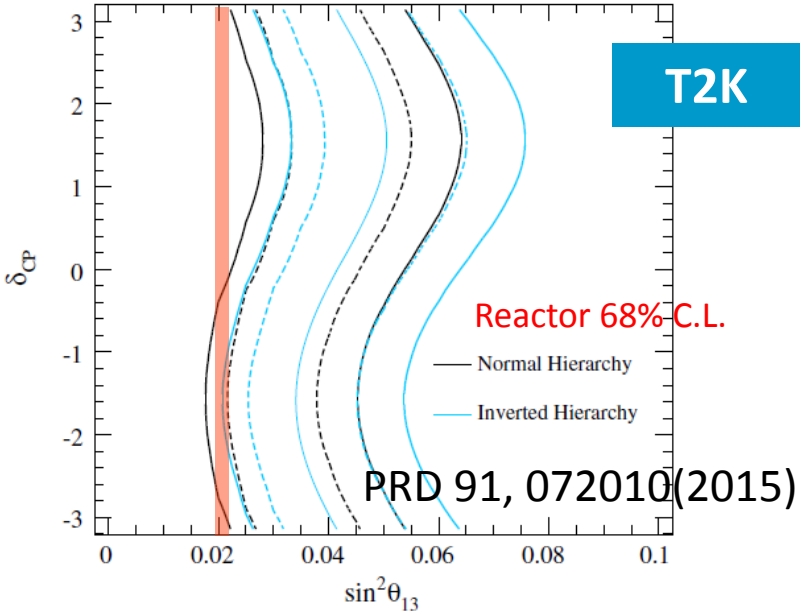
Independent measurement of θ_{13} via neutron capture on hydrogen at Daya Bay

Xiangpan Ji (Tsinghua University)
On behalf of the Daya Bay Collaboration
CPS/HEP 2016

Importance of Precision Measurement of θ_{13}

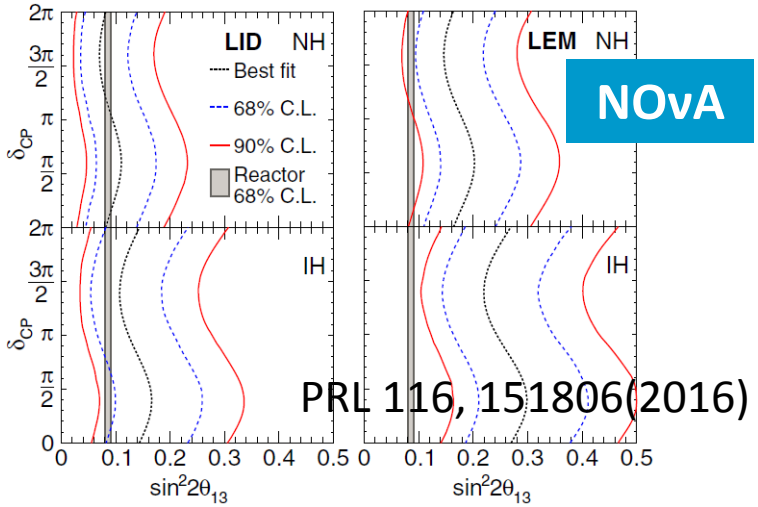
- Precise θ_{13} is crucial to search for the *CP* phase δ in lepton sector



PRD 91, 072010(2015)

- Definite θ_{13} results are obtained from Gd capture studies

An independent measurement at Daya Bay → H capture study



PRL 116, 151806(2016)

Reactor Antineutrinos

- Reactor is a free and rich $\overline{\nu}_e$ source
  - β-decays in a commercial fission reactor core produce ~ 10^{20} ν/s

- $\overline{\nu}_e$ are detected via Inverse Beta Decay (IBD)

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

$$+H \rightarrow D + \gamma \qquad \text{2.2 MeV, ~200 μs}$$

$$+Gd \rightarrow Gd^* \rightarrow \gamma's \qquad \text{~8 MeV, ~30 μs}$$

Prompt event: e^+ deposits energy and annihilates

Delayed event: n thermalizes and captured on H or Gd

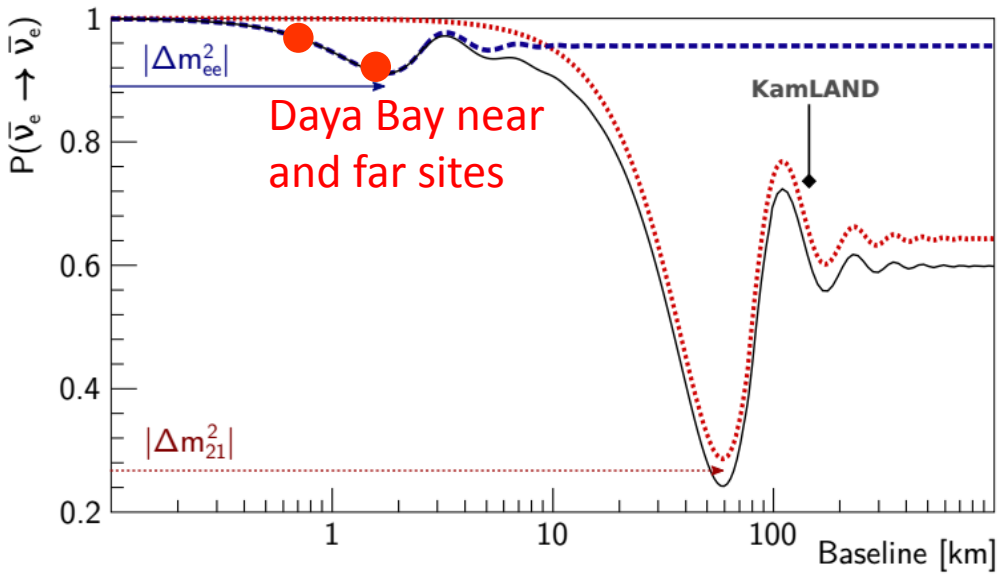
Two IBD samples: nH and nGd

Precision Measurement of θ_{13}

Extract θ_{13} from Far/Near relative measurment

$$\frac{N_f}{N_n} = \left(\frac{N_{\mathrm{p},f}}{N_{\mathrm{p},n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\left[\frac{P_{\mathrm{sur}}(E,L_f)}{P_{\mathrm{sur}}(E,L_n)}\right]$$

