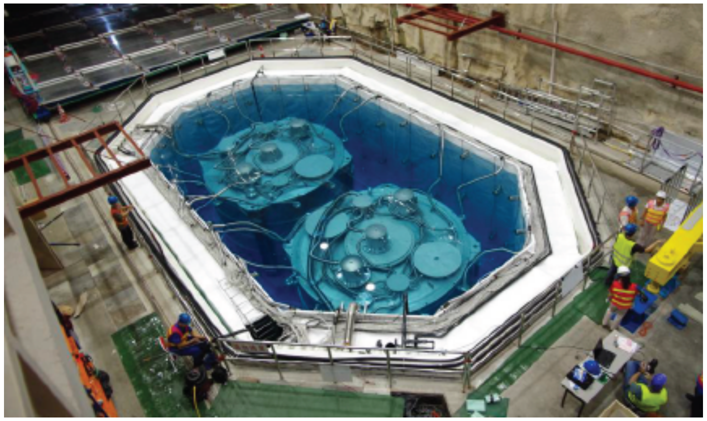
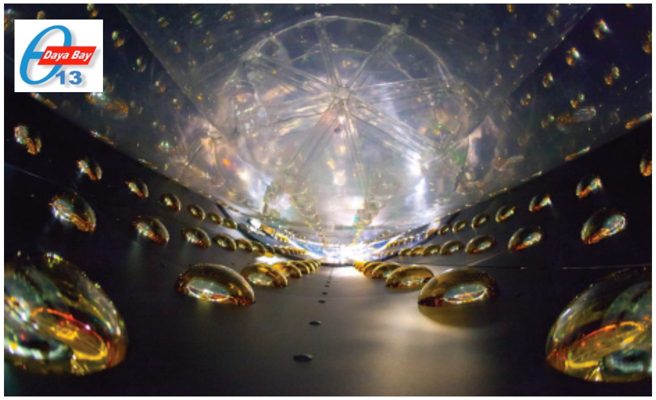


Results - Daya Bay, RENO, and Double Chooz

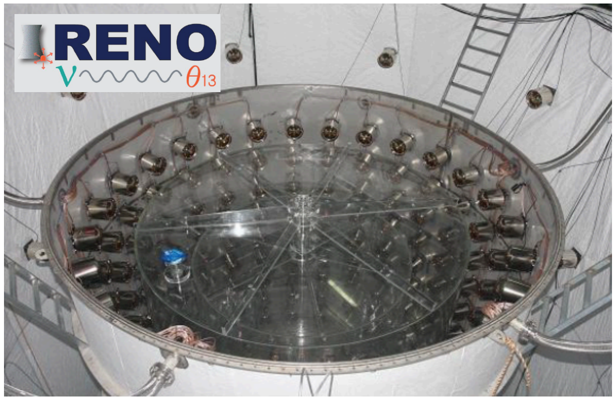
Henry Band

Yale University

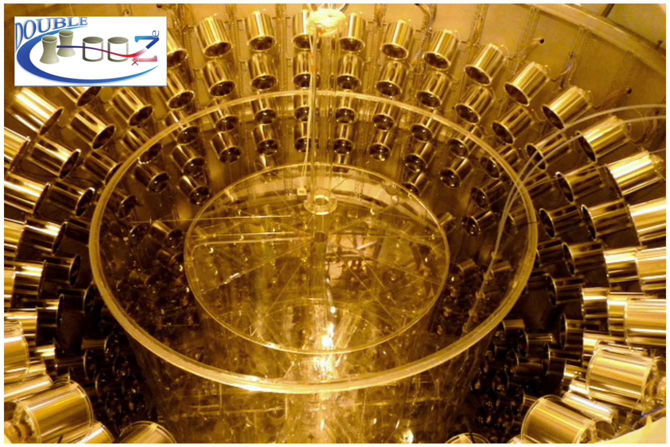
For the Daya Bay Collaboration



Outline



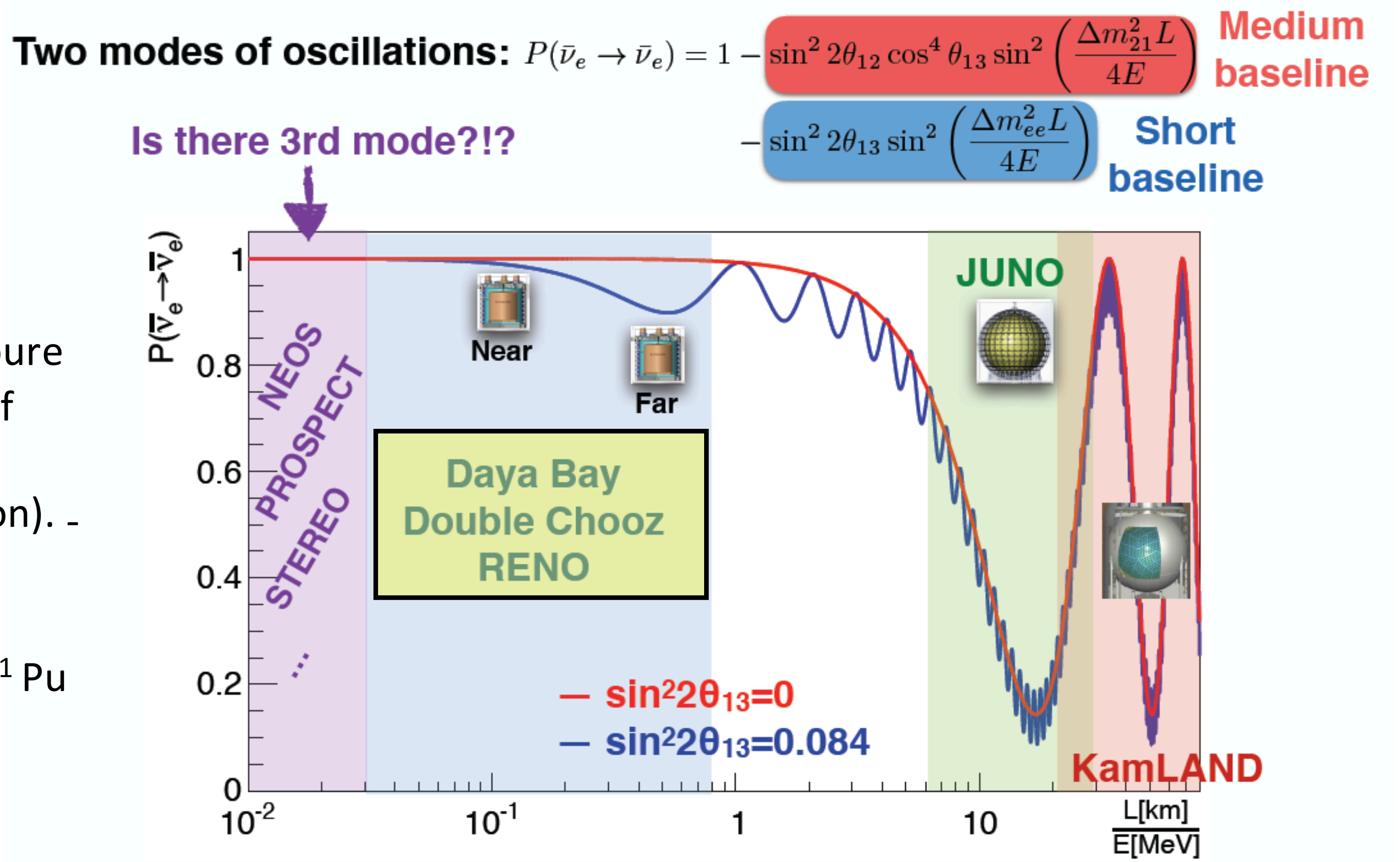
- Introduction
- θ_{13} experiments, near/ far detectors, similarities and differences
- Recent improvements - increased statistics, improved analysis, better calibration
- $\mathrm{Sin}^2 2\theta_{13}$ and Δm^2_{ee}
- Reactor neutrino anomaly, flux deficit, spectrum shape, fuel evolution
- Other results



Reactor Antineutrino oscillations

Reactors produce pure $\bar{\nu}_e$ from $\boldsymbol{\beta}$-decays of neutron rich fission fragments ~(6/fission).

> 99.9% of $\bar{\nu}_e$ from ^{235}U, ^{238}U, ^{239}Pu, ^{241} Pu



- Keys
  - Relative near/far measurements to reduce modeling systematics
- High-statistics
- Background suppression
- Control of systematics errors

Antineutrino Detection

- **Inverse β-decay (IBD)**: coincidence of two consecutive signals

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

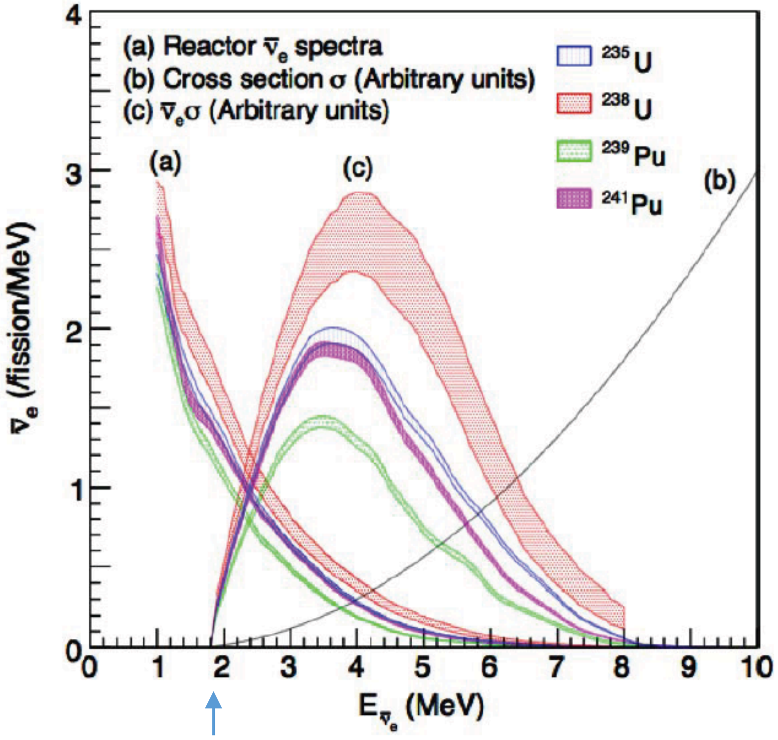
$E_e \sim E_\nu - 0.8$ MeV

~30μs

(0.1% Gd)

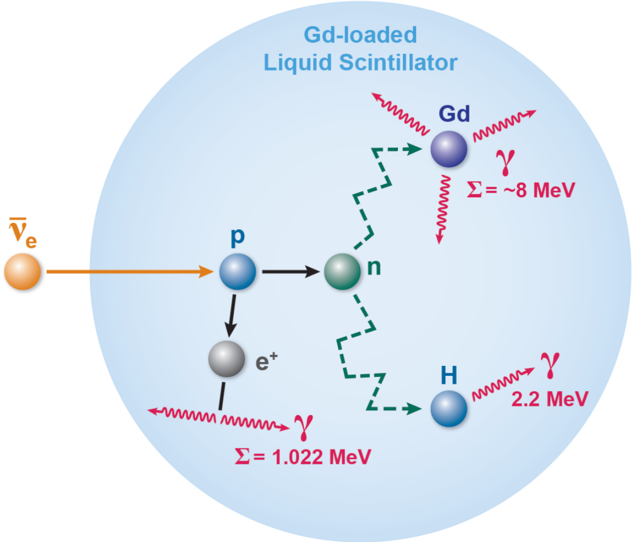
$\rightarrow + \mathrm{p} \rightarrow \mathrm{D} + \gamma$ (2.2 MeV) (delayed signal) ~15%

$\rightarrow + \mathrm{Gd} \rightarrow \mathrm{Gd}^* \rightarrow \mathrm{Gd} + \gamma$'s (8 MeV) (delayed signal) ~85%



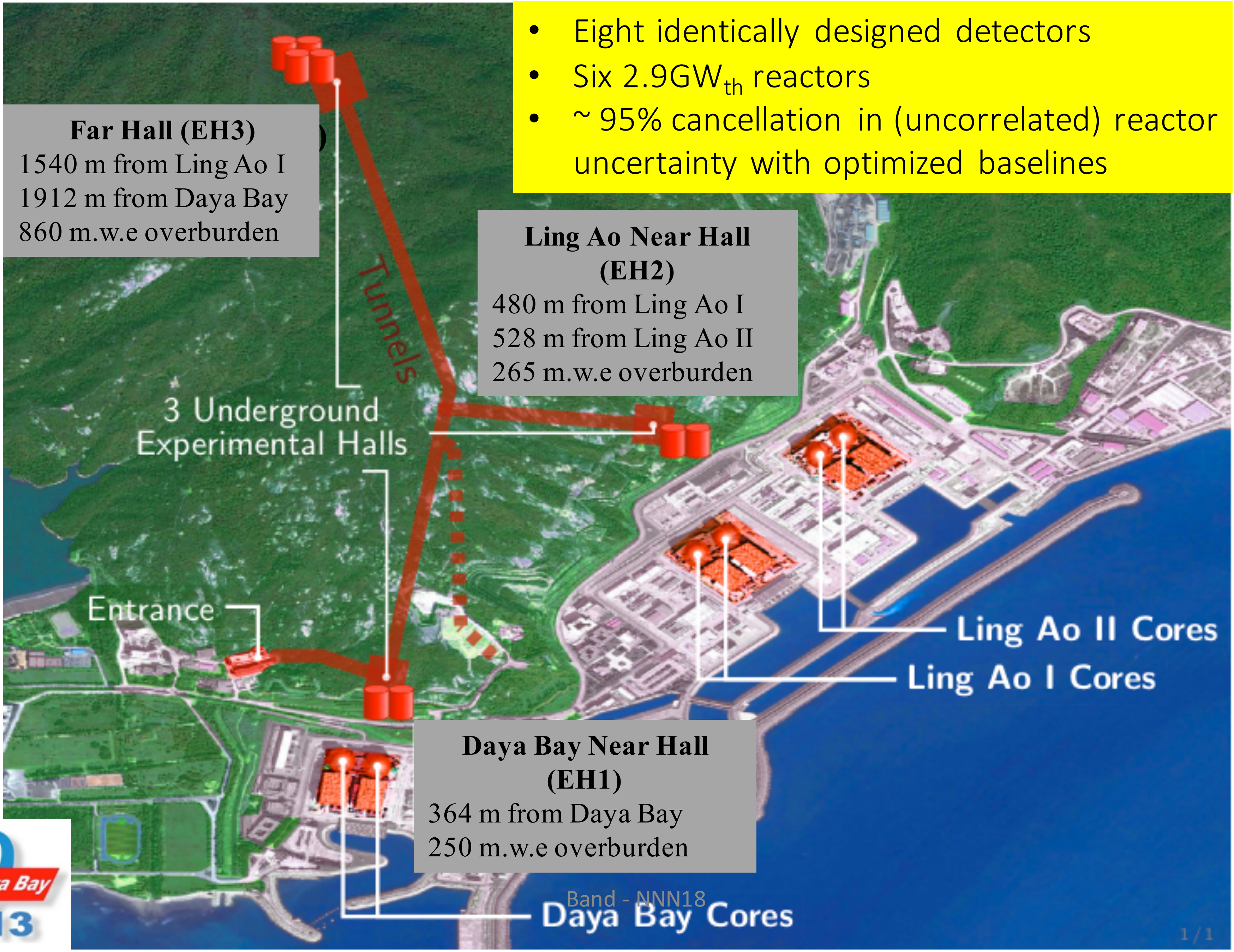
1.8 MeV

- Powerful background rejection
- Positron preserves most information about antineutrino energy



