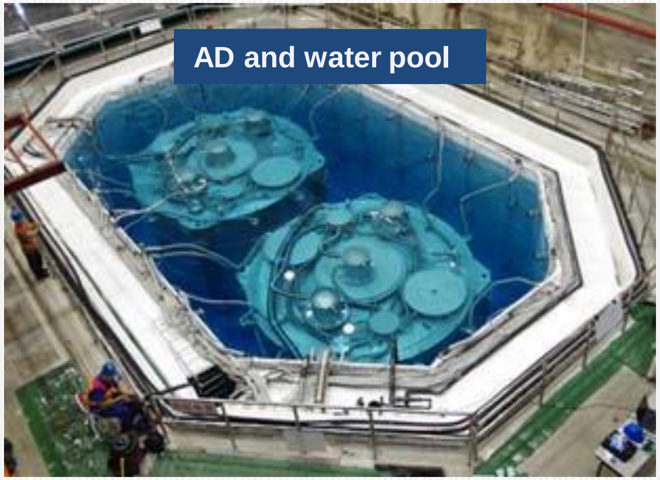

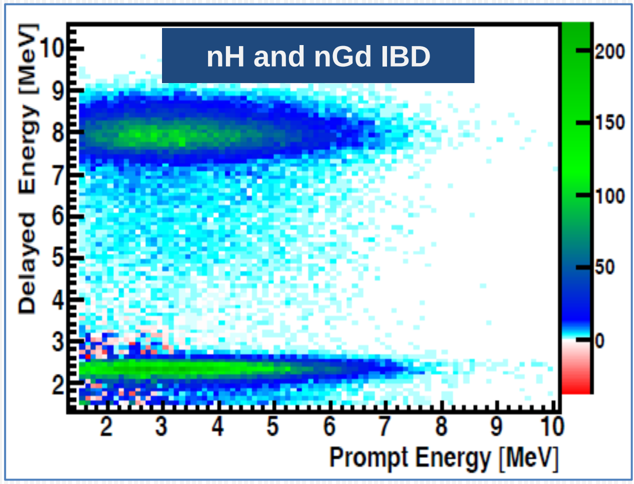

An Independent Observation of Electron-Antineutrino Disappearance at Daya Bay

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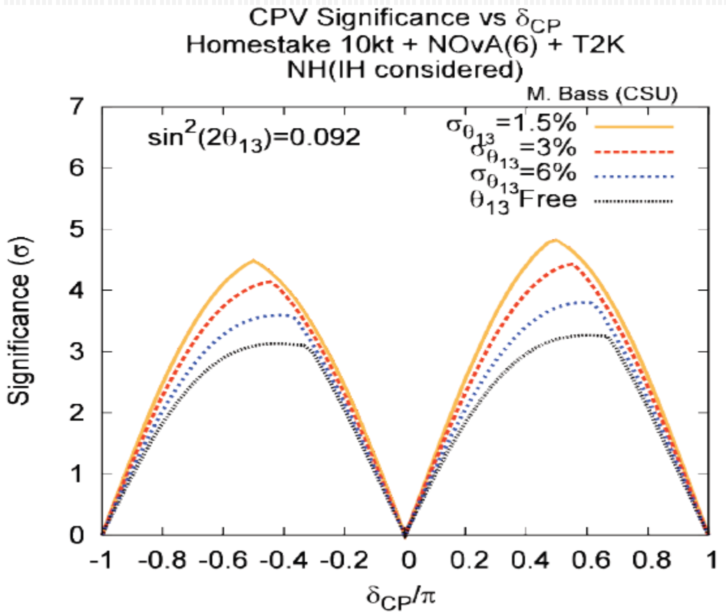
(on behalf of the Daya Bay Collaboration)

Rencontres de Moriond
Mar. 15-22, 2014

θ_{13} Measurement

1. Precise θ_{13} is a critical input for neutrino related theories and experiments



arXiv:1309.7961

The more precise, the faster we reach a better sensitivity to discover CPV in lepton sector.

2. The definite direct θ_{13} measurement is only from Gd capture studies. We need an independent method with a comparable precision.

Antineutrino Detection & Oscillation Measurement

- Detection of electron-antineutrino: Inverse-Beta Decay (IBD)

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

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

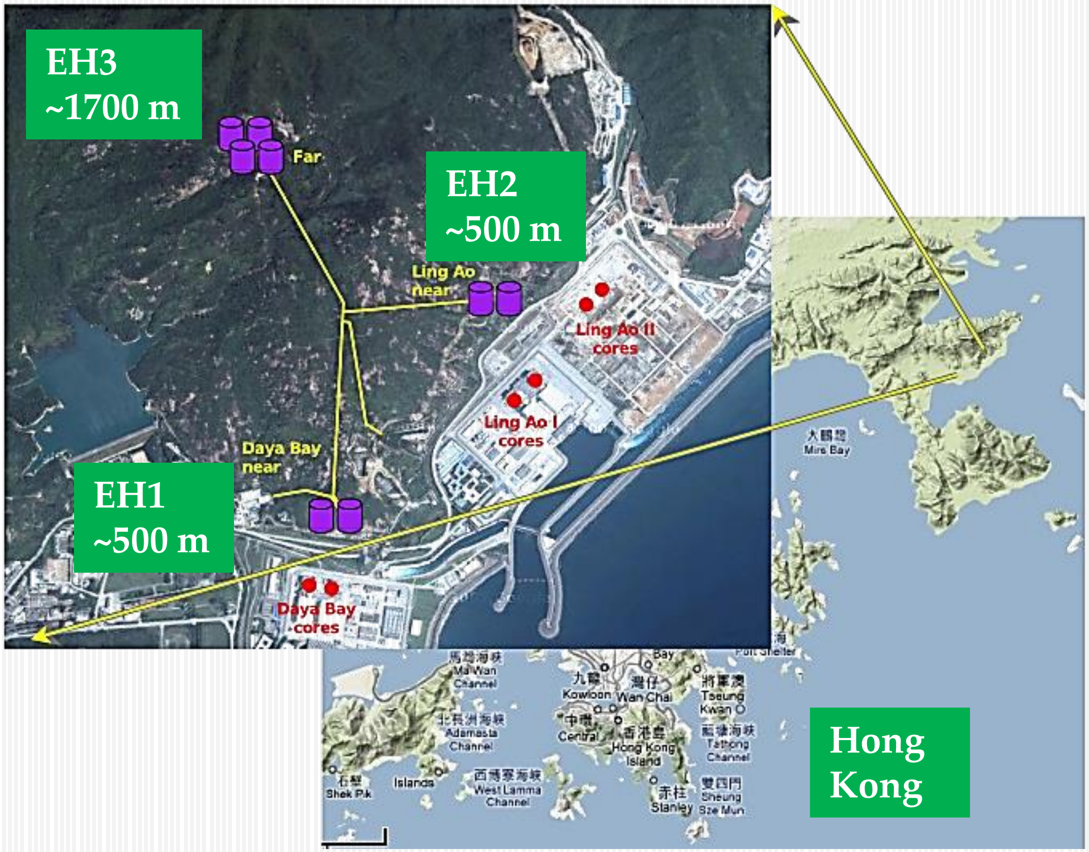
Prompt: e^+.
Delayed: n capture on H or Gd.
Two IBD samples: nH and nGd