- Far/Near relative measurement suppress reactor related uncertainties
- Functionally identical detectors to verify and reduce detector related errors

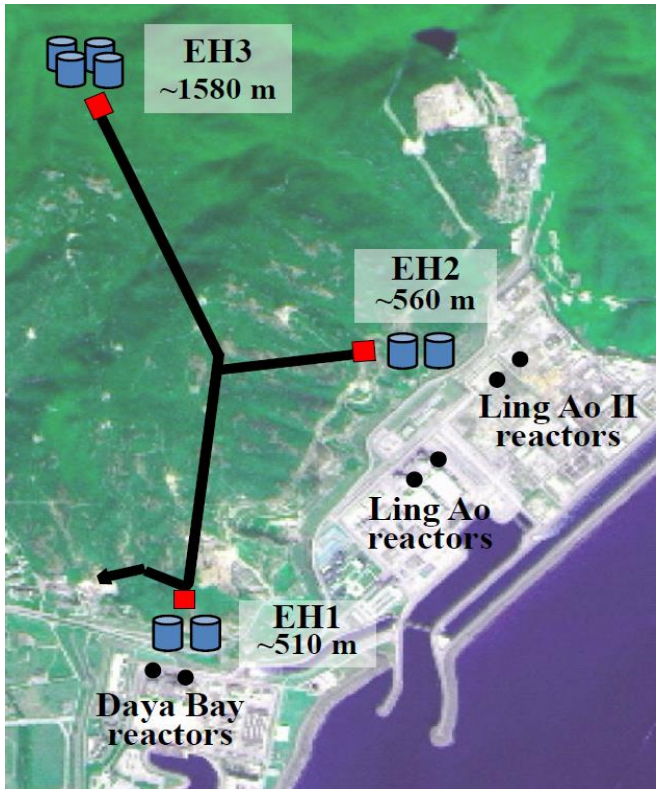


$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$

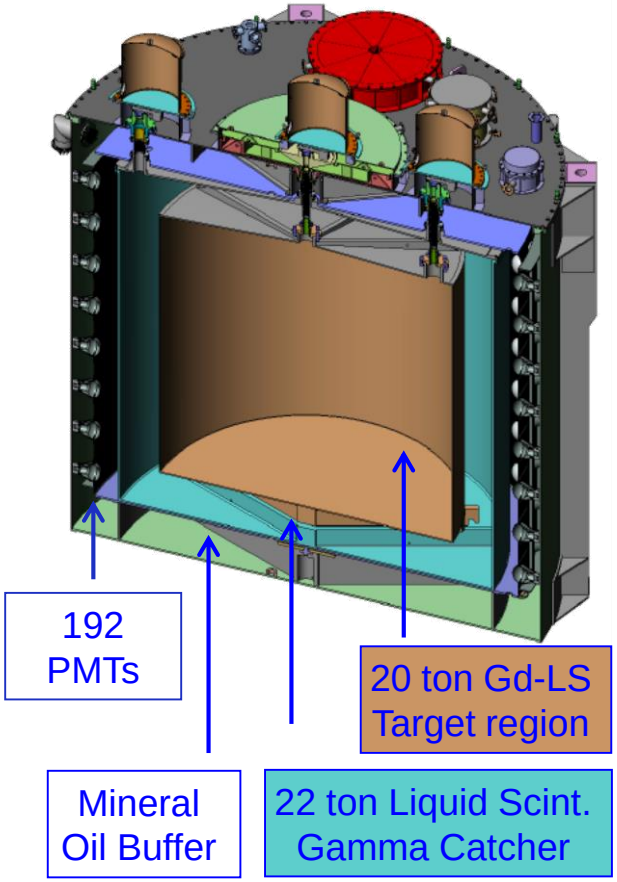
Daya Bay Experiment

Three sites

- Two near and one far



Antineutrnio detector (AD)

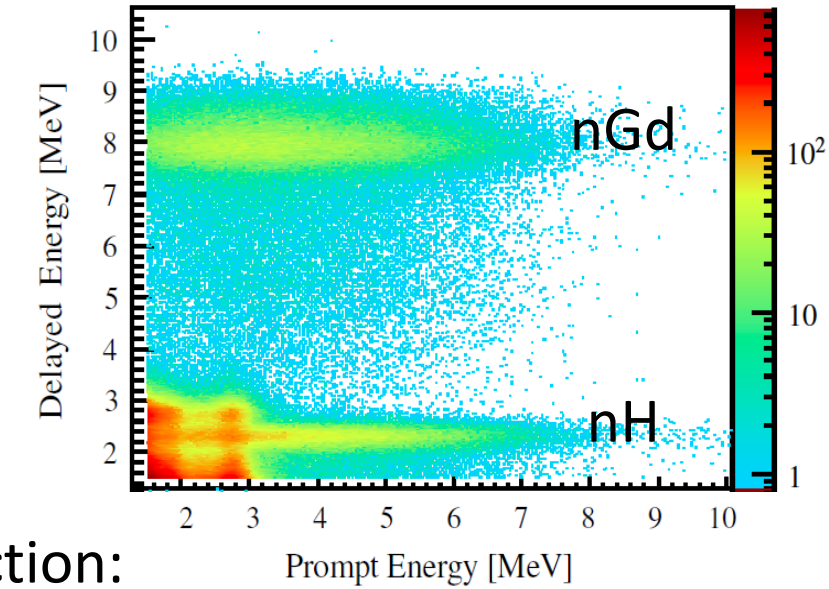


nH IBD Candidate Selection

Challenges relative to nGd:

- Low delayed energy 2.2 MeV
- Longer capture time 200 μs
- Larger accidental background
- Larger energy leakage in LS

