Reactor Neutrino Oscillations in Daya Bay

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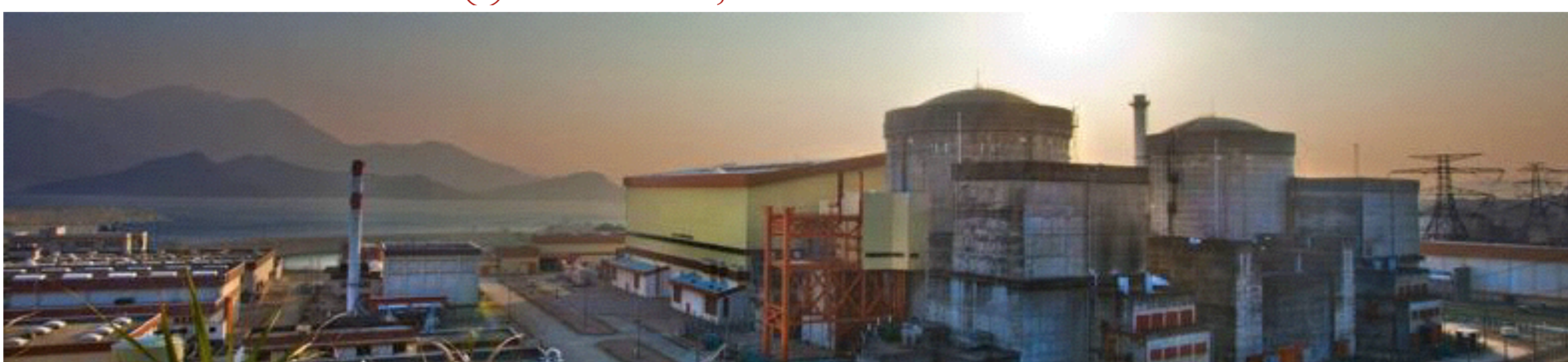
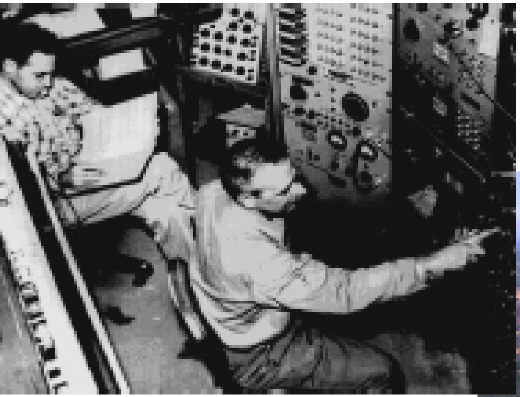
@NOW2022, Ostuni Rosa Marina



anti- Neutrino Physics at Reactors

Reines & Cowen

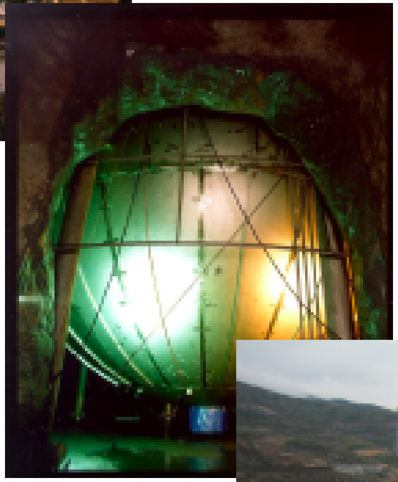


1956
First observation of neutrinos

1980s & 1990s
Reactor neutrino flux measurements in U.S. and Europe

1995
Nobel Prize to Fred Reines at UC Irvine

R. Davis



2002
Discovery of reactor antineutrino oscillation

M. Koshiba

2006 and beyond
Precision measurement of θ_{13}
Mass hierarchy, Exploring feasibility of CP violation studies

Past Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactors in Japan

Reactor antineutrino oscillation

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

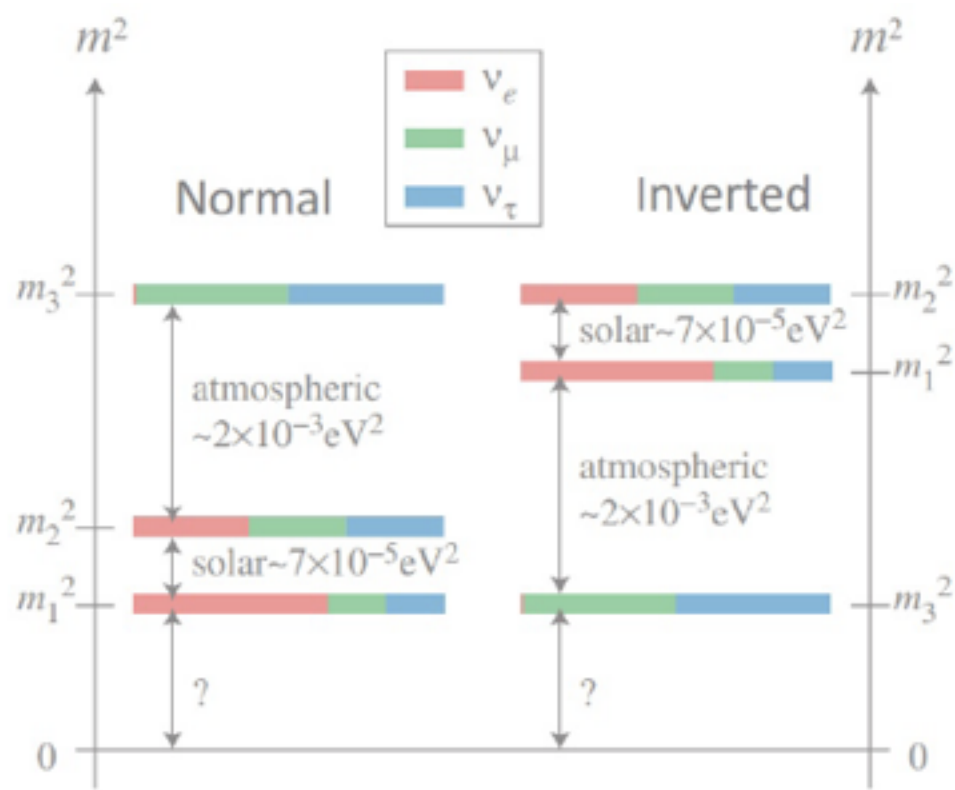
Solar / Long baseline reactor | Short baseline reactor / Long baseline accelerator | Atmospheric / Long baseline accelerator | Neutrinoless double beta decay

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} P_{\mathrm{sur}} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\ &\equiv 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}\sin^2\Delta_{ee} \qquad \Delta_{ji} \equiv \Delta m^2_{ji}L/4E \end{aligned}$$

$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$

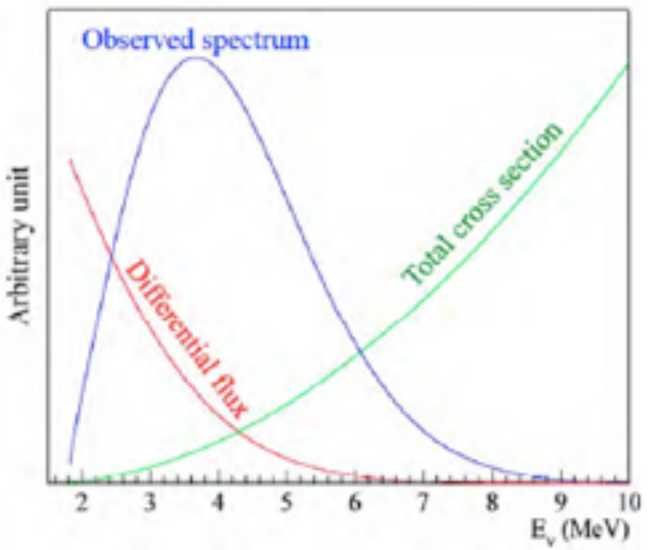
$$|\Delta m^2_{31}| \simeq \Delta m^2_{ee} \pm 2.3\times10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{32}| \simeq \Delta m^2_{ee} \mp 5.2\times10^{-5}\ \mathrm{eV}^2$$

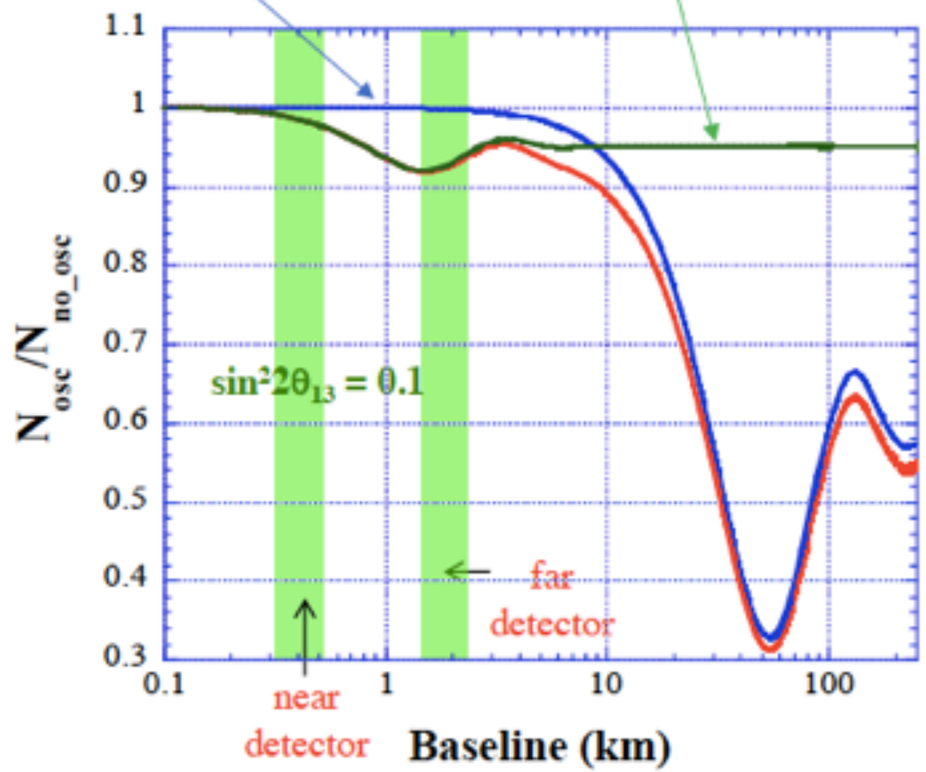


Measuring θ_{13} with Reactor $\bar{\nu}_e$

- Survival probability:

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





- Reduce systematic issues by performing relative measurement with Far/Near ratio

Detectors

- Detect inverse β-decay reaction (IBD):

prompt delayed

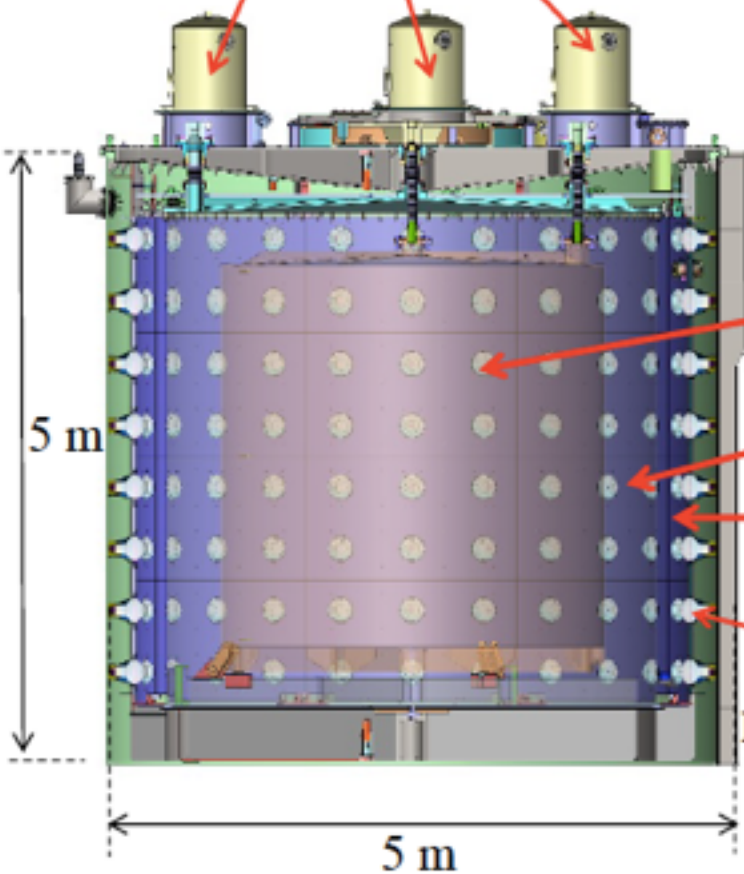
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(nH) ~180 μs $\rightarrow + p \rightarrow d + \gamma$ (2.2 MeV)

(nGd) ~30 μs for 0.1% Gd $\rightarrow + Gd \rightarrow Gd^*$

$\rightarrow Gd + \gamma$'s (~8 MeV)

Automated Calibration units
(LED, ^{68}Ge, AmC-Co)



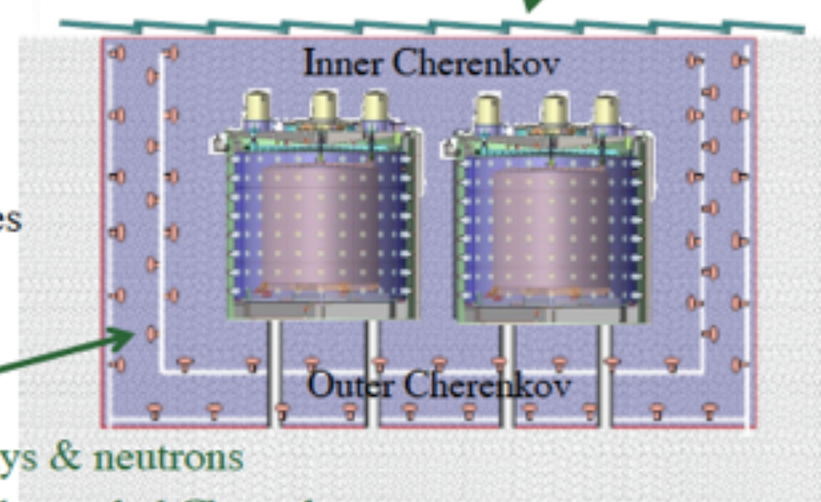
IAV: 20-t 0.1% Gd-loaded liquid scintillator (target)

OAV: 22-t LS (gamma catcher)
(LS = LAB + 3 g/l PPO + 15 mg/l Bis-MSB)

40-t mineral oil shield

192 Photomultiplier tubes (PMTs)

Four layers of RPC's to tag muons



2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

NIM A**773** (2015) 8
NIM A**811** (2016) 133

Detecting antineutrinos

Antineutrinos are detected via
inverse β decay (IBD):

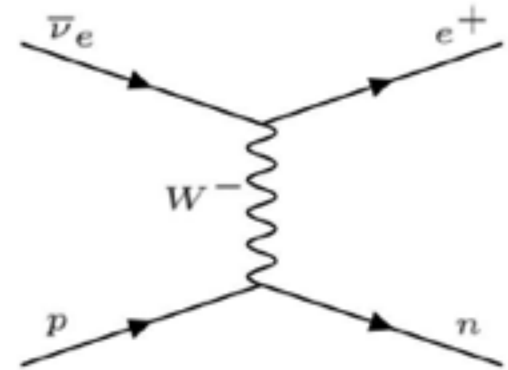
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