Daya Bay Experimental Layout

- Eight identically designed detectors
- Six 2.9GW_{th} reactors
- ~ 95% cancellation in (uncorrelated) reactor uncertainty with optimized baselines



Far Hall (EH3)
1540 m from Ling Ao I
1912 m from Daya Bay
860 m.w.e overburden

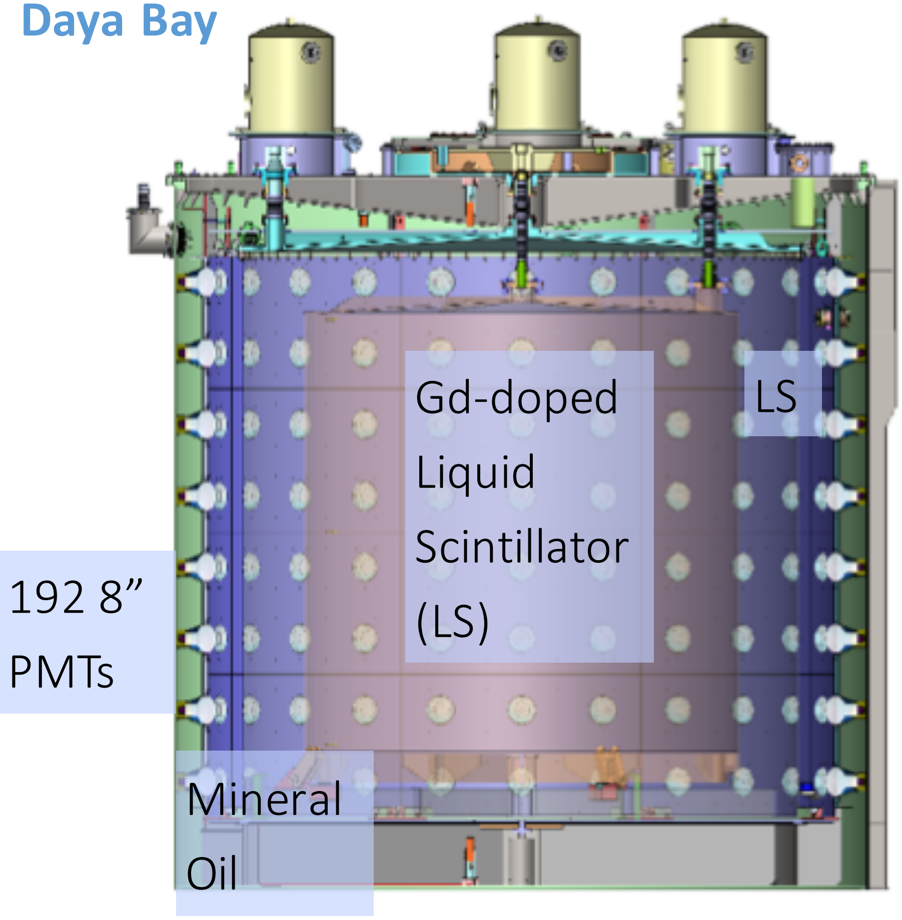
Ling Ao Near Hall (EH2)
480 m from Ling Ao I
528 m from Ling Ao II
265 m.w.e overburden

Daya Bay Near Hall (EH1)
364 m from Daya Bay
250 m.w.e overburden

Detectors

- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools

Daya Bay

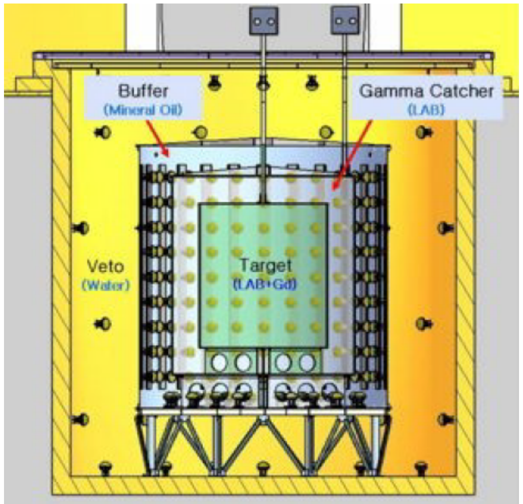


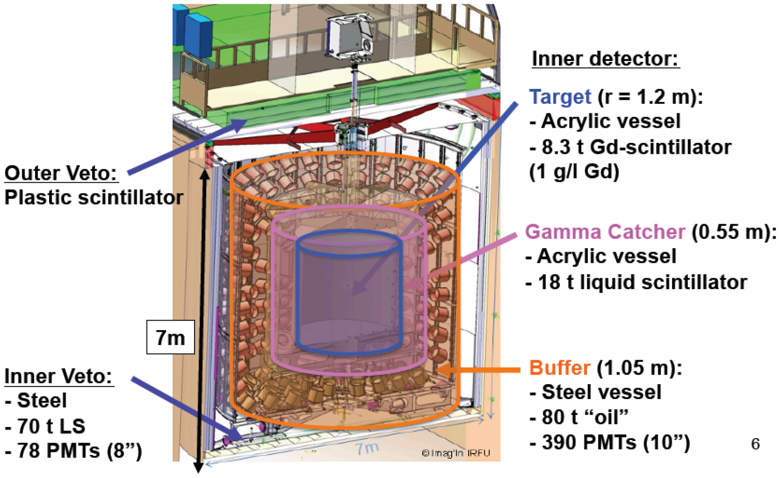
- *GdLS region defines the target mass*
- *Surrounding LS improves detection of γ-rays*
- *MO buffers outside backgrounds*
- *Water reduces backgrounds & detects muons*
- *Additional muon detection above*

[Energy resolution ≅ 8.5%/√E (MeV)](#)

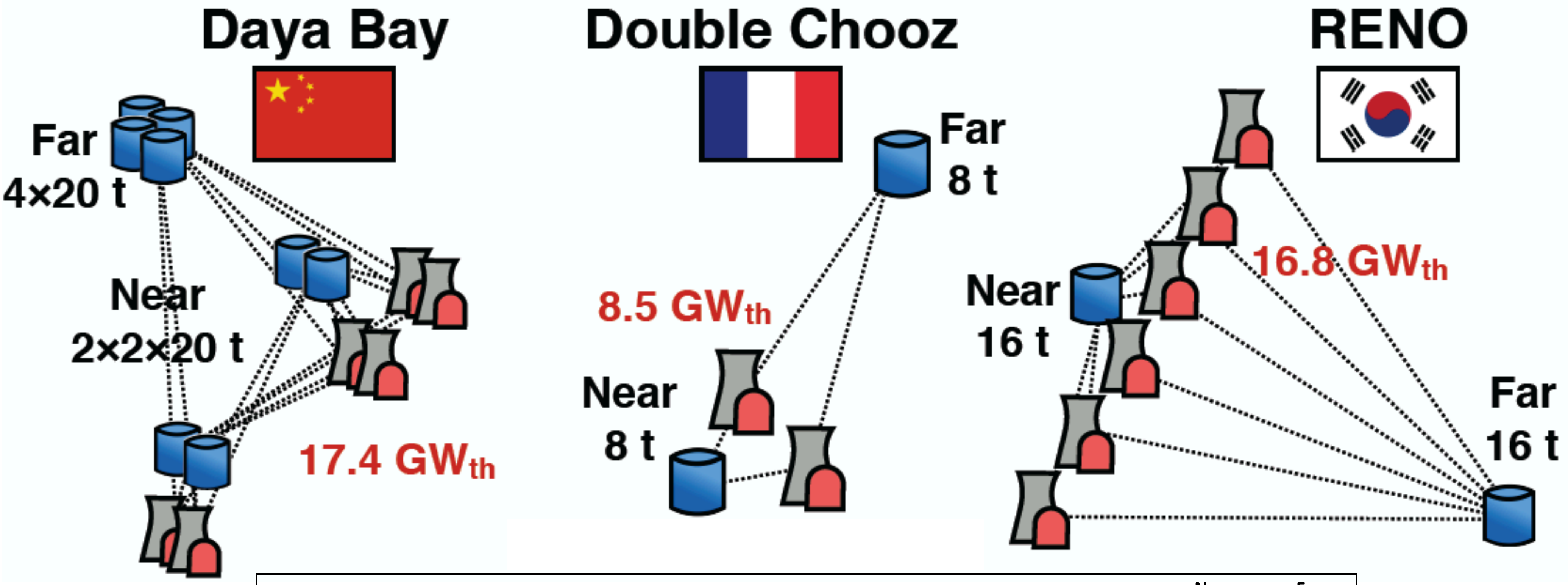
[NIM A 811, 133 (2016)](#)

RENO



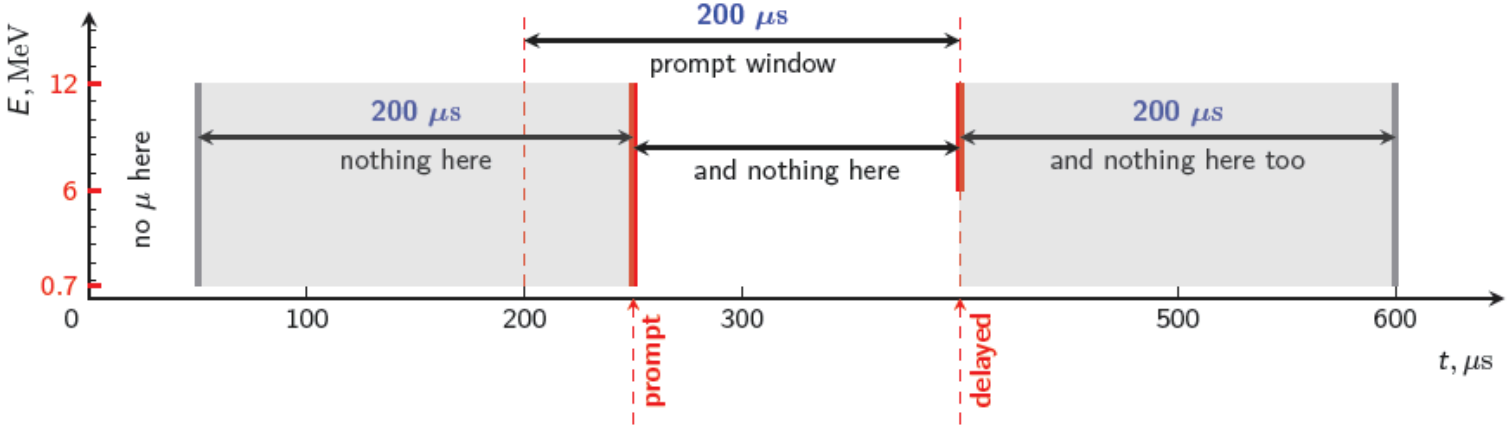


Double Chooz



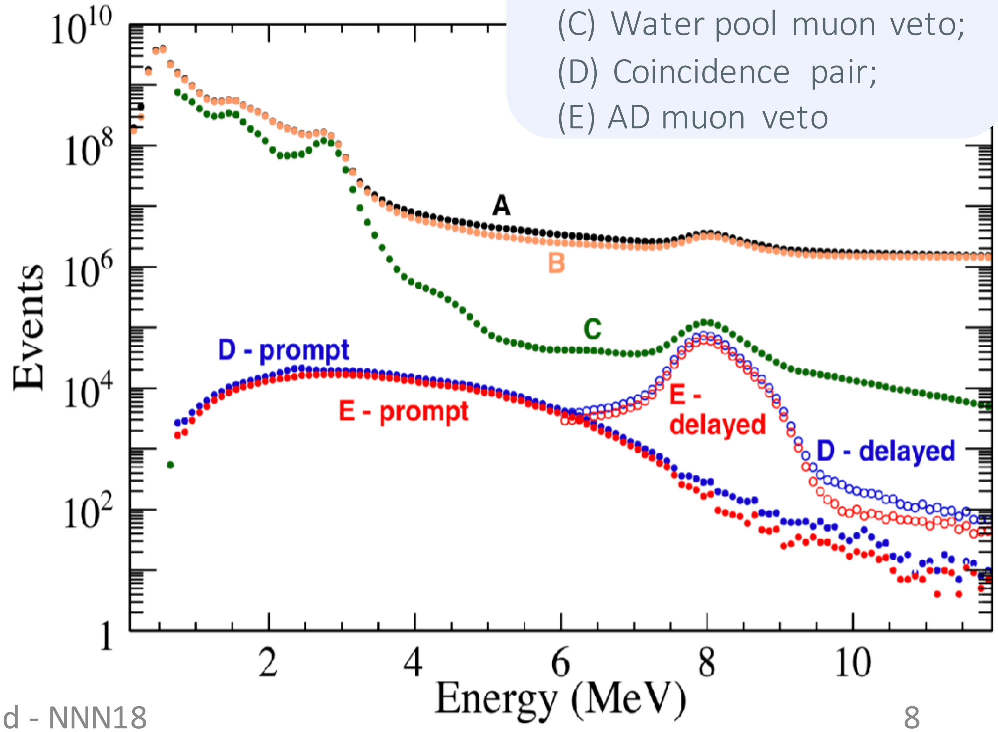
Experiment	Near/far data	Near Dector mass (ton)	Far Detector mass (ton)	Overburden near (m.w.e.)	Overburden far (m.w.e.)	Detector design	Reactor power (GWth)	Near detector baseline (km)	Far detector baseline (km)
Daya Bay	2011-2020	2*2*20	4*20	250-265	860	3 zone (GdLS, LS, MO)	6*2.9	.364-.528	1.54-1.912
Reno	2011- 2020?	16.5	16.5	120	450	3 zone (GdLS, LS, MO)	6*2.8	0.411	1.446
Double Chooz	2015-17	8.3	8.3	120	300	3 zone (GdLS, LS, MO)	2*4.25	0.415	1.05