Before delayed energy cut. Near sites



The essential differences in IBD selection:

IBD selection	nGd	nH
Prompt energy E_p	(0.7, 12) MeV	(1.5, 12) MeV
Delayed energy E_d	(6, 12) MeV	(nH peak $\pm 3\sigma$) for each AD
Coincidence time T_c	(1, 200) μs	(1, 400) μs
Coincidence distance D_c	N/A	< 50 cm

Accidental Background Subtraction

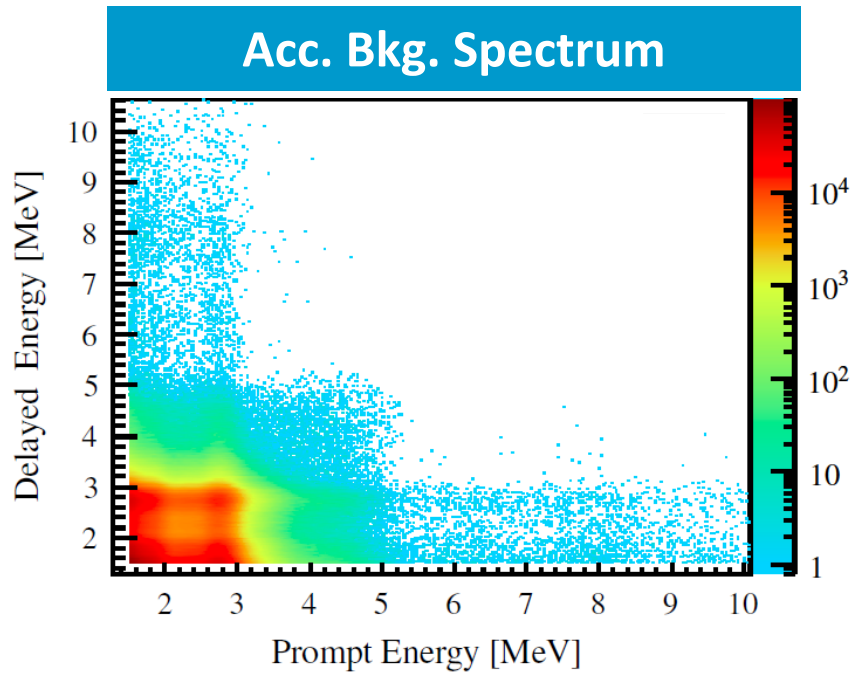
Accidental background spectrum:

1. Pair singles (>10 h separation)
2. Apply IBD selections

Accidental background rate:

$$R_{Acc} = R_s \cdot e^{-R_s T_c} \cdot R_s\, T_c e^{-R_s T_c}$$

R_s: singles rate



Far hall	Fraction of IBD rate (%)	
	nGd	nH
Accidental bkg.	2.1	116

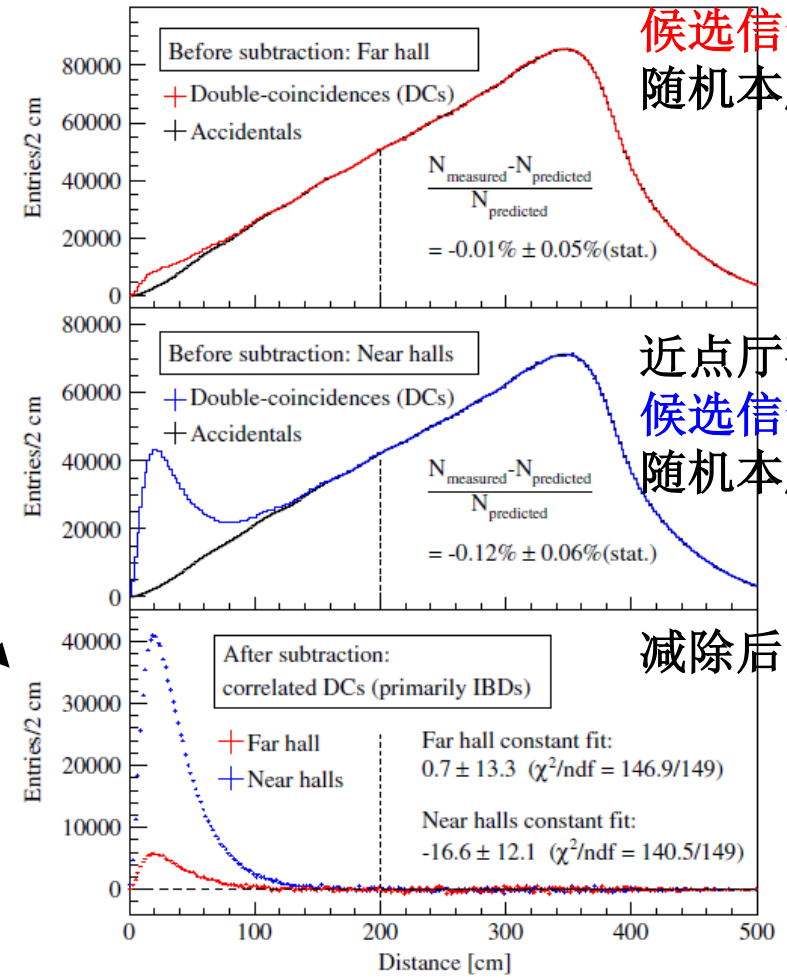
> 50 times larger than nGd

Accidental Subtraction Validation

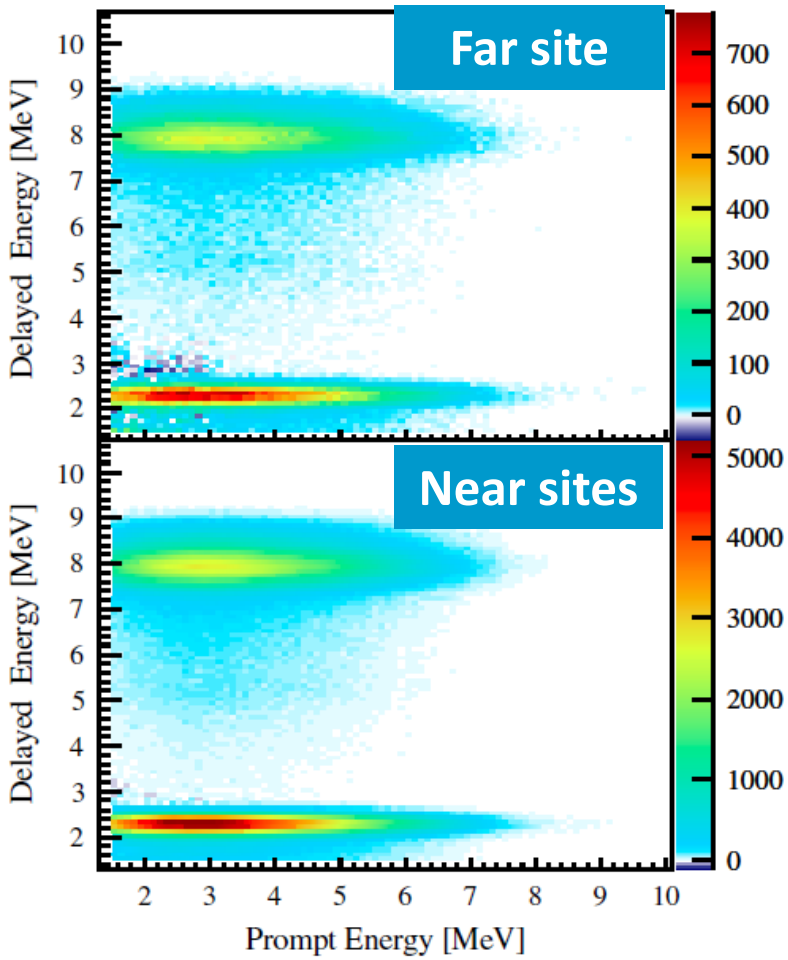
Real double correlated events rarely have distance > 2m

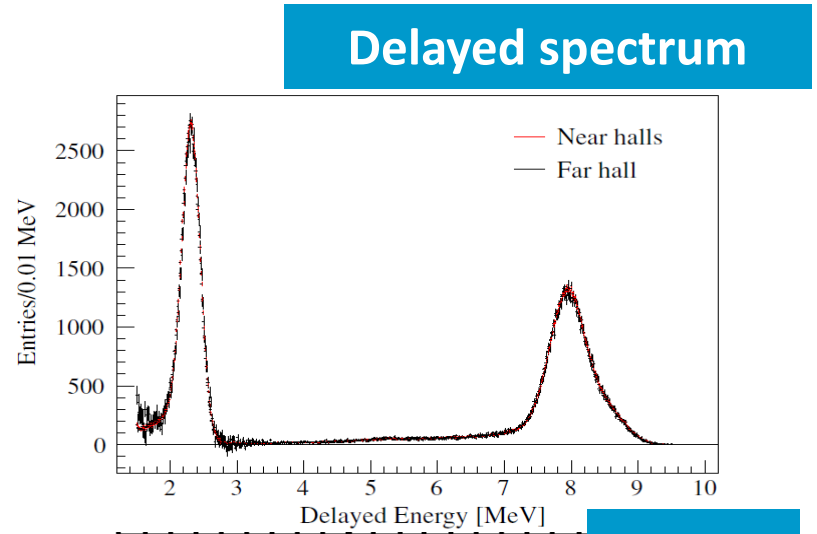
A good accidental background prediction should reproduce both the rate and spectrum > 2 m

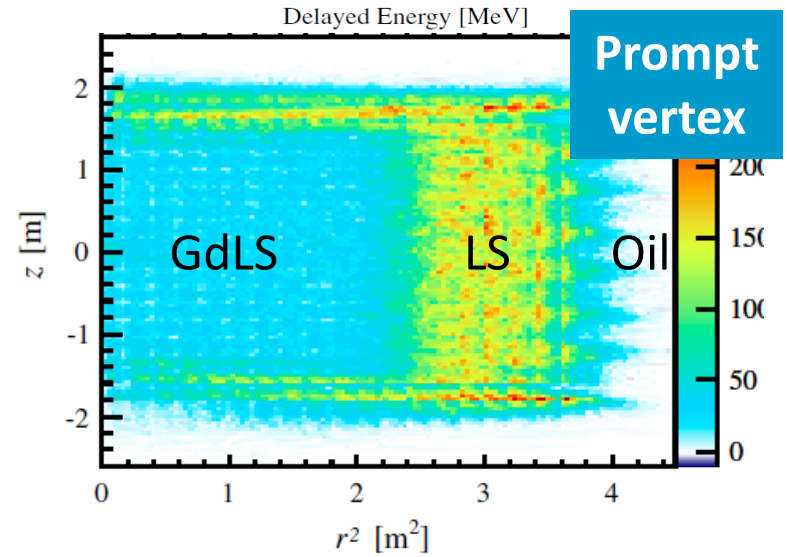
It is also validated by the neutron capture time distribution.