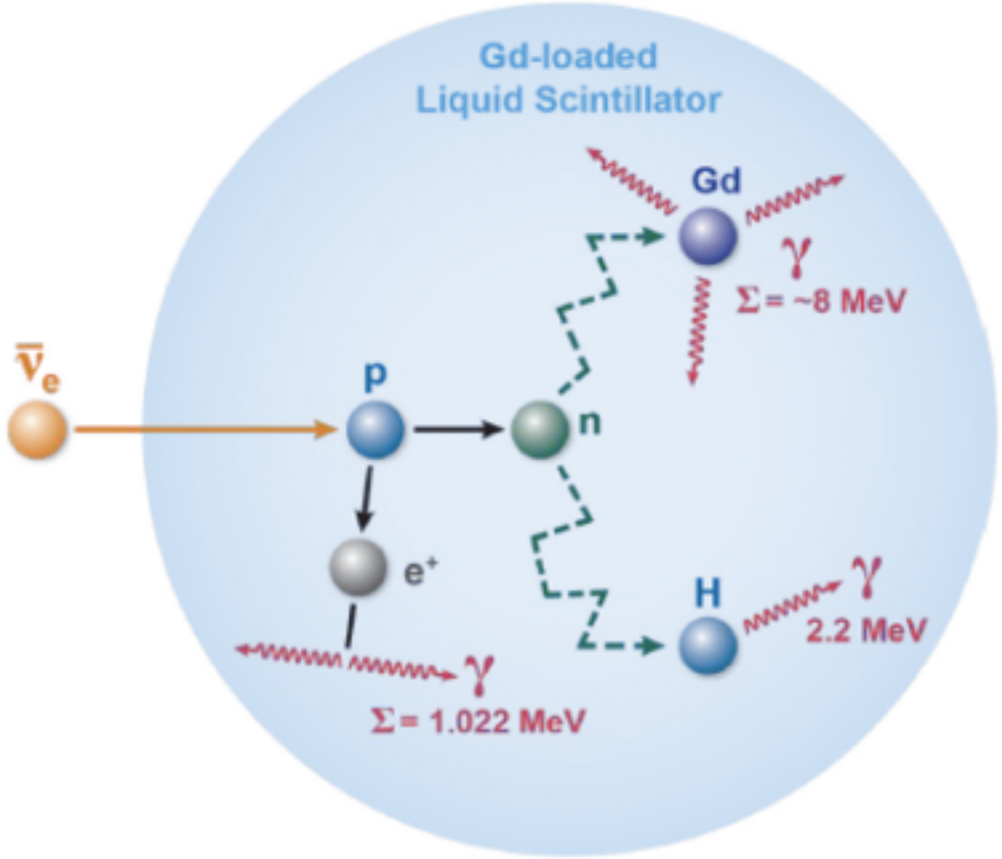
After an average of 28 μs, the neutron is captured on Gd, resulting in ~8 MeV of deexcitation gamma-rays. The coincident pulses provide a clean experimental signature, where

$$E_\nu \approx K_{e+} + 1.8 \text{ MeV}.$$

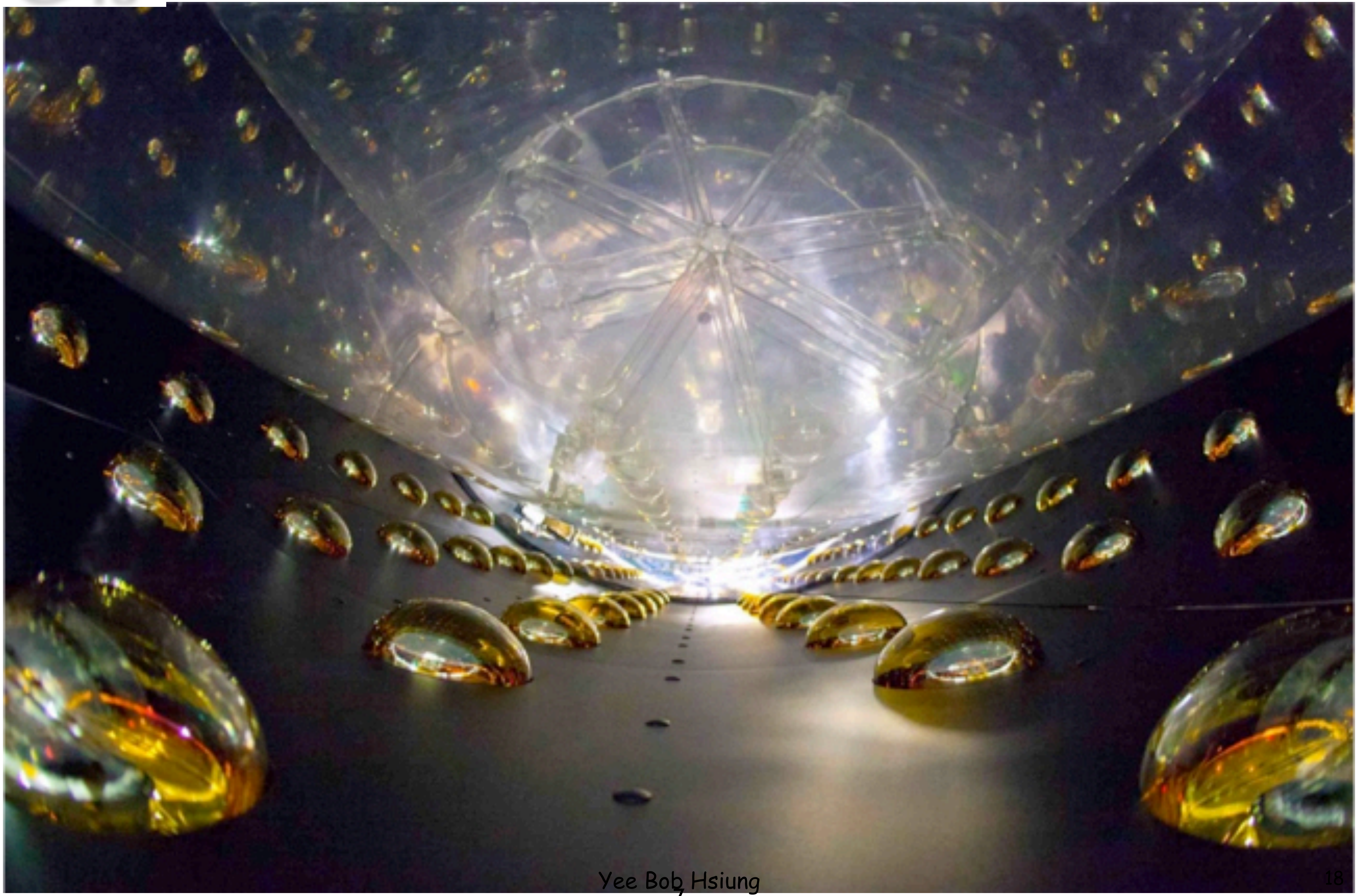
In terms of reconstructed ("prompt") energy (including annihilation γ's),

$$\mathbf{E_\nu \approx E_{prompt} + 0.8\ MeV}$$





Interior of Antineutrino Detector

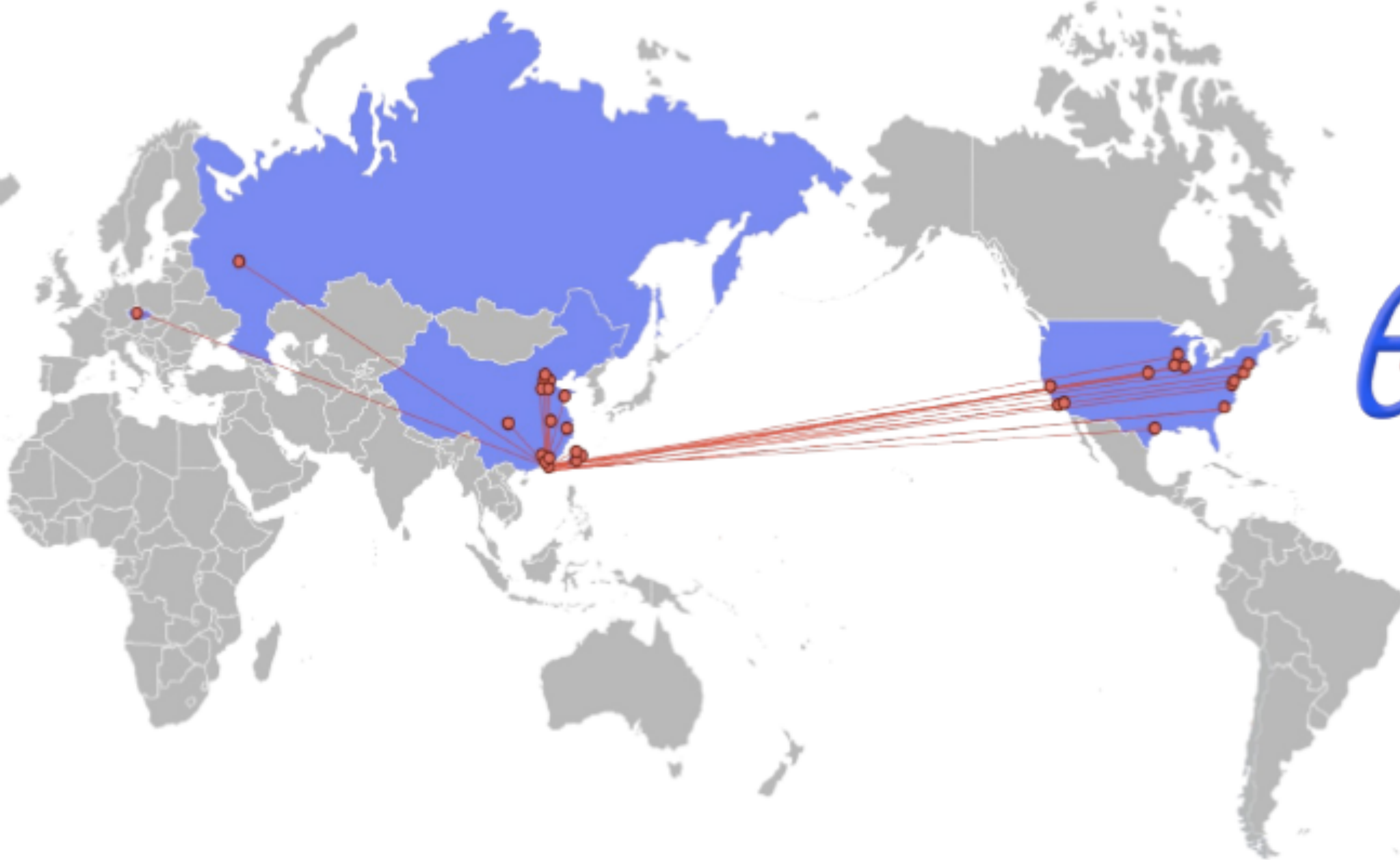


3m IAVs produced in Taiwan (2006 - 2012)

- All 3m inner acrylic vessels are produced in Taiwan
- 10mm thick wall, 15mm top /bottom covers
- Completely sealed with two penetration ports for Gd-LS filling and calibations.
- UV transparent down to 300nm wavelength

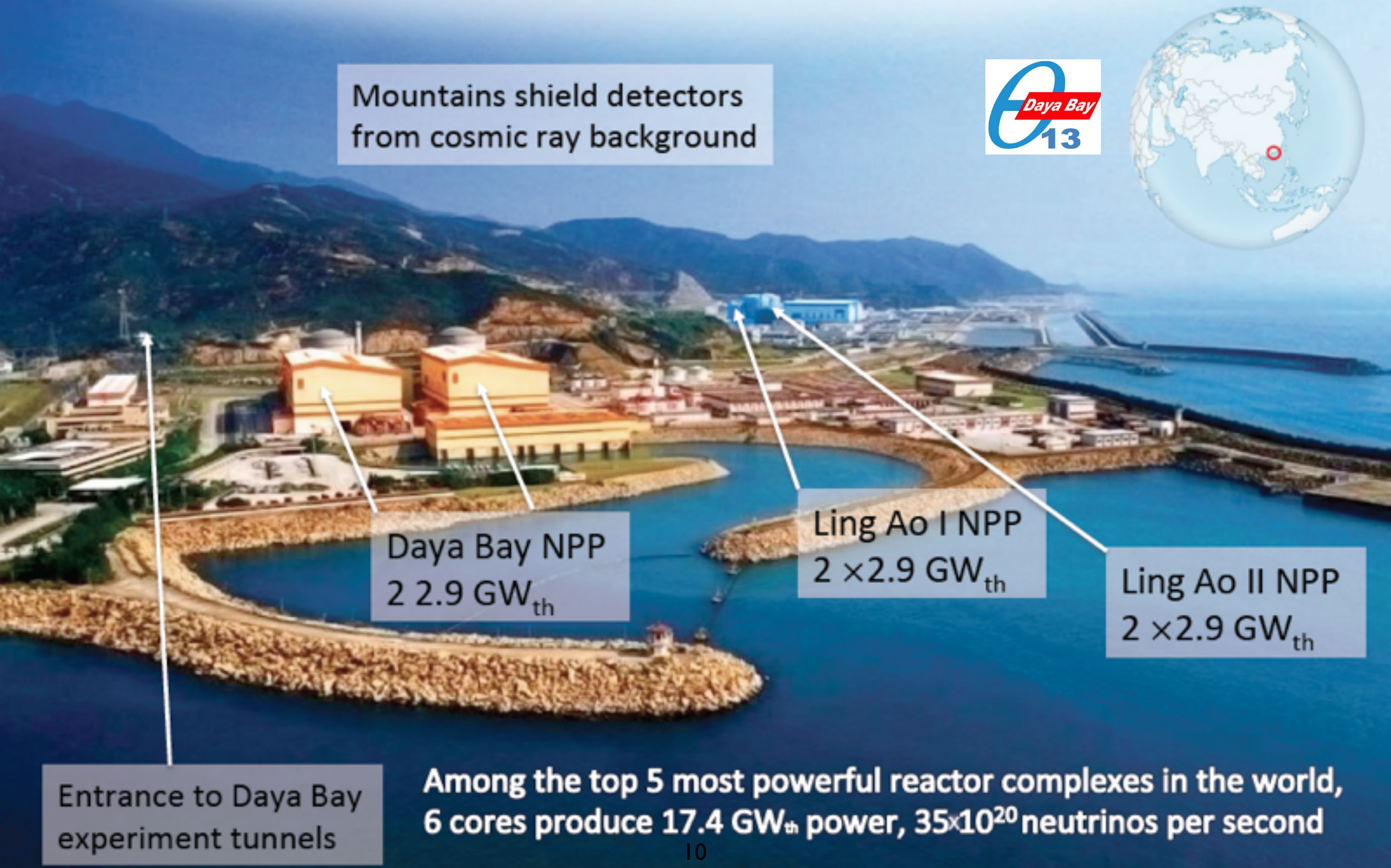
NTU, NYCU and NUU
from Taiwan

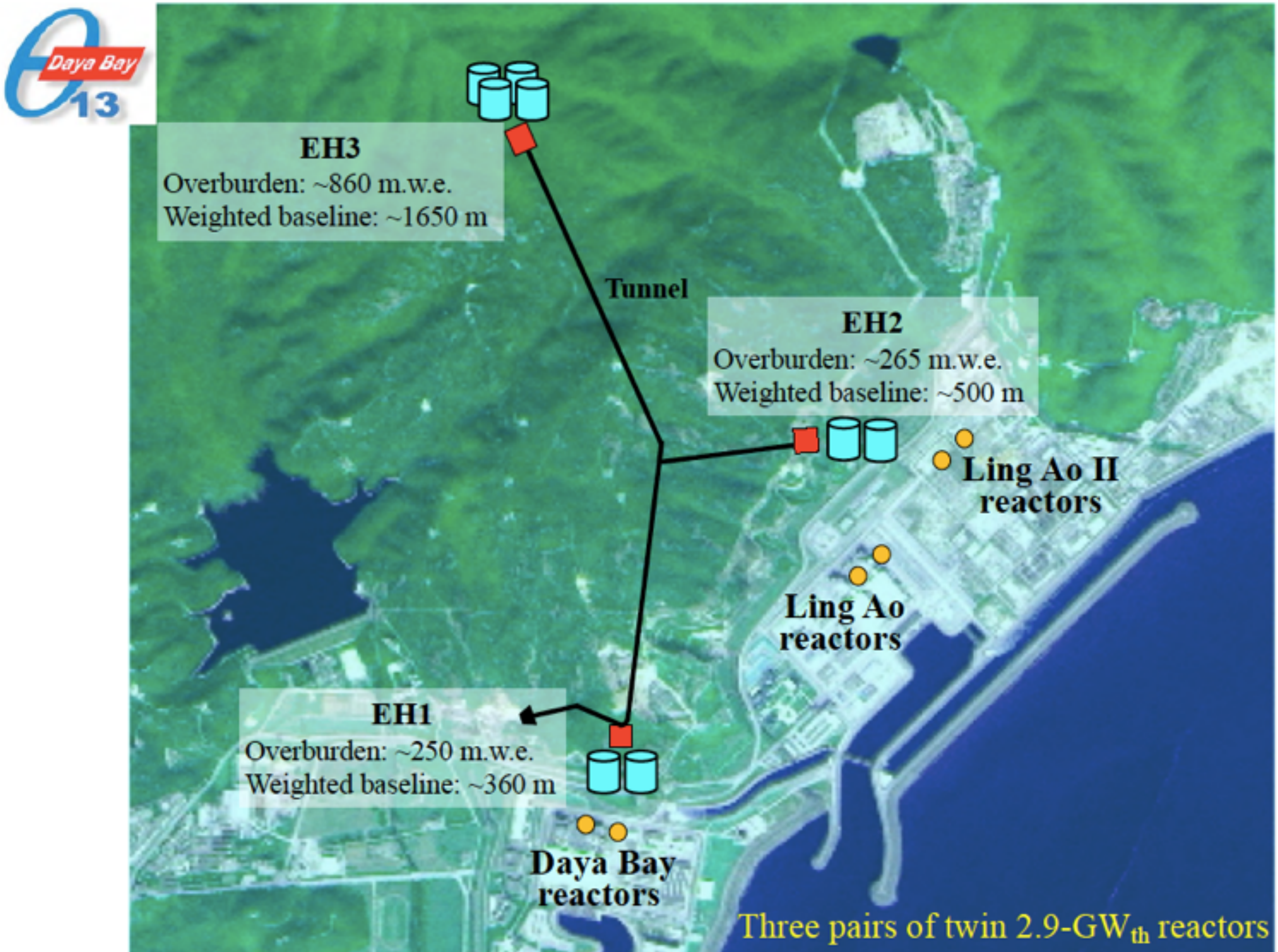
Daya Bay Collaboration



3 continents, ~200 collaborators, ~40 institutions

A Powerful Neutrino Source at an Ideal Location




Daya Bay
13
EH3
Overburden: ~860 m.w.e.
Weighted baseline: ~1650 m
Tunnel
EH2
Overburden: ~265 m.w.e.
Weighted baseline: ~500 m
Ling Ao II reactors
Ling Ao reactors
EH1
Overburden: ~250 m.w.e.
Weighted baseline: ~360 m
Daya Bay reactors
Three pairs of twin 2.9-GW$_{th}$ reactors