IBD Selection



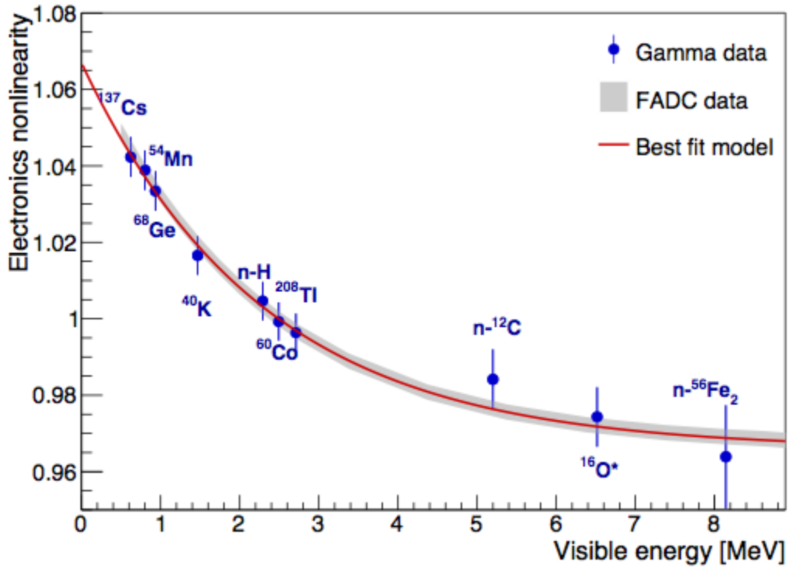
- Backgrounds
  - Accidentals
    - γ-rays and neutrons from materials & environment
  - Correlated backgrounds
    - Fast neutrons
    - Spallation produced $\boldsymbol{\beta}$n emitters (^{9}Li, ^{8}He)
  - Cuts reduce backgrounds by > 10^4
    - Delayed energy 6.0 < E < 12 MeV
    - Prompt energy 0.7 < E < 12 MeV
    - 1 $\boldsymbol{\mu}$s < Δt < 200 $\boldsymbol{\mu}$s

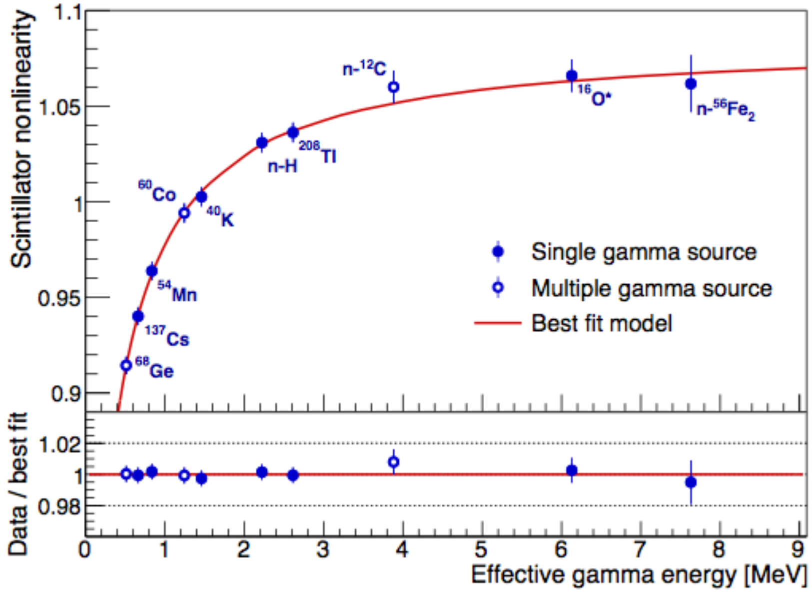
(A) All signals;
(B) PMT flasher removal;
(C) Water pool muon veto;
(D) Coincidence pair;
(E) AD muon veto

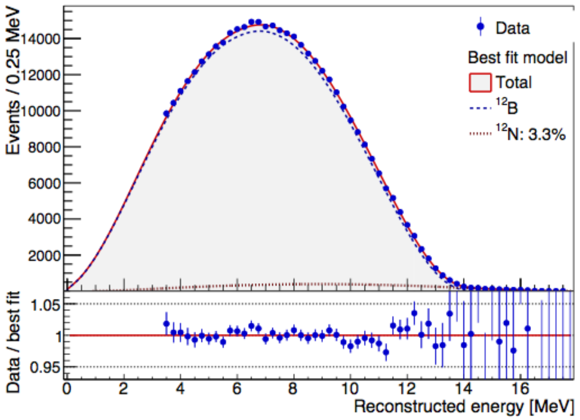


Improved calibration & modeling

- Statistical error in $\bar{\nu}_e$ rates are ~ 0.05 % (near), ~0.14% (far), background uncertainty ~ 0.12% - minimize systematic errors
- Recent work by Daya Bay to improve energy model
  - Measured non-linear electronics response with FADC readout in parallel with standard electronics NIM A895, 48-55 (2018)
  - Deployed ^{60}Co calibration sources with different encapsulating materials, to constrain optical shadowing effects
  - Constructed improved energy response model



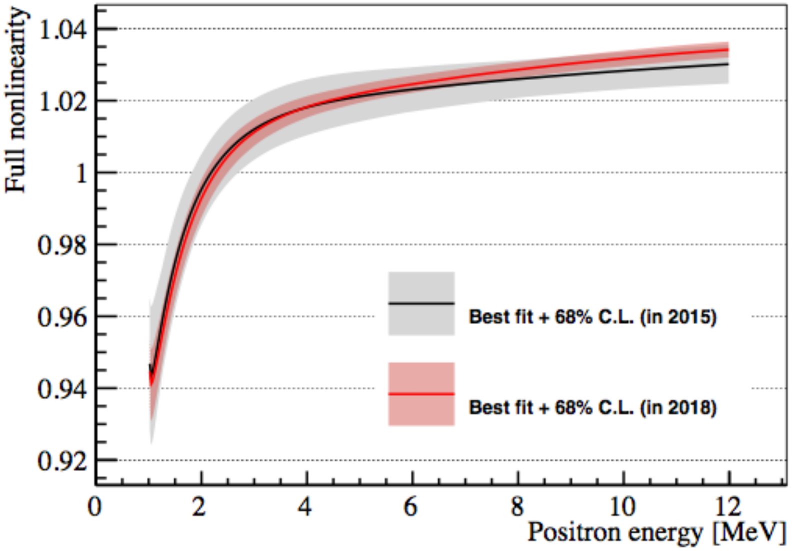


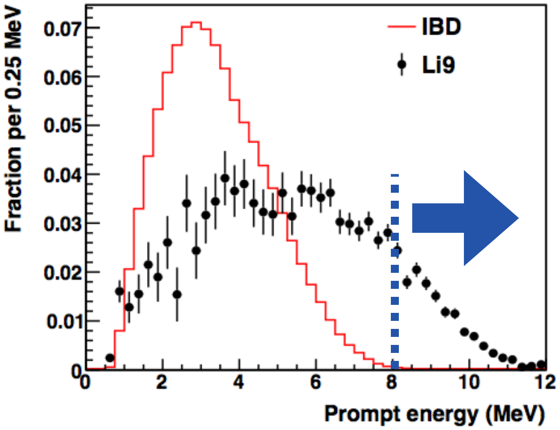


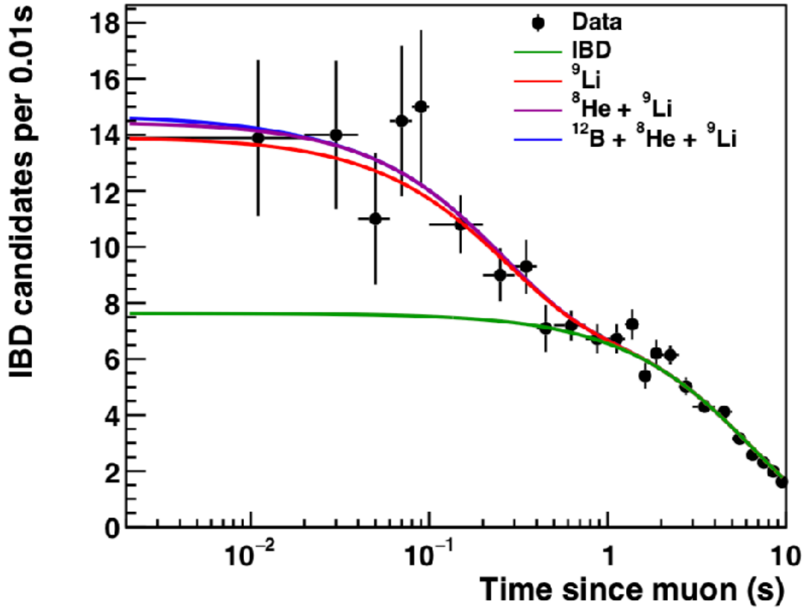
Further improvements

- New energy model reduces uncertainty from 1.0 to 0.5%
- Increased statistics allow an improved estimate of the rate β-n decays of cosmogenically produced ^{9}Li/^{8}He
- Review of the spent nuclear fuel (SNF) history with power plant reduced its uncertainty from 100% to 30% (SNF=0.3% of total rate)

