Daya Bay and joint reactor neutrino analysis

Logan Lebanowski (Tsinghua University)

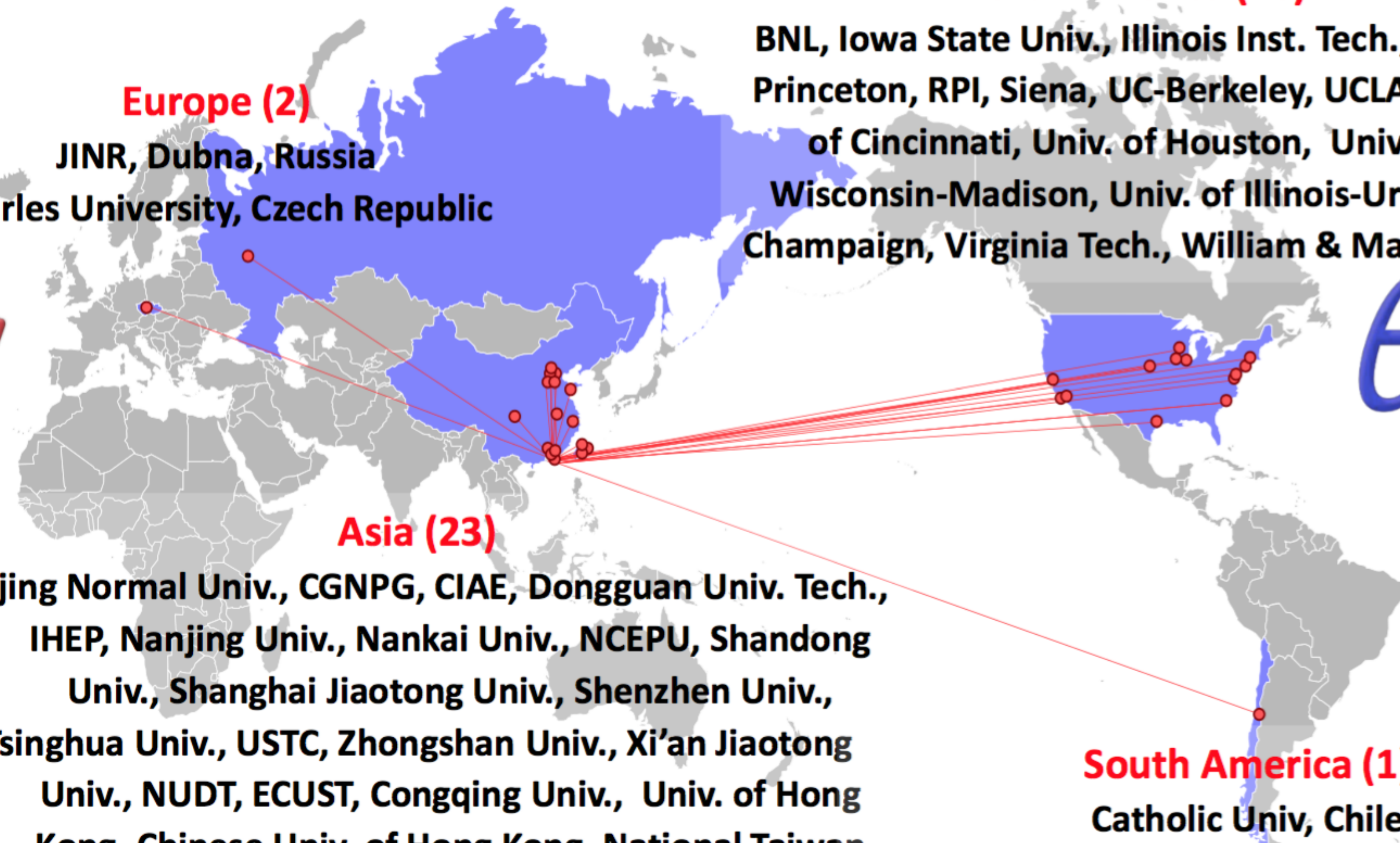
on behalf of the Daya Bay collaboration

2016/11/4 - NNN16, Beijing

Contents

Daya Bay collaboration

203 collaborators from 42 institutions:



North America (16)

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

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

Asia (23)

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

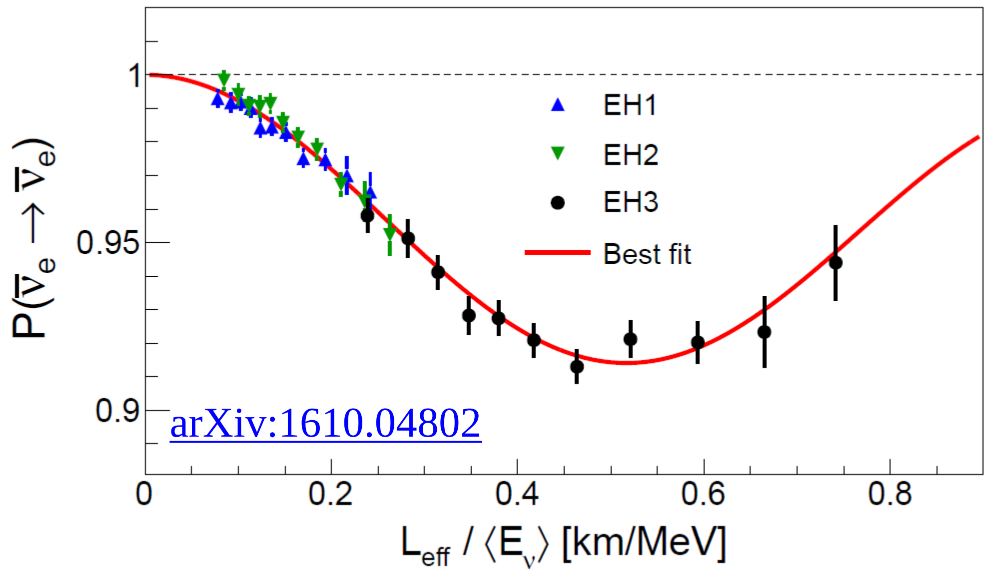
South America (1)

Catholic Univ, Chile

Daya Bay experiment

Measurement of electron antineutrino disappearance in $0 \lesssim L/E \lesssim 1$ [km/MeV] enables a measurement of $\sin^2 2\theta_{13}$ and Δm^2_{ee} (independent of δ_{CP}):

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(1.27 \Delta m^2_{ee} \frac{L}{E}\right)$$

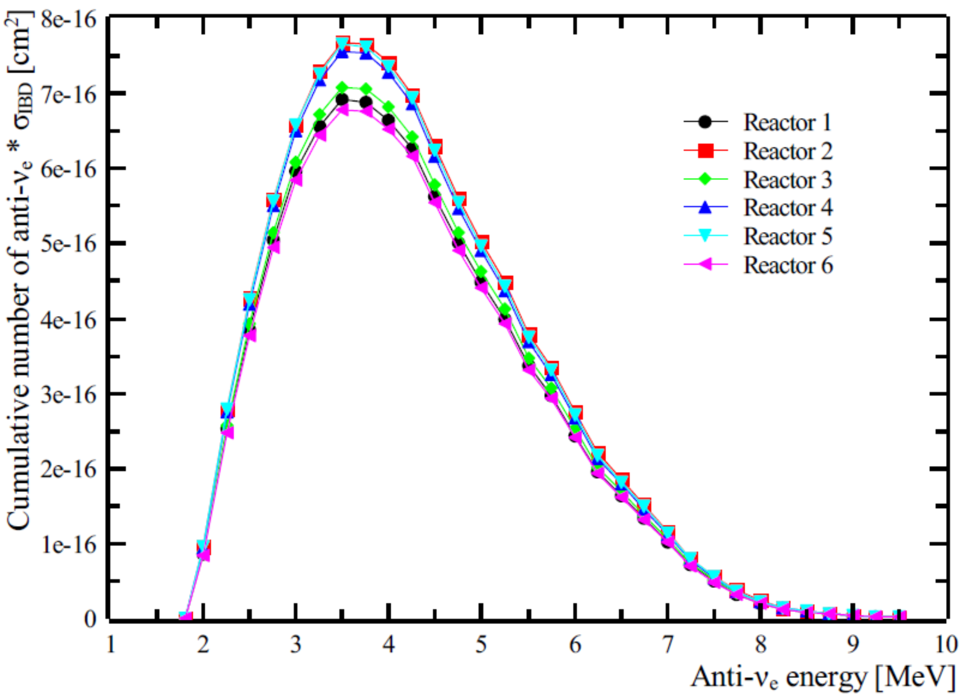


$$\sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

Daya Bay experiment

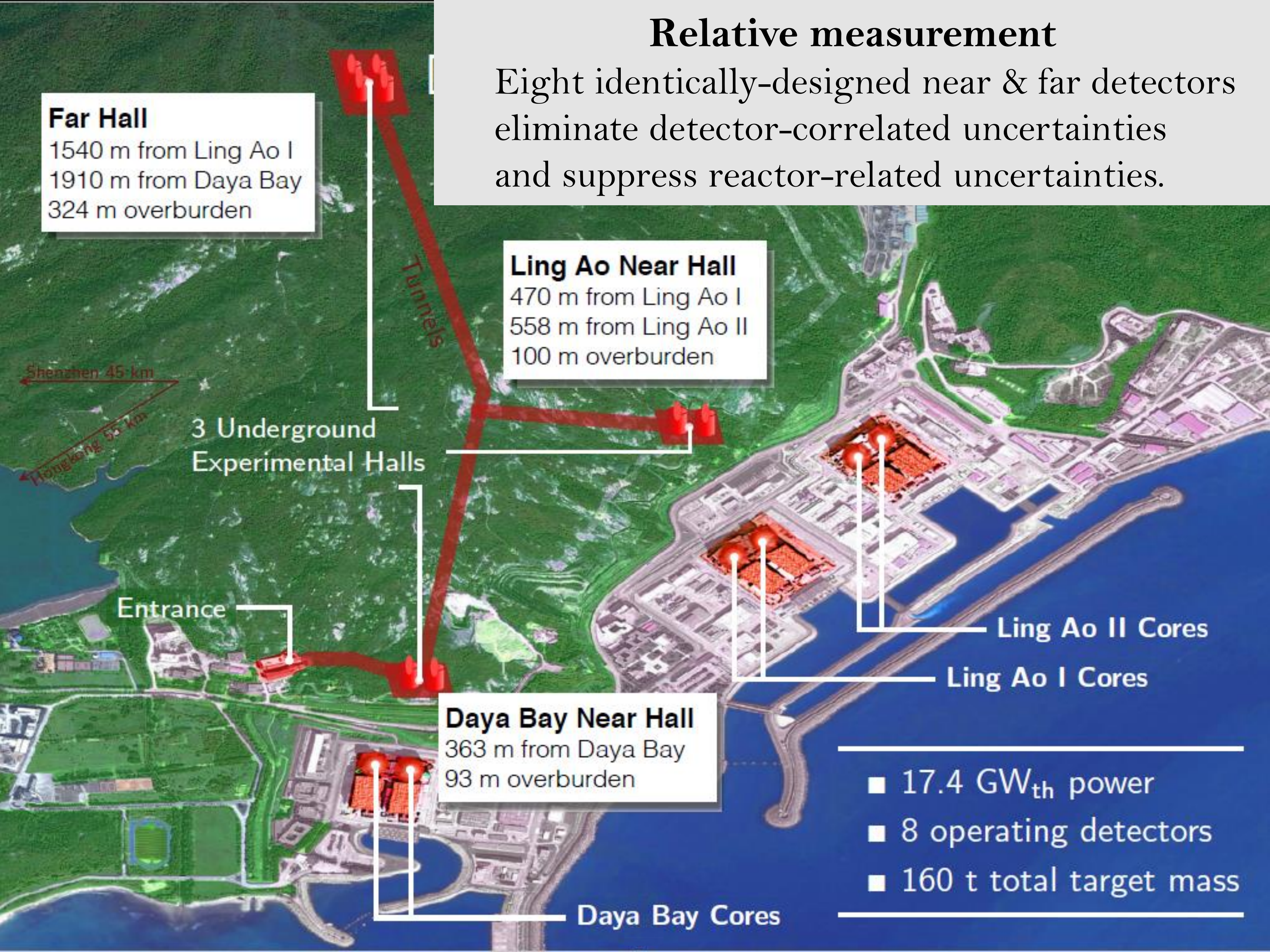
3×10^{21} $\bar{\nu}_e$ are produced each second by six nuclear reactors.