Keys to a precise measurement of θ_{13}

1) **Baseline Optimization**

2) **High statistics**: powerful nuclear reactors, big detectors, long run-time

3) **Reduction of systematic errors**:

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{P_{Far}(L_{Far})}{P_{Near}(L_{Near})}\right)$$

antineutrino flux — $1/r^2$ — number of protons — detection efficiency — yield $\sin^2 2\theta_{13}$

(i) **Detector-related**: identically designed detectors, calibration

(ii) **Reactor-related**: relative near-far measurements ← largest uncertainty in previous measurements

4) **Background reduction**: use of water shield and veto

All of these features make Daya Bay a powerful experiment that can measure θ_{13} very precisely but also make a strong impact in other areas

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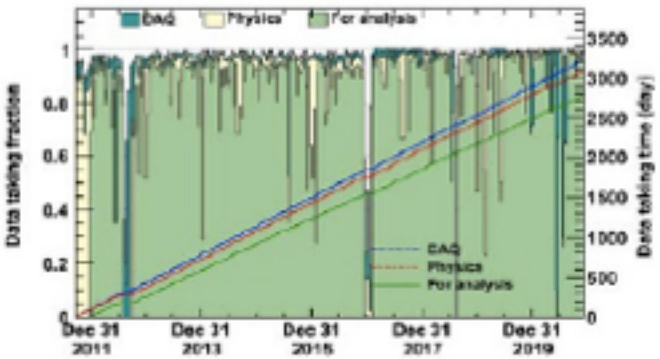
Brief History of Onsite Operation

- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021

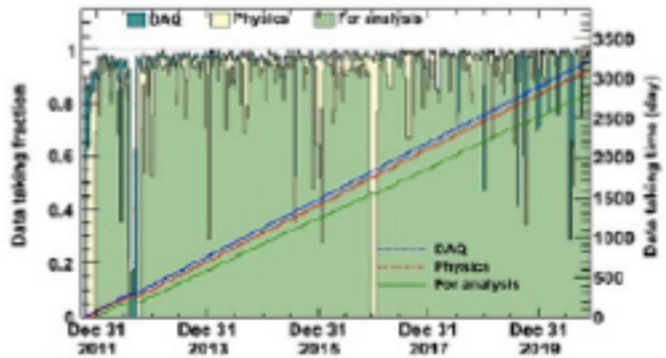
Paper in progress

Full dataset!

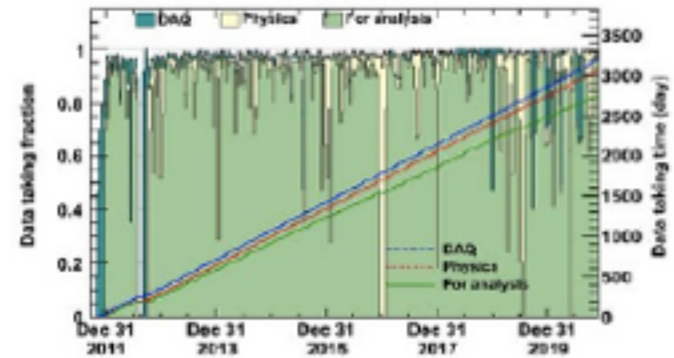
EH1



EH2



EH3



Configuration	EH1	EH2	EH3	Start date — end date	Duration (days)
6-AD	2	1	3	24 Dec 2011 — 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 — 21 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 — 12 Dec 2020	1417
Total					3158

~2700 days of data in "good run list"; ~5.5 million antineutrinos

Oscillation Parameters: Improvements

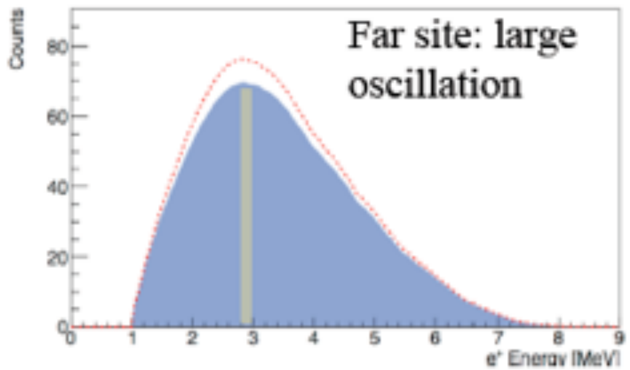
- Statistics of nGd data:

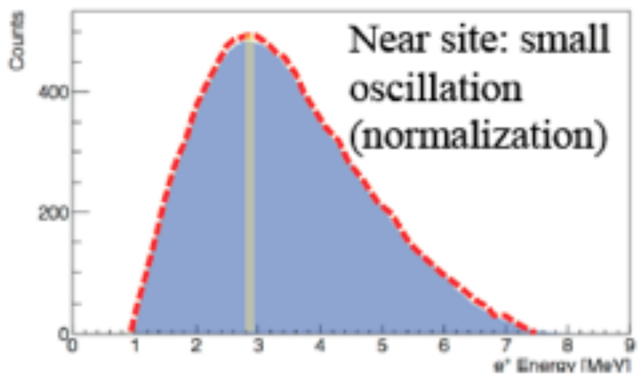
Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022	3158	2,236,810	2,544,894	764,414	5,546,118

- Analysis:
  - Energy calibration
    - Electronics non-linearity calibrated at the channel-by-channel level
    - Improved non-uniformity correction
  - New correlated background after 2017
    - Remove additional very rare PMT flashers
    - Suppress and identify untagged muon events
  - Correlated background
    - New approach for determining the ^{9}Li/^{8}He background

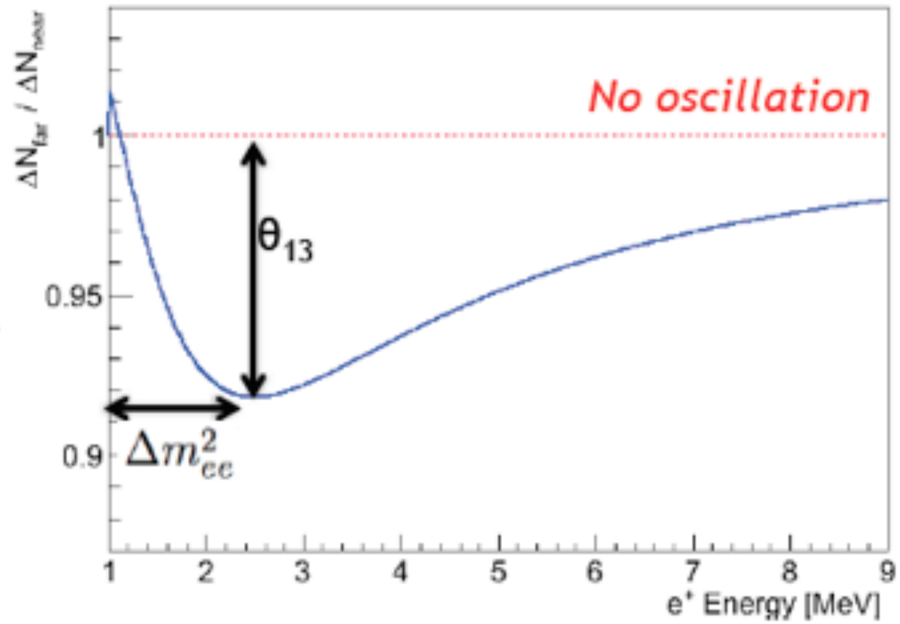
Spectral Measurement

- A spectral measurement allows to measure both θ_{13} and the mass splitting:





Compare each energy



But require good understanding of the detectors' energy response!

- Which mass splitting do we measure? Define an effective mass splitting Δm^2_{ee}:

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

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

so that: $|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.17 \times 10^{-5}\mathrm{eV}^2$ +: Normal Hierarchy –: Inverted Hierarchy

Non-linear Energy Response

Due to nature of liquid scintillator (LS) and charge measurement of electronics

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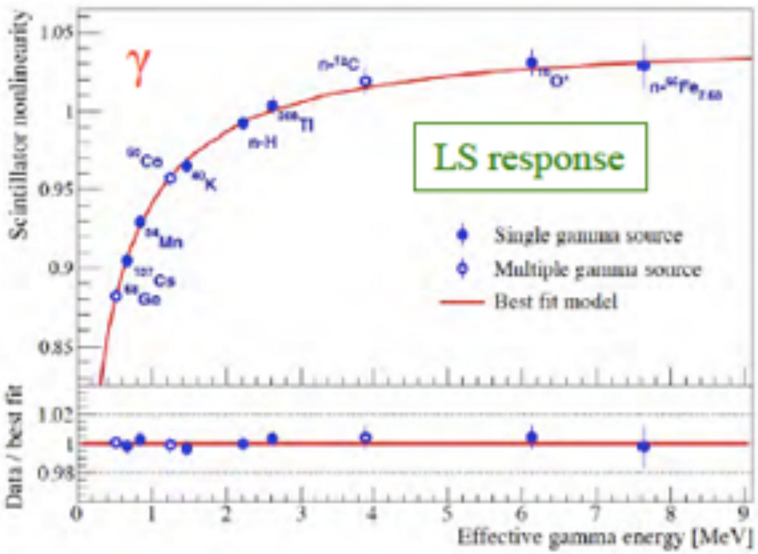
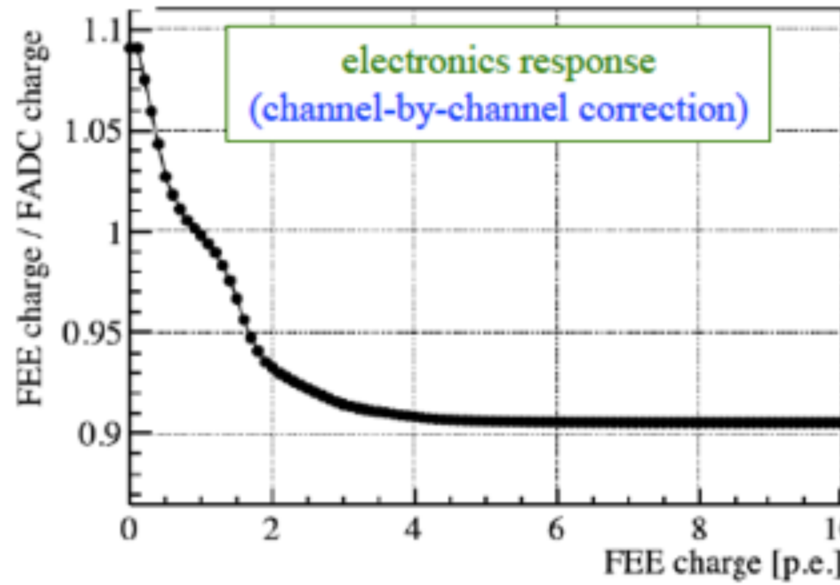
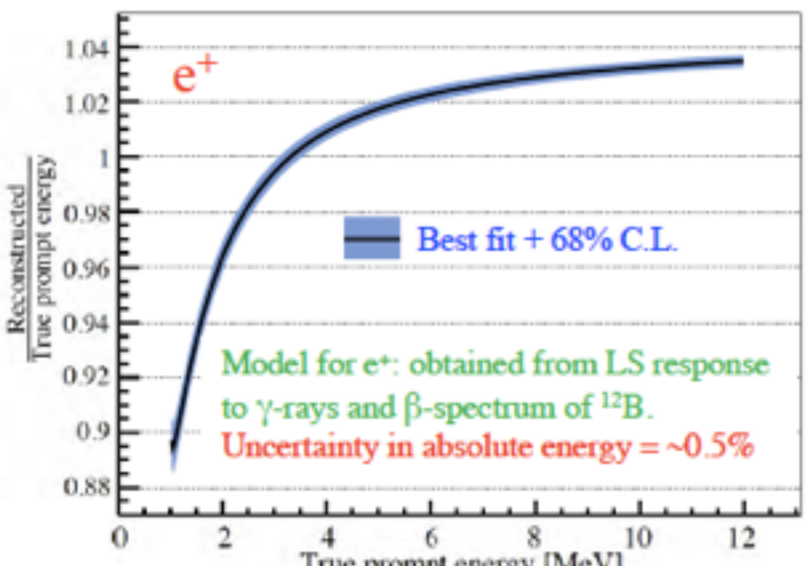
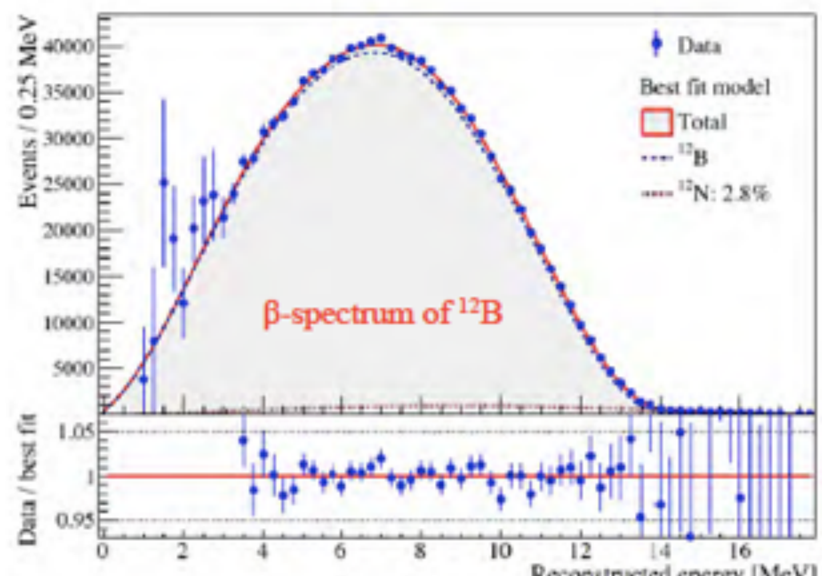




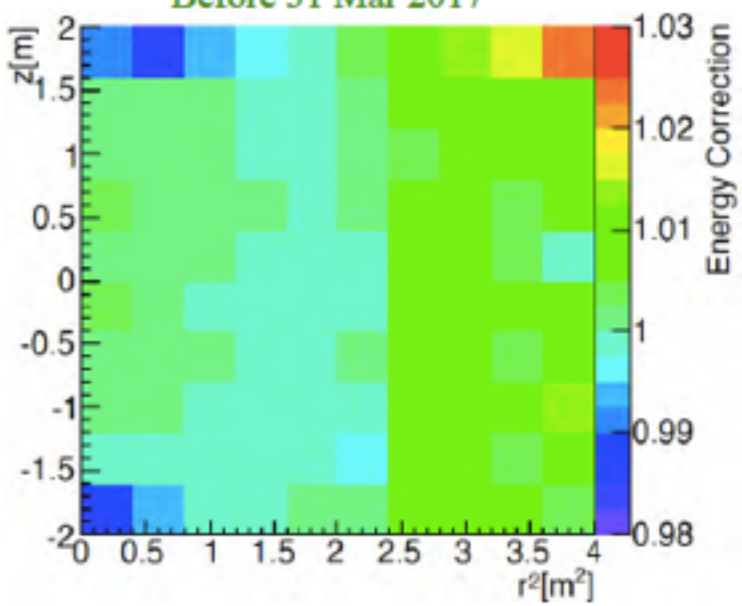




Improved Non-uniformity of Energy Scale

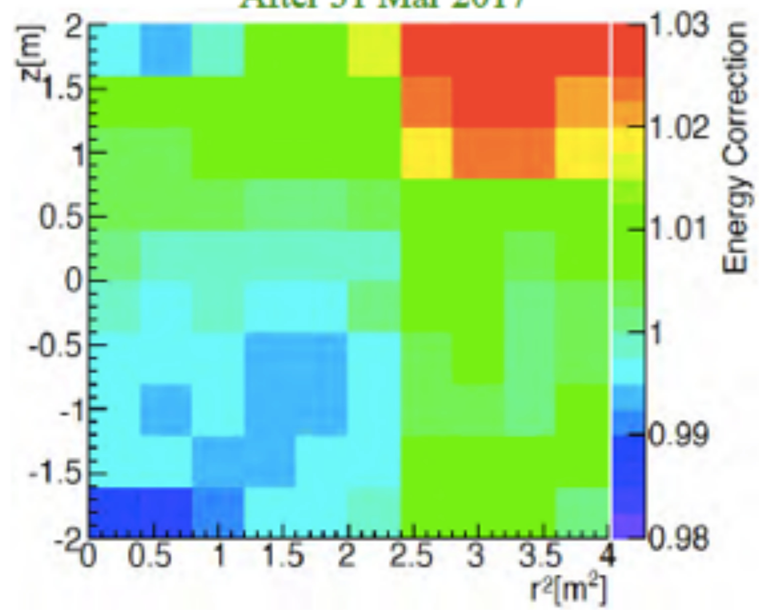
- Additional non-uniformity on top of already-corrected geometric non-uniformity
  - Residual effect of the Earth magnetic field
  - Dead PMTs or high-voltage supply channels
- Corrections
  - Use γ's from spallation-neutron capture on Gd and α's from natural radioactive isotopes
  - Time dependent, referencing to the γ's from spallation-neutron capture