After Accidental Subtraction







Other Backgrounds

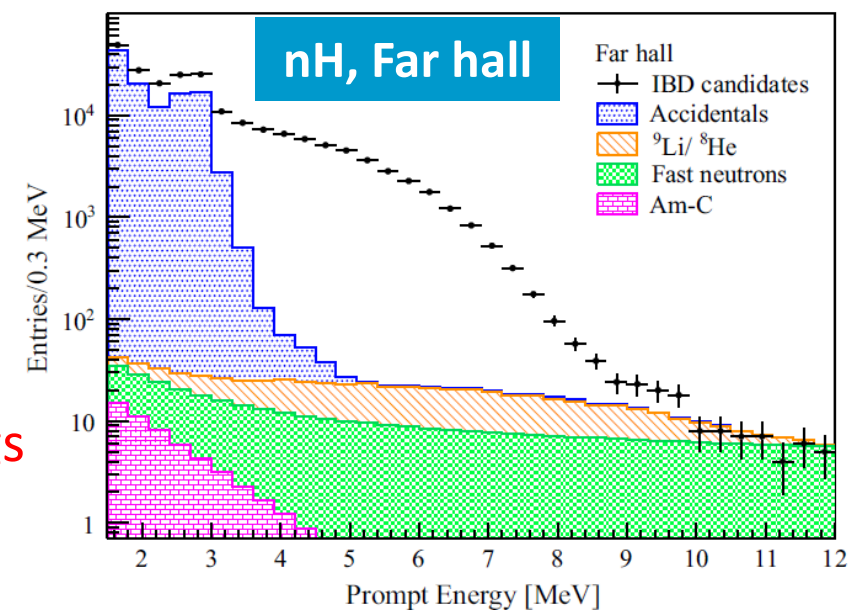
^{9}Li/^{8}He: determined from their time-correlation with cosmic-ray muons (especially shower muons).

Fast neutron: prompt energy below 12 MeV is extrapolated from higher energy and validated by MC and enriched fast neutron samples.

Am-C background: from calibration source is studied with a strong Am-C source and extrapolated to normal source intensities.

The delayed signals of all the three bkgs are induced by neutron capture

Far hall	Fraction of IBD rate (%)	
	nGd	nH
Accidental	2.1	116
^{9}Li/^{8}He	0.36	0.39
Fast neutron	0.068	0.32
Am-C	0.24	0.06



Efficiency and Identicalness

- Expected number of IBDs in an AD from GdLS, LS, and acrylic volumes

$$N = \Phi \varepsilon_\mu \varepsilon_m \left[\sum_{v}^{\text{GdLS,LS,acry}} N_{p,v} \varepsilon_{E_p,v} \varepsilon_{T,v} \varepsilon_{E_d,v} \right] \varepsilon_D$$

- Φ: number of IBDs per target proton (cross section $\otimes$ reactor $\overline{\nu}_e$ flux $\otimes$ oscillation)
- ε_μ(muon veto), ε_m(multiplicity cut), and N_p(number of protons): Well measured
- ε_{E_p}: prompt energy cut efficiency
- ε_T: time cut efficiency
- ε_{E_d}: delayed energy cut efficiency
- ε_D: distance cut efficiency

Dominant part (89%) to the overall AD-uncorrelated uncertainty

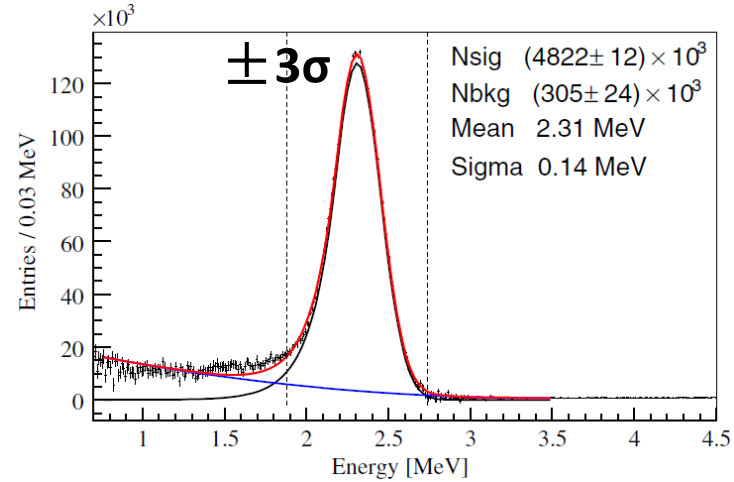
$\varepsilon_{E_p} \varepsilon_T \varepsilon_{E_d}$ are 14%, 50% and 5% in the GdLS, LS and acrylic volumes

ε_D is 75%

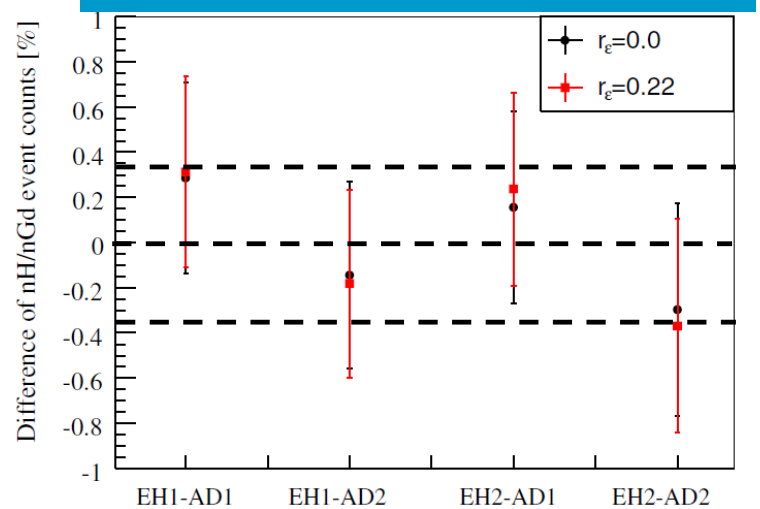
Delayed Energy

- The mean and width of 3σ cut are determined for each AD
- Uncertainty is estimated with spallation neutron nH/nGd event ratios among near-site ADs
- Uncertainty is also estimated by nH-IBDs delayed spectra, consistent result observed
- 0.35% AD-uncorrelated uncertainty