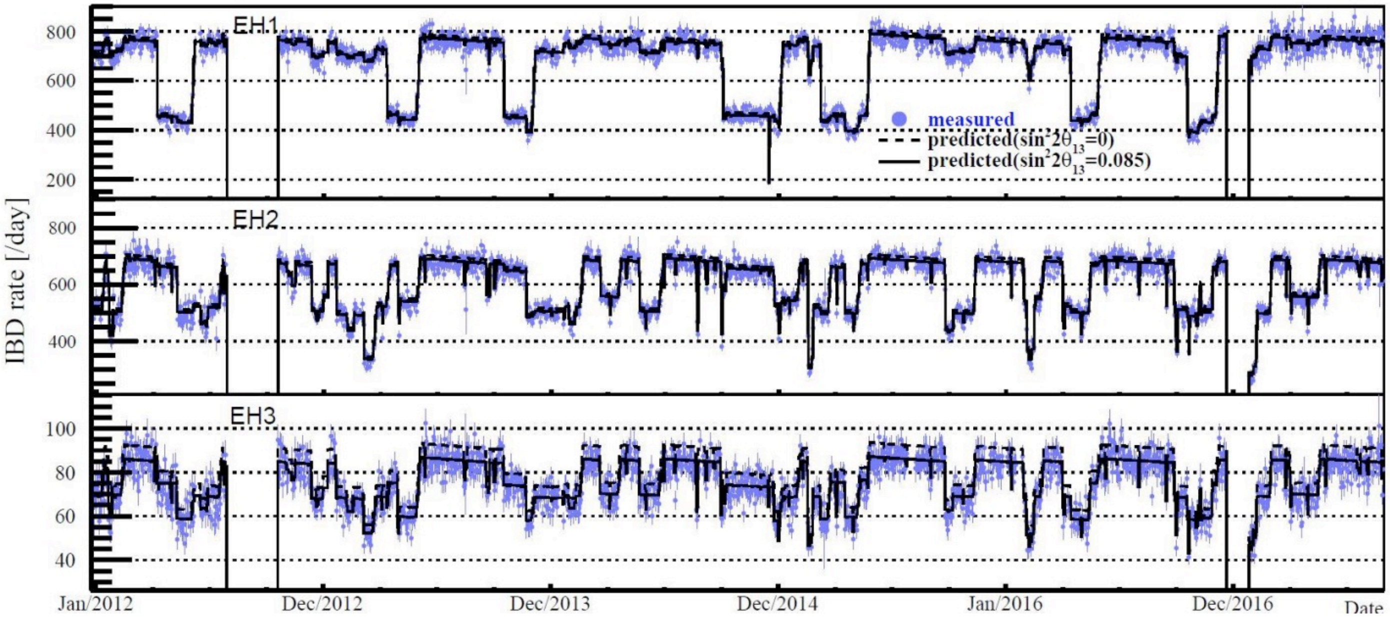
Energy model







Daya Bay - 1958 days of data Dec 24, 2011 to Aug 30, 2017



Far detectors
$0.5\ 10^6$ events

Near detectors
$3.5\ 10^6$ events

ArXiv:1809.02261

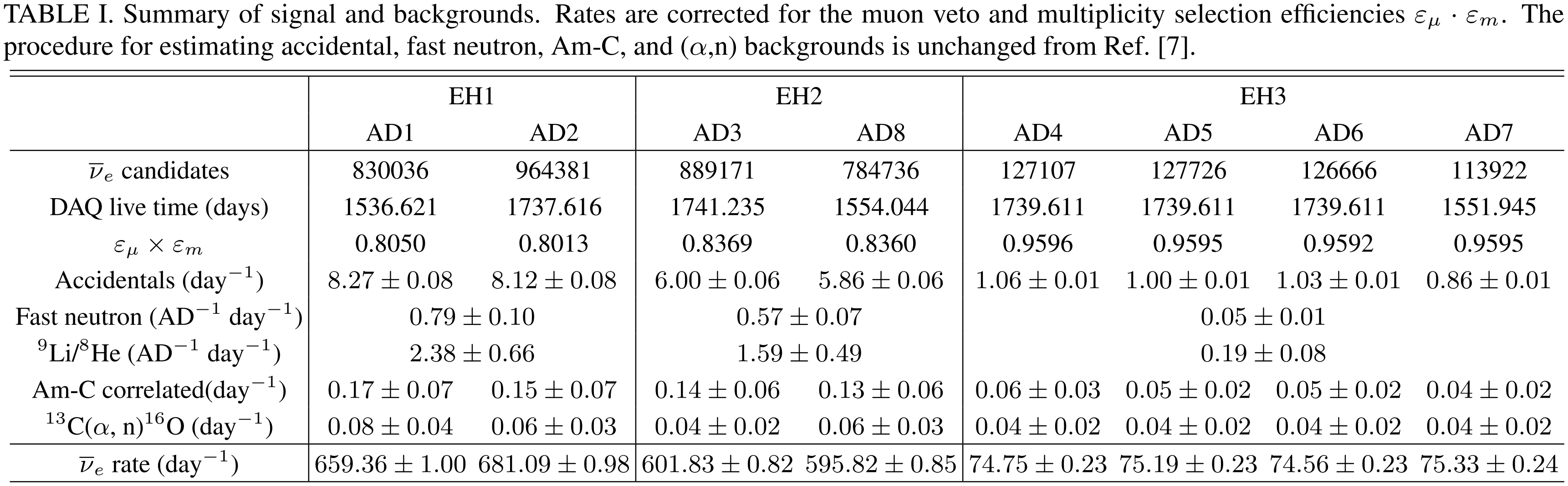


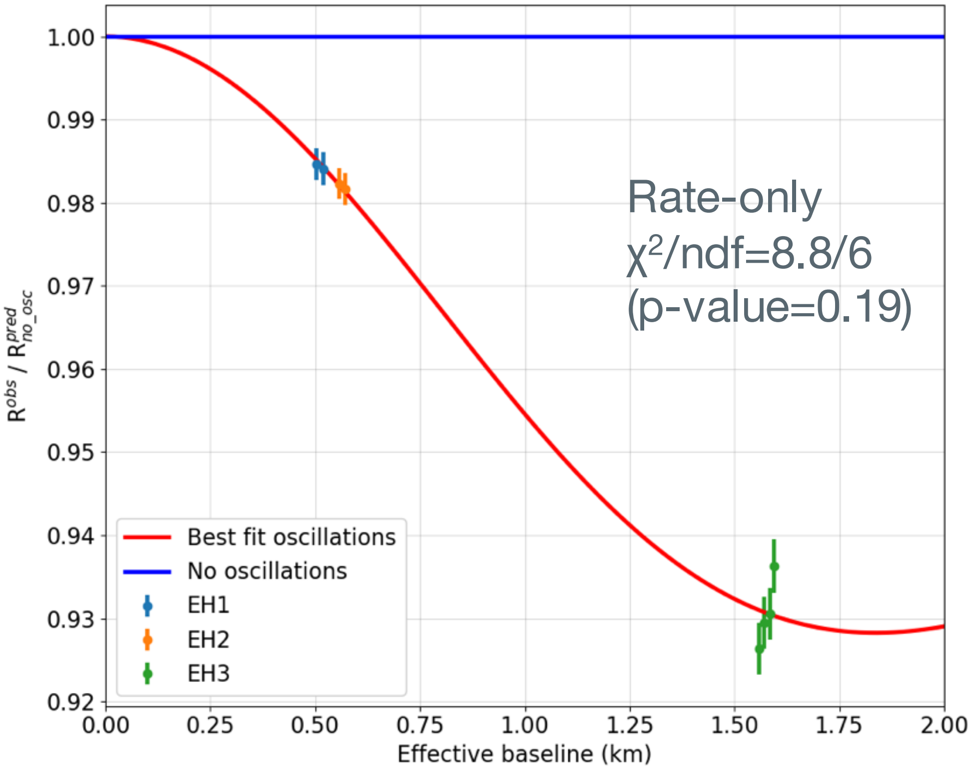
TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The procedure for estimating accidental, fast neutron, Am-C, and (α,n) backgrounds is unchanged from Ref. [7].

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
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
$\overline{\nu}_e$ 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

Daya Bay

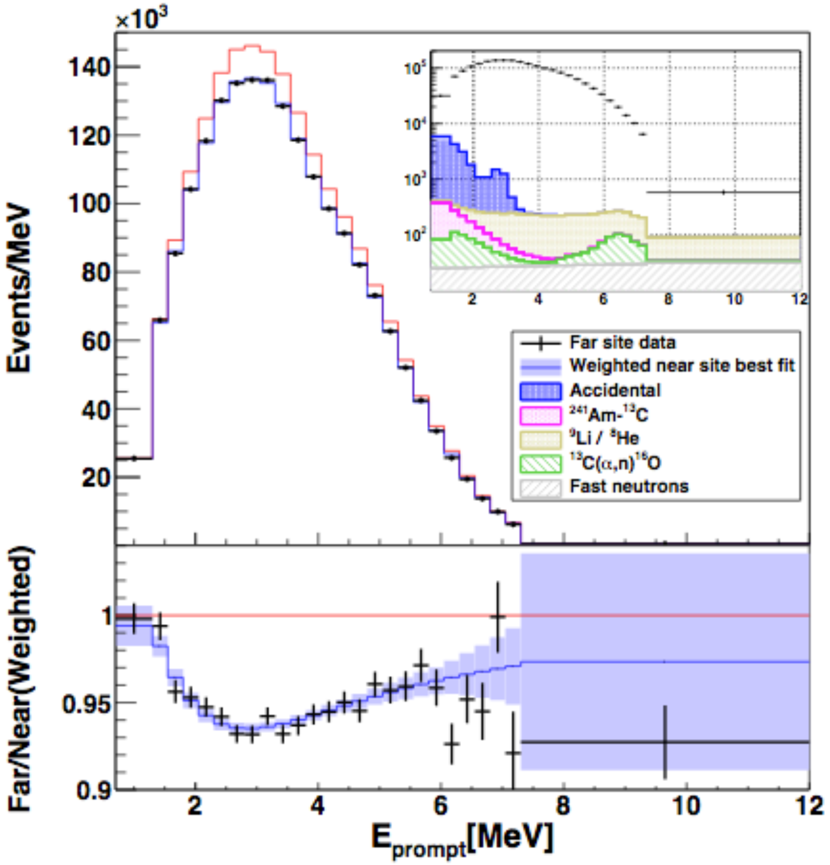
ArXiv:1809.02261

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis



Rate-only
χ^2/ndf=8.8/6
(p-value=0.19)

Rate+shape
χ^2/ndf=148.0/154

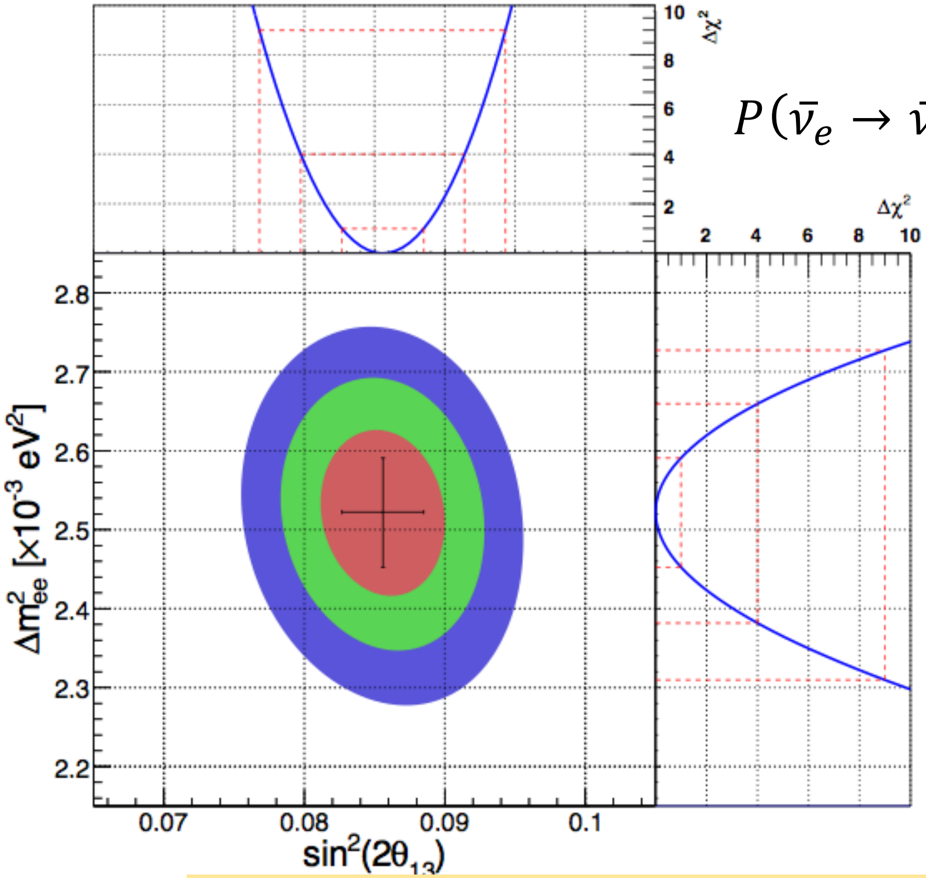


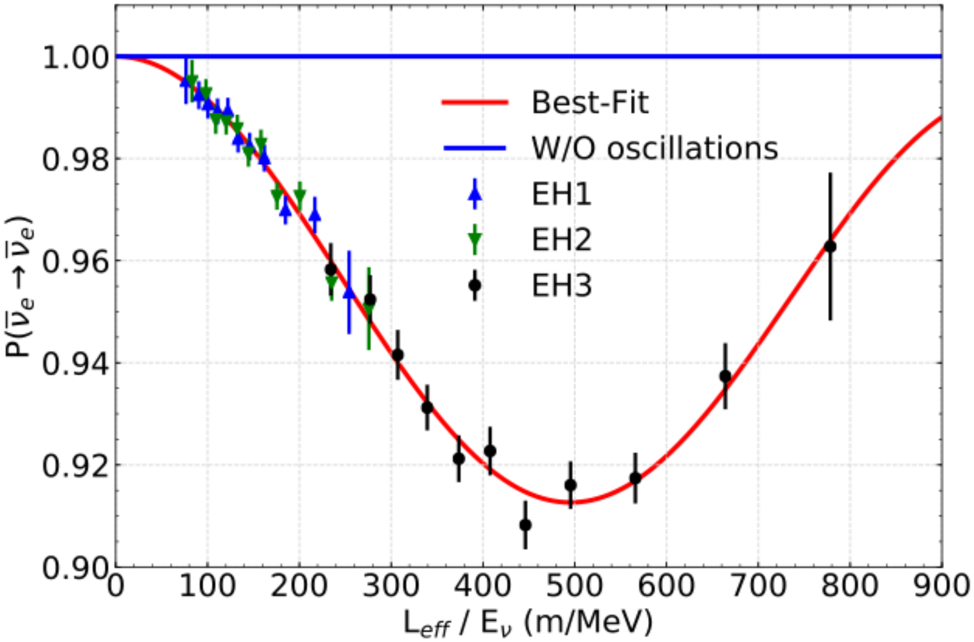
Daya Bay

ArXiv:1809.02261

- Oscillation Results with 1958 Days
- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267\Delta \mathrm{m}^2_{\mathrm{ee}} L}{E} - \text{solar term}$$





$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{\mathrm{ee}}| = (2.522 + 0.068 - 0.070) \times 10^{-3}\ \mathrm{eV}^2$$

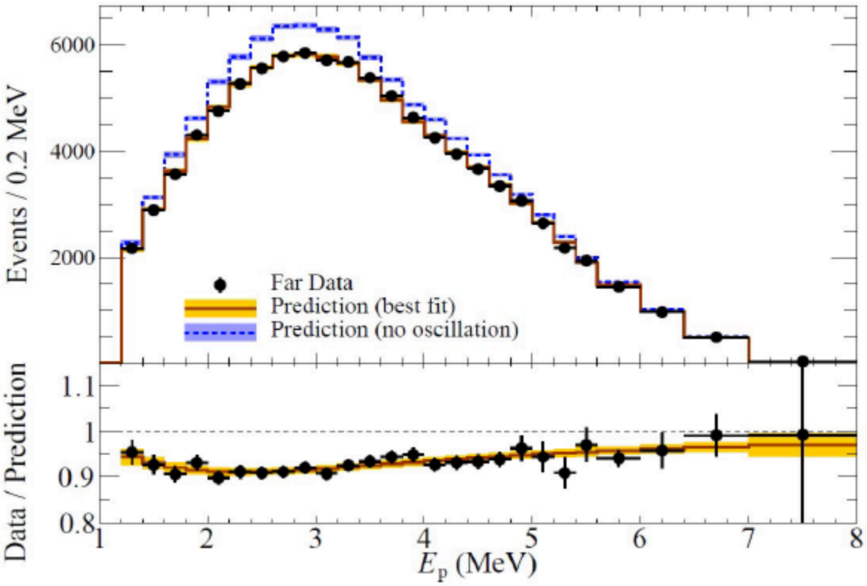
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

RENO & Double Chooz

RENO

ArXiv:1806.00248

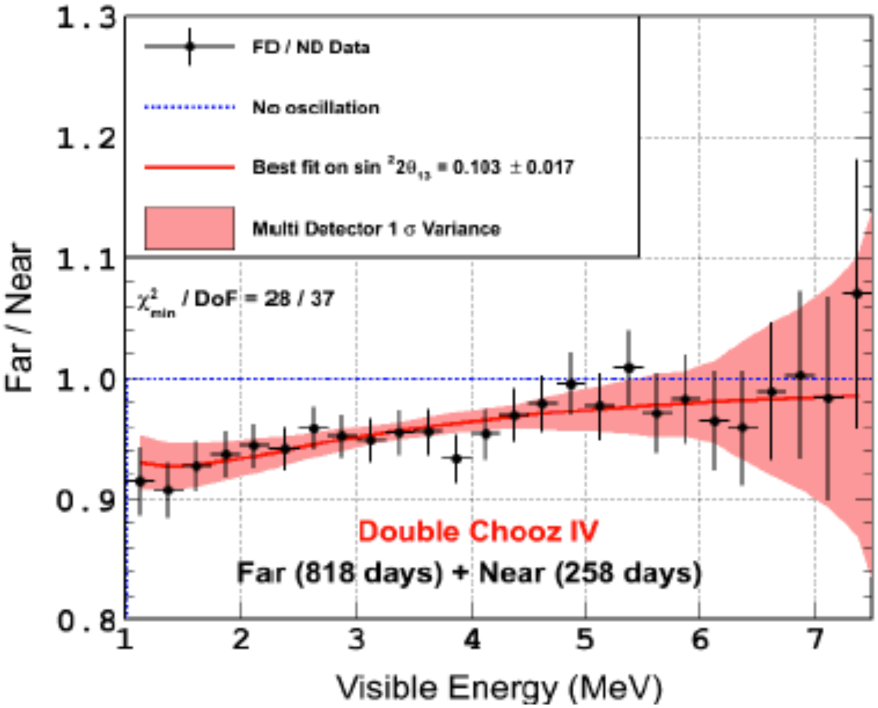
0.1 10^6 (far), 0.85 10^6 (near)



Double Chooz

Buck - Neutrino 2018

9.0 10^4 (far), 2.1 10^5 (near)