Before 31 Mar 2017



Example: EH2 AD2

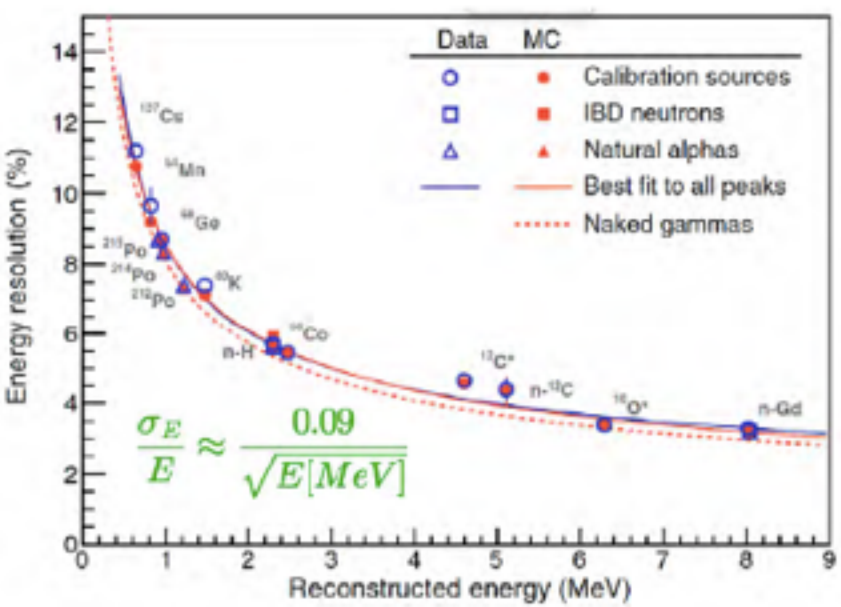
After 31 Mar 2017

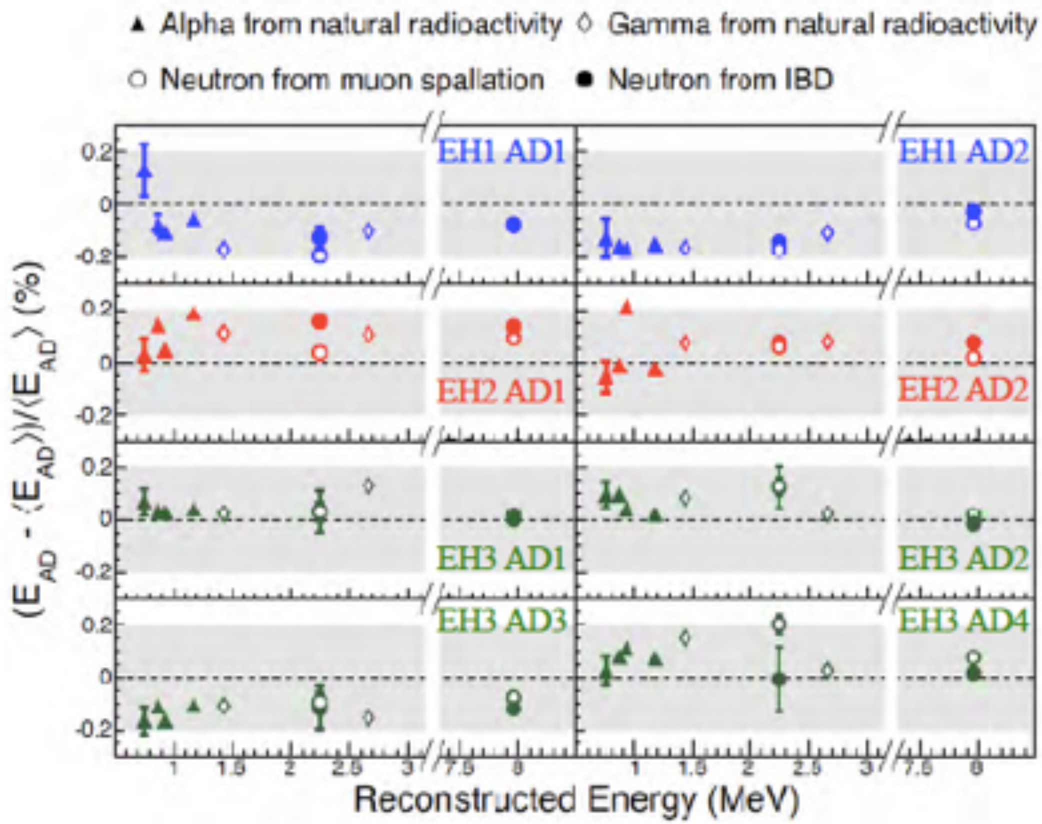


- The largest additional correction is about 3%

Energy Scale

- Gain of photomultiplier tubes
  - Single-photoelectron dark noise
  - Weekly LED monitoring
- Energy calibration
  - Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
  - Spallation neutrons
  - Natural radioactivity





Relative uncertainty in energy scale: ~0.2%

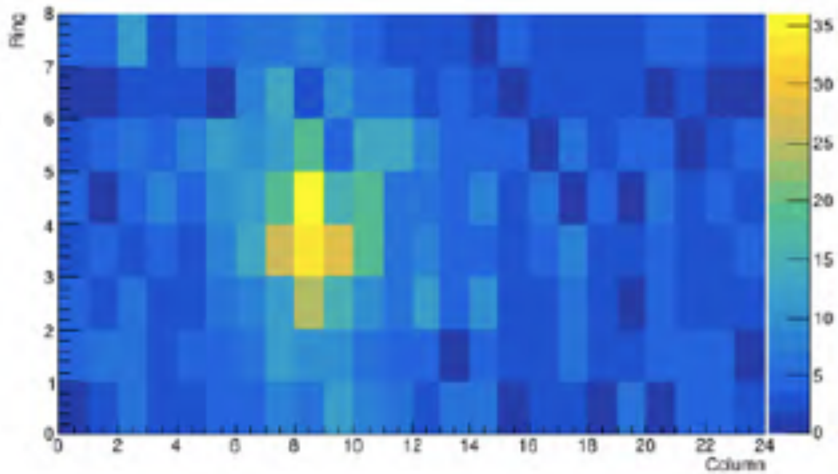
Background

- Uncorrelated background
  - Accidental
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the AD
  - $^{9}Li/^{8}He$
    - spallation product produced by cosmic-ray muons inside the AD
  - ^{241}Am-^{13}C
    - neutron calibration source resides inside the ACU
  - $^{13}C(\alpha,n)^{16}O$
    - α from decay of natural radioactive isotope in the liquid scintillator
  - Residual PMT flasher
  - Muon-x

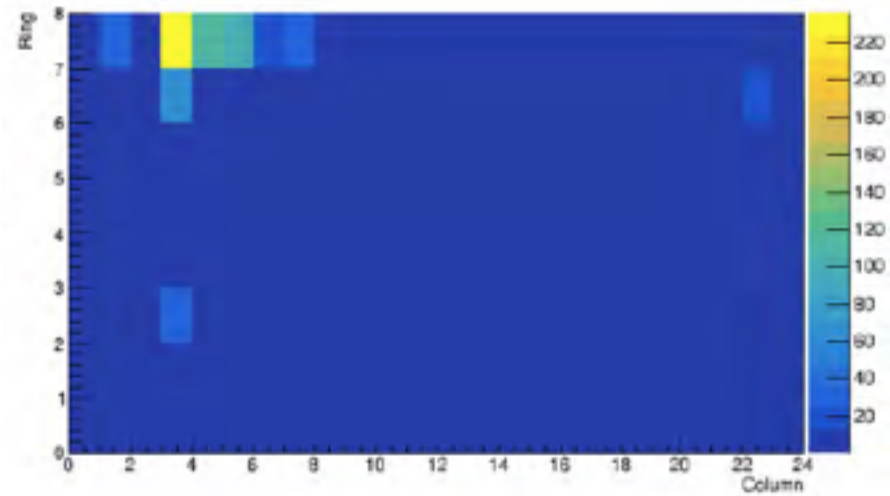
} new background

Residual PMT Flashers

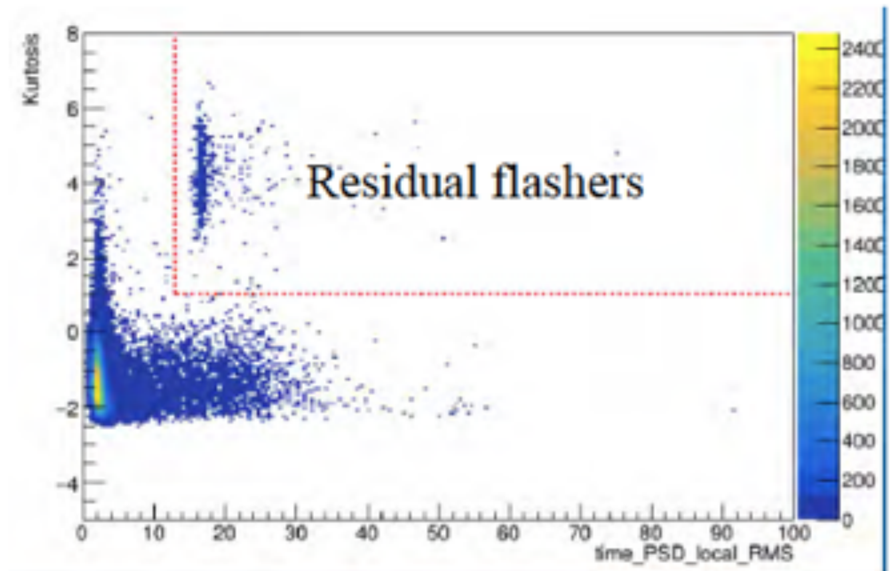
A typical singles event



A residual flasher event

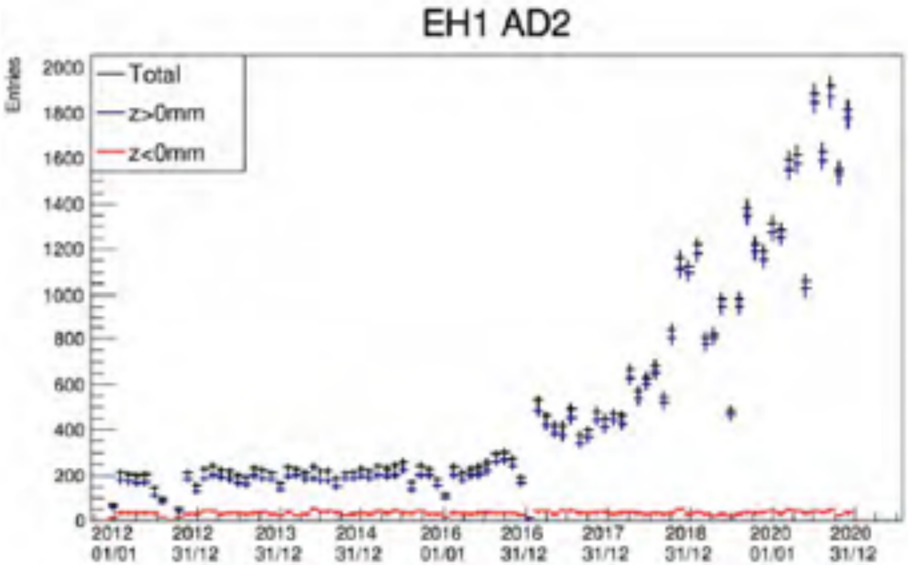


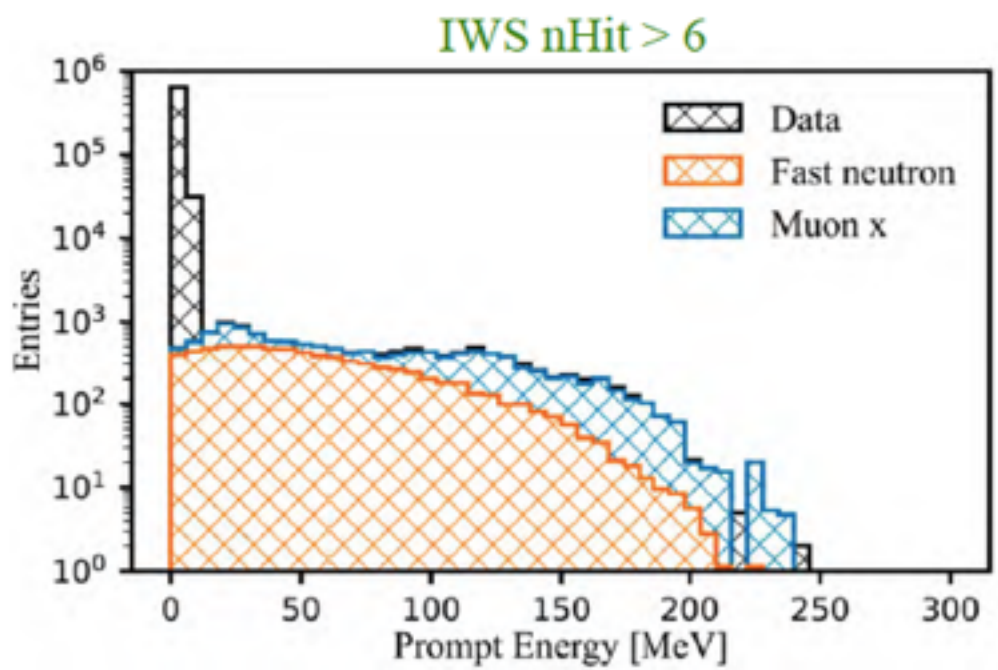
- Located near the top of some ADs
- Removed by cutting on Kurtosis and time_PSD_local_RMS
- After rejecting residual flashers,
  - Contamination in the IBD sample is negligible
  - Retain 99.997% of the IBD candidates



Muon-x Background

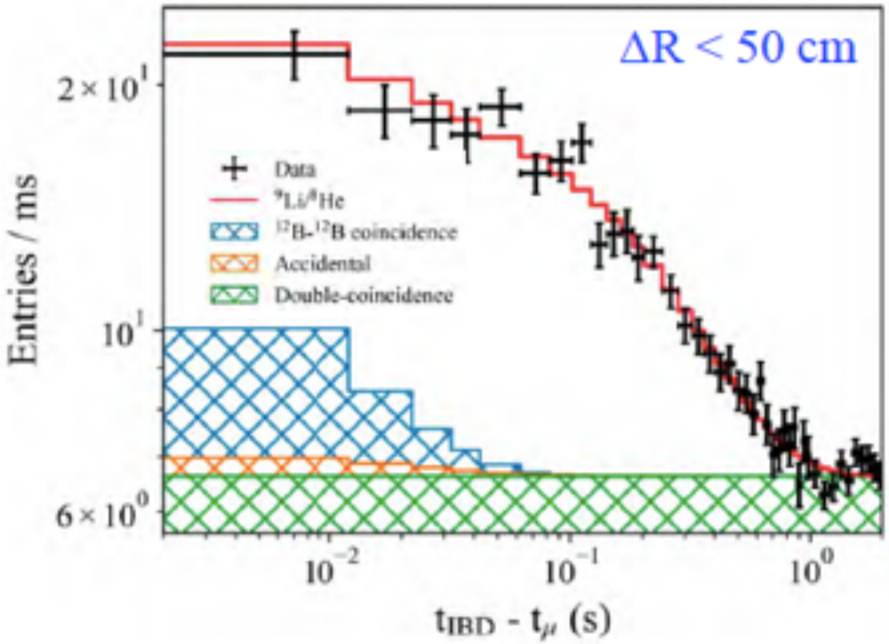
- Gradual failure of PMTs or high-voltage channels in the inner water Cherenkov counter (IWS) in the water pool since January 2017
  - Reduction in muon detection efficiency
  - Muon decays and additional spallation (muon x) in the top half of some ADs
- Lower the hit multiplicity of PMTs (nHit) in IWS from 12 to 7 to tag muons
  - Reject about 80% of muon decays
  - Extend cut on E_{prompt} from 12 MeV to 250 MeV to determine the rate and spectrum for fast neutron and muon x