Detecting $\bar{\nu}_e$ via the inverse beta decay (IBD) reaction, the predicted reactor $\bar{\nu}_e$ energy spectra are:

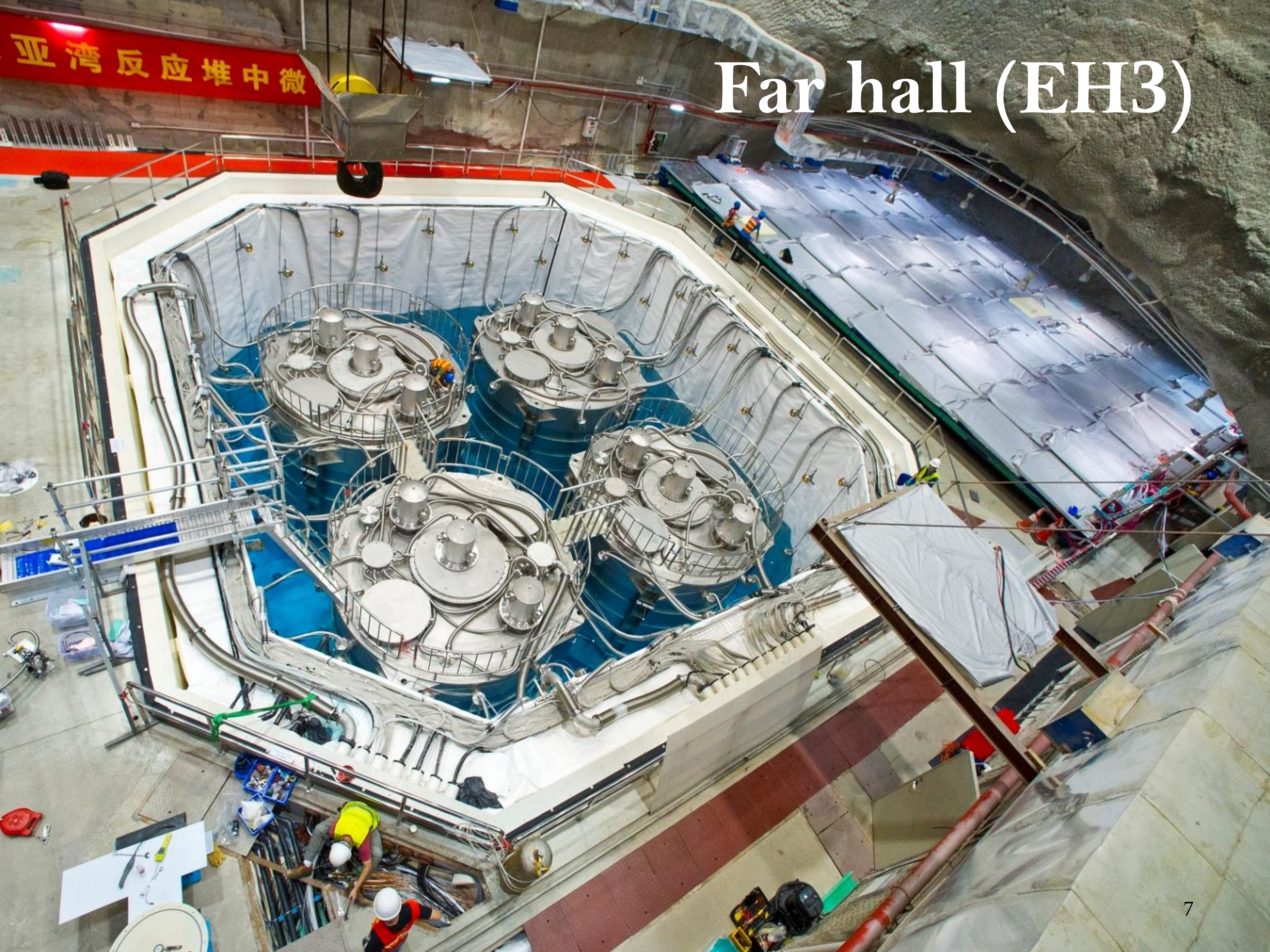


Relative measurement

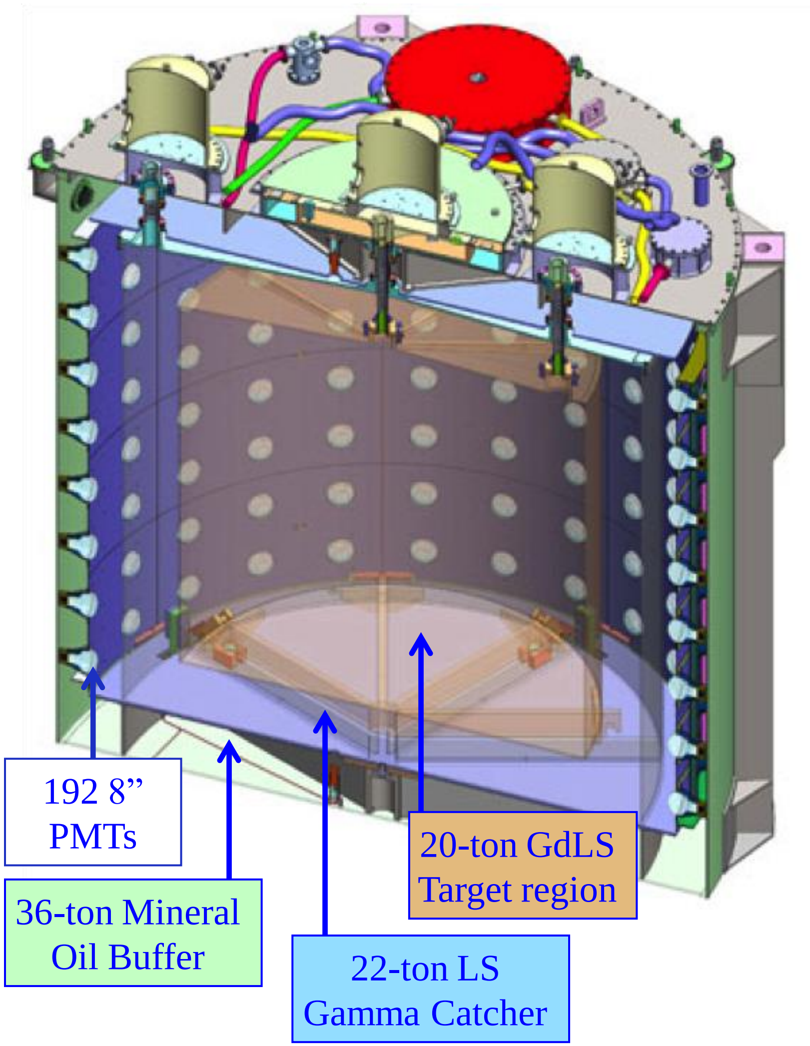
Eight identically-designed near & far detectors eliminate detector-correlated uncertainties and suppress reactor-related uncertainties.



Far hall (EH3)



Antineutrino Detector (AD)



Inner target is 20 tons of Gd-doped liquid scintillator (GdLS).

Surrounding volume is 22 tons of LS to improve the efficiency of detecting gammas escaping the inner target.

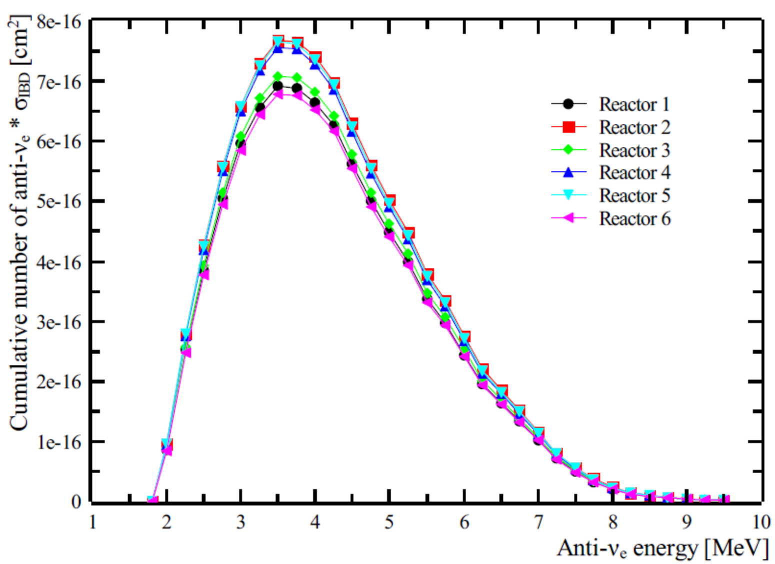
Outer buffer volume of mineral oil to shield against radiation entering the LS.

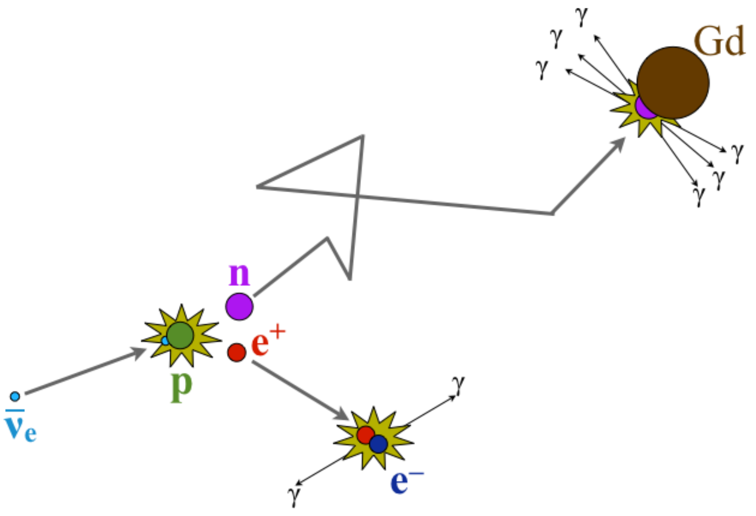
IBD

Detect reactor antineutrinos via IBD reaction:

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

reactor detector prompt event delayed event



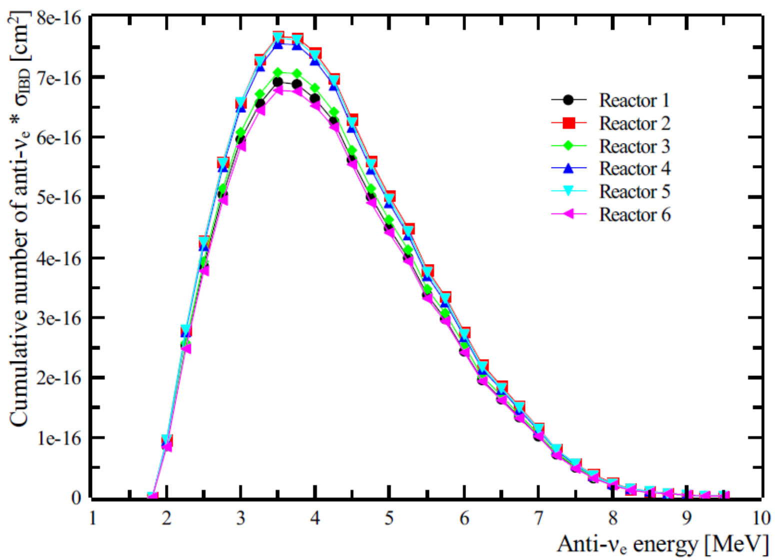


IBD

Detect reactor antineutrinos via IBD reaction:

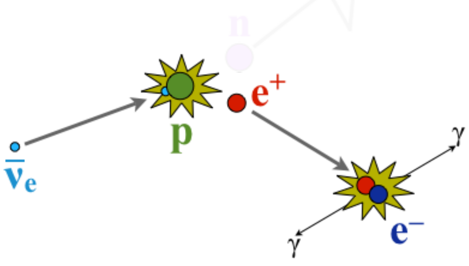
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

reactor — detector — prompt event — delayed event



e^+ carries 99% of final state energy.

$$E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.8\ \text{MeV}$$

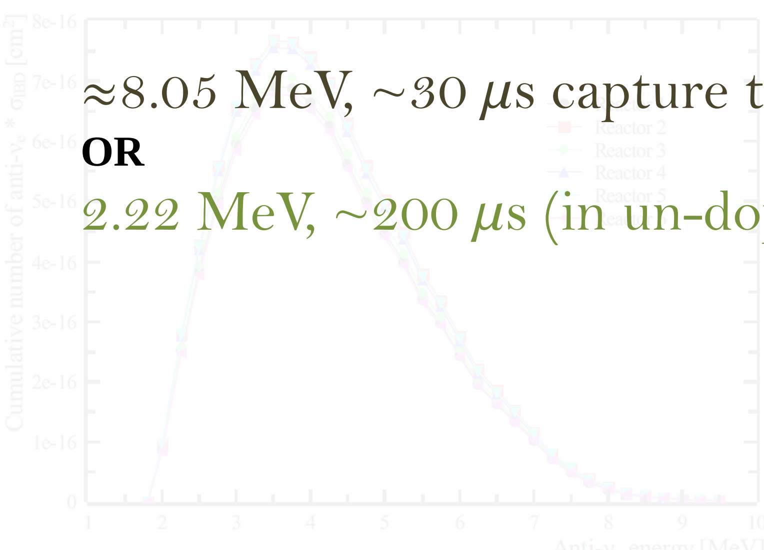


IBD

Detect reactor antineutrinos via IBD reaction:

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

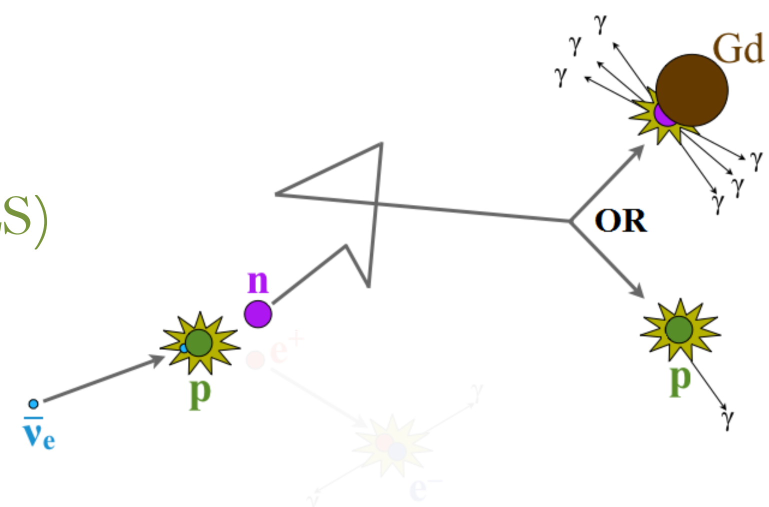
reactor | detector | prompt event | delayed event



$\approx$8.05 MeV, $\sim$30 μs capture time

OR

2.22 MeV, $\sim$200 μs (in un-doped LS)



Antineutrino sample

Basic parameters of the experiment:

- 3×10^{21} $\bar{\nu}_e$ per second from reactors
- 0.8×10^{-42} cm^2 per IBD (E_ν = 4 MeV)
- 6×10^{30} H atoms (protons) (far hall)
- 1.6 km flux-weighted baseline (far hall)
- 80% IBD selection efficiency
- 1230 days

➡ 310k IBDs (far hall)

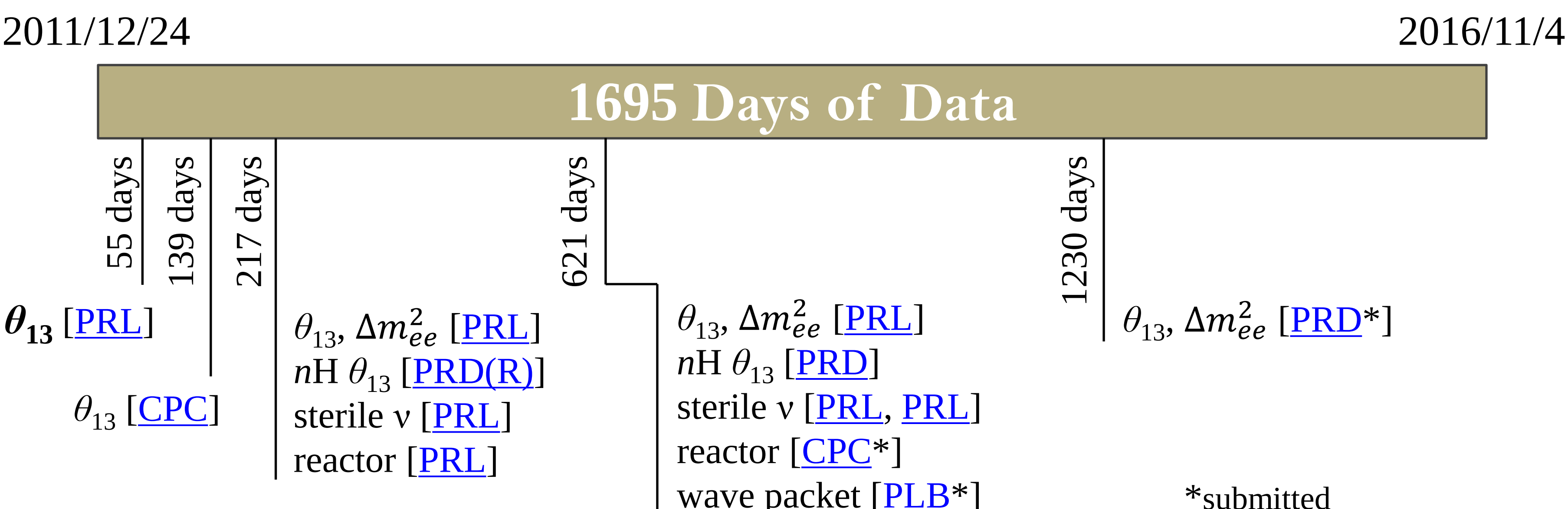
0.18% statistical uncertainty (far hall)

Dominant uncertainty

Data acquisition

Most recent oscillation results

- *n*Gd analysis: 1230 days [arXiv:1610.04802]
- *n*H analysis: 621 days [PR D93 (2016) no.7, 072011]
- expected: ~2500 days (to 2020)
  - statistics may still dominate the total uncertainty.

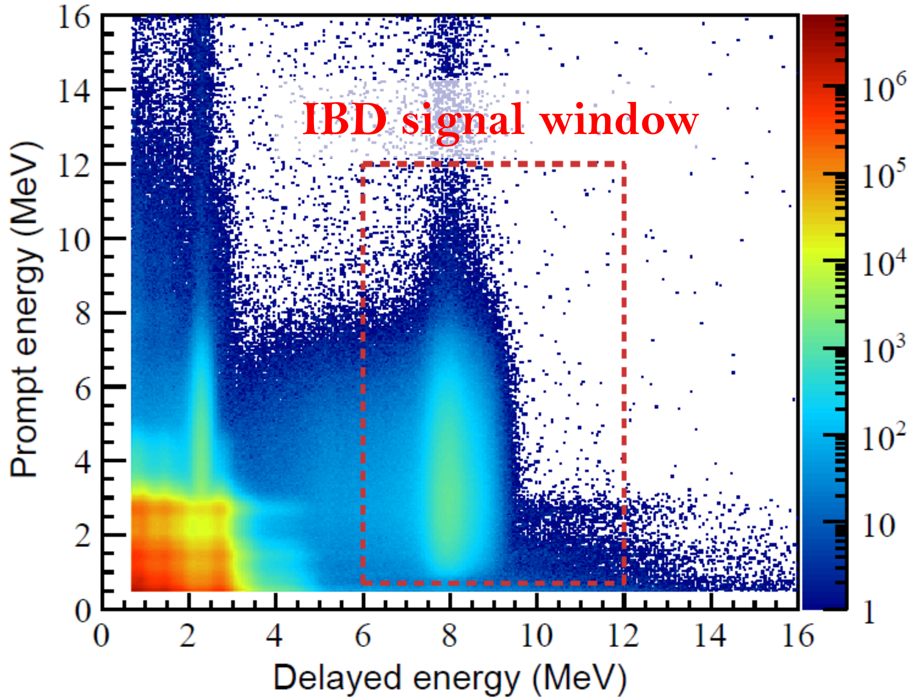


IBD selection

<u>Selection criteria</u>

- reject PMT flashes
- muon-event vetoes
- $0.7 < E_{\text{prompt}} < 12$ MeV
- $6.0 < E_{\text{delayed}} < 12$ MeV
- $1 < t_{\text{capture}} < 200$ µs
- multiple-event vetoes

	Efficiency
Delayed energy cut	92.7%
Prompt energy cut	99.8%
Multiplicity cut	
Capture time cut	98.7%
Gd capture fraction	84.2%
Spill-in	104.9%
Livetime	-
Combined	80.6%

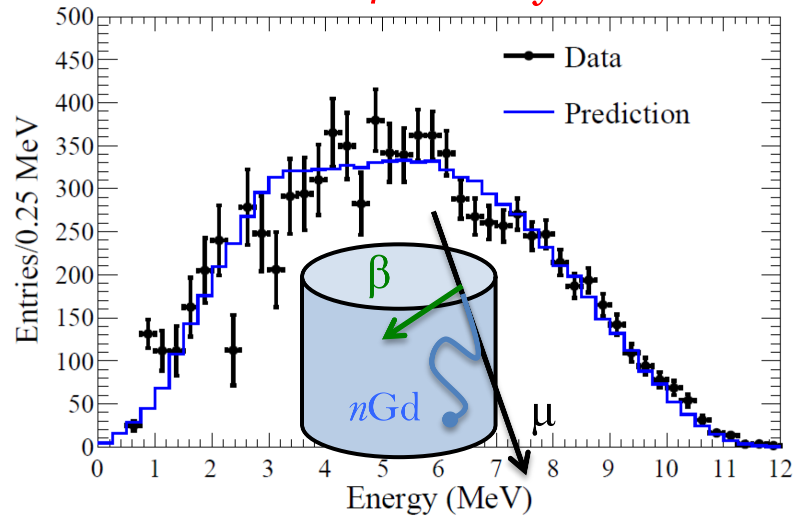


IBD backgrounds (1)