- Extract θ_{13} from
  - Far/Near IBD events ratio, and ← Rate analysis
  - IBD spectrum distortion of the Far and Near sites ← Shape analysis

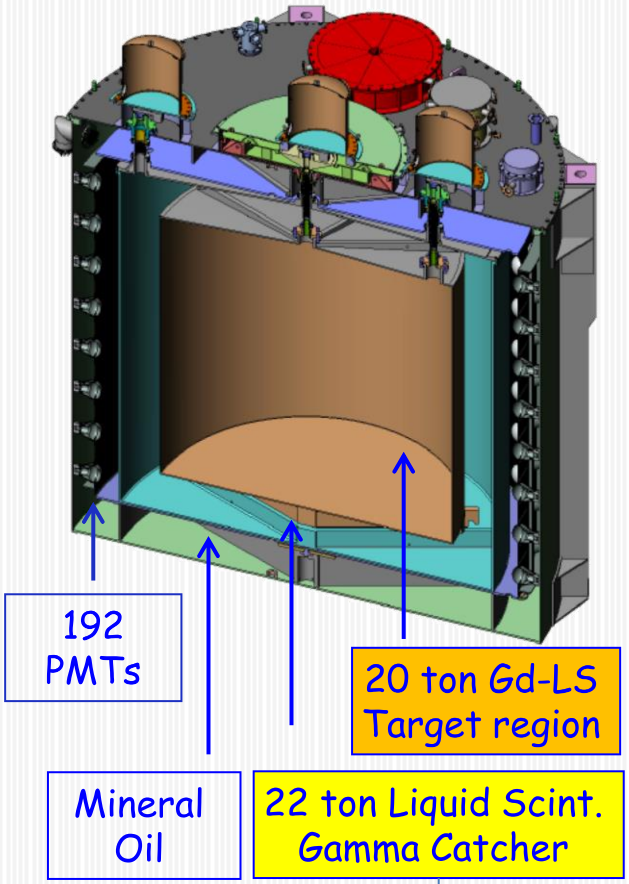
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Daya Bay Experiment

- Three Sites



- Anti-neutrino Detector (AD)

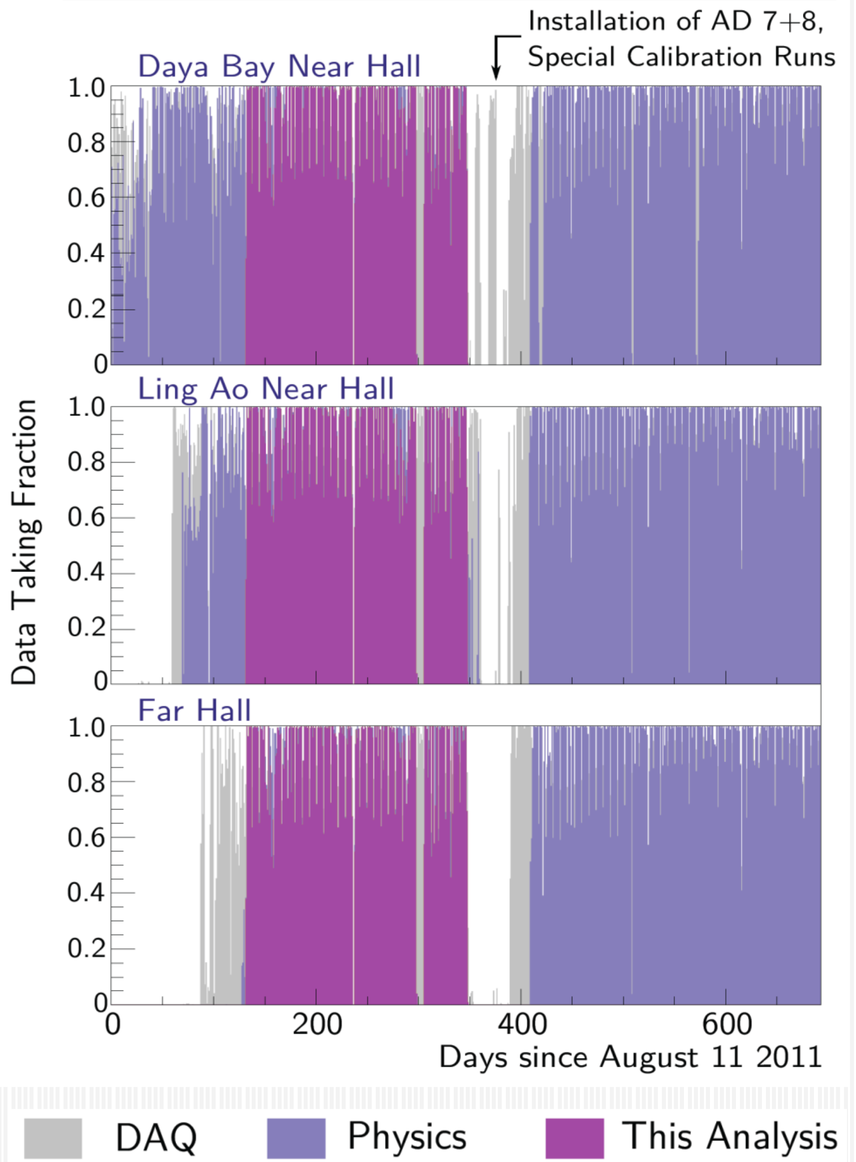


The raw nH signal statistics is slightly higher than nGd

Data Taking and Analysis Status

- **Frist oscillation analysis**
  - 55 days of data, 6 ADs (3 Near, 3 Far)
  - PRL 108, 171803 (2012)
- **Improved oscillation analysis**
  - 139 days of data, 6 ADs
  - CPC 37, 011001 (2013)
- **First nGd shape analysis**
  - 217 days of all 6 AD period
  - Phys. Rev. Lett. 112, 061801 (2014)
- **This talk: First nH rate analysis**
  - 217 days of all 6 AD period