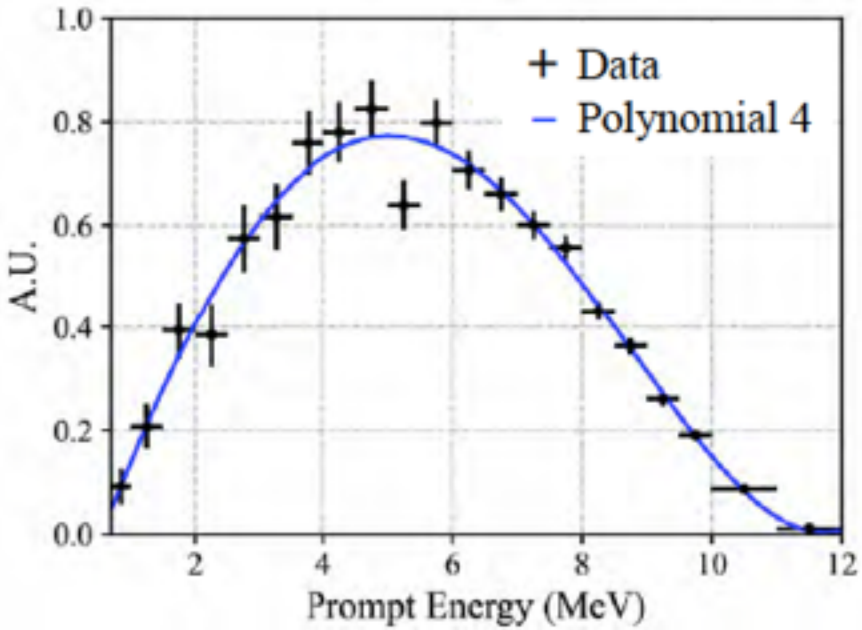




$^{9}Li/^{8}He$ Background

- $^{9}Li/^{8}He$
  - β-n decay
  - τ_{Li} = 257.2 ms τ_{He} = 171.7 ms
- Perform a multi-dimensional fit using
  - Time interval after the preceding muon ($t_{IBD} - t_{\mu}$)
  - Prompt energy (E_{prompt})
  - Distance between the prompt and delayed signals (ΔR)
  - Low-energy (E_{vis} < 2 GeV) and high-energy (E_{vis} > 2 GeV) muon samples from all three halls simultaneously

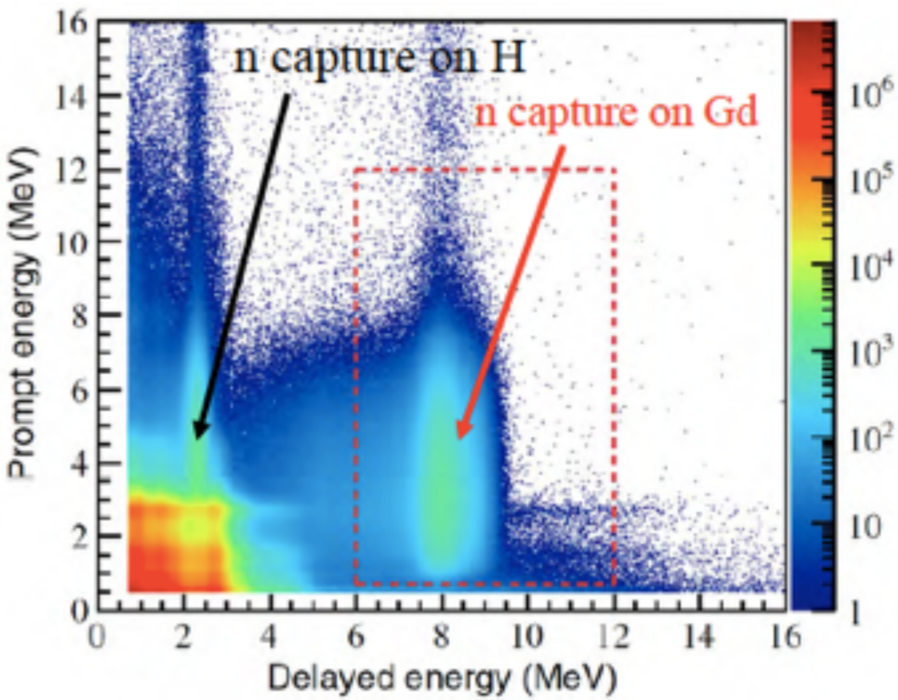




Selection of $\overline{\nu}_e$ Candidates

PRD95 (2017) 072006

- Remove flashing PMT events
- Veto muon events
- Require 0.7 MeV < E_{prompt} < 12 MeV, 6 MeV < $E_{delayed}$ < 12 MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity cut: select time-isolated energy pairs



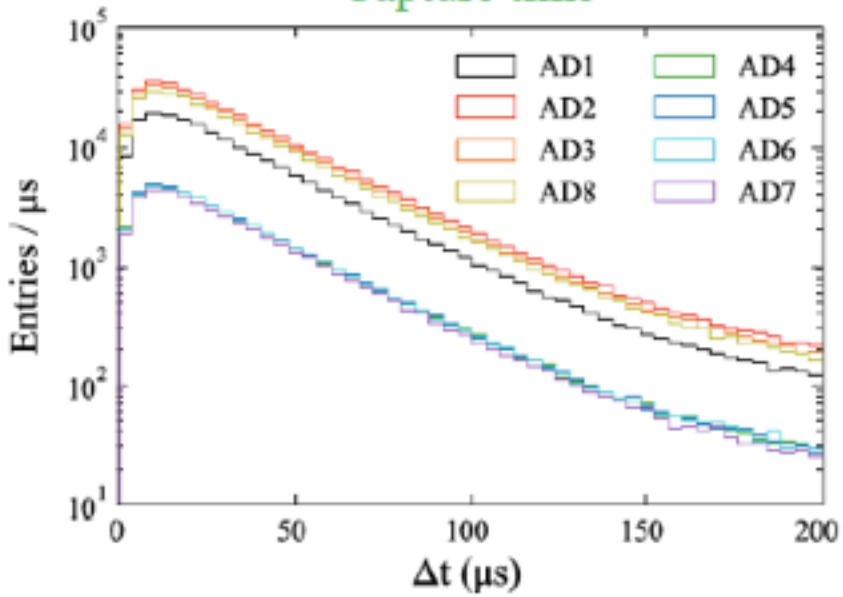
Detection efficiencies

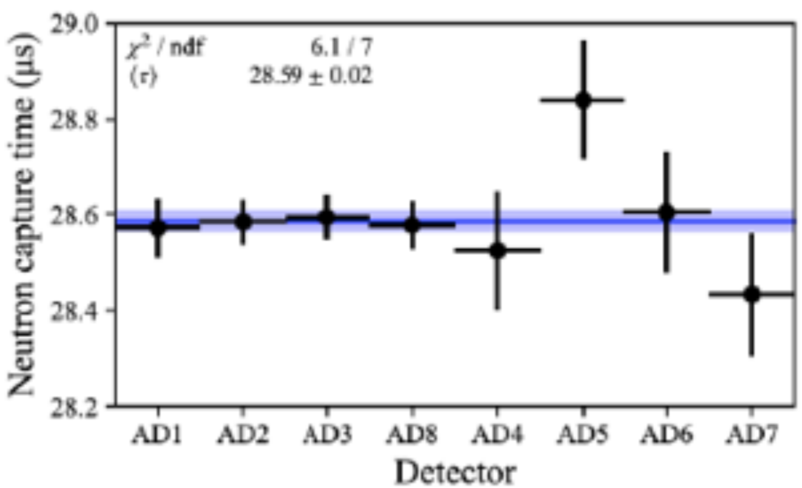
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

Performance of Antineutrino Detectors

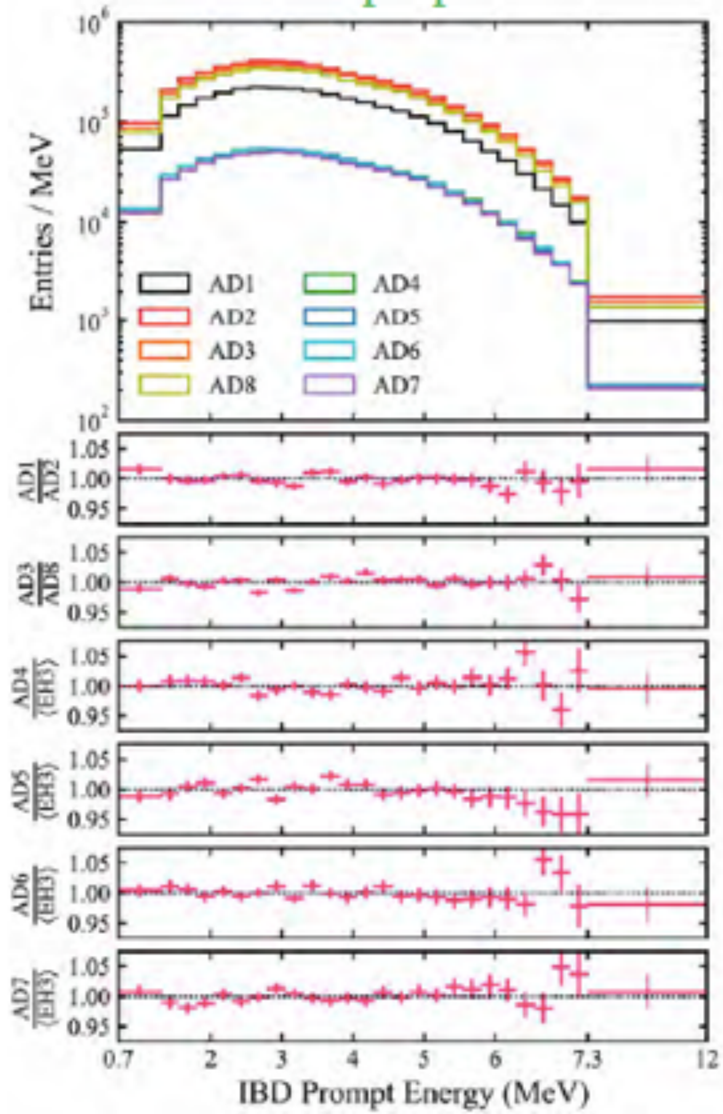
IBD candidates including background (< 3%)

Capture time





Prompt spectrum

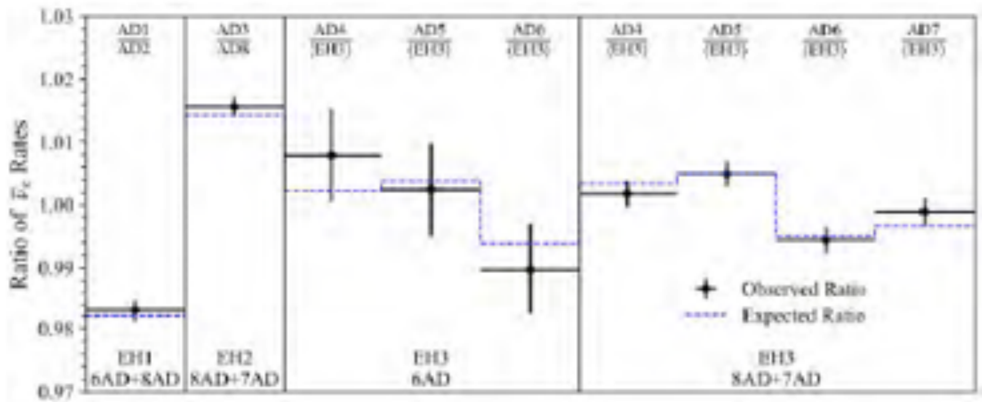


Antineutrino detectors in the same hall have similar performance

IBD Rate

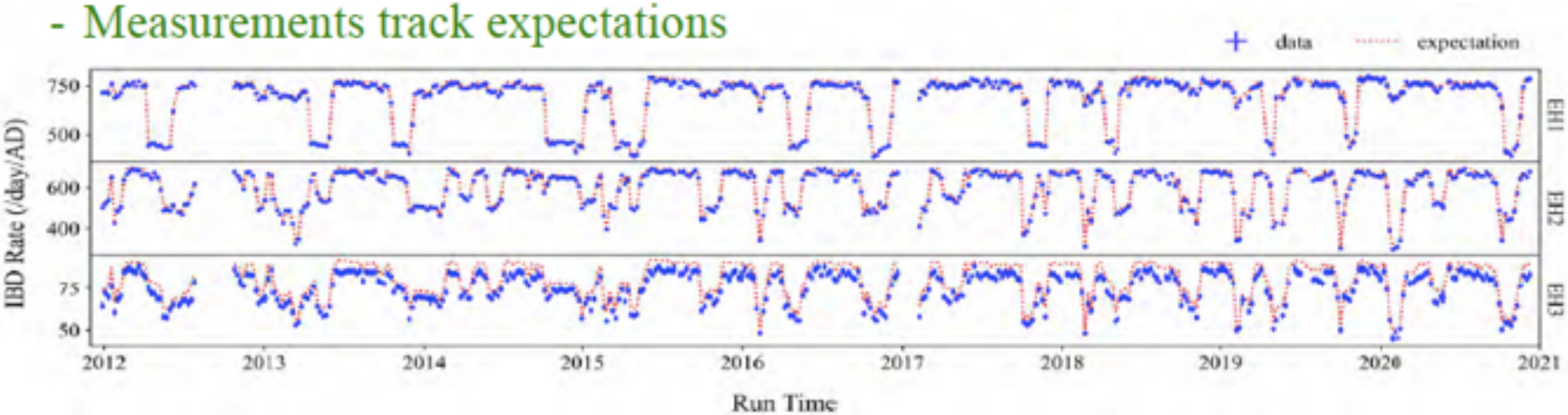
Background-subtracted

- Side-by-side comparison
  - Measurements consistent with predictions

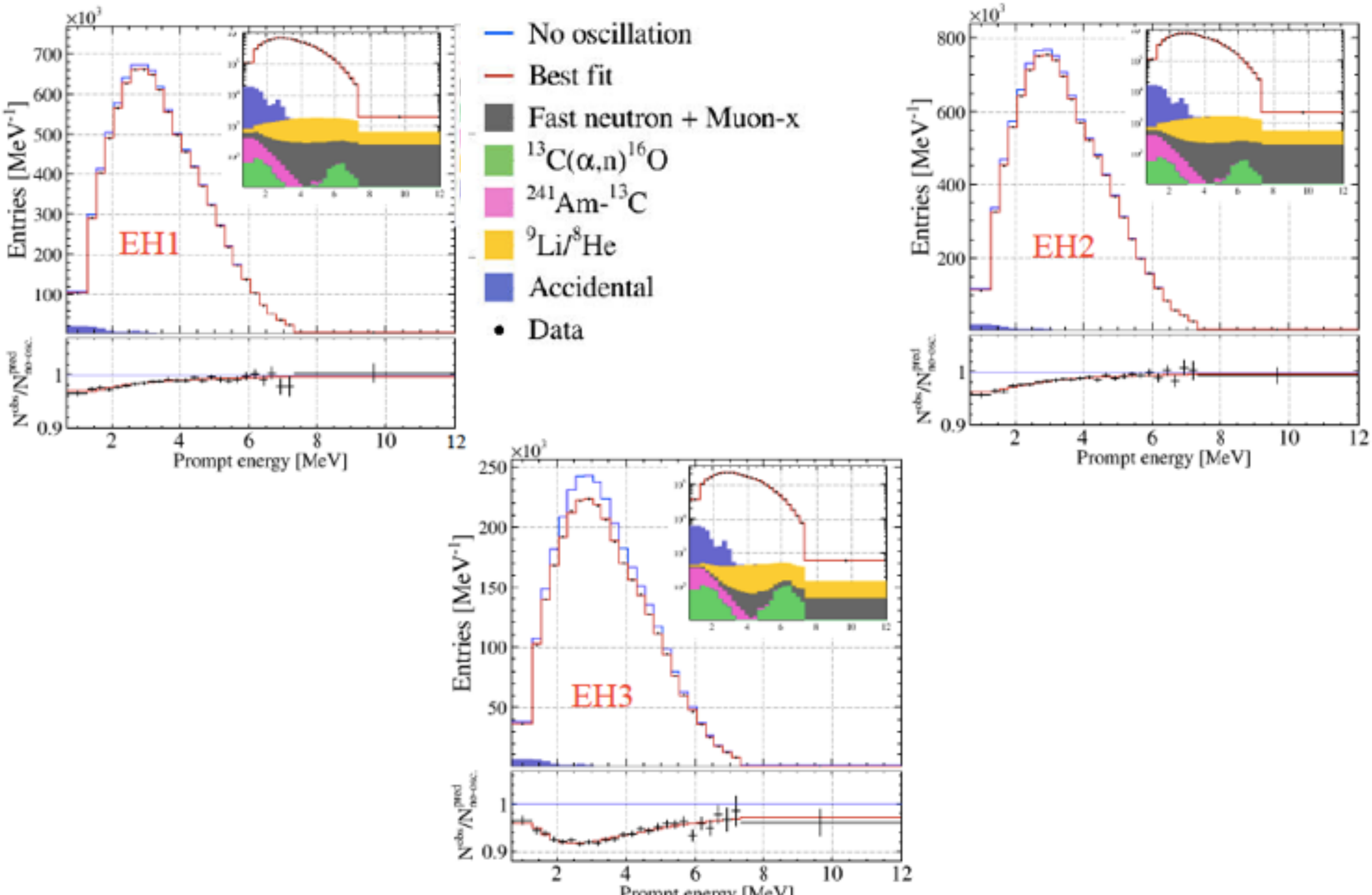


Errors include relative detection efficiency of 0.13%

- Correlation with operation of reactors
  - Expectation based on weekly reactor operational information
  - Measurements track expectations