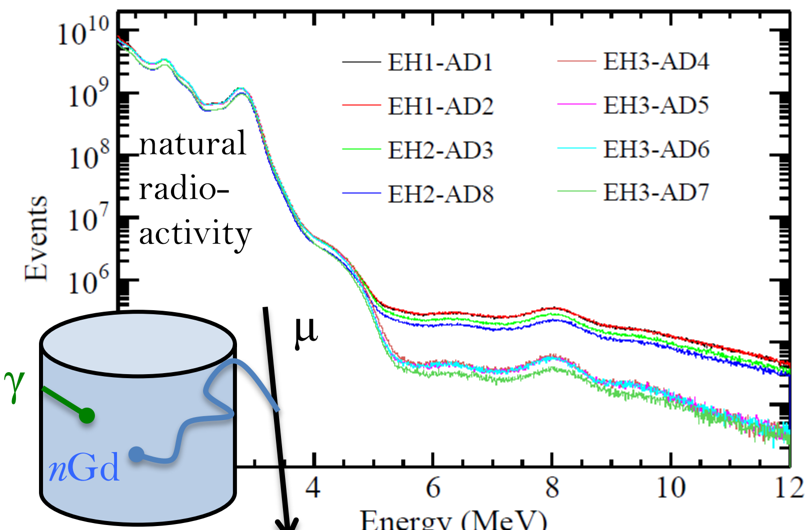
Backgrounds include

1. **^{9}Li β-n decays** (dominant bkgd. unc.)
2. **Fast neutrons**
3. **Accidentals**
4. Am-C neutron calibration sources
5. $^{13}C(\alpha,n)^{16}O$

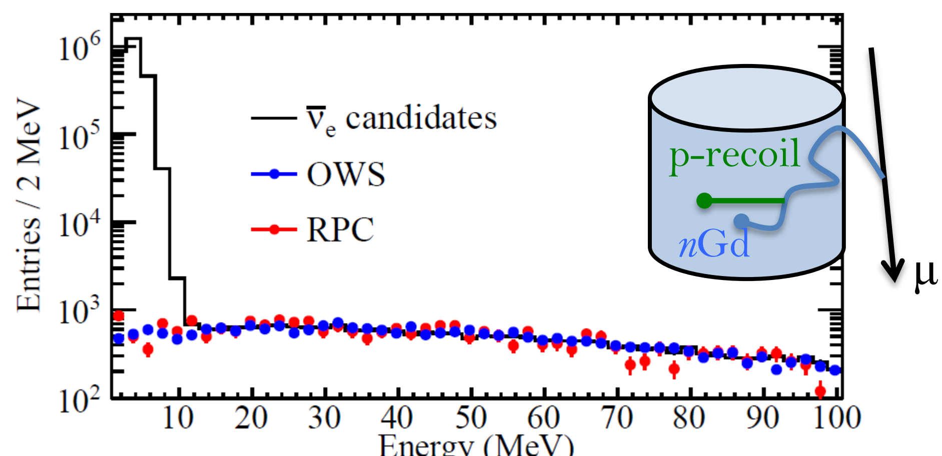
^{9}Li β-n decays



Accidentals



Fast neutrons

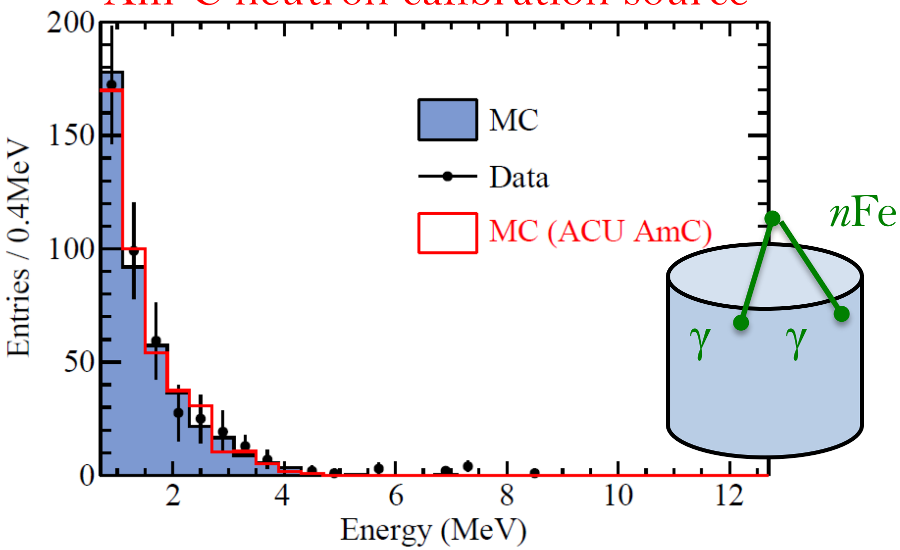


IBD backgrounds (2)

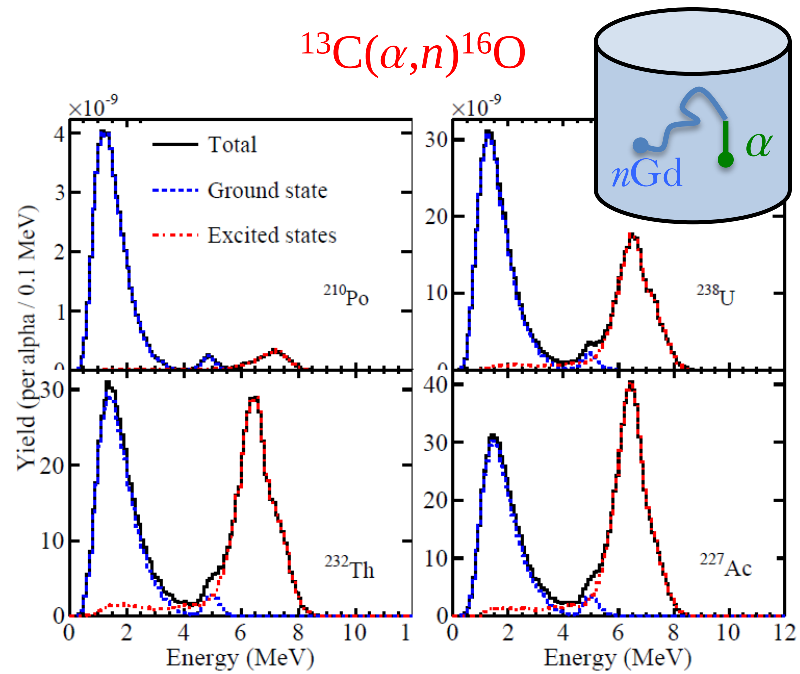
Backgrounds include

1. ^{9}Li β-n decays (dominant bkgd. unc.)
2. Fast neutrons
3. Accidentals
4. **Am-C neutron calibration sources**
5. **^{13}C(α,n)^{16}O**

Am-C neutron calibration source



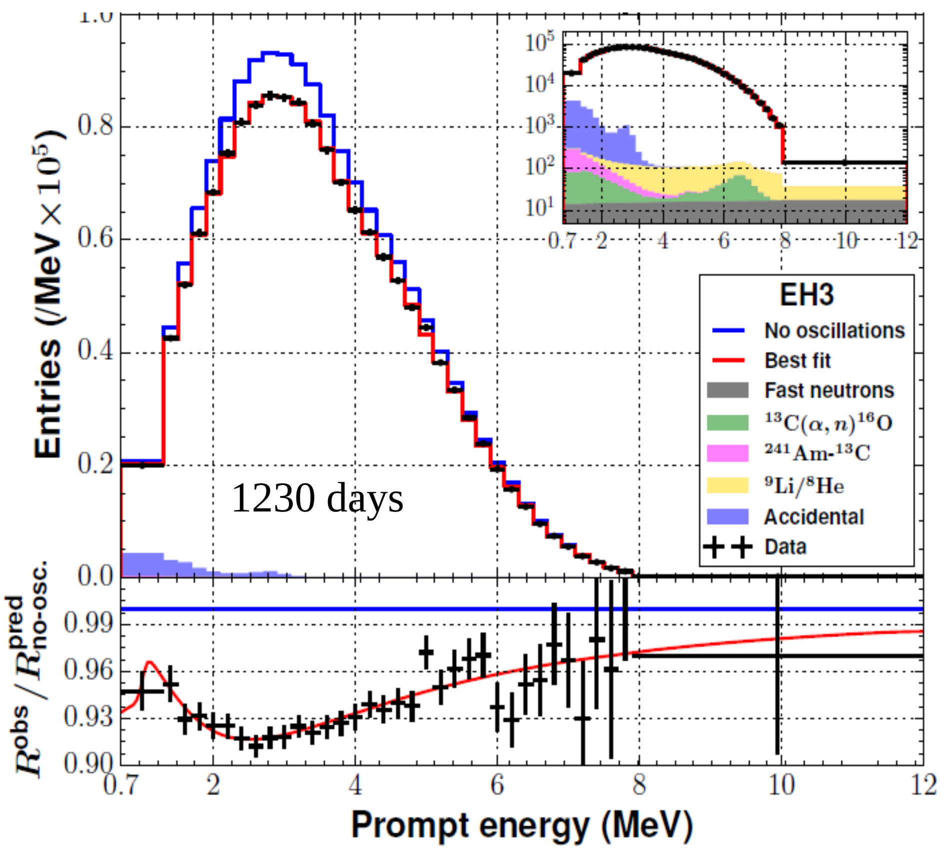
^{13}C(α,n)^{16}O



Summary of IBD candidates

- Over 2.5M (300k) IBDs in total (the far hall)
- $\leq 2\%$ backgrounds

1230 days	EH1	EH2	EH3
IBDs [$\times 10^6$]	1.20	1.03	0.31
B/S ratio [%]	1.8±0.2	1.5±0.1	2.0±**0.1**

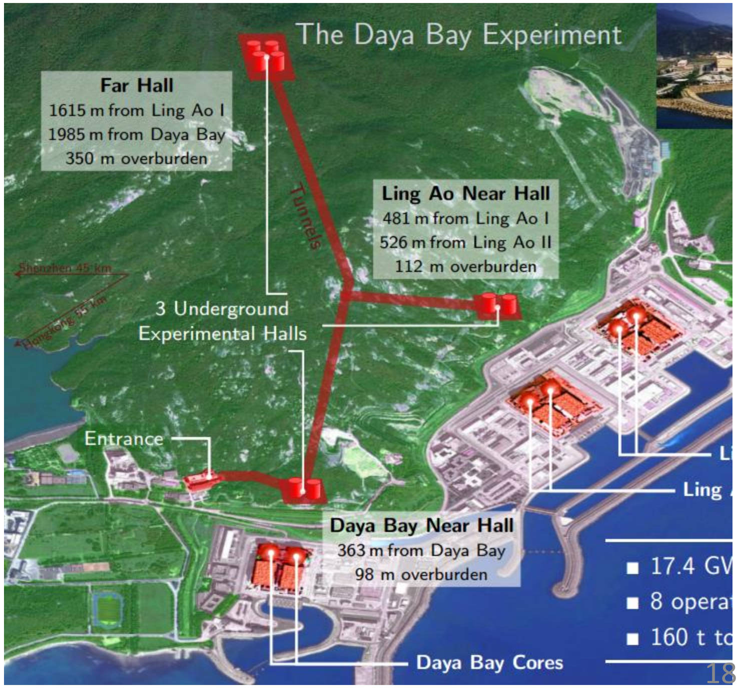


Reactor-related uncertainty

Total reactor-uncorrelated uncertainty of predicted IBDs associated with a single reactor: 0.9%.

uncorrelated		
power	W_{th}	0.5%
fission fraction	f	0.6%
spent fuel	SNF	0.3%
off-equilibrium	C^{ne}	0.3%
combined		0.9%

The large correlation of $\bar{\nu}_e$ flux among all three halls suppresses the uncertainty by a factor of 20: 0.9% → **0.045%**.