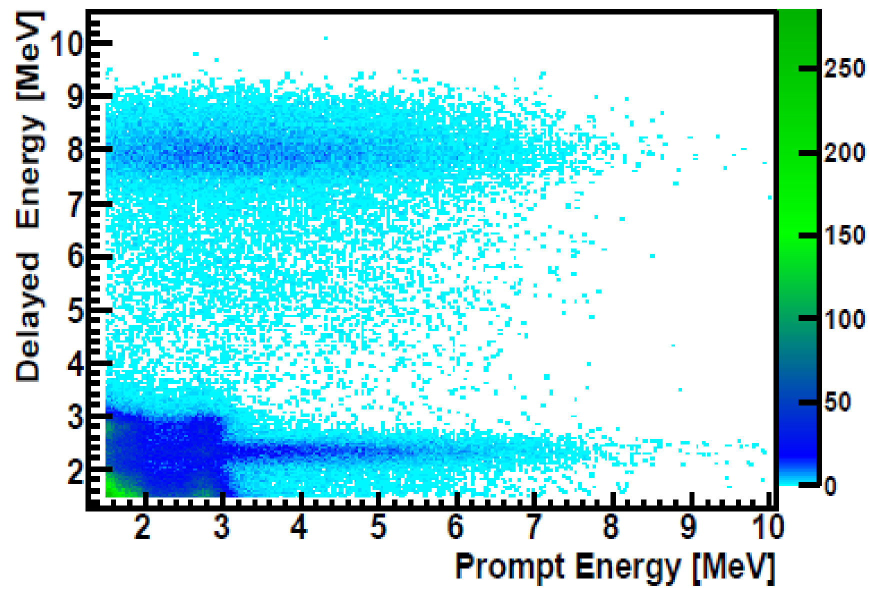
nH signals have been used before by Double Chooz, Kamland and Super Kaminokande.



nH Candidate Selection

nH: 1. Low delayed energy 2.2 MeV
2. Long capture time 200 μs in LS
3. More energy leakage at boundary
4. High accidental background

Before Delayed 3σ cut. Far site



Beside similar basic requirement as nGd

- Remove low E event (< 1.5 MeV)
- Coincidence window T_C: 1-400 μs.
  (Single - SC, Double - DC, Multi - MC)
- Distance between delayed & prompt vertices < 0.5 m
- Floating Delayed cut: 3σ around measured nH peak

Background Category

S/N with Acc Bkg is ~1:1
Rather different from nGd sample
Suppressed by:

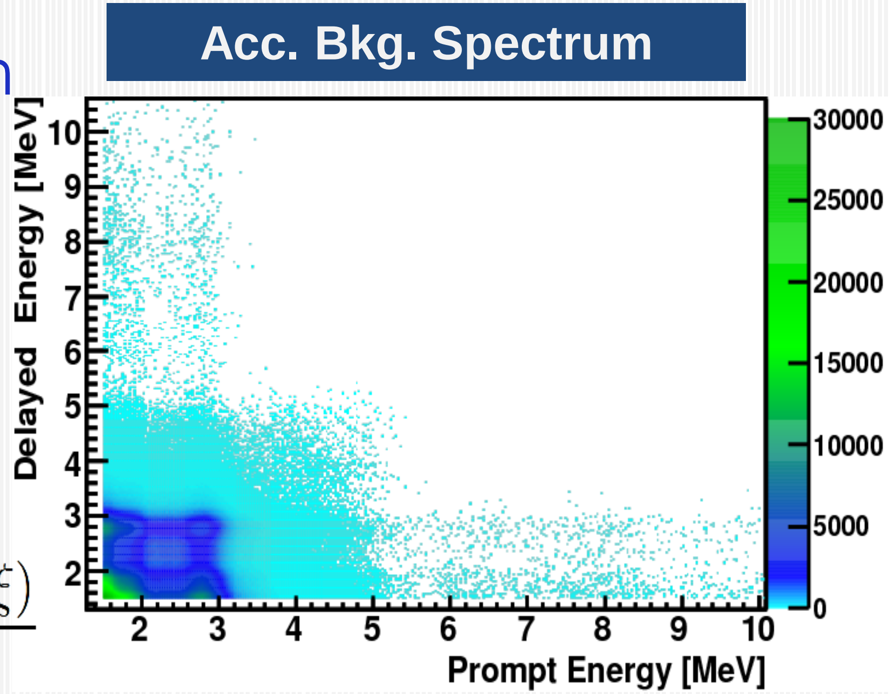
- Accidental background
  - Distance cut
  - Coincidence time cut
  - Low energy cut > 1.5 MeV
- Coincidence background
  - Li9/He8 background
  - Fast neutron background
  - ^{241}Am - ^{13}C background (one of calibration source)

> - The delayed signals of the coincidence background are all induced by neutrons
> - After the Acc. Bkg. subtraction, we can directly observe all spectra of neutron related quantities, nH peak, Dist., capture time

Accidental Background Subtraction

- Acc. Bkg. differential spectrum
  1. Pair SC (>10 h separation)
     $N_{ABS-tot}$
  2. Pass the same IBD cuts
     $N_{ABS-cut}(\xi)$ ξ: any quantity
- Differential IBD spectrum in ξ:

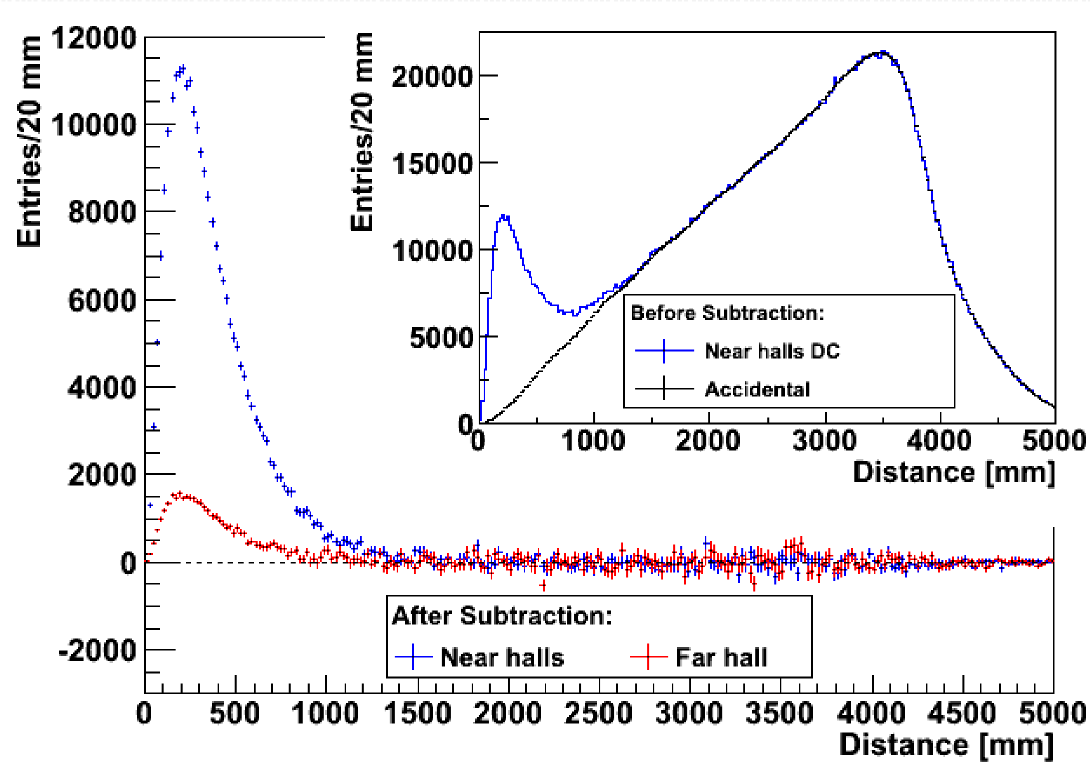
$$N_{IBD}(\xi) = N_{DC}(\xi) - R \cdot T_{live} \cdot \frac{N_{ABS-cut}(\xi)}{N_{ABS-tot}}$$