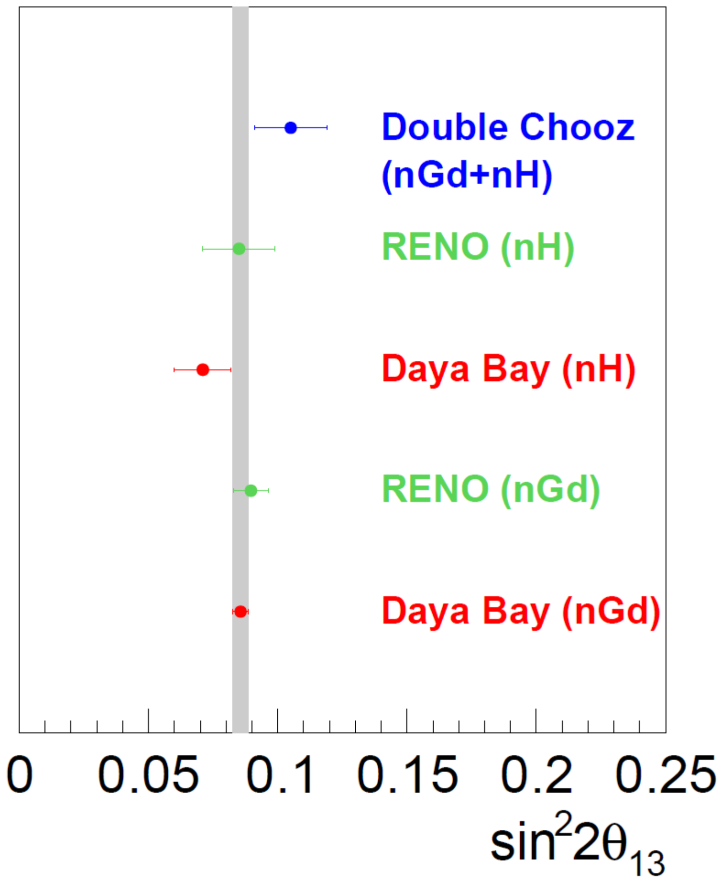
$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0068$$
$$|\Delta m^2_{ee}| = (2.68 \ \pm 0.14)\times 10^{-3}\ \mathrm{eV}^2$$

combined nGd+nC+nH

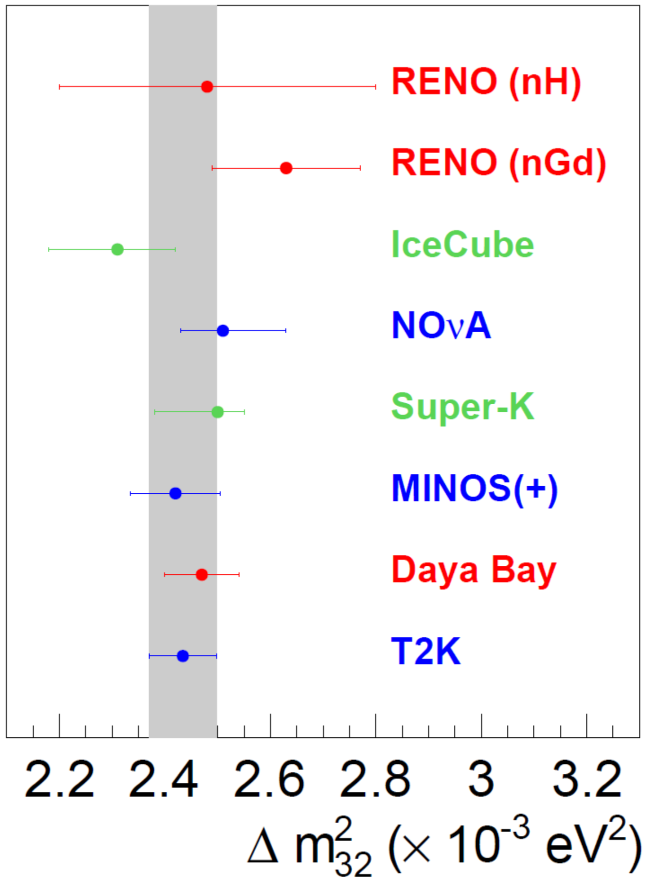
$$\sin^2 2\theta_{13} = 0.105 \pm 0.014$$

Global Comparison

results presented at
Neutrino 2018 conference



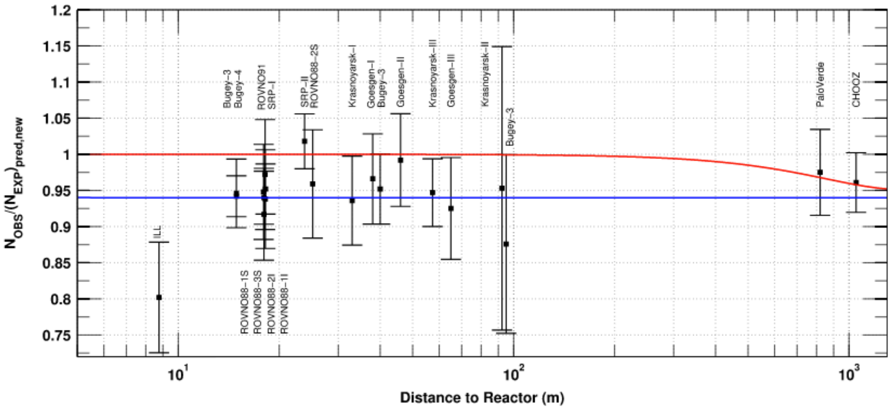
Normal Ordering Assumed



- Daya Bay – best precision of θ_{13} in the foreseeable future
- Agreement of Δm^2_{32} between accelerator & reactor experiments
- Analysis of nH events in all detectors consistent with nGd events

Antineutrino Flux - Absolute rate, spectrum shape, fuel evolution

- A re-evaluation of the $\bar{\nu}_e$ theoretical flux prediction from reactors by (Huber-Mueller) in 2011 revealed a ~6% deficit in rates measured by many short baseline experiments. This "reactor antineutrino anomaly " (RAA) lead to the prediction of "sterile" neutrinos to explain the deficit.
- Discrepancies between the predicted antineutrino and measured energy spectrum (a "bump" between 4<E<6 MeV) were seen by the θ_{13} experiments in 2014.

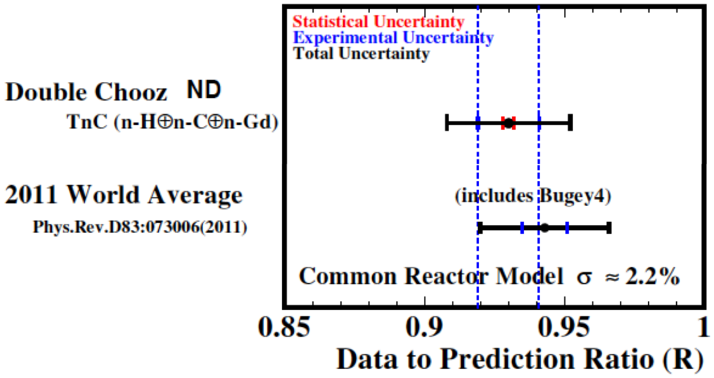


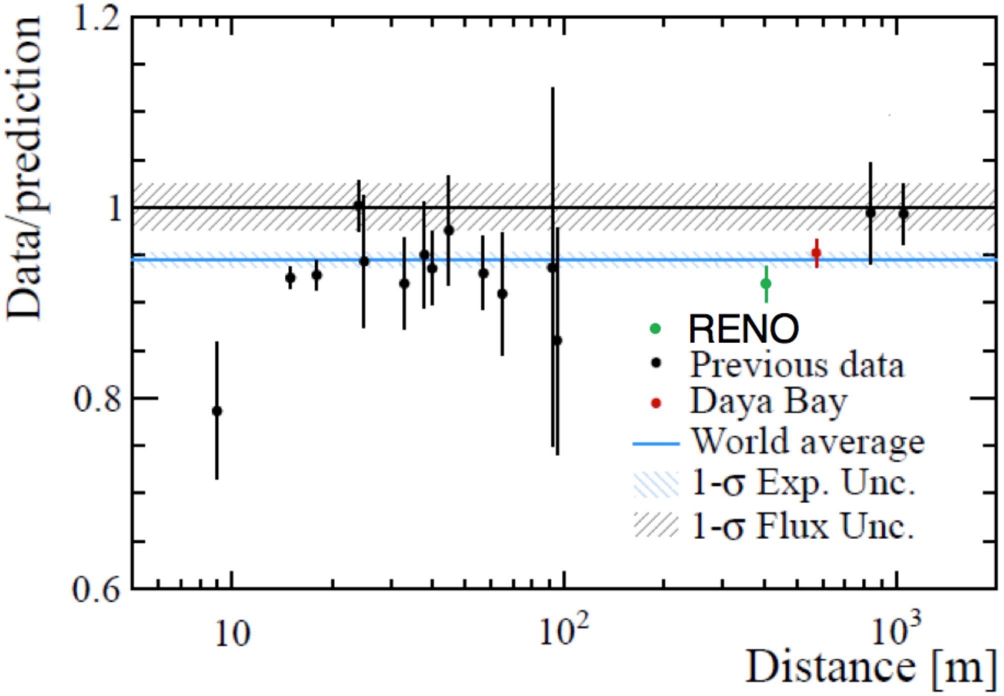
Phys. Rev. D 83 (2011)

- By measuring the changes in $\bar{\nu}_e$ rate with reactor fuel burnup and re-fueling cycles, the individual contributions of each fuel type to the ν_e spectrum could be measured. In 2017, Daya Bay measured a ~2.8σ smaller contribution from ^{235}U than expected.

Absolute reactor flux

- Updated analysis with reduced systematic errors
  - Daya Bay 1260 days ArXiv:1808.10836
    - $R_{\text{data/pred}}$ (Huber-Mueller) $= 0.952 \pm 0.014(\text{exp.}) \pm 0.023(\text{model})$
    - $\sigma_f = (5.91 \pm 0.09) \times \frac{10^{-43}\,\text{cm}^2}{\text{fission}}$
  - RENO 2200 days Yu @ Neutrino2018
    - $R_{\text{data/pred}}$ (H-M) $0.918 \pm 0.018(\text{exp.})$
    - $\sigma_f = (5.79 \pm 0.11) \times \frac{10^{-43}\,\text{cm}^2}{\text{fission}}$
  - Double Chooz Buck @Neutrino2018

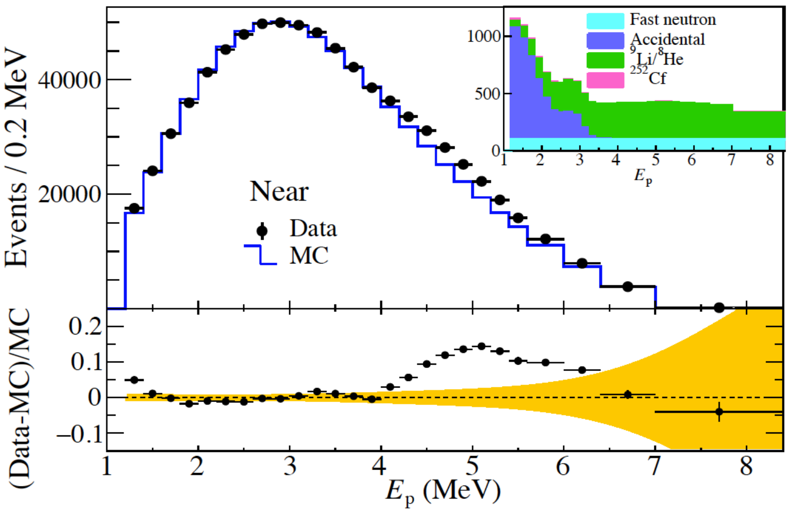


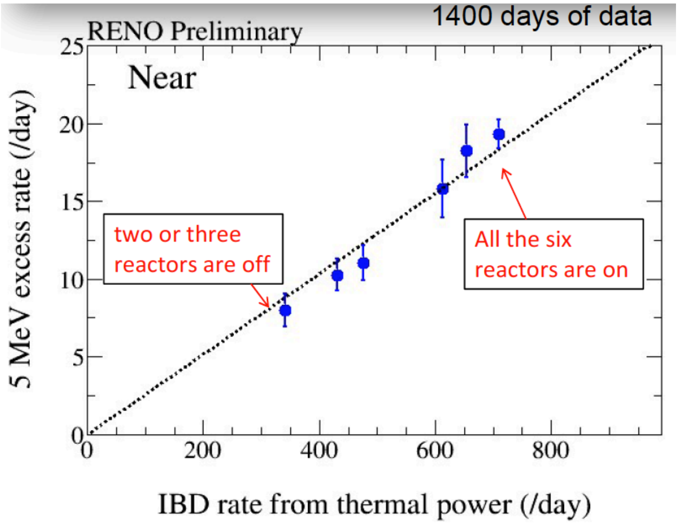


Energy spectrum

- All 3 experiments see deviations from the expected shape in the 4-6 MeV region

RENO ArXiv:1806.00248





1400 days of data

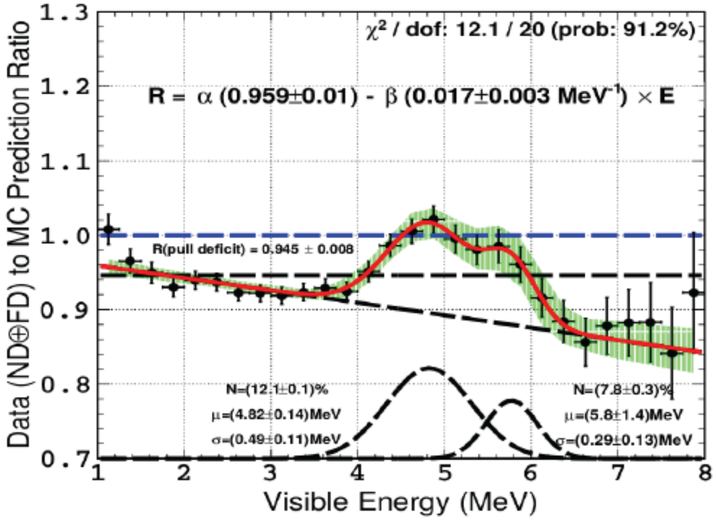
two or three reactors are off

All the six reactors are on

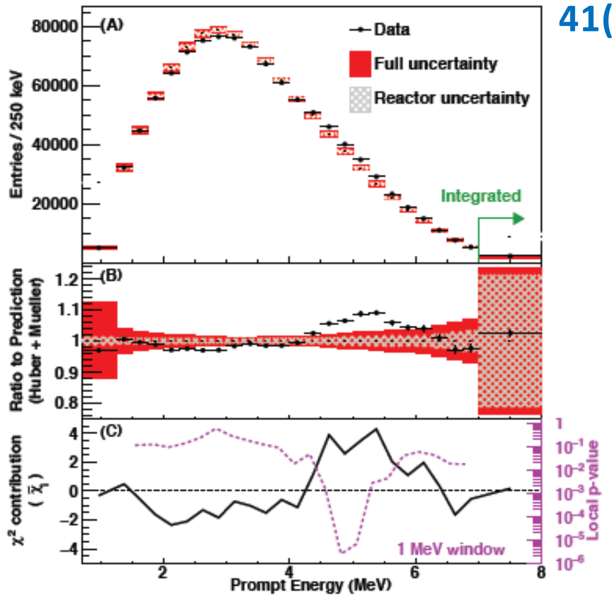
The excess seems to scale with reactor power

Yu @ Neutrino2018

Double Chooz Buck @Neutrino2018

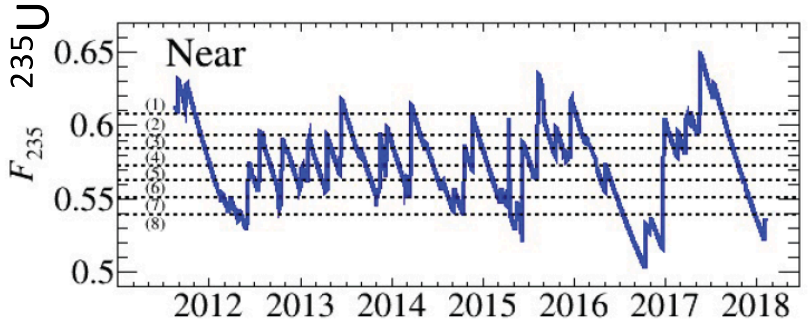


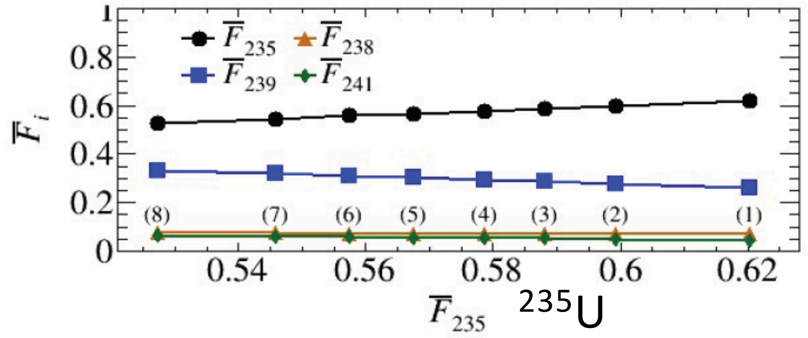
Daya Bay Chinese Phys. C 41(1) (2017).