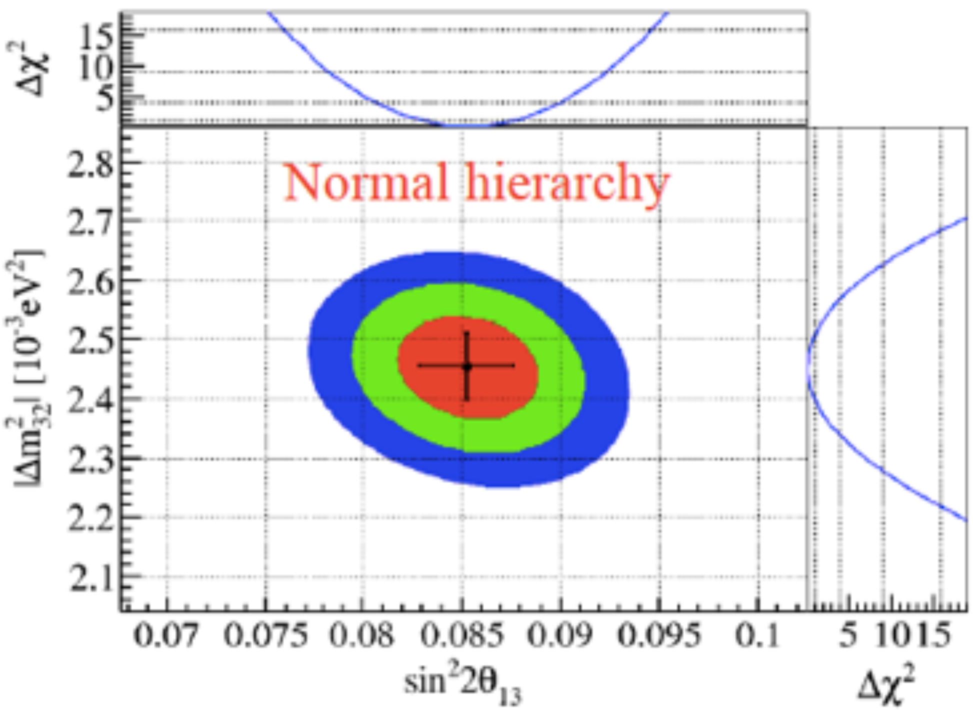
Prompt-energy Spectra

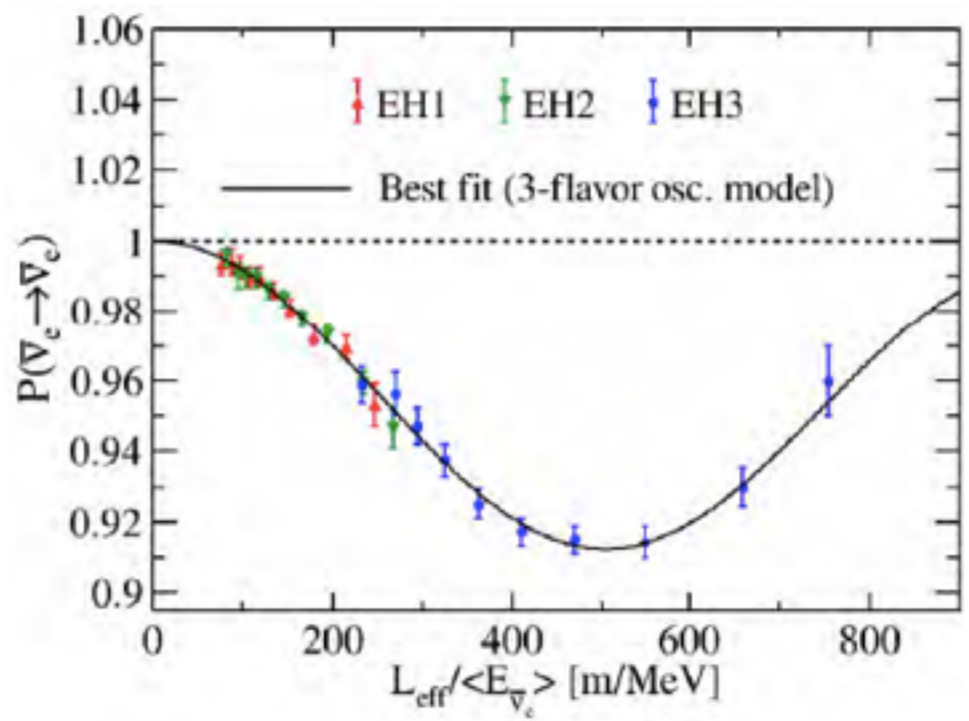


Fitter's prediction

- Use Huber-Mueller isotope spectra
  - With non-equlibirium correction
  - Plus spent nuclear fuel contribution
  - Shape/normalization allowed to vary (pull terms)
- Fold with reactor power and fission fractions (from power company) to predict antineutrino flux
- Propagate to ADs ($1/R^2$, oscillation)
- Convert to positron energy (kinematics)
- Apply effects of energy leakage, nonlinearity, resolution (w/ pulls)
- Add predicted backgrounds (w/ pulls)

Improved $\sin^2 2\theta_{13}$ and Δm^2_{32}





Best-fit results: χ^2/ndf = 559/518

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

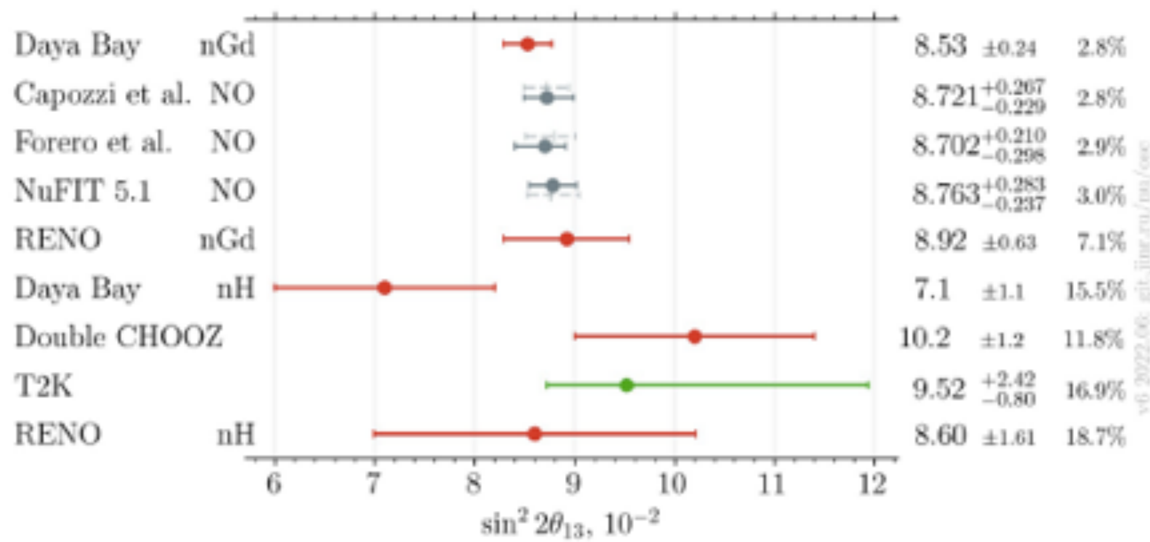
Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

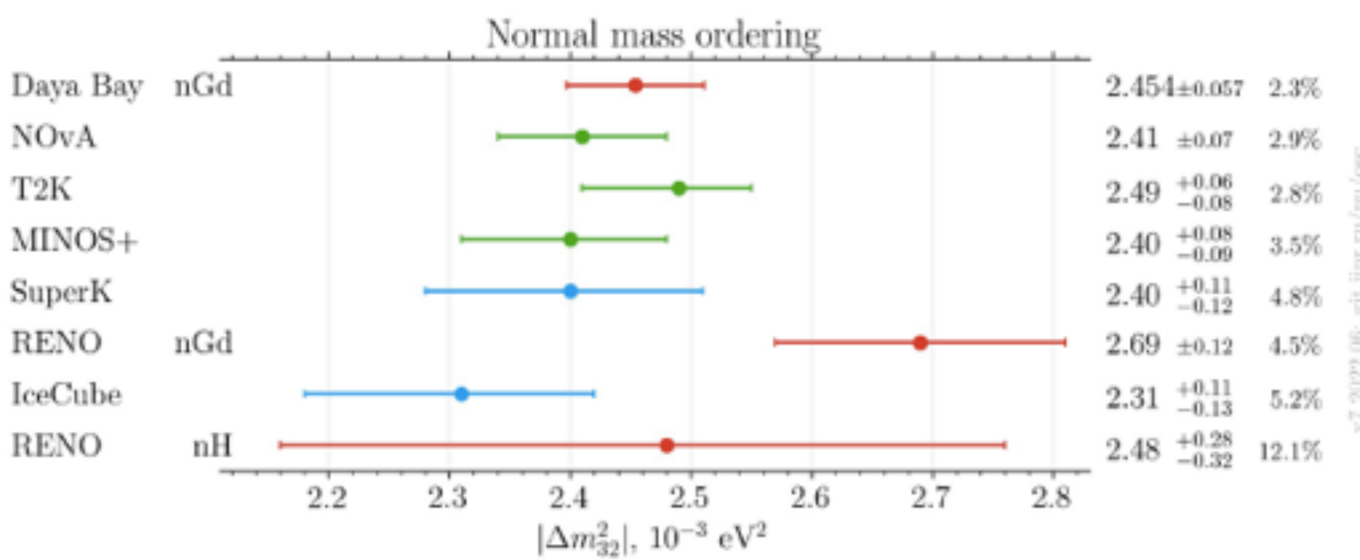
(2.3% precision)

Global comparison

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

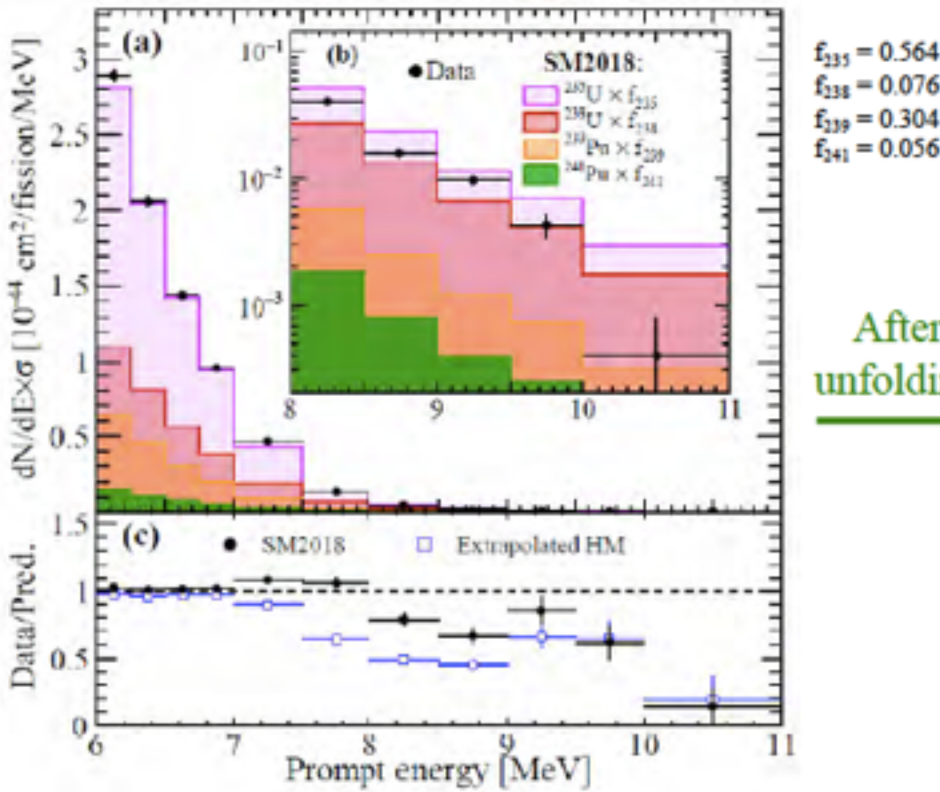


Δm^2_{32}



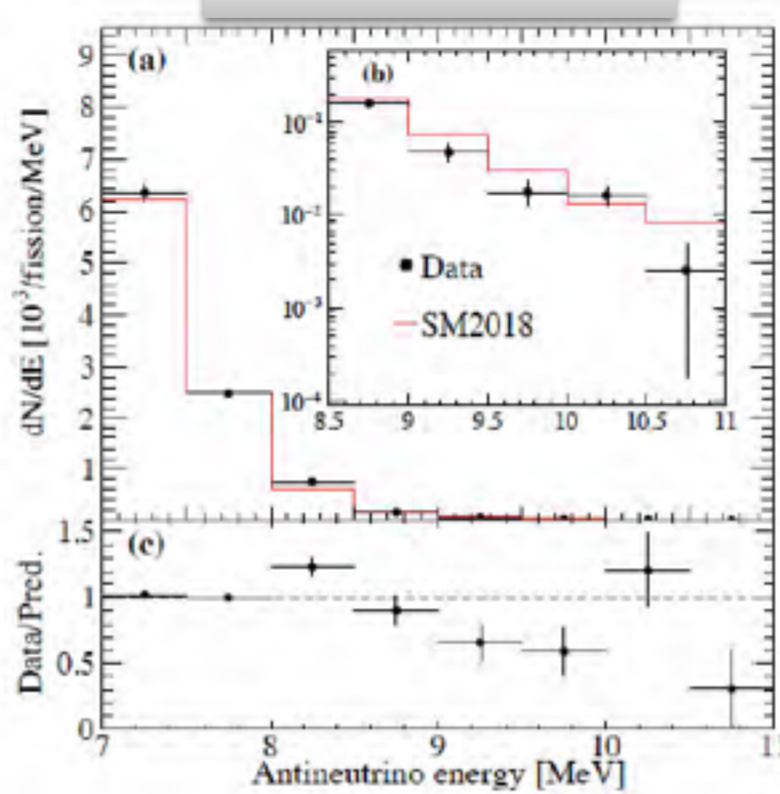
First Evidence of Reactor $\overline{\nu}_e$ with E > 10 MeV

- Can come from high-Q β-decay of short-lived isotopes, e.g. ^{88,90}Br, ^{94,96,98}Rb
- Use the 1958-day data set to extract IBD and background events together from a fit,
  - obtain 2500 IBD events with $8 < E_{prompt} < 12$ MeV



After unfolding

arXiv: 2203.0668 [hep-ex]



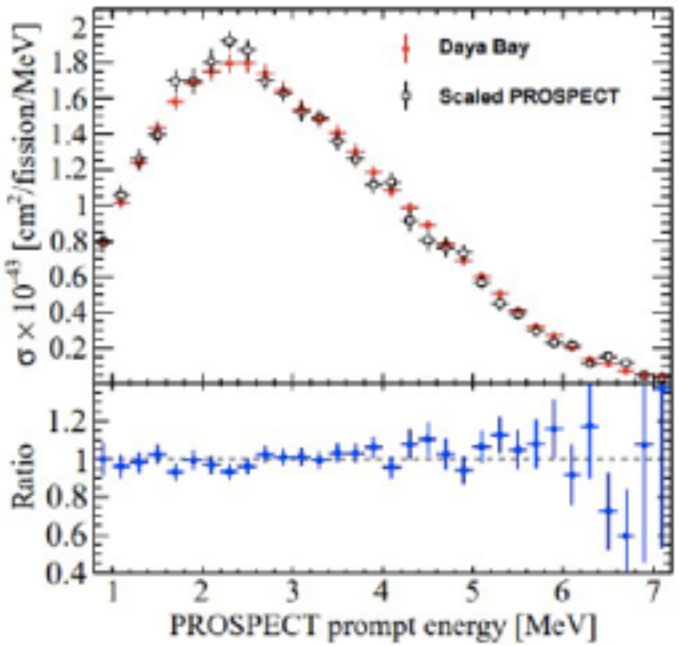
- Updated Summation Model (SM2018):
  - 3% more for 6-8 MeV, 29% less for 8-11 MeV
- Extrapolated HM:
  - Larger disagreement above 7 MeV

- Hypothesis of no reactor $\overline{\nu}_e$ with $E_\nu > 10$ MeV is ruled out at 6.2σ

Phys. Rev. Lett. **128**, 081801 (2022)

Joint spectra with PROSPECT

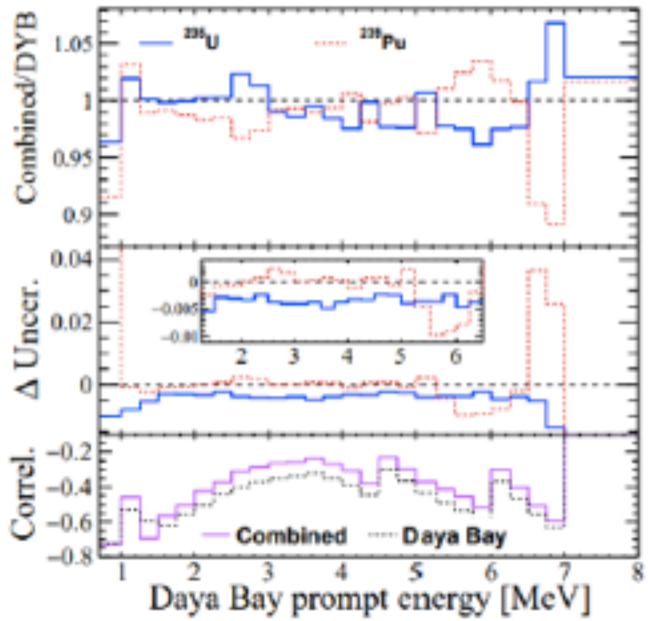
After energy response “translation”, Daya Bay and PROSPECT prompt spectra are in agreement



Both Daya Bay (LEU) and PROSPECT (HEU) can extract ^{235}U, ^{239}Pu spectra from their data