- Acc. Bkg. rate: $R = R_s \times e^{-R_sT_c} \times R_sT_ce^{-R_sT_c}$

R_s: Genuine singles rate
Average event rate before and after removing DC and MC events. Their differences induce 0.18%, 0.16% and 0.05% uncertainty for EH1, 2 and 3 Acc. Bkg., respectively.
arXiv:1301.5085 (2013)

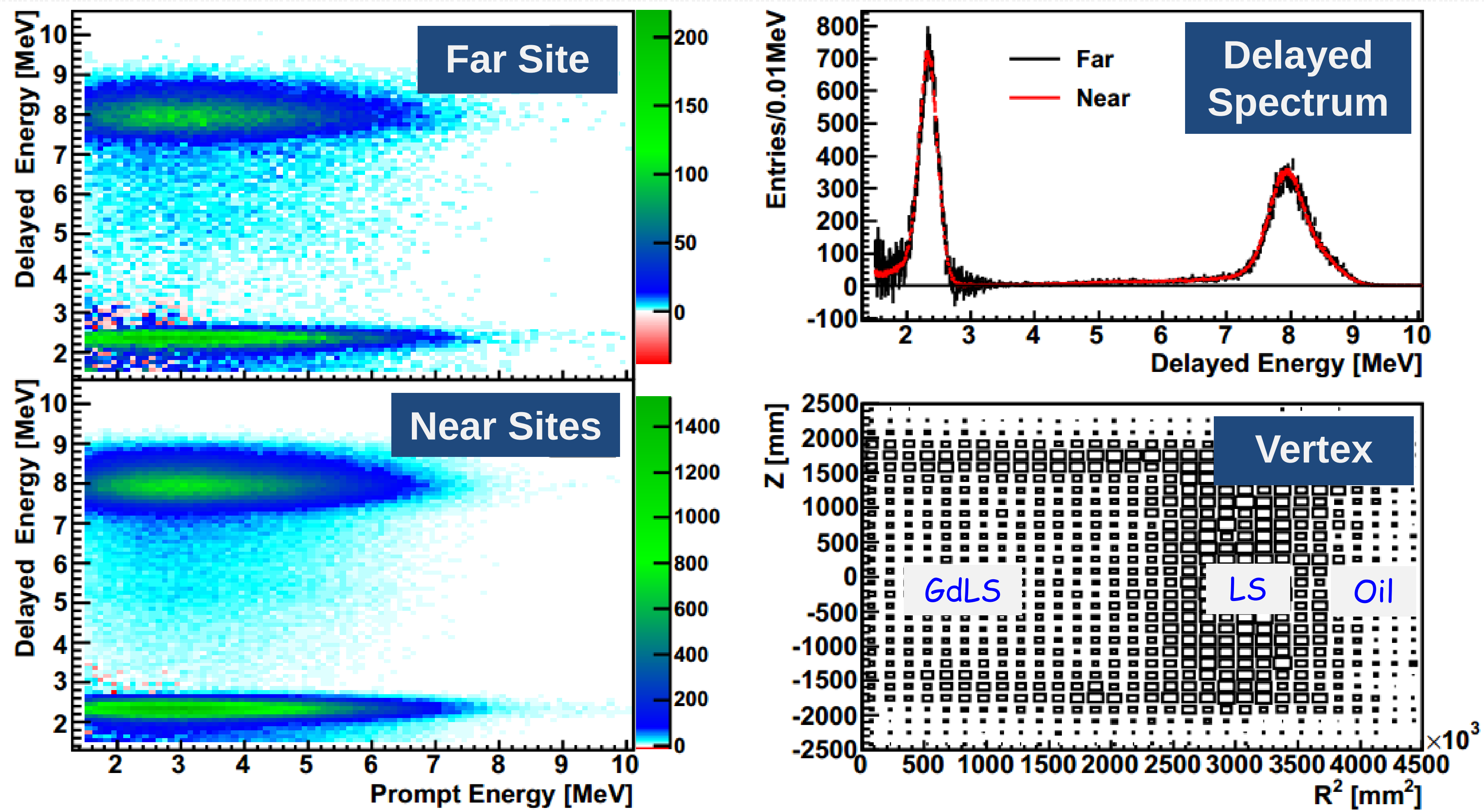
Accidental Subtraction Validation



- Real coincidence events rarely have distances > 2 m
- A good accidental background prediction should faithfully reproduce both the rate and spectrum > 2 m
- Validated the uncertainty precisely

> - It is also validated by the neutron capture distribution since only accidentals have coincidence time longer than 1.5 ms.
> - Dist. and time cuts are optimized according to the far site S/N.