Spallation neutron. EH1-AD1



Difference of nH/nGd events



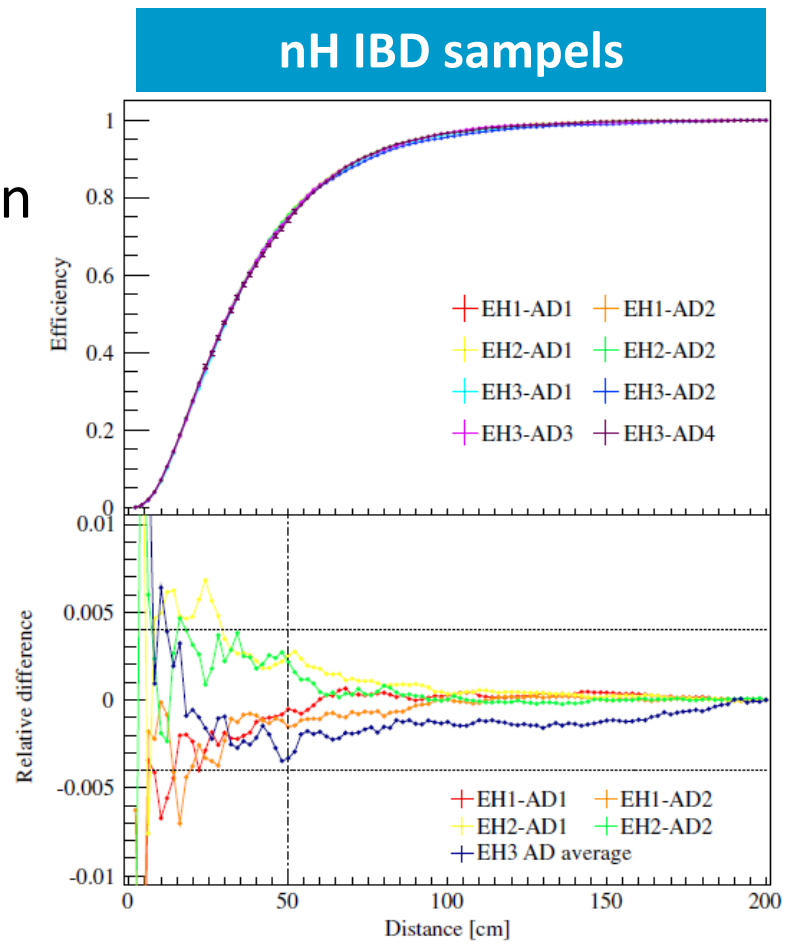
Distance between Prompt and Delayed Vertices

- ε_D is determined by data

  After accidental background subtraction, the distance distribution can be directly observed.

- Uncertainty of the efficiency is estimated by the relative difference among ADs.

- 0.4% AD-uncorrelated uncertainty



AD-uncorrelated uncertainty

	Uncertainties (%)	Correlation to nGd
Target protons ($N_{p,\mathrm{GdLS}}$)	0.03	1
Target protons ($N_{p,\mathrm{LS}}$)	0.13	0
Target protons ($N_{p,\mathrm{acry}}$)	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	**0.57**	**0.07**

- All the uncertainties are data-driven estimated
- Largest uncertainties
  - Delayed energy cut
  - Distance cut
- Correlation with nGd
  - Distance cut, not used for nGd
  - Delayed energy cut,
    nH: floating 3σ cut
    nGd: fixed at (6, 12) MeV

A "detector related" coupling of 0.07 indicates an independent measurement

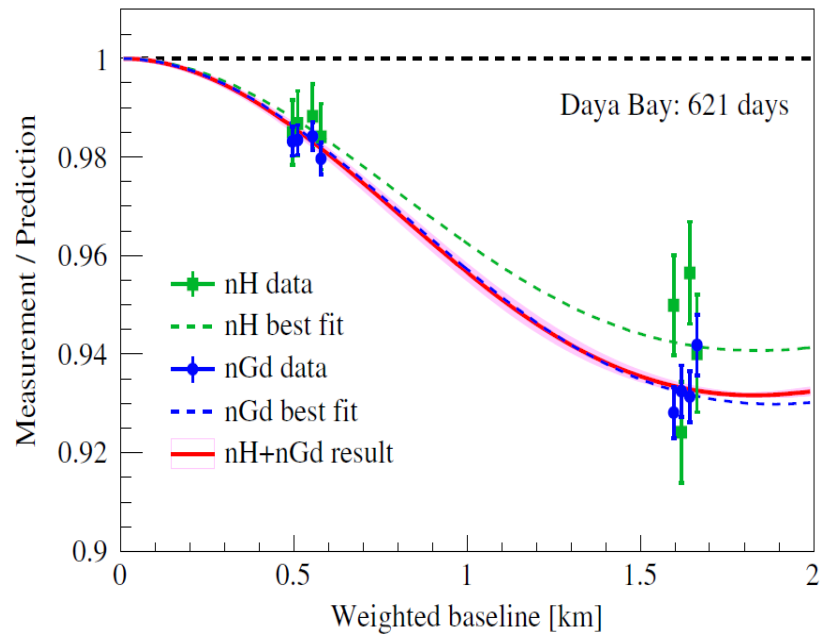
$\sin^2 2\theta_{13}$ Result

- nH rate analysis, χ^2 fitting with full pull terms gives

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

  with χ^2/NDF = 6.3/6

- Between nH- and nGd-IBD analysis, an overall correlation coefficient value is estimated at 0.02