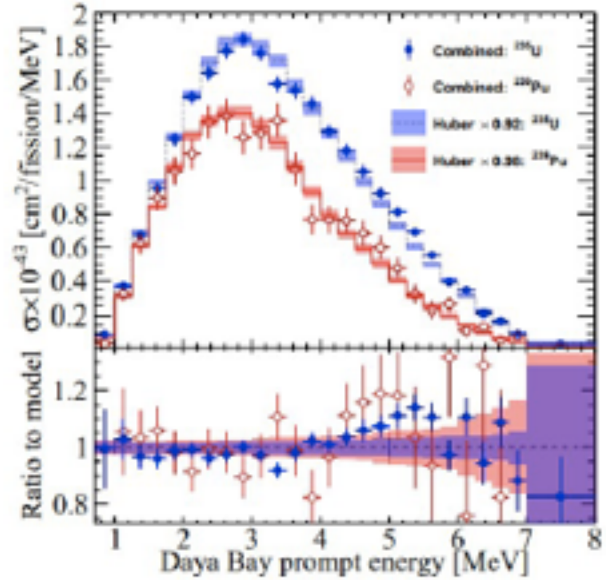
Combined spectra can be obtained by using PROSPECT's spectra as constraint in Daya Bay's fit

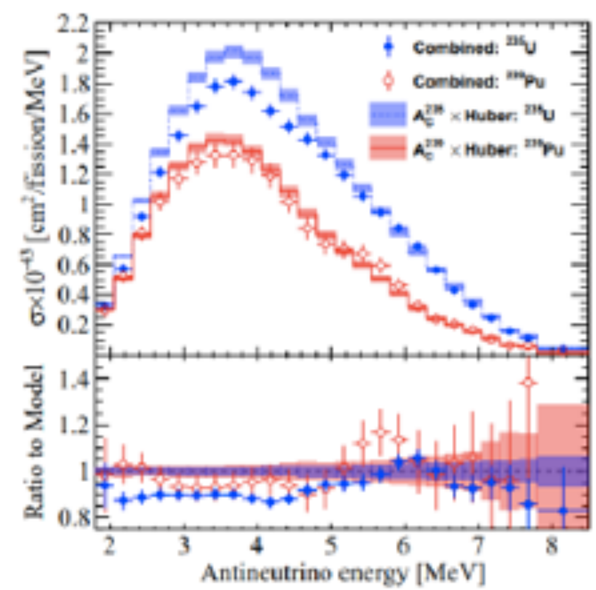
Combined ^{235}U spectrum's uncertainty is reduced from 3.5% to 3% around 3 MeV; anticorrelation of ^{235}U and ^{239}Pu reduced



Antineutrino spectra are obtained by unfolding the prompt spectra of ^{235}U and ^{239}Pu

Comparison to Huber-Mueller spectral shape





Sterile Neutrinos

- Sterile neutrinos are among the leading candidates to resolve outstanding puzzles in astronomy and cosmology

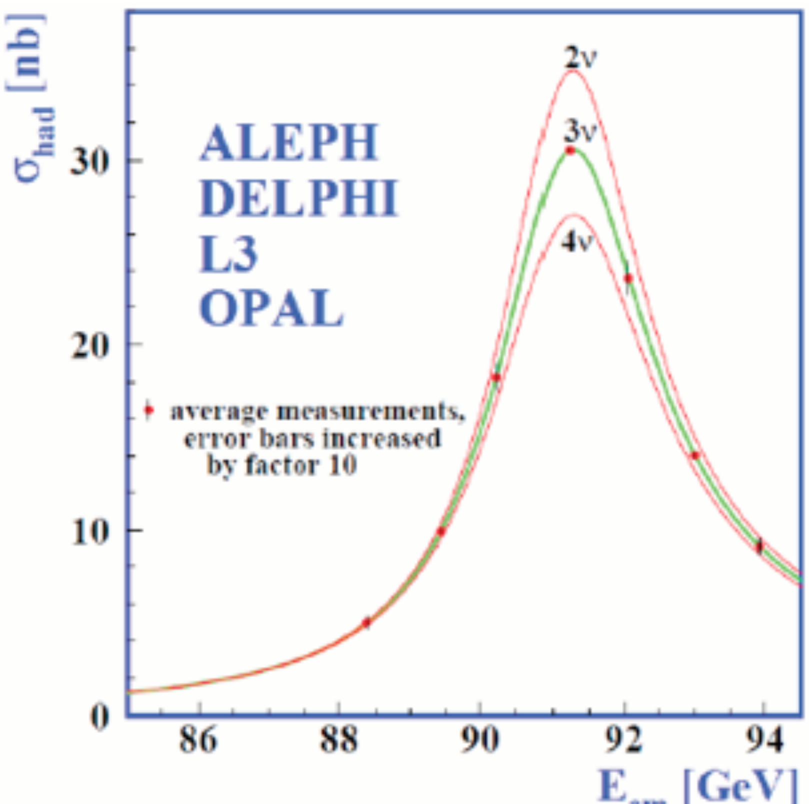
  ✔ On a solid basis theoretically

  ✔ Good motivation from cosmology (dark matter & CMB)

  ✔ Can explain some of the anomalies seen in neutrino physics (will look at one in the next section)

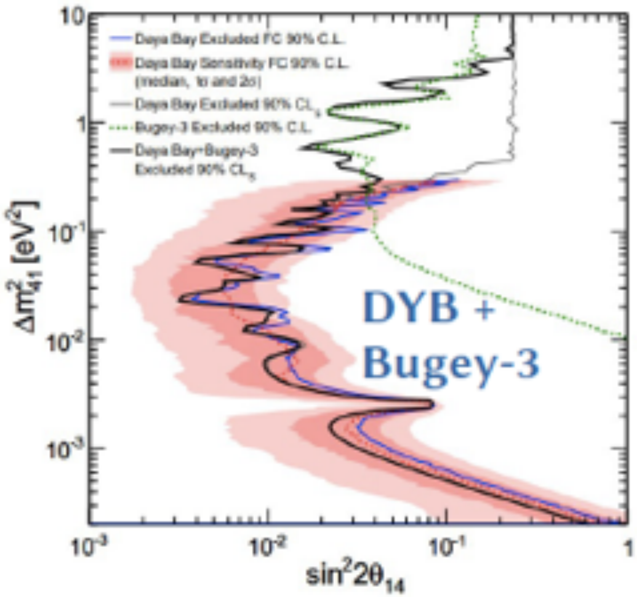
- Why sterile? →

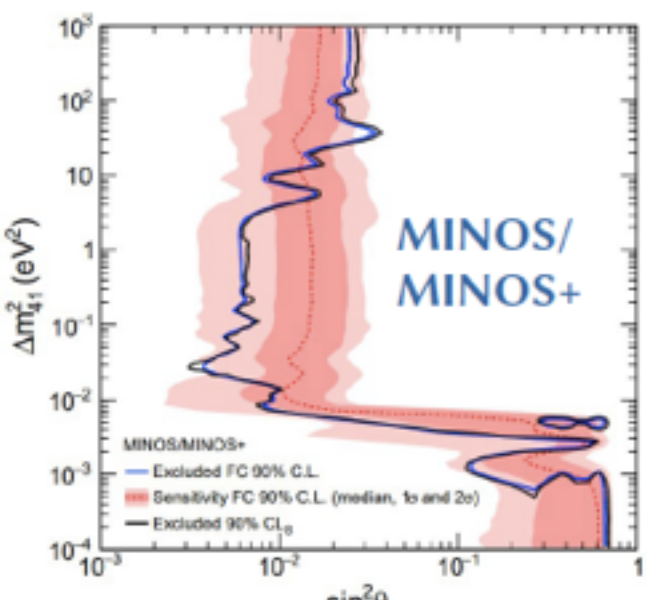
(the "bullet cluster")

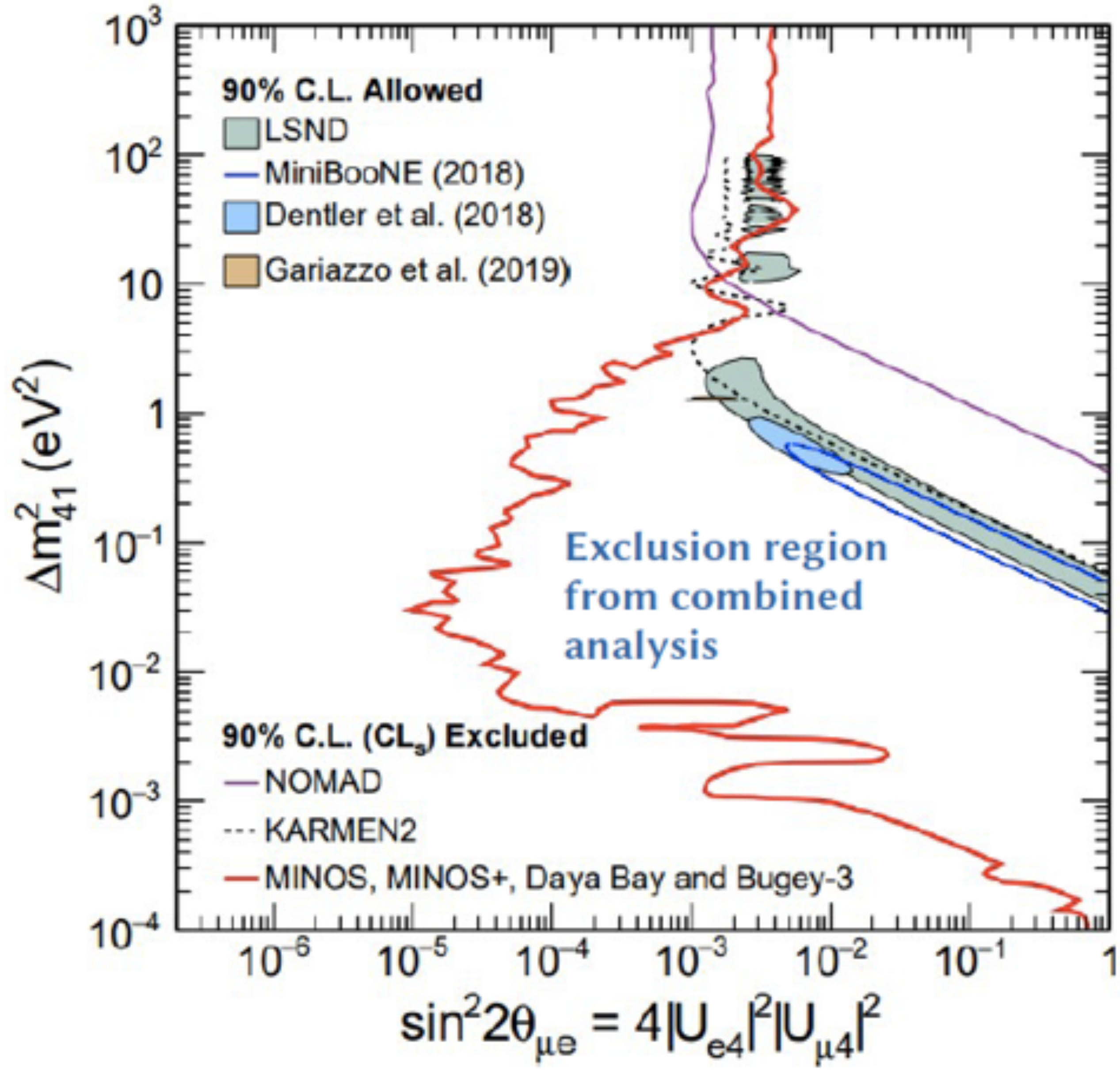


Phys. Rev. Lett. 125, 071801 (2020)

Joint sterile search w/ MINOS(+)







Conclusion

- With full 3158-day dataset, Daya Bay has measured $\sin^2 2\theta_{13}$ and $\Delta m^2_{32}/\Delta m^2_{ee}$ to precisions of 2.8% and 2.3%, respectively
  - Likely to remain the most precise measurement of $\sin^2 2\theta_{13}$ for the foreseeable future
- Using 1958 days of data, Daya Bay has provided the first detailed measurement of high-energy reactor antineutrinos
  - Reactor antineutrinos above 10 MeV observed at 6.2σ
- Many other significant recent results
- Some upcoming results
  - Spectral oscillation analysis with neutron capture on hydrogen
  - Updated sterile neutrino search
  - Updated fuel evolution measurement

More physics from Daya Bay

- Some highlights:
  - Search for events associated with gravitational waves
  - Fuel evolution measurement
  - Unfolded antineutrino spectra
  - Joint measurement of antineutrino spectra w/ PROSPECT
  - Joint sterile neutrino search w/ MINOS/MINOS+
  - Measurement of seasonal variation of muon flux
  - Oscillation analysis using neutron capture on hydrogen
  - ...and more!

- http://dayabay.ihep.ac.cn/twiki/bin/view/Public/DybPublications

The Daya Bay Collaboration

Grazie! Thank You! 고마워요! 謝謝!

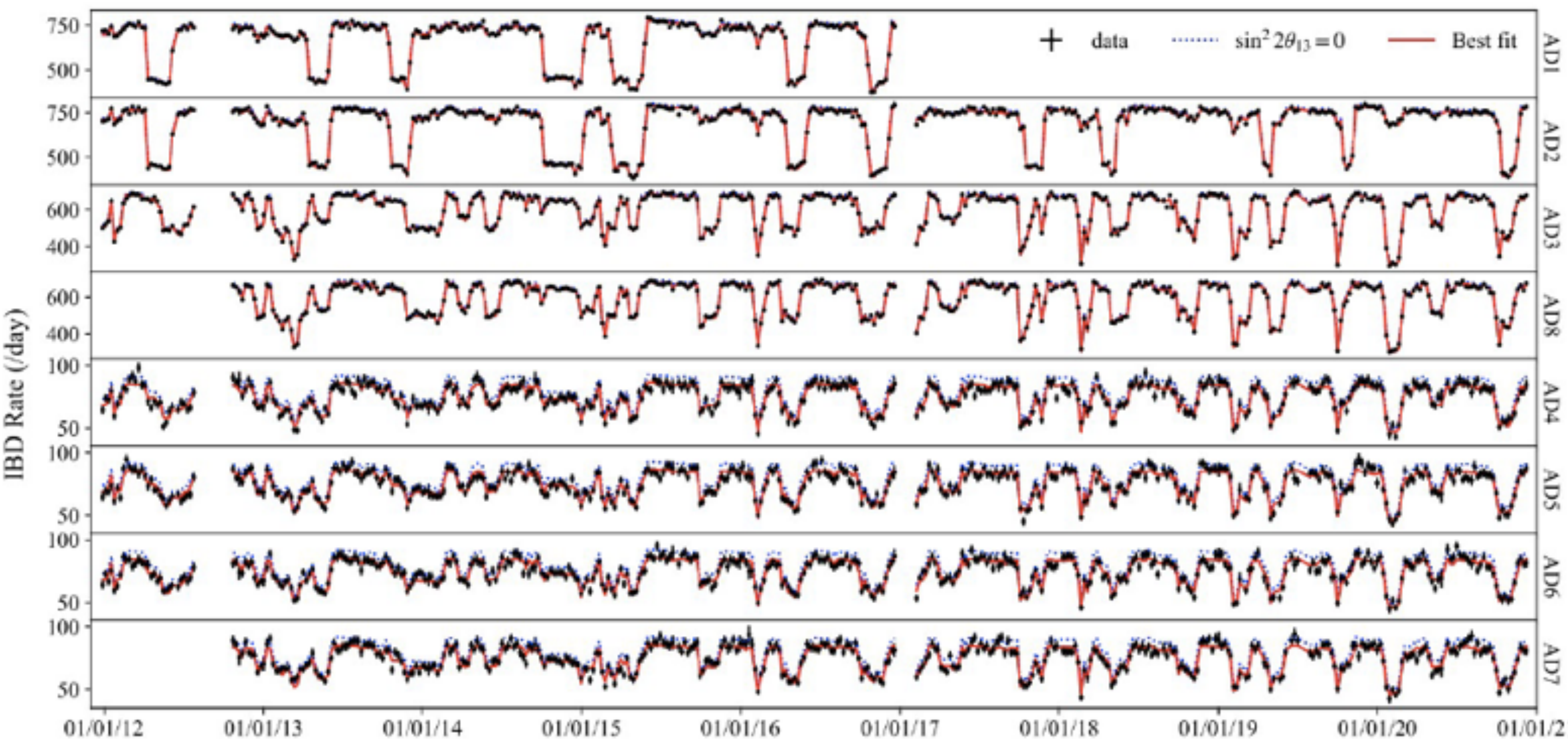
Backup

Summary table

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.11	2689.88	2502.816	2689.156	2689.156	2689.156	2501.531
ϵ_μ	0.8006	0.7973	0.8387	0.8366	0.9815	0.9815	0.9814	0.9814
$\bar{\epsilon}_m$	0.9671	0.9678	0.969	0.9688	0.9693	0.9693	0.9692	0.9693
Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast neutron & muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li, ^{8}He [AD^{-1} day^{-1}]	2.97 ± 0.53		2.09 ± 0.36		0.25 ± 0.03			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{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	0.03 ± 0.02	0.04 ± 0.02
$\bar{\nu}_e$ rate, $R_{\bar{\nu}_e}$ [day^{-1}]	657.11 ± 0.94	685.09 ± 0.81	599.83 ± 0.65	592.07 ± 0.67	75.03 ± 0.18	75.22 ± 0.18	74.42 ± 0.18	74.94 ± 0.18