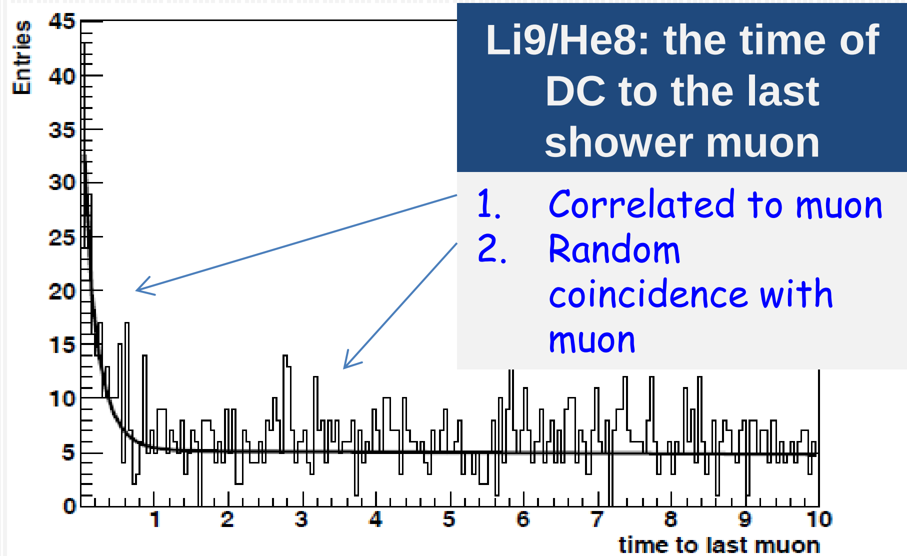
After Accidental Subtraction

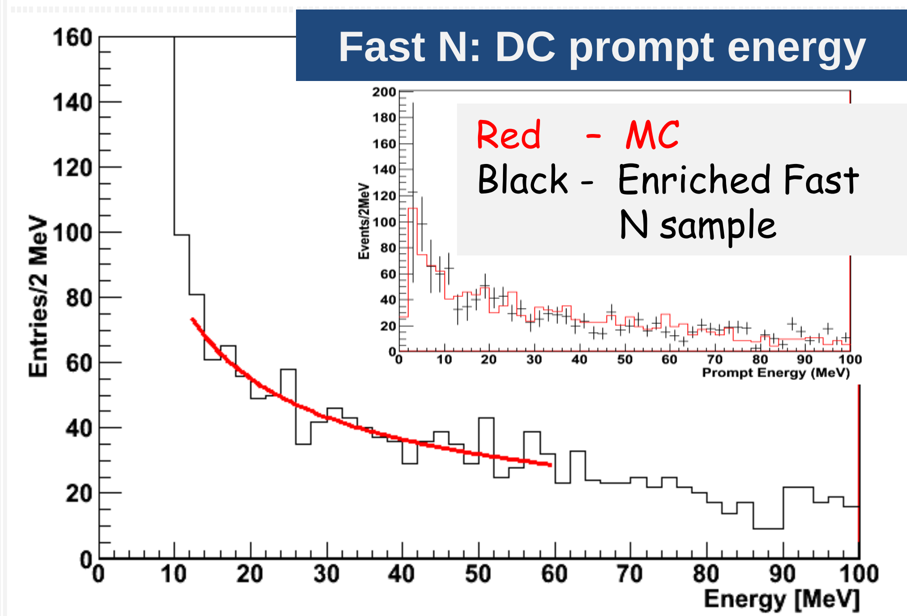


Mean and width of measured nH peaks are determined for each AD.

Correlated Backgrounds

- The Li9/He8 Bkg. is induced by cosmic-ray muons (especially shower muons). So their times can be correlated.
- Studied the prompt spectrum of fast N Bkg. beyond 12 MeV, then extrapolated to low energy. Validated by MC and enriched fast N sample.
- AmC: Studied with a strong AmC source and extrapolated to the normal calibration source intensities.





Efficiency and Identicalness

- The signals are from: GdLS, LS, and acrylic vessel

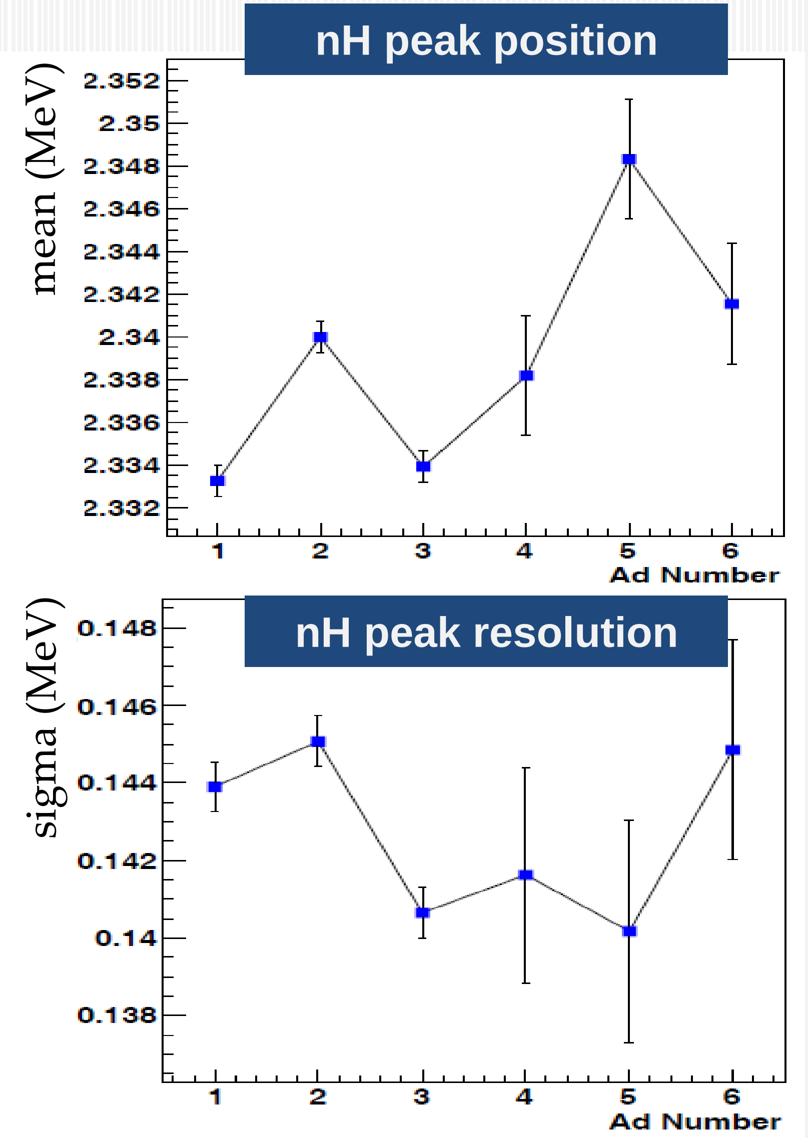
$$N = \phi\sigma\varepsilon_\mu\varepsilon_m \left[\sum_v^{\text{GdLS, LS, Acry.}} N_{p,v} f_v \varepsilon_{ep,v}\varepsilon_{ed,v}\varepsilon_{t,v} \right] \varepsilon_d$$

  - ϕ (Neutrino flux), σ (cross section): same as the previous Daya Bay paper
  - ε_m (Muon veto), ε_m (Multiplicity cut), N_p (Number of protons) and *f* (Hydrogen capture fraction): Well measured
  - ε_{ep}: Prompt energy cut efficiency
  - ε_{ed}: Delayed energy cut efficiency
  - ε_t: Time cut efficiency
  - ε_d: Distance cut efficiency