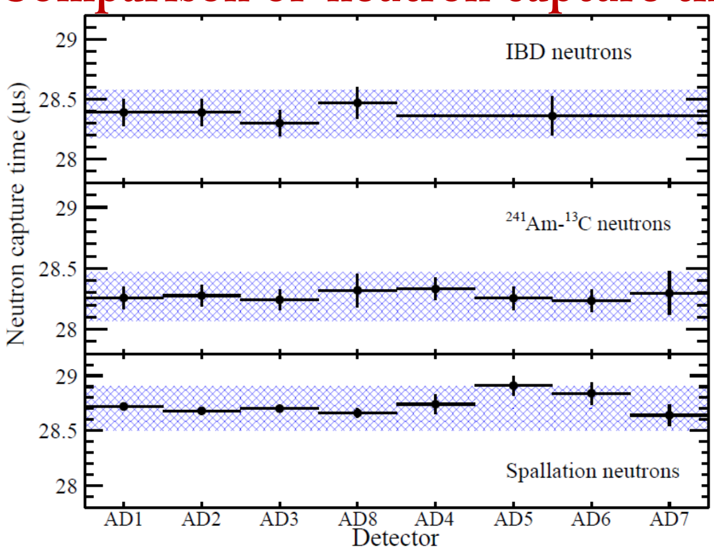
IBD selection efficiency uncertainty

Total AD-uncorrelated uncertainty of efficiency: **0.13%** (relative).

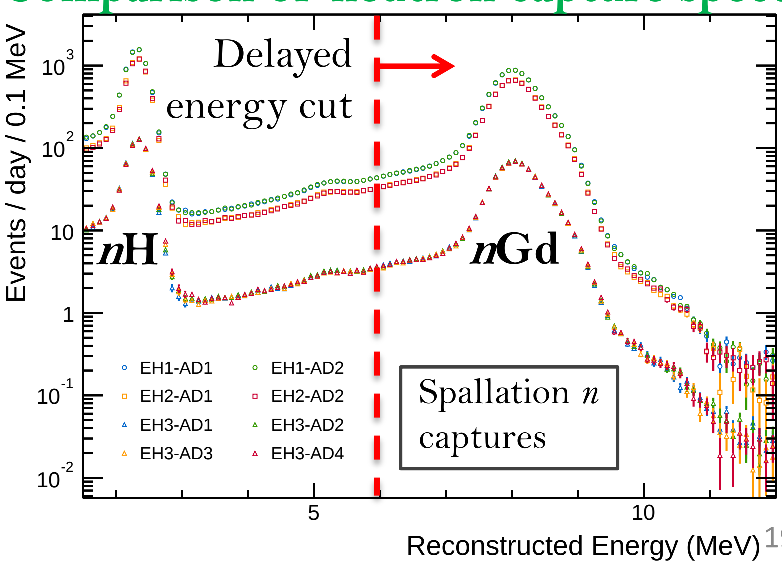
Dominated by the Gd capture fraction and the delayed energy cut [6, 12] MeV.

	Efficiency	Uncorrelated
Target protons	-	0.03%
Flasher cut	99.98%	0.01%
Delayed energy cut	92.7%	0.08%
Prompt energy cut	99.8%	0.01%
Multiplicity cut		0.01%
Capture time cut	98.7%	0.01%
Gd capture fraction	84.2%	0.10%
Spill-in	104.9%	0.02%
Livetime	-	0.01%
Combined	80.6%	0.13%

Comparison of neutron capture times



Comparison of neutron capture spectra



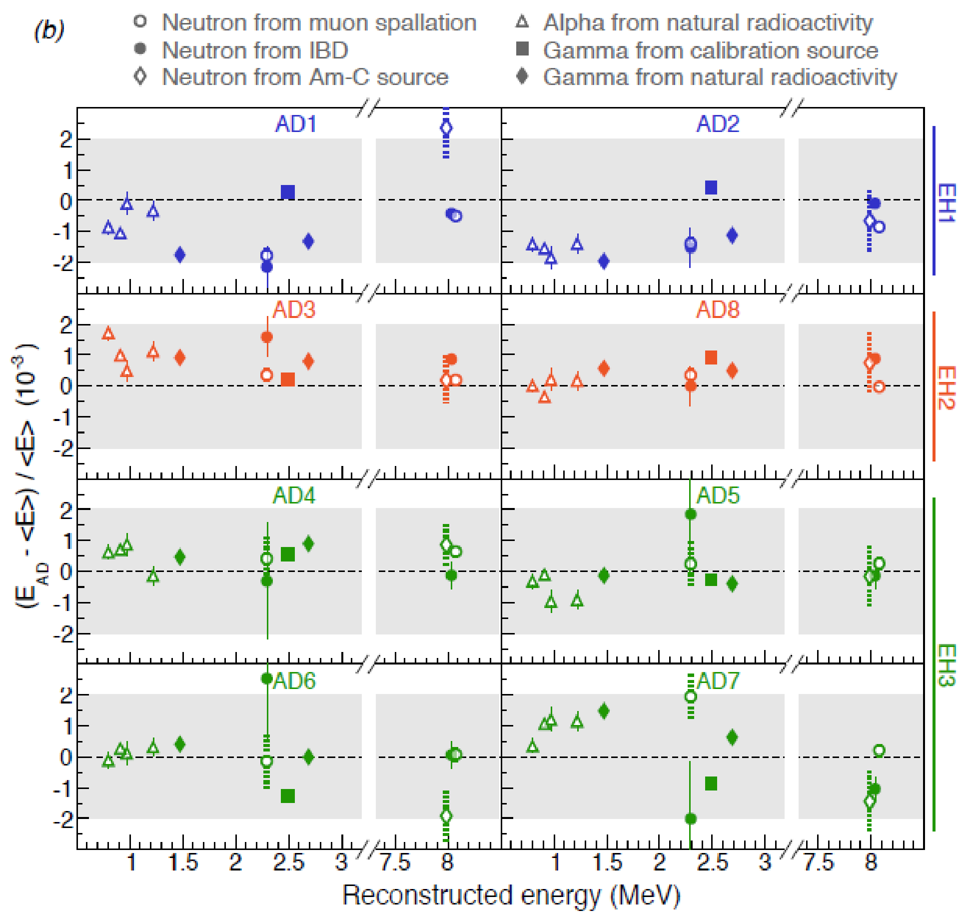
Energy scale uncertainty

The energy scale impacts the efficiency of the energy cuts and the measurement of Δm^2_{ee}.

The total uncertainty of the AD-uncorrelated energy scale is < 0.2%.

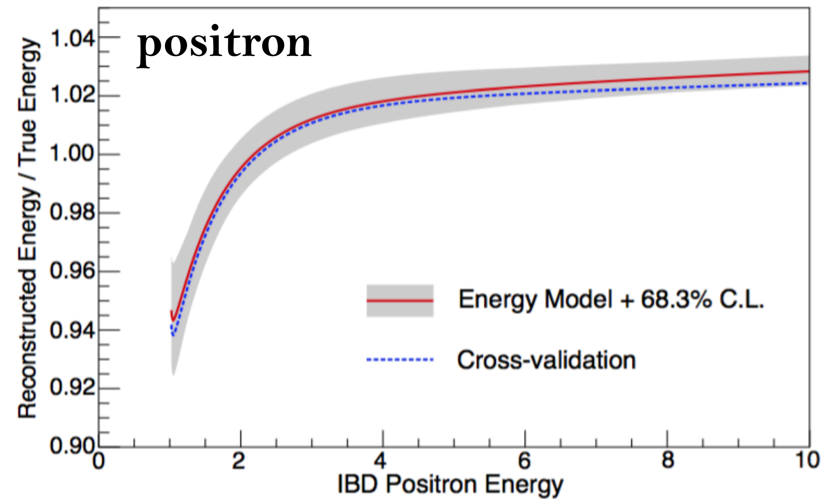
It is determined by comparing the energy between ADs for:

- regular data
  (natural α's and γ's, neutrons from IBD and muon spallation)
- weekly calibrations
  (^{68}Ge and ^{60}Co γ sources, ^{241}Am-^{13}C neutrons)



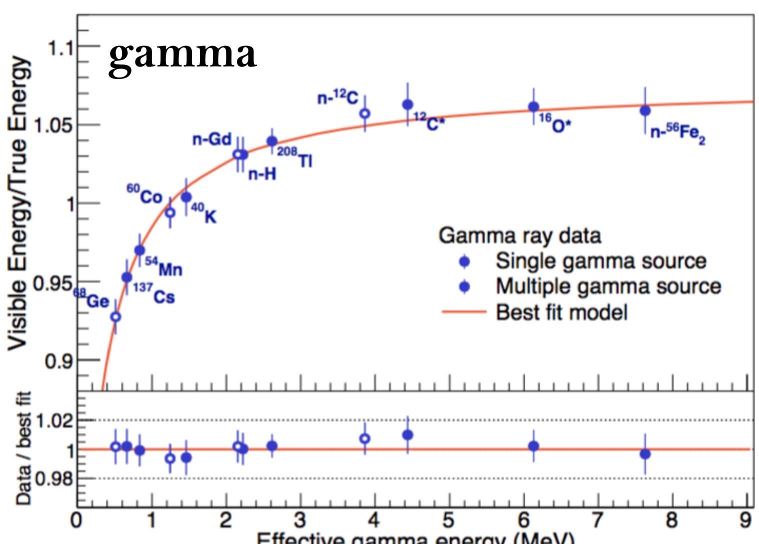
Energy nonlinearity

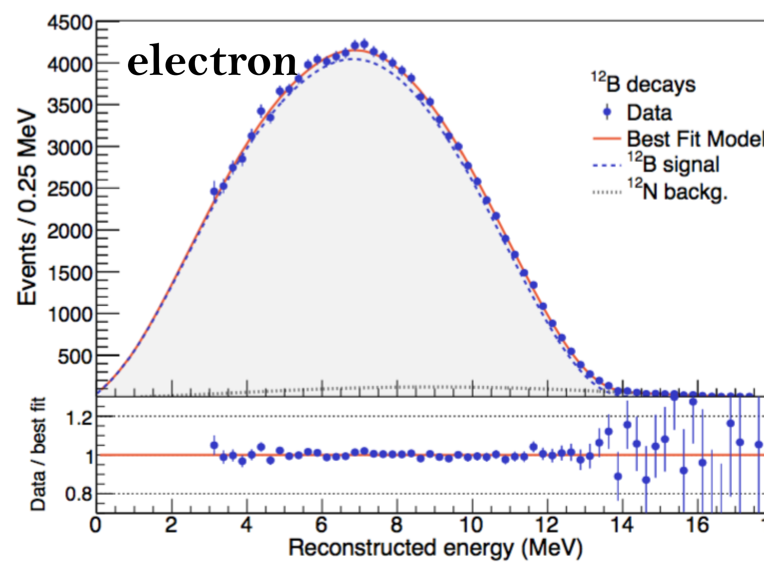
The energy nonlinearity (scintillator and electronics) impacts the measurement of Δm^2_{ee}.