Reactor Fuel evolution

- Composition of the reactor core changes with time
- Partially reset by refueling operations every 12-18 months



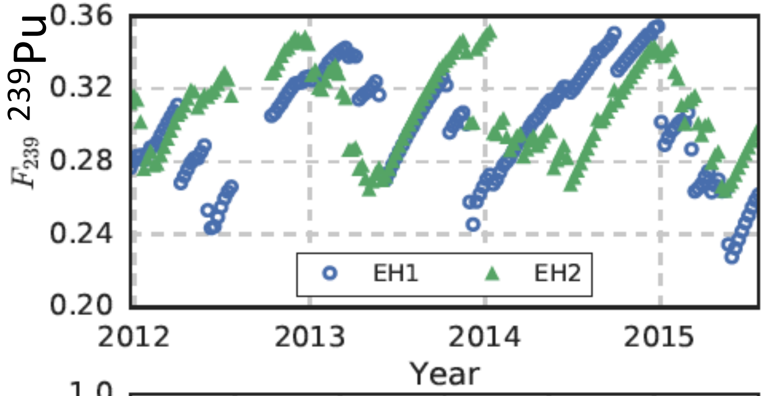


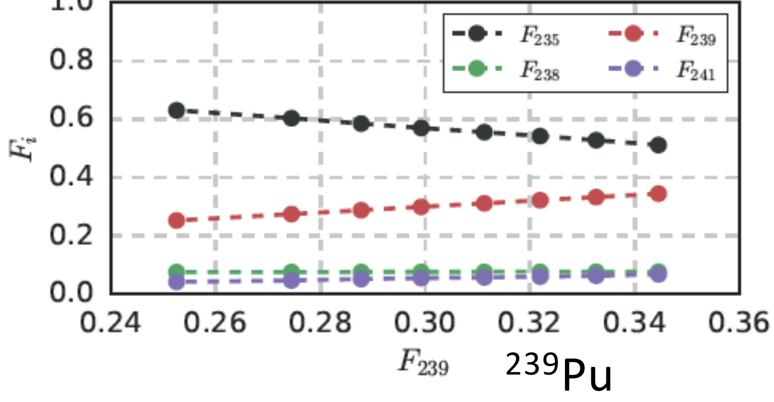
Average fission fraction

f_{235}: f_{239}: f_{238}: f_{241}= 0.573 : 0.299 : 0.073 : 0.055

^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu

RENO ArXiv:1806.00574





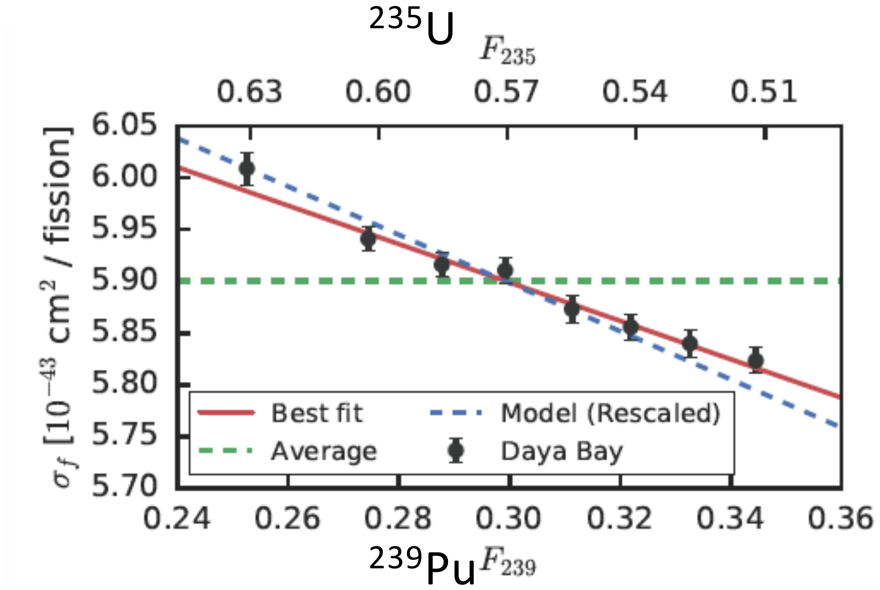
Daya Bay ArXiv:1704.01082

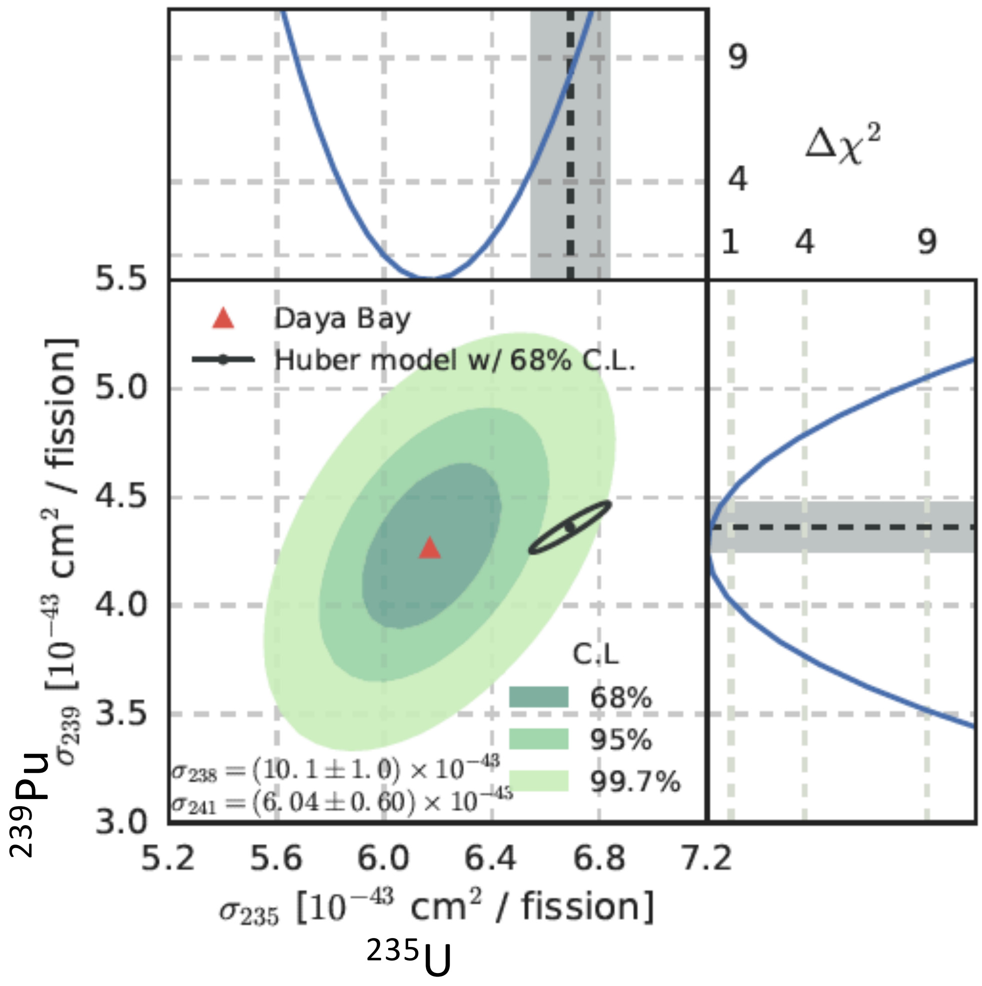
Phys.Rev.Lett. 118 (2017) no.25, 251801

Daya Bay

Phys.Rev.Lett. 118 (2017) no.25, 251801

1230 days





Best fit IBD yields

^{235}U 6.17 ± 0.17 10^{-43} cm^2/fission

^{238}Pu 4.27 ± 0.26 10^{-43} cm^2/fission

compare to model predictions

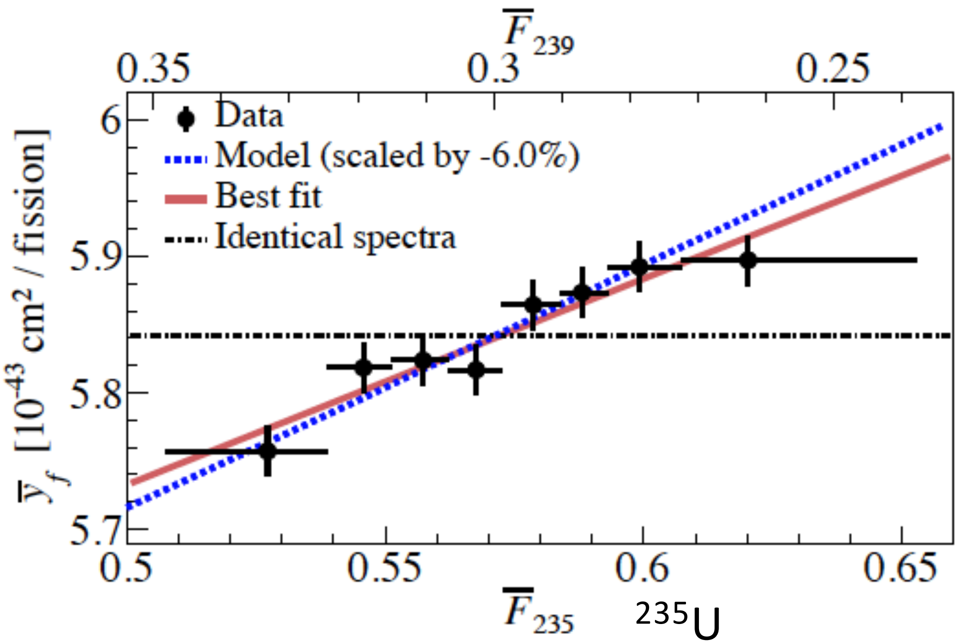
^{235}U 6.69± 0.15 10^{-43} cm^2/fission