} Different systematic uncertainties than nGd

Prompt Energy

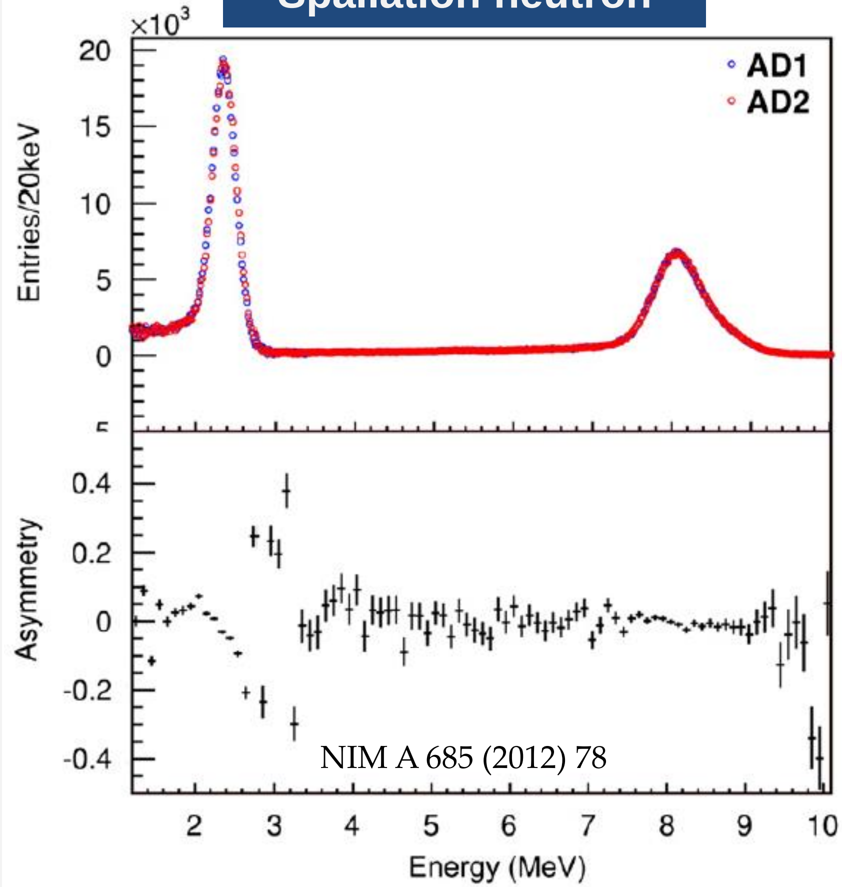
- ε_{ep} is measured with MC
- ~4% efficiency loss at 1.5 MeV
- Oscillation effect is considered
  - But with the Daya Bay baselines, the caused changes of the measured θ_{13} is minor.
- Estimated with energy scale and resolution differences at nH peaks
- <0.1% uncorrelated error



Delayed Energy

- ε_{ed}: measured with MC
  - nGd tail events considered
- Related to the 2.2 MeV γ's path length in detector
  - No correlation with energy scale
  - Weak correlation with AD-by-AD geometry differences
- Studied with spallation neutron nH/nGd ratios of nearby ADs
  - The same muon flux
  - nGd acceptances are well measured.
- 0.5% uncorrelated error

Spallation neutron



$$\text{Diff}=\frac{\frac{nH1}{nGd1}-\frac{nH2}{nGd2}}{\frac{nH1}{nGd1}+\frac{nH2}{nGd2}}=0.5\%$$

Neutron Capture Time

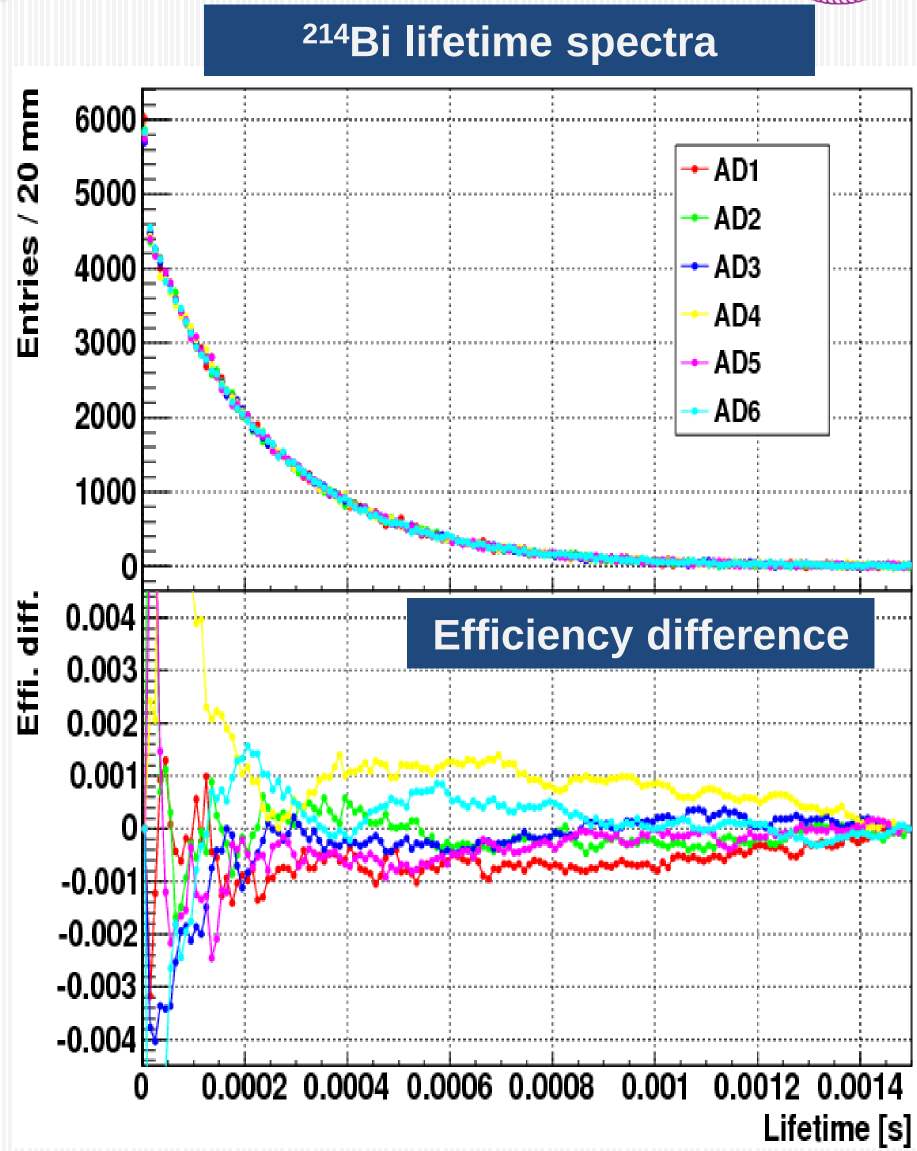
- ε_t is measured with MC
- Intrinsic uncertainty