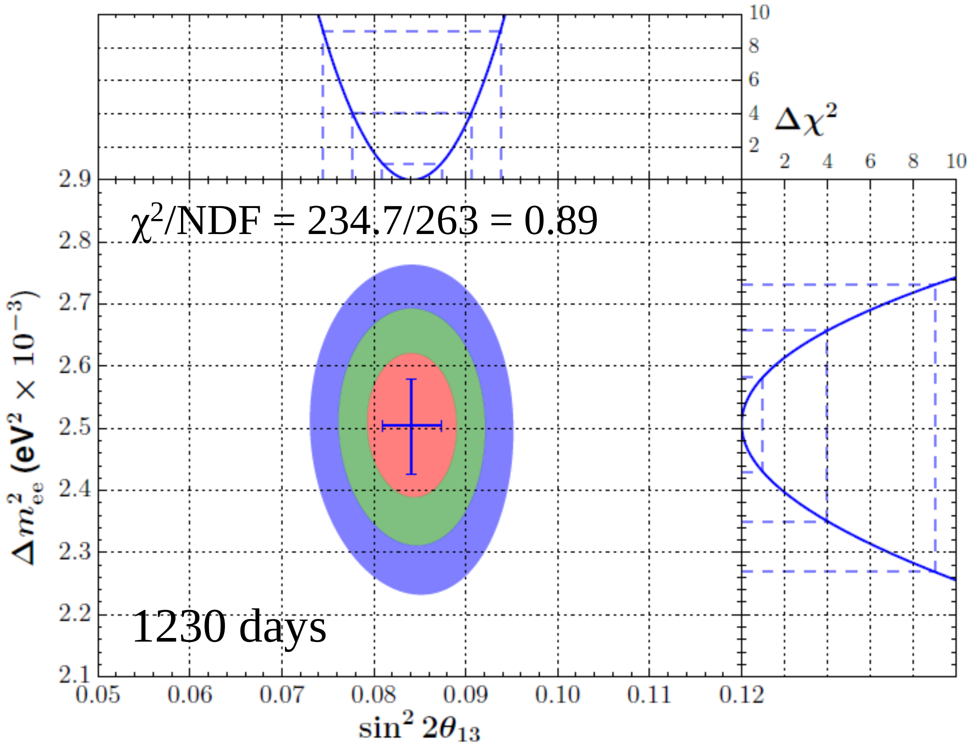
Model for IBD positron is derived from measured gamma and electron responses.

~1% AD-correlated uncertainty.





Oscillation analysis result



$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$$

Multiple analyses yield consistent results.

[arXiv:1610.04802]

$\sin^2 2\theta_{13}$ from *n*H analysis

Statistically-independent measurement of $\sin^2 2\theta_{13}$

Challenging analysis:

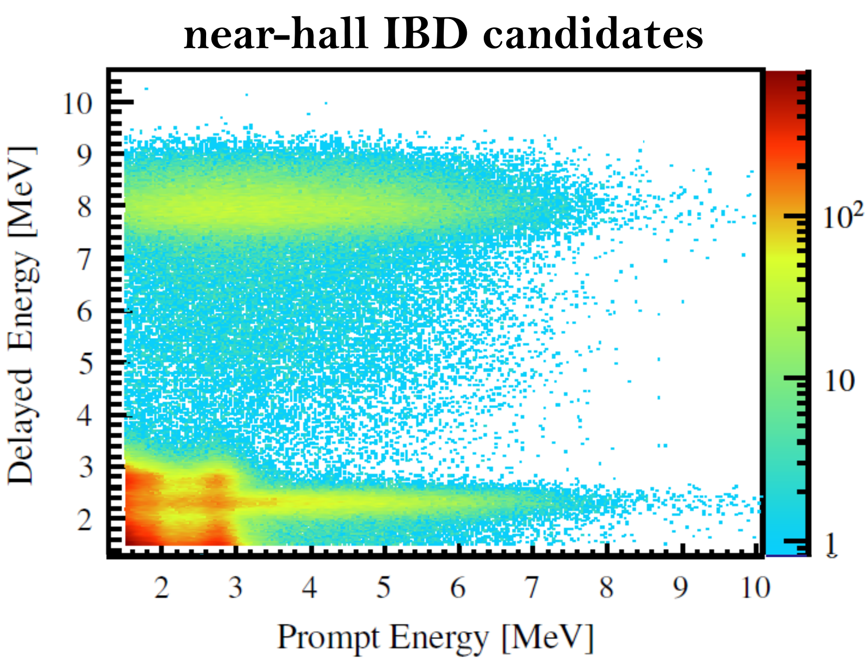
- Greater accidental background (× ~100)
- Greater energy leakage in LS volume (× 20)

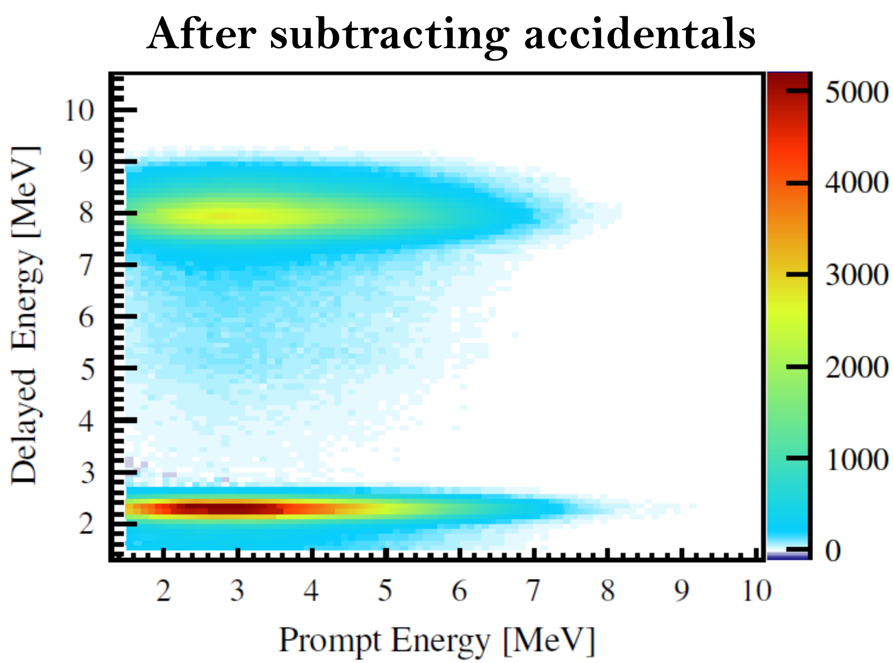
The essential differences in IBD selection:

	***n*H (2.2 MeV)**	***n*Gd (8 MeV)**
t_{capture}	[1,400] μs	[1,200] μs
E_{prompt}	[1.5,12] MeV	[0.7,12] MeV
E_{delay}	±3σ (± ≈0.43 MeV)	[6,12] MeV
Distance	< 50 cm	N/A

nH accidental background

The distance cut between prompt and delayed events removes 98% of accidentals at a cost of 25% IBDs. The remaining accidentals are effectively subtracted:

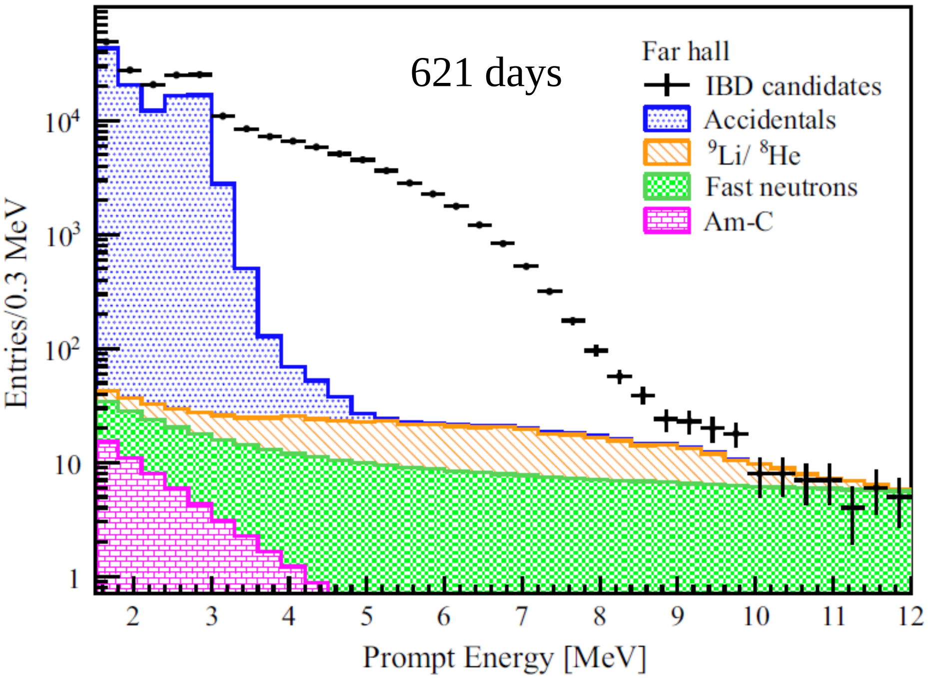




Summary of *n*H IBD candidates

- About 0.8M (100k) IBDs in total (the far hall)
- Two orders of magnitude more backgrounds, but not much more systematic uncertainty.

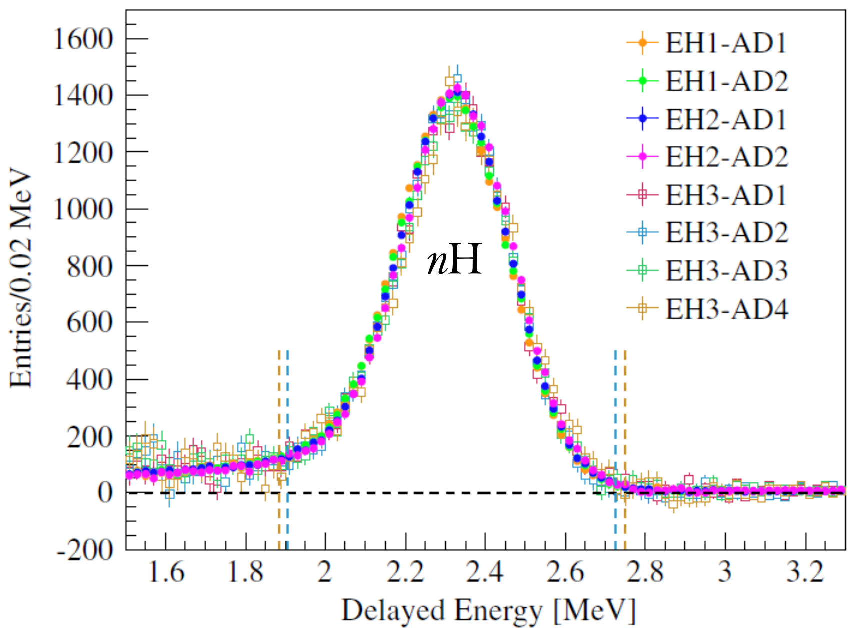
621 days	EH1	EH2	EH3
IBDs [$\times 10^6$]	0.39	0.30	0.10
B/S ratio [%]	15±0.2	15±0.2	120±**0.2**



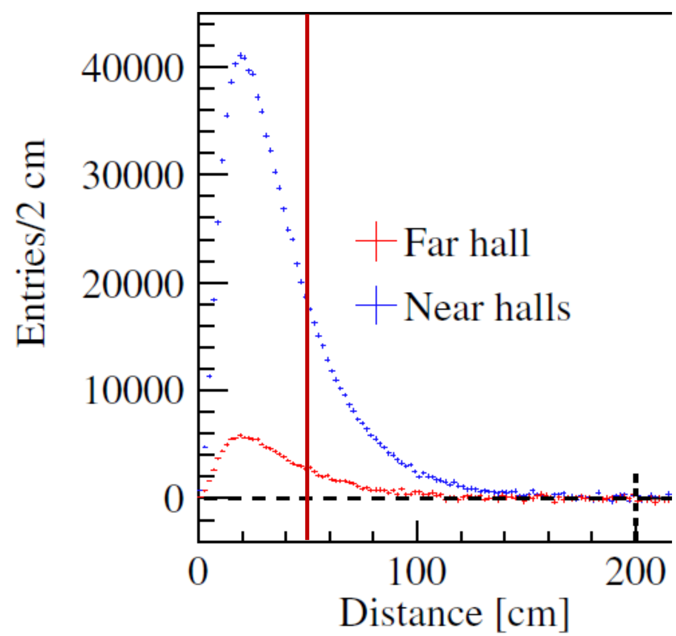
nH systematics

Statistical uncertainty is still dominant, however the delayed energy cut and distance cut introduce large uncertainties: 0.35% (0.08% for nGd) and 0.40%, respectively.
The energy scale uncertainty is 0.5% (0.2% for nGd).