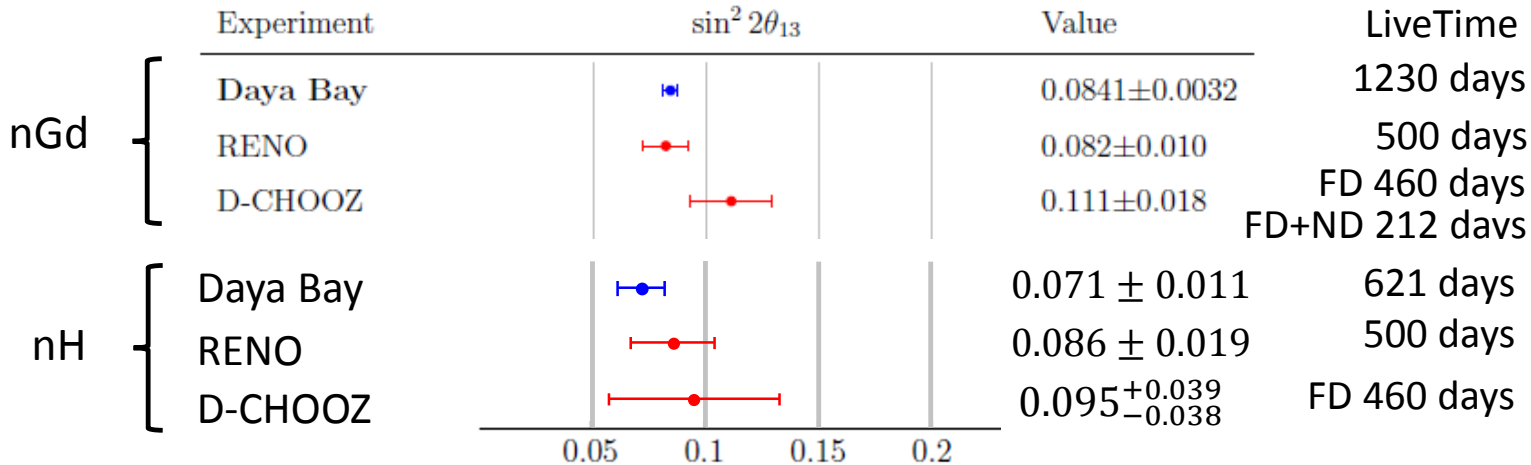
- Combined with the Daya Bay nGd rate+shape result (same period)

  ($\sin^2 2\theta_{13} = 0.084 \pm 0.005$, PRL 115, 111802)

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

Strong independent observation of reactor neutrino oscillation and θ_{13} measurement

Comparison of θ_{13} Measurement



- The nH measurement is consistent with nGd at Daya Bay
- The most precise nH measurement yielding θ_{13} and one of the most precise measurement overall

Summary

- An independent observation of reactor $\overline{\nu}_e$ oscillaiton
- The most precise nH measurement yielding θ_{13}
- The precision of $\sin^2 2\theta_{13}$ is improved with combination
- nH shape analysis is in progress, $|\Delta m^2_{ee}|$ and better precision in $\sin^2 2\theta_{13}$
- Several key methods (Accidental bkg, data-driven detector uncertainty) have been developed and can be applied in other experiments using nH IBDs, e.g. JUNO, RENO-50

Thank you!

Three Neutrino Oscillation: PMNS Mtrix

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

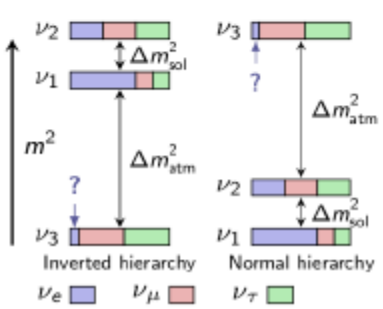
How they interact

How they propagate

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

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

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

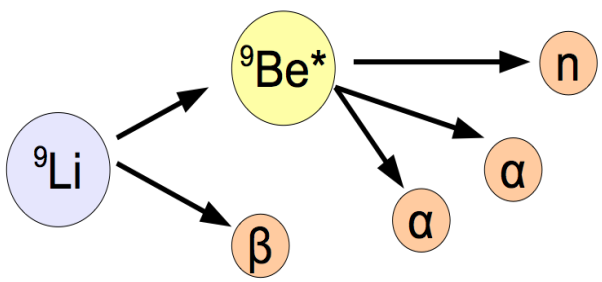


Other Backgrounds

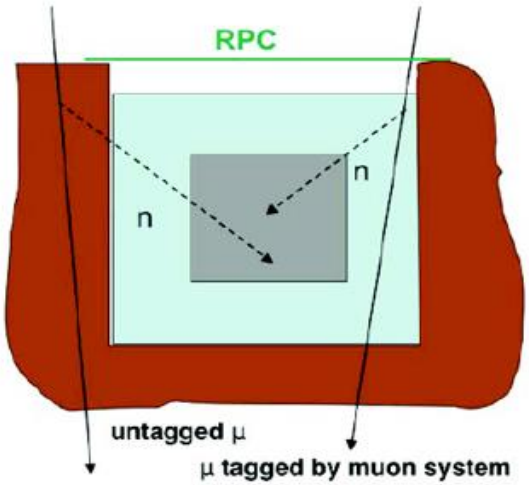
(1) 9Li/8He background

β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



(2)Fast-neutron background



(3) Am-C calibration source background

- Studied with a strong Am-C source and extrapolated to the normal calibration source intensities.