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

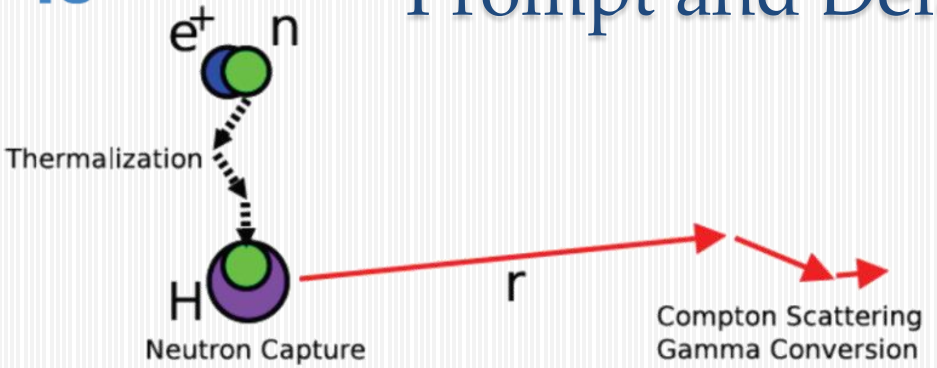
- The uncertainty induced by n_i (each isotopes' number density) is 0.1%. (Chemical measurement)
- Timing measurement is validated with ^{214}Bi

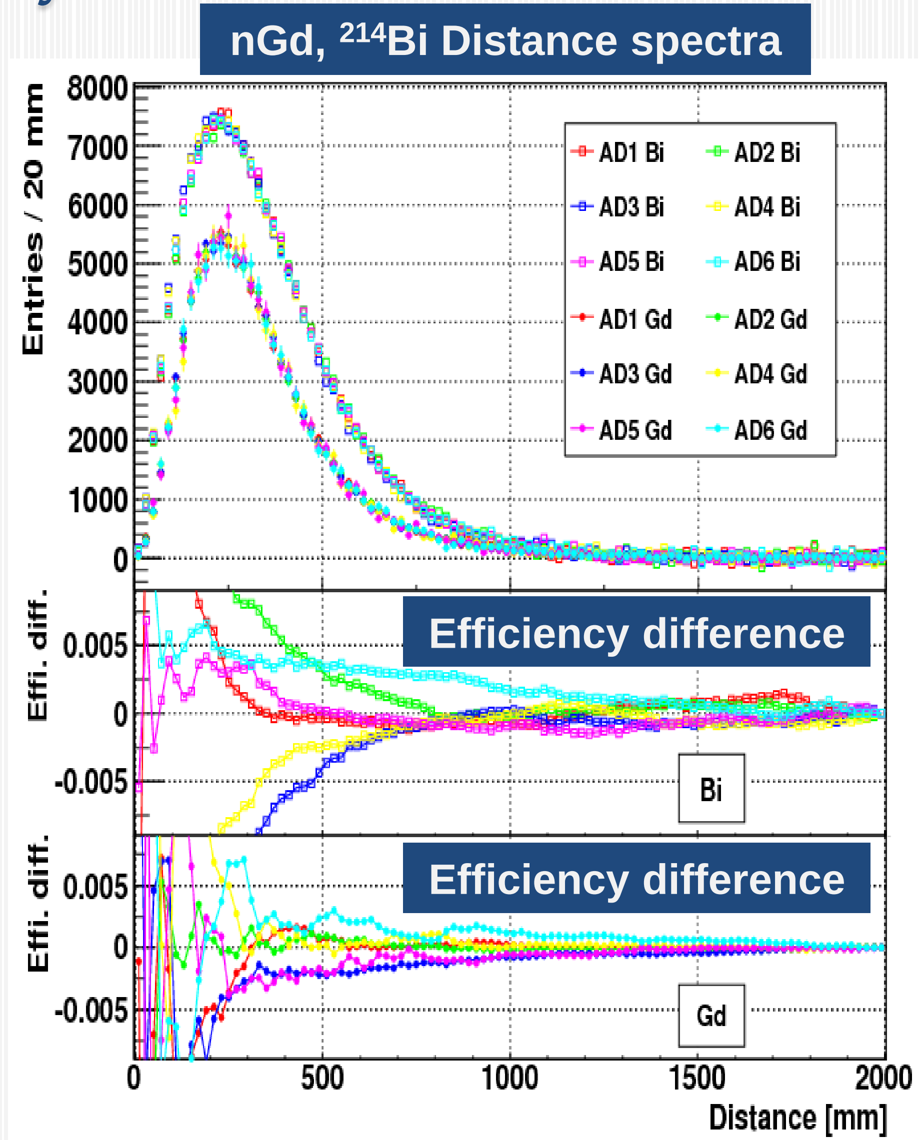
  After Acc. Bkg. subtraction time distribution can be directly observed.

- 0.14% uncorrelated error



Distance between the Prompt and Delayed Vertices





- ε_d is measured with data
  After Acc. Bkg. subtraction distance distribution can be directly observed.
- Studied the relative difference of all ADs with
  - nH sample
  - nGd sample
  - ^{214}Bi sample
- 0.4% uncorrelated error

Signal and Background Summary

- $\frac{S}{S+B} = \frac{IBD}{IBD+Bkg.}$ for the nH analysis
  - EH1: ~86%   EH2: ~86%   EH3: ~43%
- The accidental background is dominant
- Other backgrounds are minor. $\frac{Non-Acc.-Bkg.}{IBD}$
  - For all sites: ~1%
- $\frac{nH\ IBD}{nGd\ IBD}$ for the same period (nGd IBD has a better measurement, and can be used as a reference)
  - For all sites: ~0.65
  - For AD1, 2 and 3, they agree to within 0.6%, which agrees with the per-detector uncorrelated uncertainty estimation in the next slide.

Per-detector Uncorrelated Uncertainty

	v	Uncorrelated Uncertainty	Coupled
$N_{p,v}$	GdLS	0.03%	yes
	LS	0.13%	no
	Acrylic	0.50%	no
$\varepsilon_{ep,v}$	GdLS LS Acrylic	0.1%	yes
$\varepsilon_{ed,v}$	GdLS LS Acrylic	0.5%	no
$\varepsilon_{t,v}$	GdLS LS Acrylic	0.14%	yes
ε_{d}	-	0.4%	no
Combined		0.67%	

Preliminary

- Largest uncertainties
  - Delayed energy cut
  - Distance cut
- Coupling (correlation with nGd analysis)
  - Delayed energy cut: nH: Floating 3σ cut nGd: Fixed at 6 MeV
  - Distance cut: Not in use for nGd

This is the total of per-detector uncorrelated uncertainty, i.e. signal prediction uncertainty. The measured nH/nGd ratios validate this estimation.