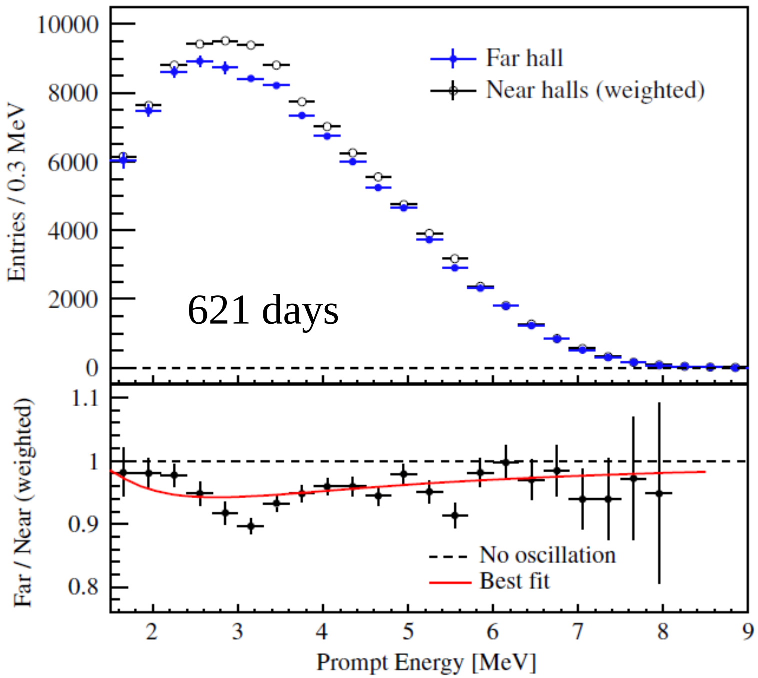
Delayed energy cut

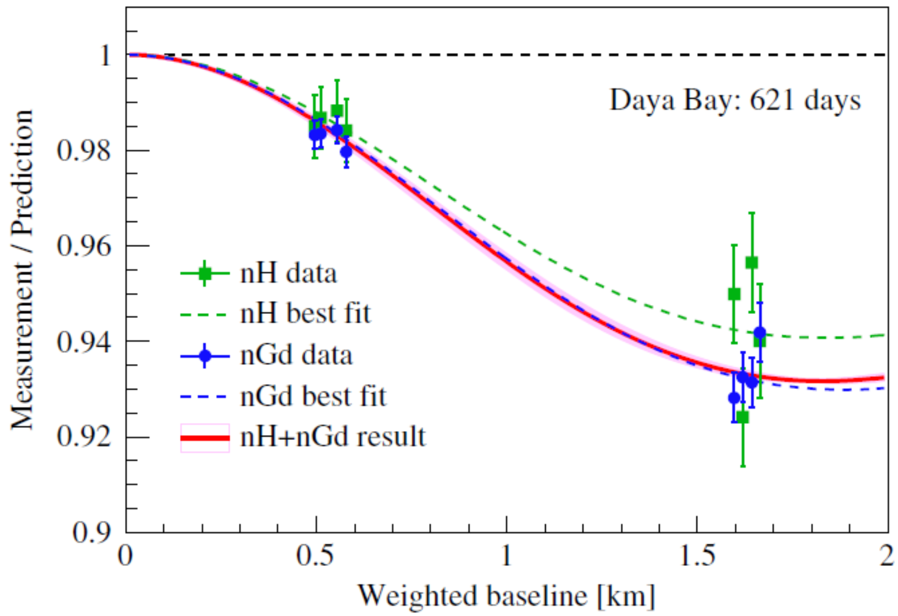


Distance cut



*n*H oscillation analysis result





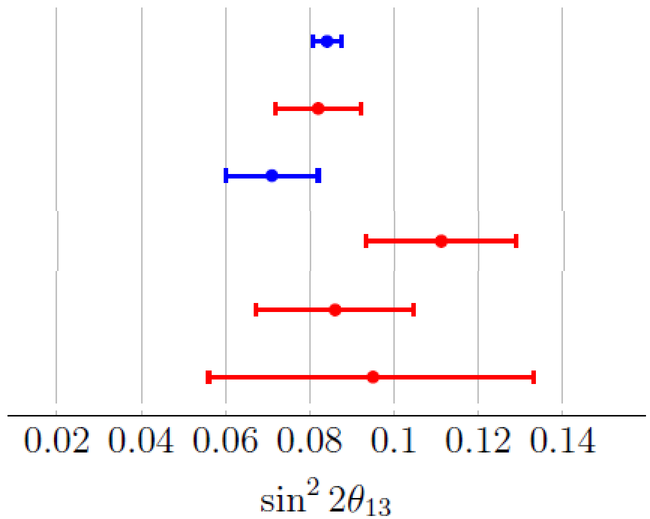
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011 \quad (\chi^2/\mathrm{NDF} = 6.3/6, \text{rate only})$$

Correlation with the *n*Gd analysis is estimated to be 0.02.
Combining the analyses (both 621 days) produced an 8% improvement.

[PR D93 (2016) no.7, 072011]

Global comparison (1)

	Experiment (reactor-only)		Value
1230 days	**Daya Bay**	nGd	0.0841±0.0033
	RENO	nGd	0.082±0.010
621 days	**Daya Bay**	nH	0.071±0.011
	D-CHOOZ	nGd	0.111±0.018
	RENO	nH	0.086±0.019
	D-CHOOZ	nH	$0.095^{+0.038}_{-0.039}$

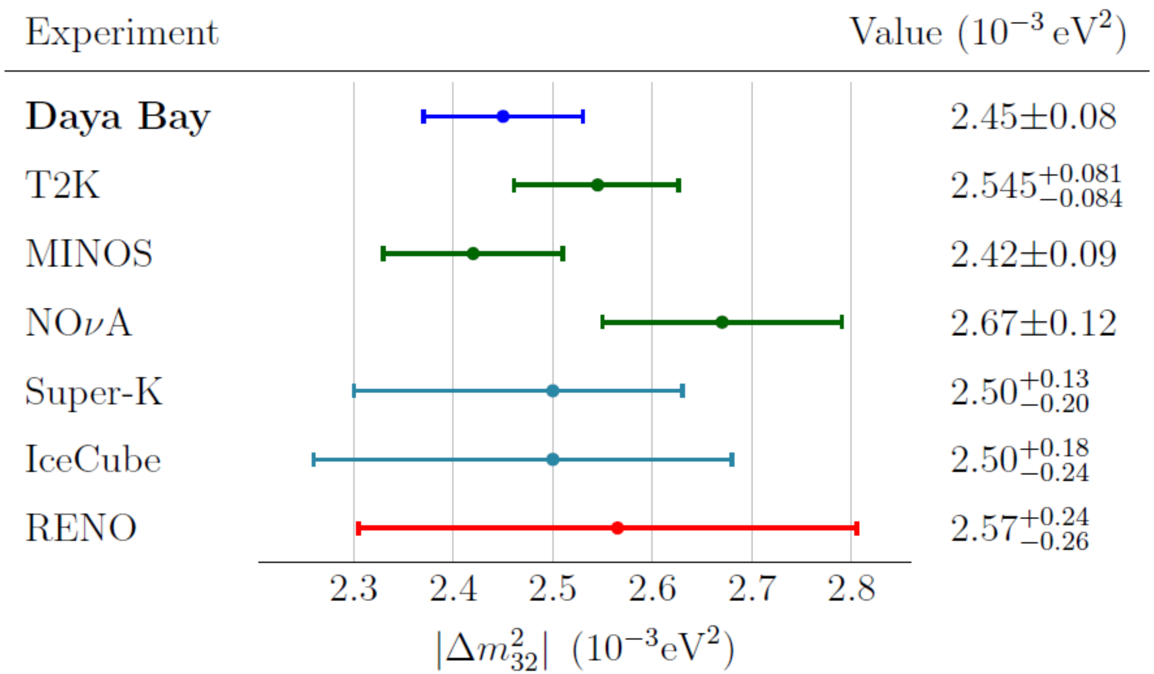


Global comparison (2)

At Daya Bay,
$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05\times10^{-3}\ \mathrm{eV}^2$

NH: Δm^2_{32} = [2.45±0.08] × $10^{-3}\ \mathrm{eV}^2$
IH: Δm^2_{32} = [-2.55±0.08] × $10^{-3}\ \mathrm{eV}^2$

1230 days



(normal hierarchy)

Reactor experiment joint analysis

on behalf of the Double Chooz, RENO, and Daya Bay collaborations

The First Workshop on Reactor Neutrino Experiments was held at Seoul National University on 2016 October 16-18.

No more than 10 members from each collaboration attended.

Details of the oscillation analyses were presented and discussed.

Questions for each collaboration were compiled before the workshop.

Results of the workshop

It was agreed to first focus on the measurement of the cosmogenic backgrounds with the goal to finish in about a year.

Each experiment is in charge of following up on one of the categories of systematic uncertainties (background, detector, reactor).

Agreed to set up a task force to look at the challenges of a joint effort.

Will hold monthly meetings to discuss progress.

The next face-to-face meeting of the three collaborations is tentatively planned for 2017 Summer.

Detecting supernovae at Daya Bay

Daya Bay utilizes both *n*Gd and *n*H IBDs → GdLS and LS volumes.

IBDs are watched for using modified prompt event energy windows (~100% efficient for supernova $\bar{\nu}_e$ energies):

*n*Gd (0.7, 50) MeV *n*H (3.5, 50) MeV

Supernova neutrino detectors in SNEWS and their capabilities. N_{IBD} is the expected number of IBD events from a SN at 10 kpc, with an emission of 5×10^{52} erg in $\bar{\nu}_e$'s, and an average $\bar{\nu}_e$ energy around 12 MeV, which is compatible with SN 1987A measurements.