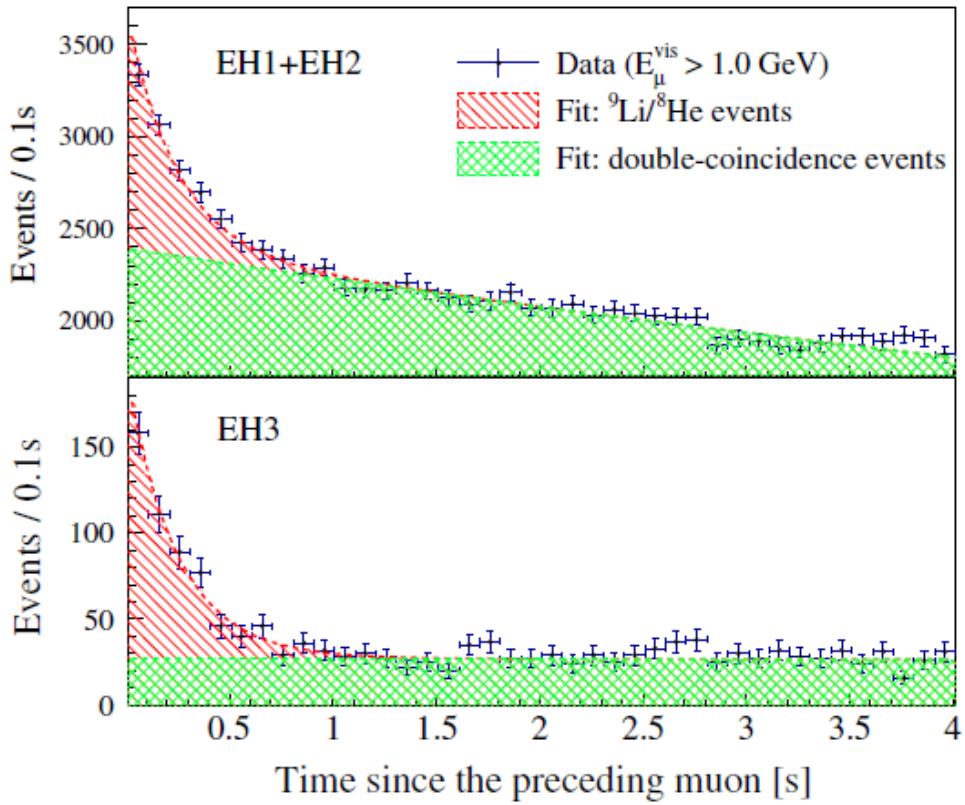
9Li/8He Background

The background is induced by cosmogenic muons

The time between 9Li/8He events are correlated with the muons

The background was estimated by modeling the time correlation

Time of DC to the preceding muon

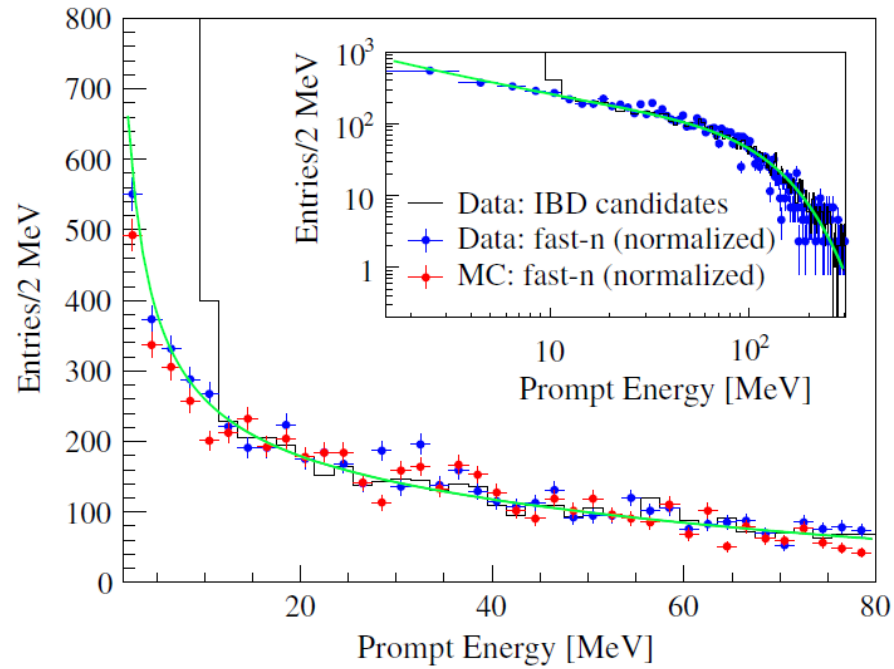


Fast-neutron Background

Studied the prompt spectrum of fast-n from
(1) IBD candidates beyond 12 MeV
(2) OWS identified events
(3) MC

The background was estimated as the number of events within the prompt energy selection window in the normalized OWS-identified

Fit function: $N(E) = N_0 \left(\frac{E}{E_0}\right)^{-a-\frac{E}{E_0}}$

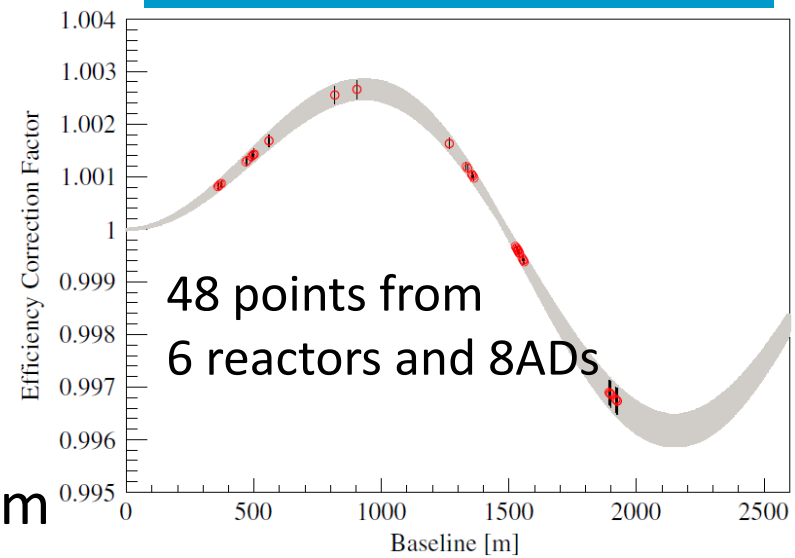


Consistent spectrum distribution

Prompt Energy

- ε_{E_p} is estimated by MC
- Uncertainty of the efficiency is estimated with energy scale differences at nH gamma and ^{212}Bi alpha peaks among ADs
- 0.10% AD-uncorrelated uncertainty
- Oscillation effect is considered
  - Shape of neutrino energy spectrum changes with baseline
  - Without correction, the $\sin^2 2\theta_{13}$ result is about 4% larger

Efficiency correction with baseline. LS region



Neutron Capture Time

- ε_T is estimated by MC
- Intrinsic uncertainty

$$\frac{1}{\tau} = \frac{v_n}{\lambda} = v_n \sum_i n_i \sigma_i(v_n)$$

Measured n_i (each isotope's number density) different among ADs induce 0.02% uncertainty

- Electronics induced uncertainty estimated by ^{214}Bi sample < 0.1%
- 1 μs cut induced uncertainty 0.1%
- 0.14% AD-uncorrelated uncertainty in total

Time efficiency from ^{214}Bi sample