Result and Combination

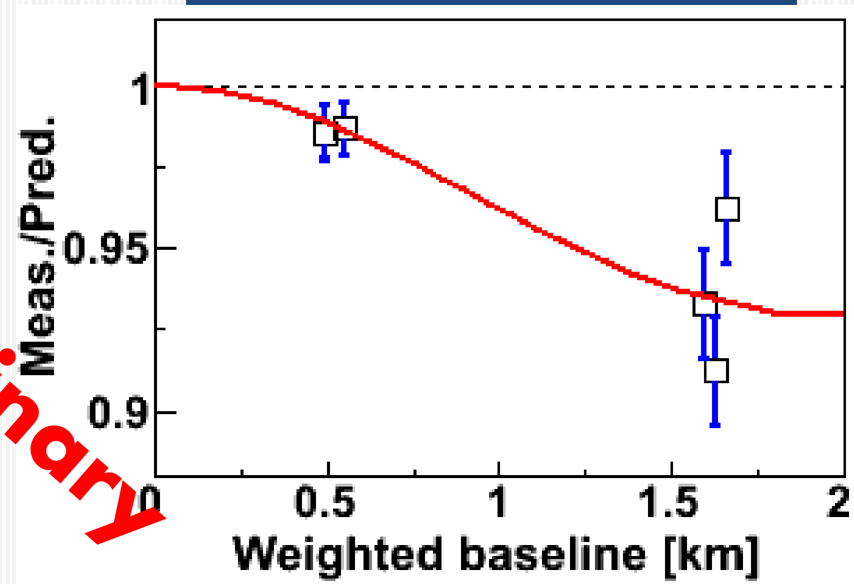
- χ^2 Fitting with pull terms
- For this nH rate study

$\sin^2 2\theta_{13} = 0.082 \pm 0.018$

with χ^2/ndf=4.6/4

  - $\Delta\chi^2 = 20$ if θ_{13} is set to 0
  - Fit with stat. error $\sin^2 2\theta_{13}$ error = 0.015
  - Fit with all uncoupled uncertainties $\sin^2 2\theta_{13}$ error = 0.017

For this nH analysis

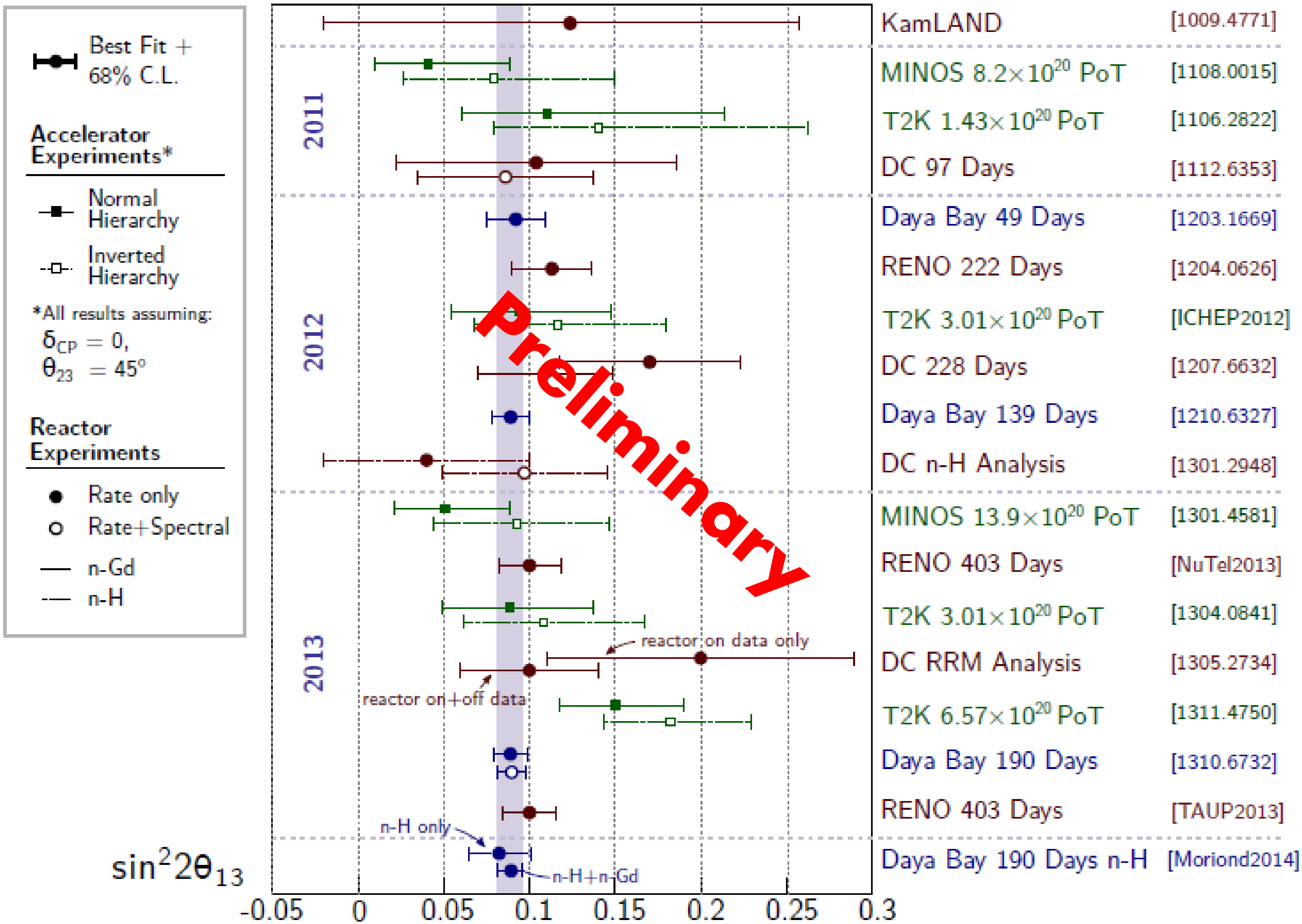


- Combined with the Daya Bay nGd rate+shape result ($\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ PRL 112, 061801)

→ $\sin^2 2\theta_{13} = 0.089^{+0.007}_{-0.008}$

A new strong independent evidence of reactor neutrino oscillation and θ_{13} measurement

Global Comparison of θ_{13} Measurement



Summary and Outlook

- **A new *independent* observation of reactor $\bar{\nu}_e$ oscillation**
- **First precise measurement *beyond* Gd capture**
- **The Daya Bay precision is *improved* slightly.**

- nH shape analysis is in progress, $|\Delta m^2_{ee}|$
- Several keys methods are invented for future IBD spectrum measurements with nH, for example, at Daya Bay or JUNO.

Thank you.