Detector	Type	Location	Mass (kt)	N_{IBD}	E_{th} (MeV)
IceCube	[a]L.S. Ch.	Antarctic	0.6/PMT	N/A	–
Super-K	Water Ch.	Japan	32	7000	7.0
LVD	Scint.	Italy	1	300	4.0
KamLAND	Scint.	Japan	1	300	0.35
Borexino	Scint.	Italy	0.3	100	0.2
Daya Bay	[b]M.S. Scint.	China	0.33	110	0.7

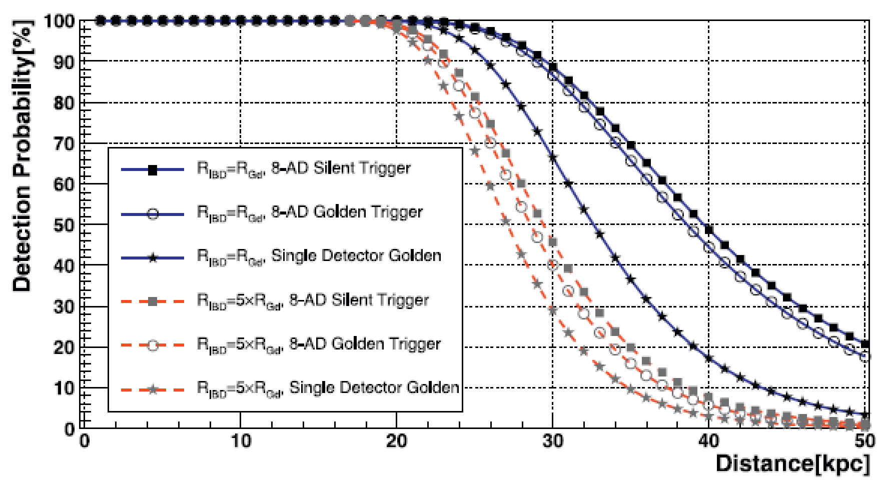
[a] Long-string Cherenkov.
[b] Multiple-site scintillator.

[Astropart.Phys. 75 (2016) 38-43]

Detecting supernovae at Daya Bay

- Watch for an increase in the IBD rates of multiple ADs within sliding 10-second windows.
- The three spatially-separated experimental halls greatly reduce the impact of muon-induced backgrounds.
- The online trigger in the DAQ system can generate a supernova trigger in 10 s with no need for further processing → SNEWS.

Essentially 100% detection probability of a 1987A-like supernova in our galaxy.



[Astropart.Phys. 75 (2016) 38-43]

Summary

- The most precise measurements (< 4% uncertainties)

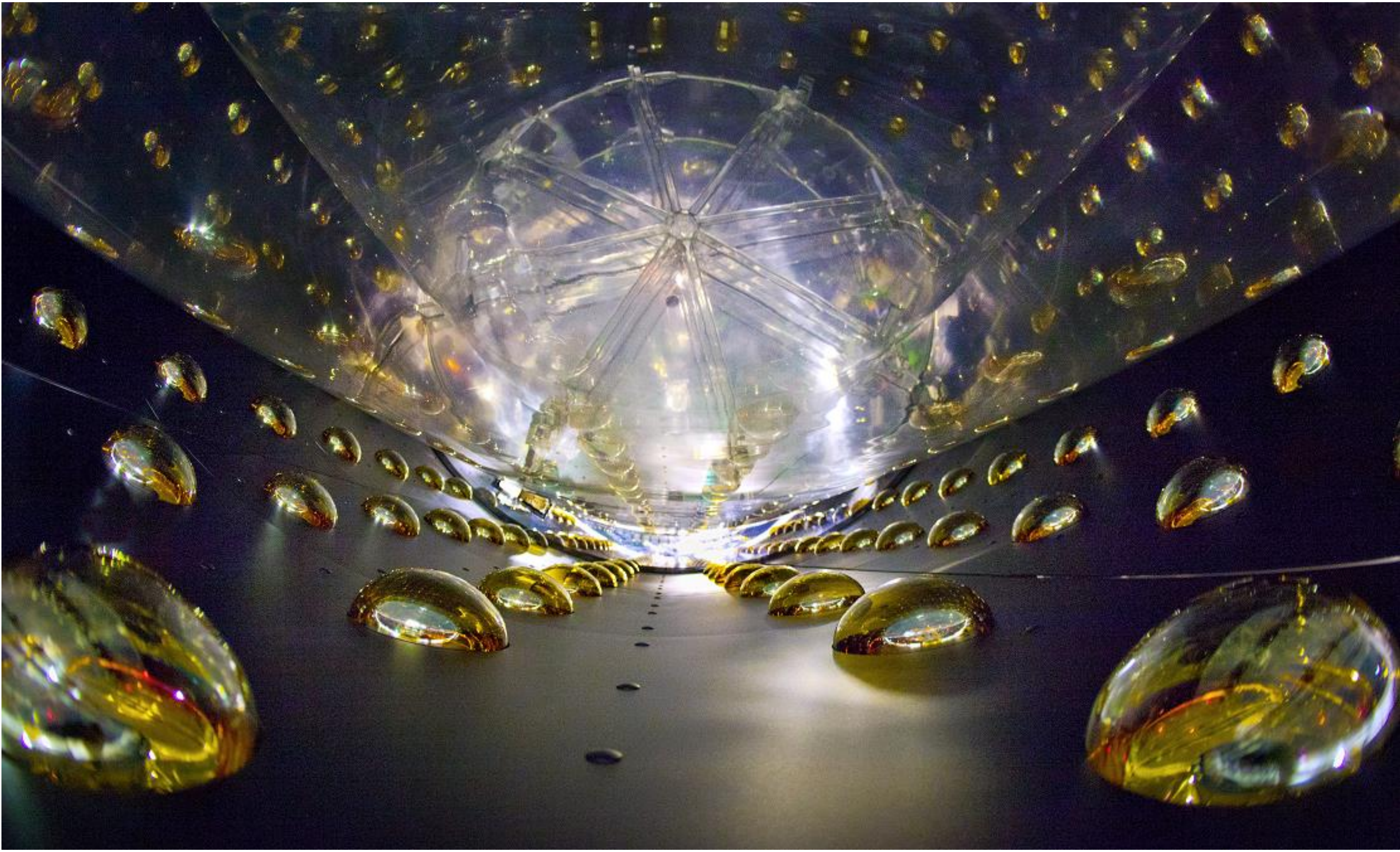
$$\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2$$

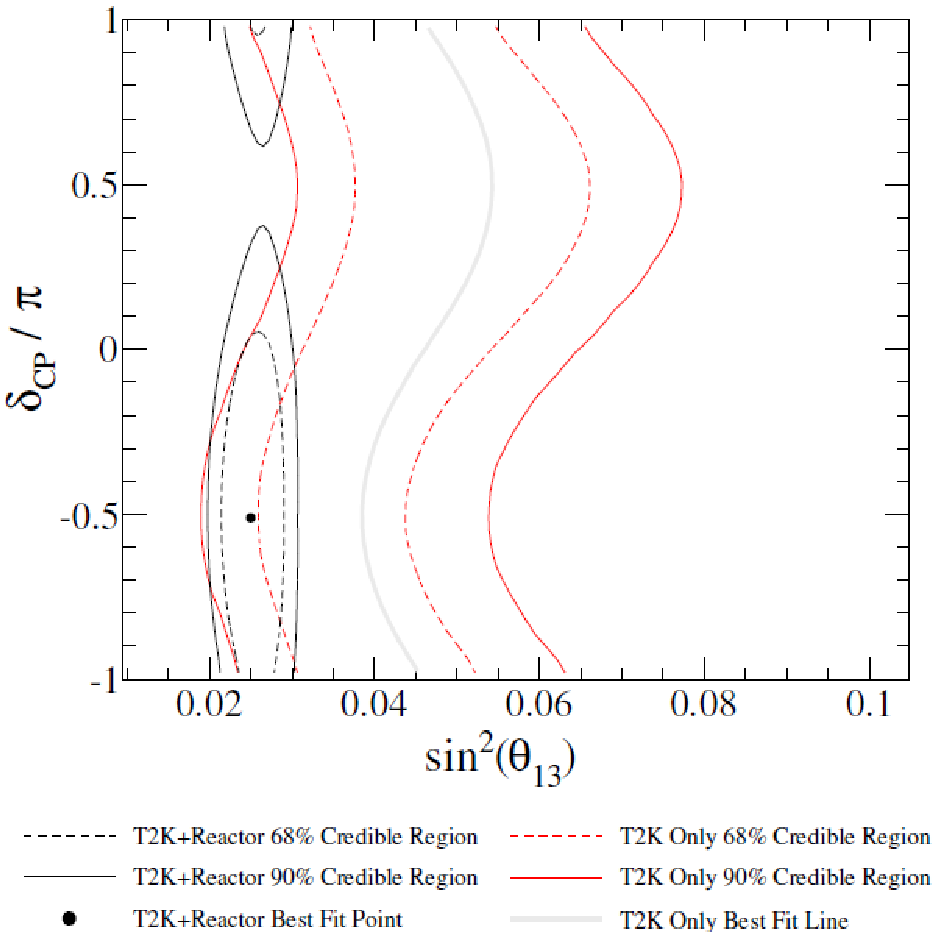
$$\begin{bmatrix} \text{NH:} & \Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2 \\ \text{IH:} & \Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ \mathrm{eV}^2 \end{bmatrix}$$

- Plan to run until 2020 → ≤3% uncertainties
- Independent $\sin^2 2\theta_{13}$ measurement from nH
  - $|\Delta m^2_{ee}|$ forthcoming
- Initial joint effort from all three θ_{13} reactor experiments
- Daya Bay is watching for supernovae

End

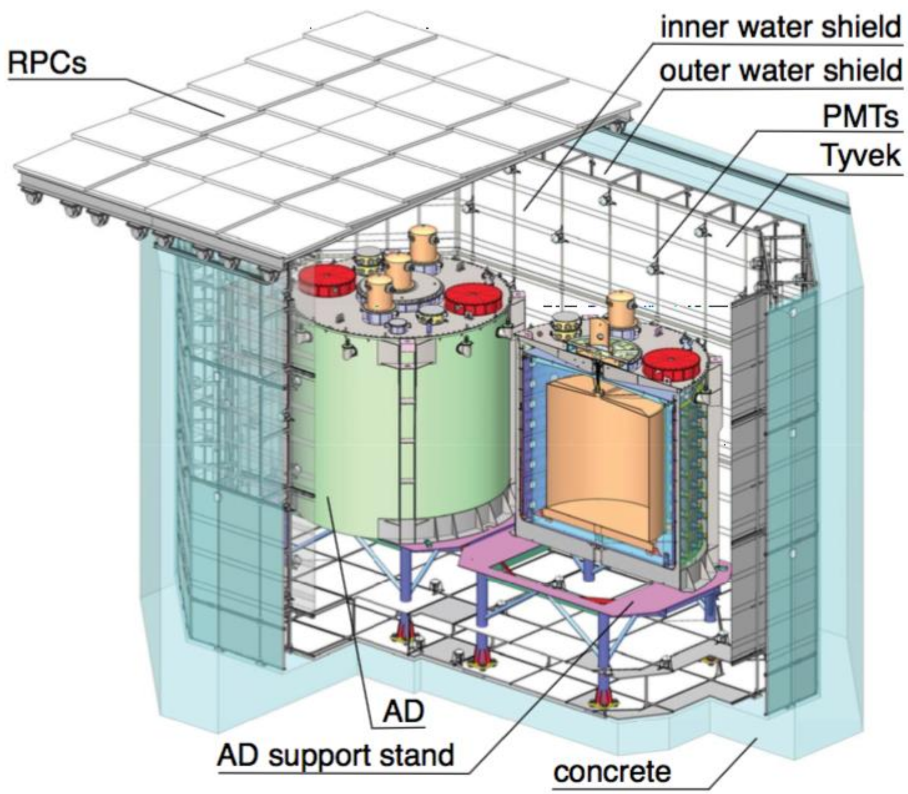


δ_{CP} $vs.$ θ_{13}



PR D91 (2015) no.7, 072010

Muon veto system



- Water Cherenkov Detectors
  - Two optically-isolated zones detect cosmogenic muons.
  - ≥ 2.5 m of water shields against radioactivity and muon spallation products.

- Resistive plate chambers
  - 4-layer modules cover water shields and provide additional muon detection.