^{238}Pu 4.36 ± 0.11 10^{-43} cm^2/fission

RENO

ArXiv:1806.00574

1808 days

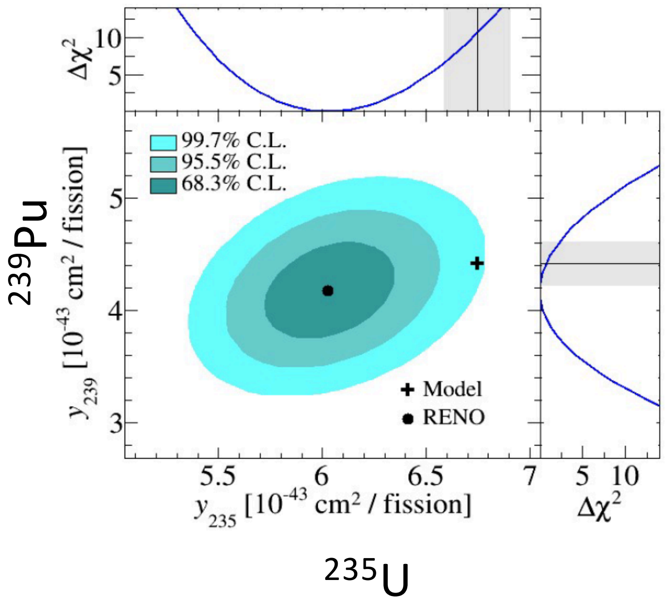


^{235}U

Measured yields per fission

^{235}U 3.0σ deficit relative to H-M

^{239}Pu 0.8σ deficit relative to H-M



^{239}Pu

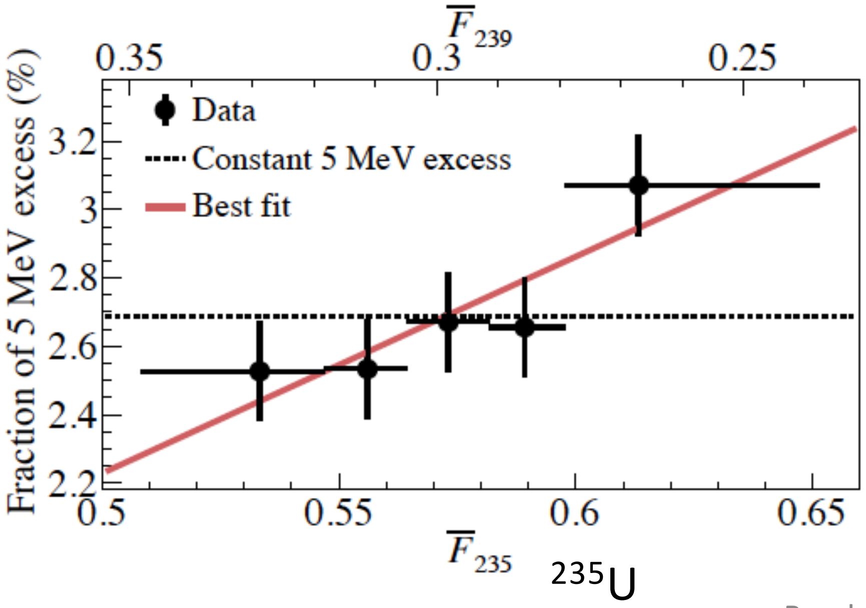
^{235}U

Best fit IBD yields

^{235}U 6.15 ± 0.19 10^{-43} cm^2/fission

^{238}Pu 4.18 ± 0.26 10^{-43} cm^2/fission

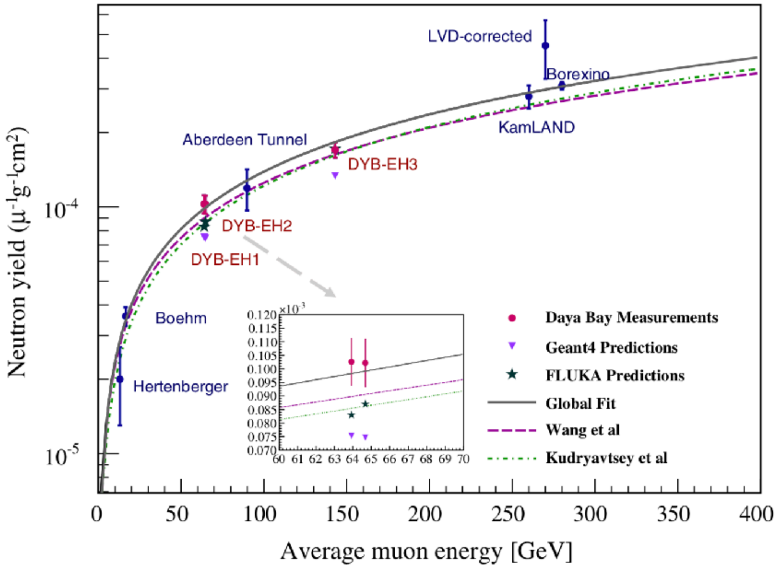
In good agreement with Daya Bay values

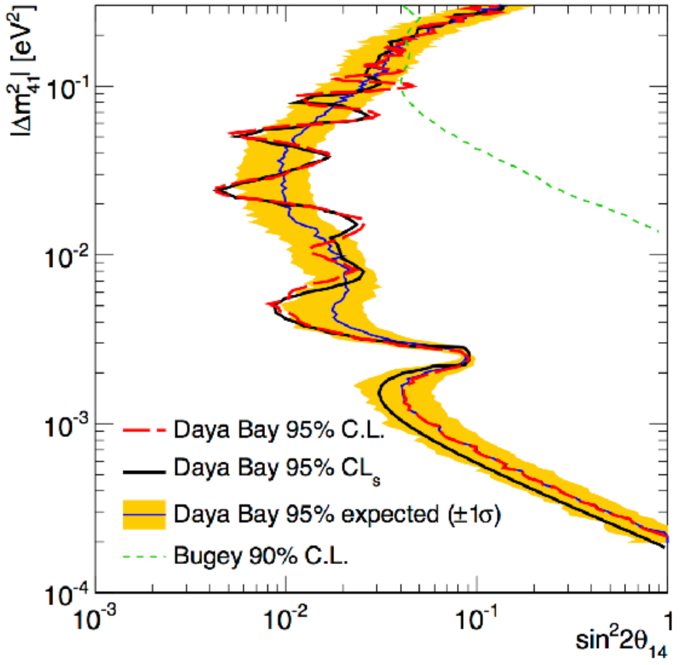


^{235}U

Other results

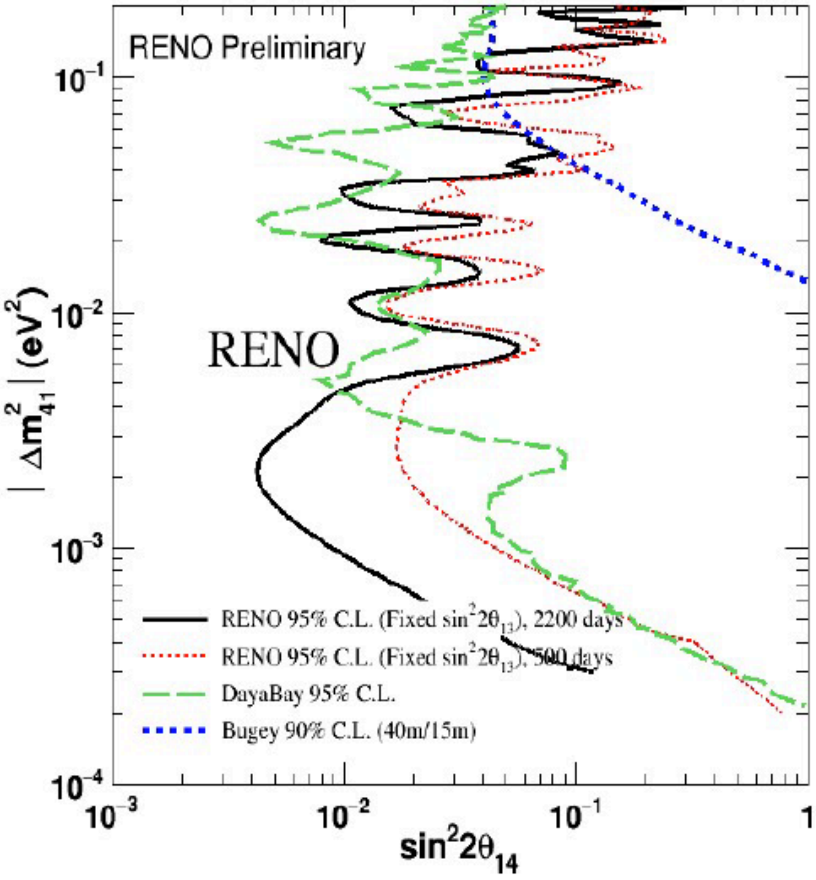
- Daya Bay
    - Search for Time-Varying Antineutrino Signal -ArXiv:1809.04660
    - Seasonal Variation of the Underground Cosmic Muon Flux - JCAP 1801 n°1 (2018)
    - Cosmogenic neutron production at Daya Bay - Phys. Rev. D97, 052009 (2018)
    - Search for neutrino decoherence Eur. Phys. J. C77, 606 (2017)
    - Improved search for a sterile neutrino (with Bugey-3 + MINOS) Phys. Rev. Lett. 117, 151801 (2016), 151802 (2016),
    - Independent measurement of θ_{13} via neutron capture on hydrogen Phys. Rev. D93, 072011 (2016)





Other results

- Double Chooz
    - Yields and production rates of cosmogenic 9Li and 8He measured with the Double Chooz near and far detectors ArXiv:1802.08048
    - Novel event classification based on spectral analysis of scintillation waveforms in Double Chooz ArXiv:1710.04315
    - Study of the light production mechanism of epoxy resins in an electric field Nucl.Instrum.Meth. A845 (2017) 404-407
    - Characterization of the Spontaneous Light Emission of the PMTs used in the Double Chooz Experiment JINST 11 (2016) no.08, P08001
    - Measurement of θ13 in Double Chooz using neutron captures on hydrogen with novel background rejection techniques JHEP 1601 (2016) 163



- RENO
    - Search for Sterile Neutrinos at RENO, I. Yu, J.W. Seo - Neutrino2018

Summary

- All 3 θ_{13} experiments have more data to analyze & continue to improve statistical and systematic errors
- Daya Bay and RENO will likely run till 2020
- Daya Bay has the most precise measurements of

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

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

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

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

expect relative error of $\sin^2 2\theta_{13} < 3\%$ by 2020

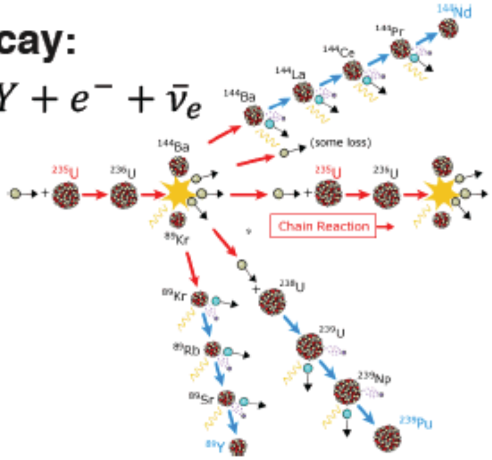
- All 3 θ_{13} experiments see similar discrepancies between data and predictions of the antineutrino flux from reactors
  - $R_{\mathrm{data/pred}}$ = 0.918 ± 0.018 (RENO), 0.952 ± 0.014 (DB), $\sim 0.940 \pm 0.011$ (DC)
  - Excess events in the 4-6 MeV region
- Compared to the Huber-Mueller model, Daya Bay (RENO) measure a ^{235}U deficit of 2.9 $\boldsymbol{\sigma}$ (3.0 $\boldsymbol{\sigma}$)

Backups

Prediction of antineutrino spectrum

Beta-Decay:

$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^- + \bar{\nu}_e$$



- ✓ pure $\bar{\nu}_e$ source
- ✓ Averaged 6 $\bar{\nu}_e$ /fission
- ✓ 6×10^{20} $\bar{\nu}_e$ /sec/3 GW_{th}

$$burnup \equiv \frac{W \cdot D}{M_{U^{in}}}$$

Total antineutrino Spectrum:

$$S(E) = \frac{W_{th}}{\sum_i f_i e_i} \sum_i f_i S_i(E) + S_{neq} + S_{SNF}$$

W_{th}: reactor thermal power

f_i: fraction of fissions due to isotope i

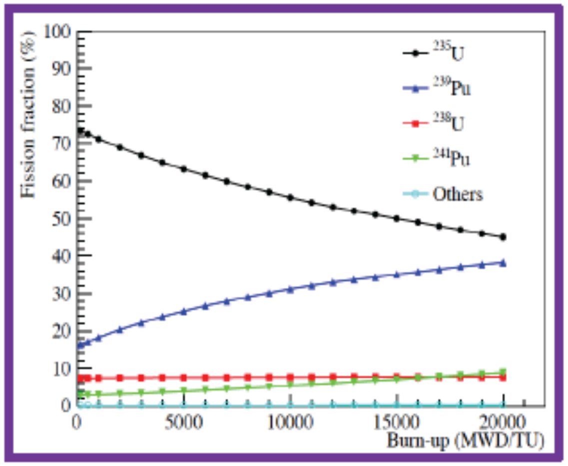
e_i: energy released/fission

$S_i(E)$: the $\bar{\nu}_e$ energy spectrum

S_{neq}: reactor non-equilibrium effects

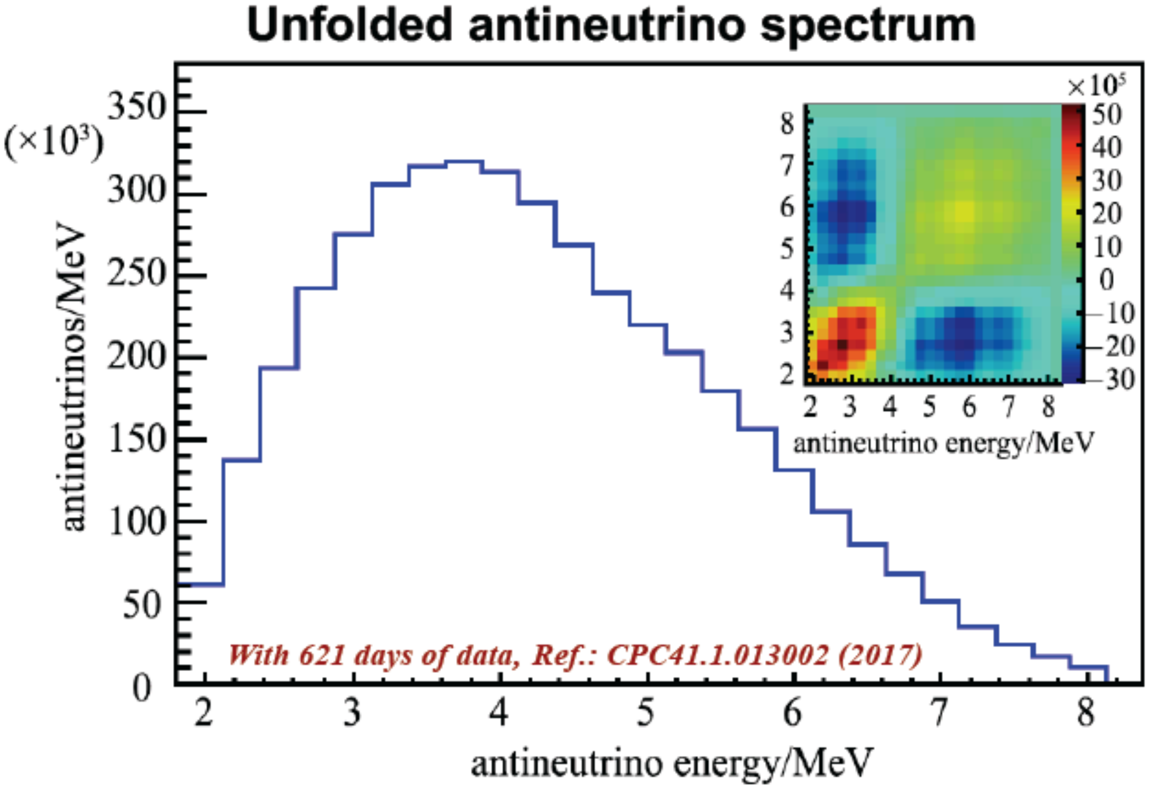
S_{SNF}: contribution from spent nuclear fuel

Isotope	Energy per Fission (MeV)
^{235}U	202.36 ± 0.26
^{238}U	205.99 ± 0.52
^{239}Pu	211.12 ± 0.34
^{241}Pu	214.26 ± 0.33



- ILL(exp. : 2.7% uncertainty) + Vogel (calculation< 10% uncertainty)
- Huber+Mueller’s new calculation (2.4% uncertainty)

Generic reactor antineutrino spectrum



With 621 days of data, Ref.: CPC41.1.013002 (2017)

- Unfolding to antineutrino energy: singular value decomposition (SVD) regularization method and Bayesian iterative method give consistent results
- A model-independent spectrum for other reactor experiments, with small correction to different fission fractions.

Flux-weighted average fission fractions

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.561	0.076	0.307	0.056

Effective Mass Splitting

- Full oscillation probability:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2 2\theta_{13}\boxed{\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4\mathrm{E}} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4\mathrm{E}}\right)} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4\mathrm{E}}$$

- Effective oscillation probability:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2 2\theta_{13}\boxed{\sin^2\frac{1.267\Delta m^2_{\mathrm{ee}}L}{E}} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4\mathrm{E}}$$

⟵ Advantages: independent of mass hierarchy and solar oscillation parameters

- For Daya Bay's L/E values, the full formula becomes:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - 4s^2_{13}c^2_{13}\left[\frac{1-\cos(2\Delta_{32} \pm \phi)}{2}\right] - (\text{solar term})$$
$$= 1 - \sin^2 2\theta_{13}\sin^2(\Delta_{32} \pm \phi/2) - (\text{solar term})$$

where: $\Delta_x = \Delta m^2_x \dfrac{L}{4E}$

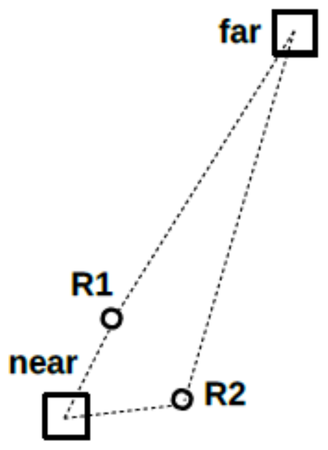
Comparing this expression with the effective one we conclude:

$$|\Delta m^2_{\mathrm{ee}}| = \left|\Delta m^2_{32}\right| \pm \left(\phi \times \frac{4E}{L}\right)/2$$
$$= \left|\Delta m^2_{32}\right| \pm (5.17\times 10^{-5})\ \mathrm{eV}^2$$

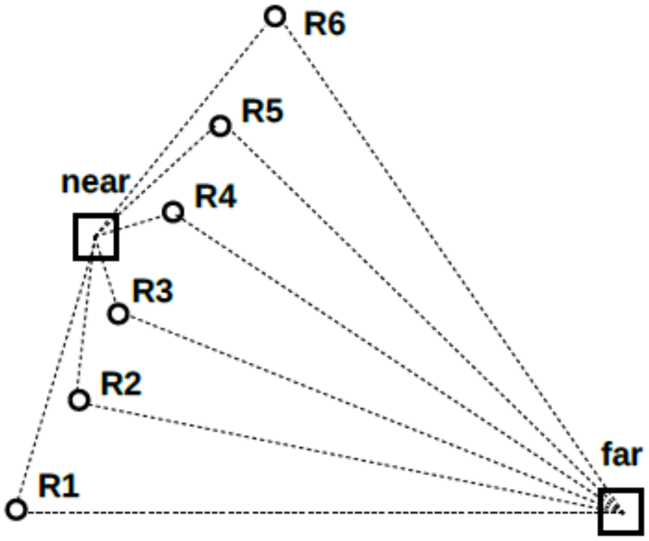
The fit is always done with the full oscillation probability.

Near/Far Ratio

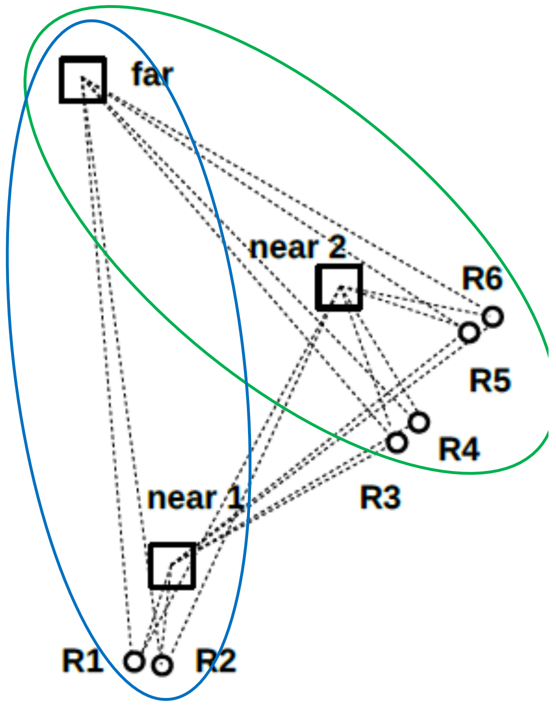
- 100% cancellation of flux uncertainty with one reactor, one near and one far detector



Double Chooz
~88% suppression of systematic uncertainties



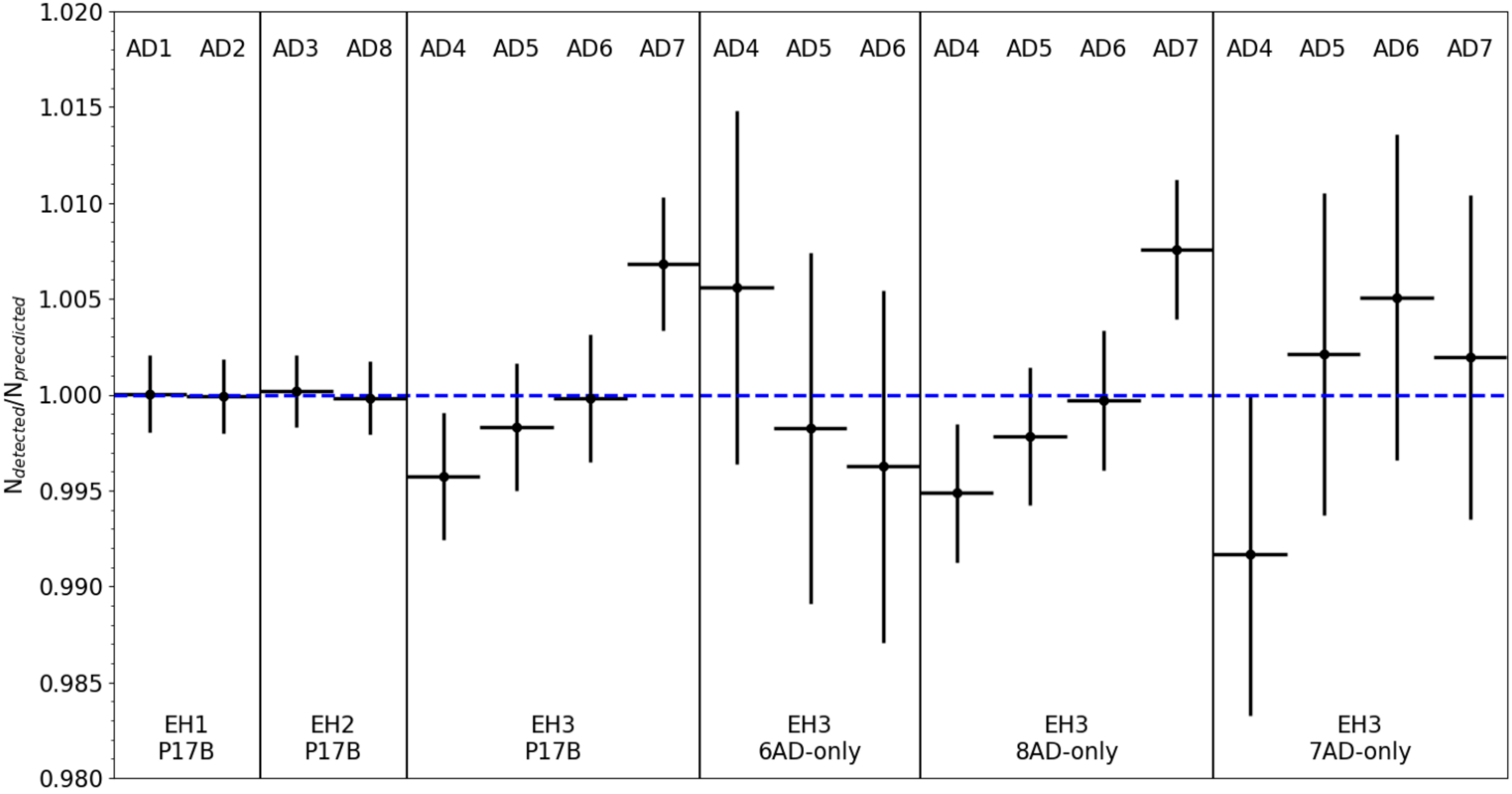
RENO
~77%



Daya Bay
~95%

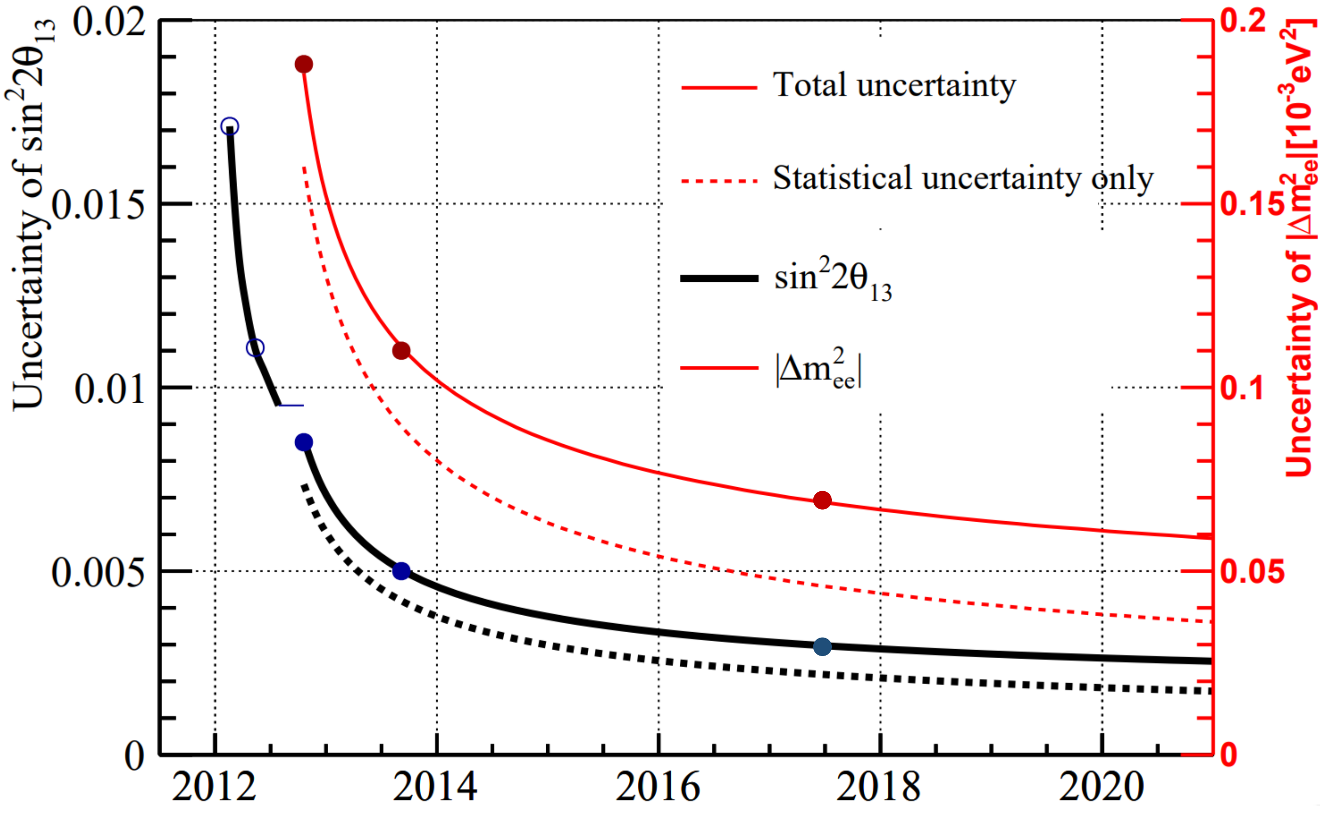
Statement (~80% suppression) in arXiv:1501.00356 regarding DYB is incorrect

Side-by-side comparison



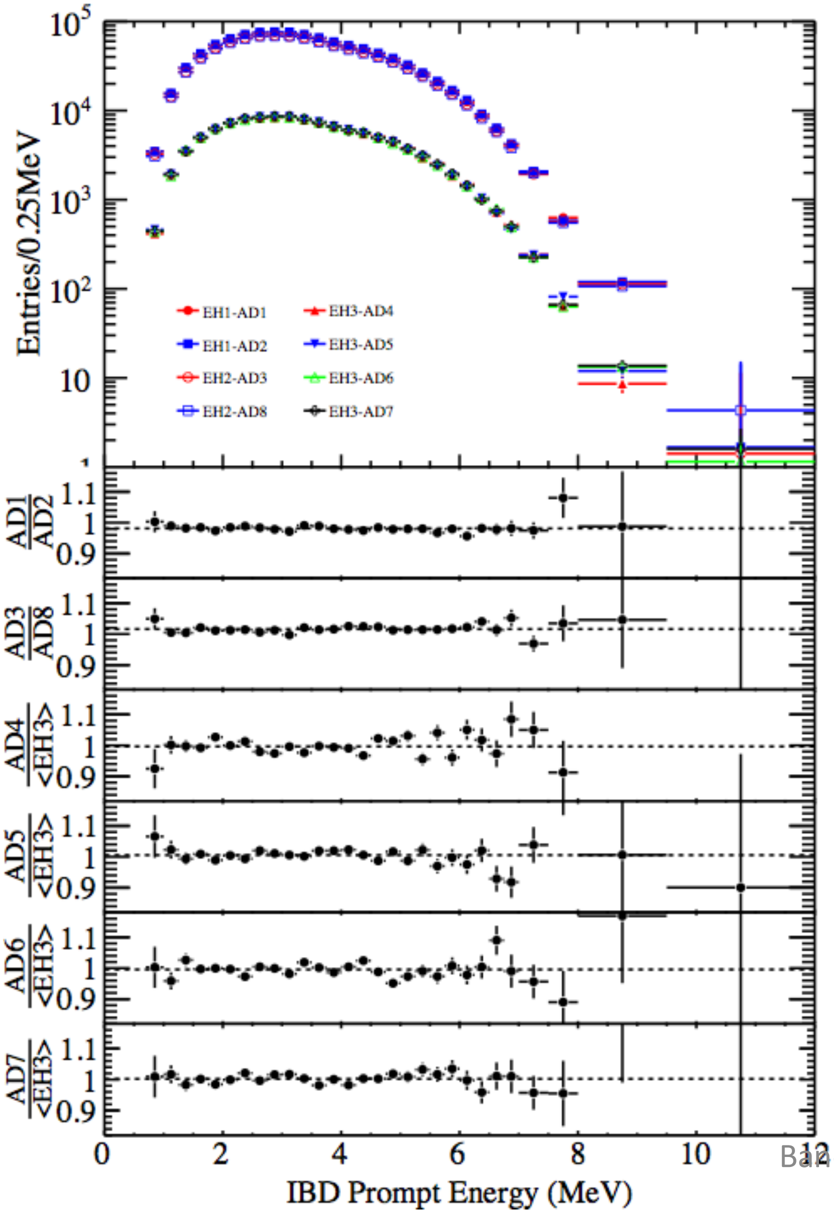
Precision on Oscillation Parameters

- Plan to run till 2020: uncertainties of $\sin^2 2\theta_{13}$ below 3%



Side-by-side Spectral Comparison

Prompt Spectra



Delayed Spectra