Backgrounds at sub-2% level

IBD rates over time



Prediction for fitting

$$F_d^i = T_d^i \Bigg(1 + \varepsilon_D + \varepsilon_d + \frac{0.072\varepsilon_d^E}{0.2} + b^i \varepsilon_d^E + \varepsilon_i + \sum_{l=1}^{4} f_l{}^i \varepsilon_l + g^i \varepsilon_d^{IAV}$$

$$+ a^i \varepsilon_R + \begin{cases} \sum_{r=1}^{6} \omega_r^d (\varepsilon_r + \varepsilon_r^n S_n^i + \varepsilon_r^s S_s^i + \varepsilon_r^f S_f^i) & \text{(6AD period)} \\ \sum_{r=1}^{6} \omega_r^d (\varepsilon_r' + \varepsilon_r^n S_n^i + \varepsilon_r^s S_s^i + \varepsilon_r^f S_f^i) & \text{(8AD period)} \\ \sum_{r=1}^{6} \omega_r^d (\varepsilon_r'' + \varepsilon_r^n S_n^i + \varepsilon_r^s S_s^i + \varepsilon_r^f S_f^i) & \text{(7AD period)} \end{cases} \Bigg)$$

$$+ B_{di}^{Li9}(1 + \eta_k^{Li9})(1 + \eta_i^{Li9Shape}) + B_{di}^{Fn}(1 + \eta_k^{Fn})(1 + \eta_i^{FnShape})$$

$$+ B_{di}^{AmC}(1 + \eta^{AmC})(1 + \eta_i^{AmCShape}) + B_{di}^{acc}(1 + \eta_d^{acc}) + B_{di}^{alphaN}(1 + \eta_d^{alphaN})$$

$$+ B_{di}^{Md}(1 + \eta_k^{Md}) \text{ (7AD period)}$$

Indices:

i = Energy bin
d = Detector
r = Reactor
k = Experimental hall

F_d^i = Best-fit prediction
T_d^i = Nominal prediction w/ oscillation
ε_D (ε_d) = Correlated (uncorr.) det. eff. pulls
ε_d^E = Relative energy scale pulls
ε_i = Bin-uncorrelated shape pulls

ε_l = Nonlinearity pulls
ε_d^{IAV} = Energy leakage pulls
ε_R = Correlated reactor flux pull
ε_r (ε_r^n, ε_r^s, ε_r^f) = Uncorr. reactor flux pulls
(non-equilibrium, spent fuel, fission frac.)
η = Background rate/shape pulls

χ^2 expression

$$\chi^2 = \min_{\gamma} \sum_{d=1}^{6}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i} + \sum_{d=1}^{8}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i} + \sum_{d=1}^{7}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i}$$
$$+ \sum_{d=1}^{8} \left[(\frac{\varepsilon_d}{\sigma_d})^2 + (\frac{\eta_d^{acc}}{\sigma_d^{acc}})^2 + (\frac{\eta_d^{alphaN}}{\sigma_d^{alphaN}})^2 + (\frac{\varepsilon_d^{E}}{\sigma_d^{E}})^2 + (\frac{\varepsilon_d^{IAV}}{\sigma_d^{IAV}})^2 \right]$$
$$+ \sum_{k=1}^{3} \left[(\frac{\eta_k^{Fn}}{\sigma_k^{Fn}})^2 + (\frac{\eta_k^{Li9}}{\sigma_k^{Li9}})^2 + (\frac{\eta_k^{Md}}{\sigma_k^{Md}})^2 \right] + (\frac{\eta^{AmC}}{\sigma^{AmC}})^2$$
$$+ \sum_{i=1}^{29} (\frac{\eta_i^{Li9Shape}}{\sigma_i^{Li9Shape}})^2 + \sum_{i=1}^{29} (\frac{\eta_i^{FnShape}}{\sigma_i^{FnShape}})^2 + \sum_{i=1}^{14} (\frac{\eta_i^{AmCShape}}{\sigma_i^{AmCShape}})^2 + \sum_{l=1}^{4} (\frac{\varepsilon_l}{\sigma_l})^2$$
$$+ \sum_{r=1}^{6} \left[(\frac{\varepsilon_r}{\sigma_r})^2 + (\frac{\varepsilon_r^{n}}{\sigma_r^{n}})^2 + (\frac{\varepsilon_r^{s}}{\sigma_r^{s}})^2 + (\frac{\varepsilon_r^{f}}{\sigma_r^{f}})^2 + (\frac{\varepsilon_r'}{\sigma_r'})^2 + (\frac{\varepsilon_r''}{\sigma_r''})^2 \right]$$

M_d^i = Measurement

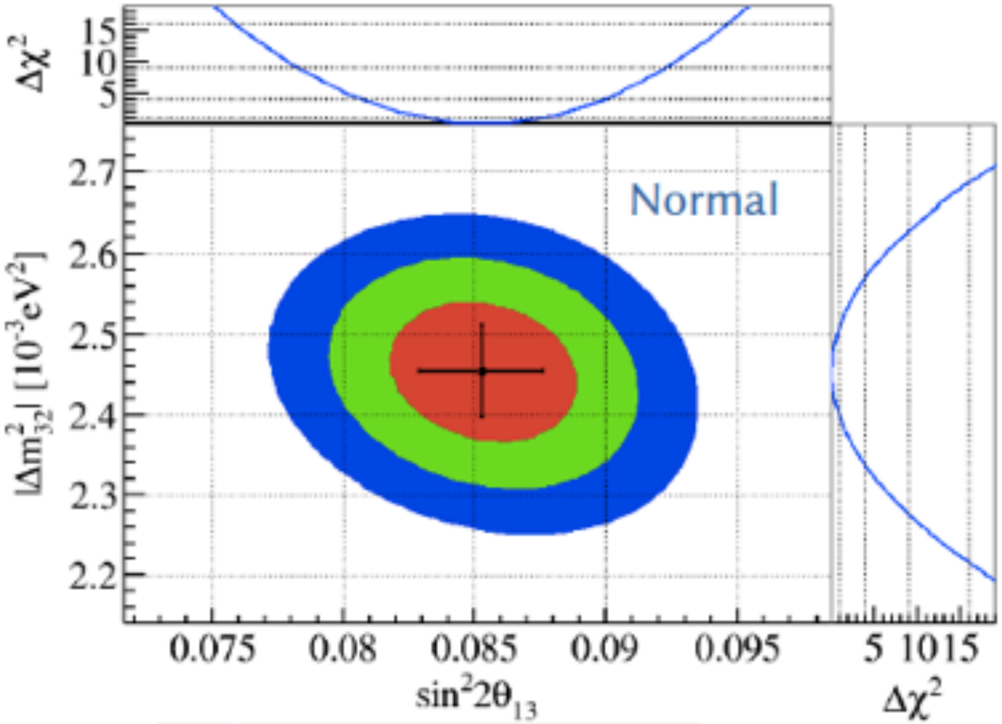
Minimize this χ^2 with respect to oscillation parameters and all pulls

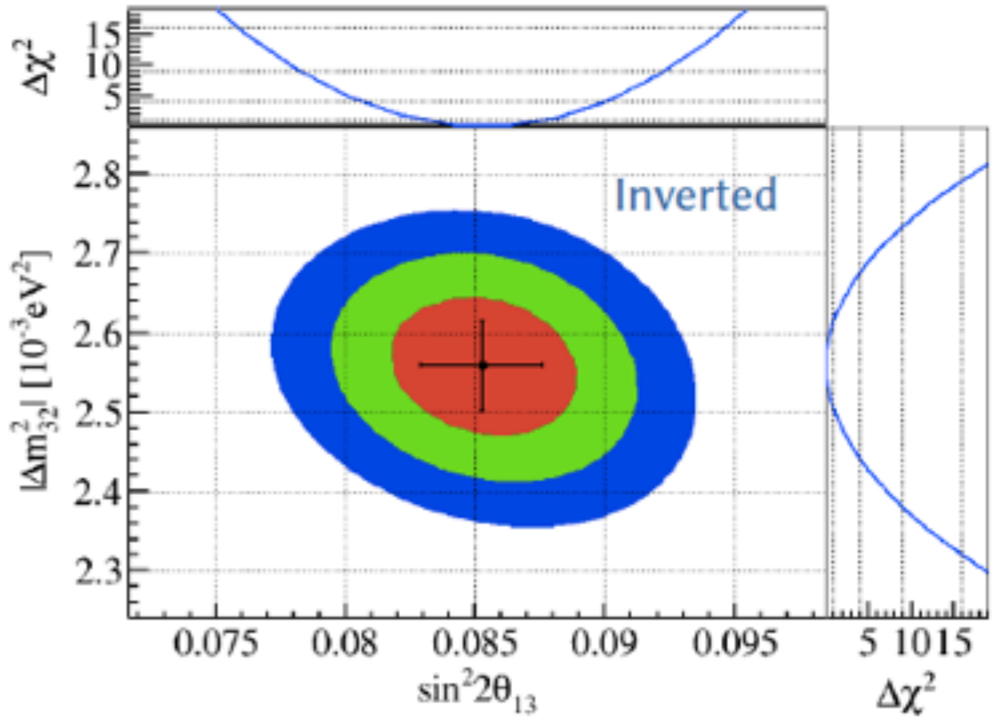
Result: Best-fit $\sin^2 2\theta_{13}$ and Δm^2!

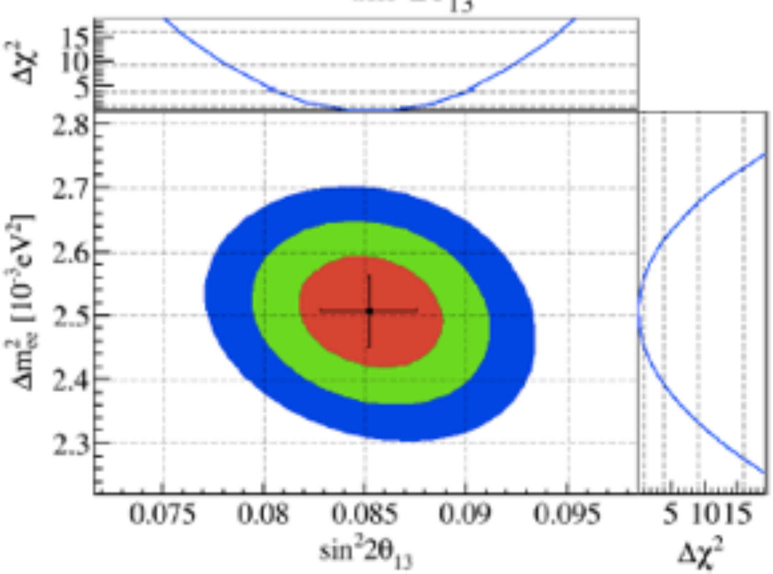
Individual 1σ bounds where $\Delta\chi^2$ crosses 1 (w/ other osc. par. fixed)

1σ (2σ, 3σ) 2D contours where $\Delta\chi^2$ crosses 2.30 (6.18, 11.83)

Oscillation parameters

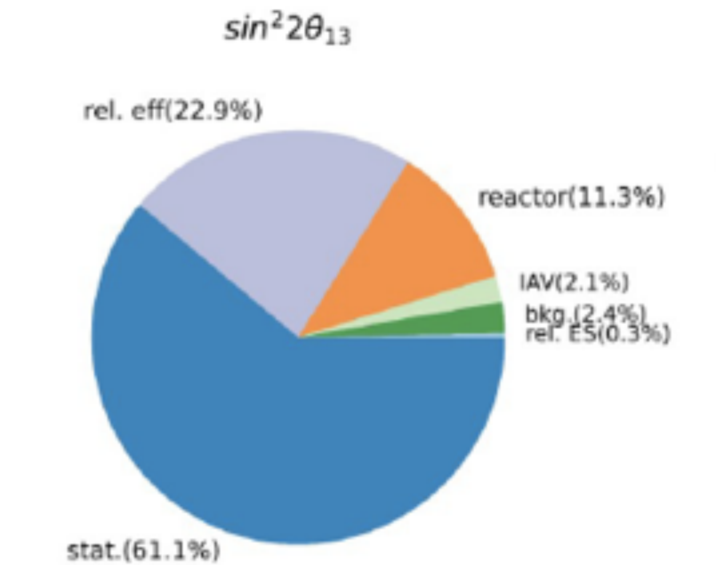


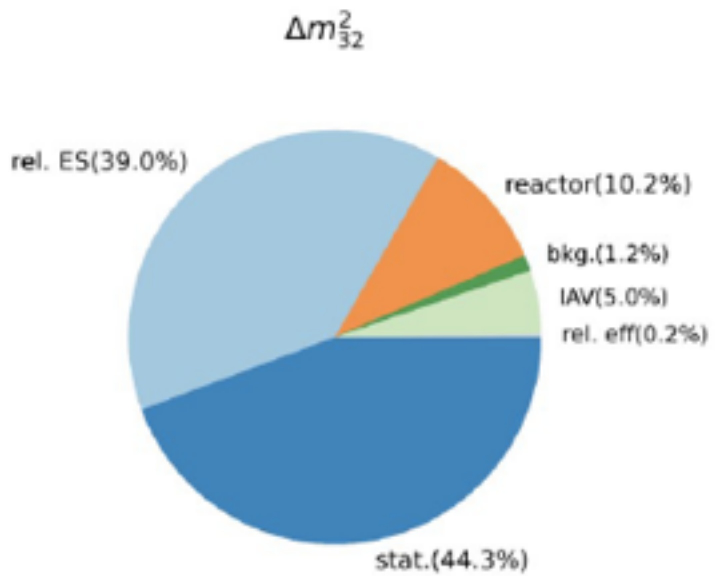




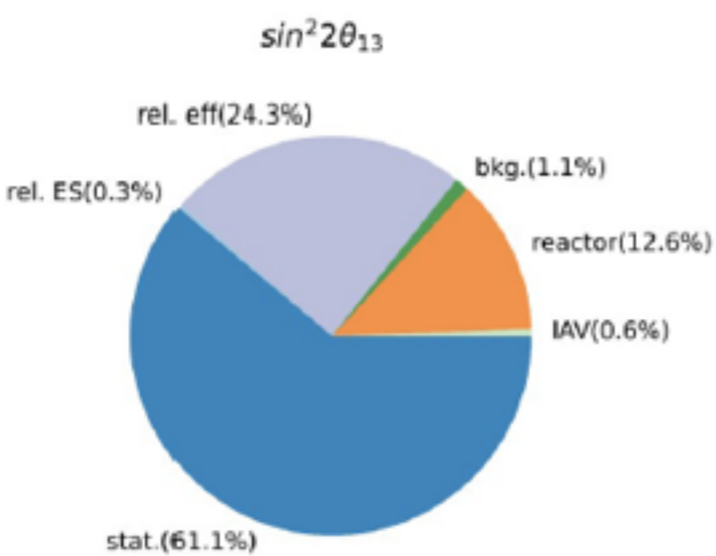
Mass order	$\sin^2 2\theta_{13}$	Δm^2 (10^{-3} eV^2)	χ^2_{min} / NDF
Normal, Δm^2_{32}	$0.0853^{+0.0024}_{-0.0024}$	$2.454^{+0.057}_{-0.057}$	559.41 / 518
Inverted, Δm^2_{32}	$0.0853^{+0.0024}_{-0.0024}$	$-(2.559^{+0.057}_{-0.057})$	559.41 / 518
Δm^2_{ee}	$0.0852^{+0.0024}_{-0.0024}$	$2.507^{+0.057}_{-0.057}$	559.42 / 518

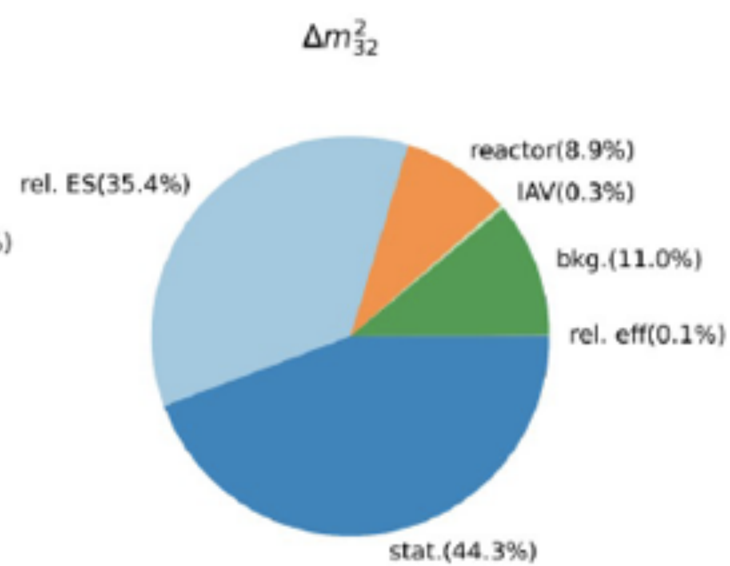
Error budget





Adding each systematic to stat-only Asimov fit





Removing each systematic from full-syst Asimov fit

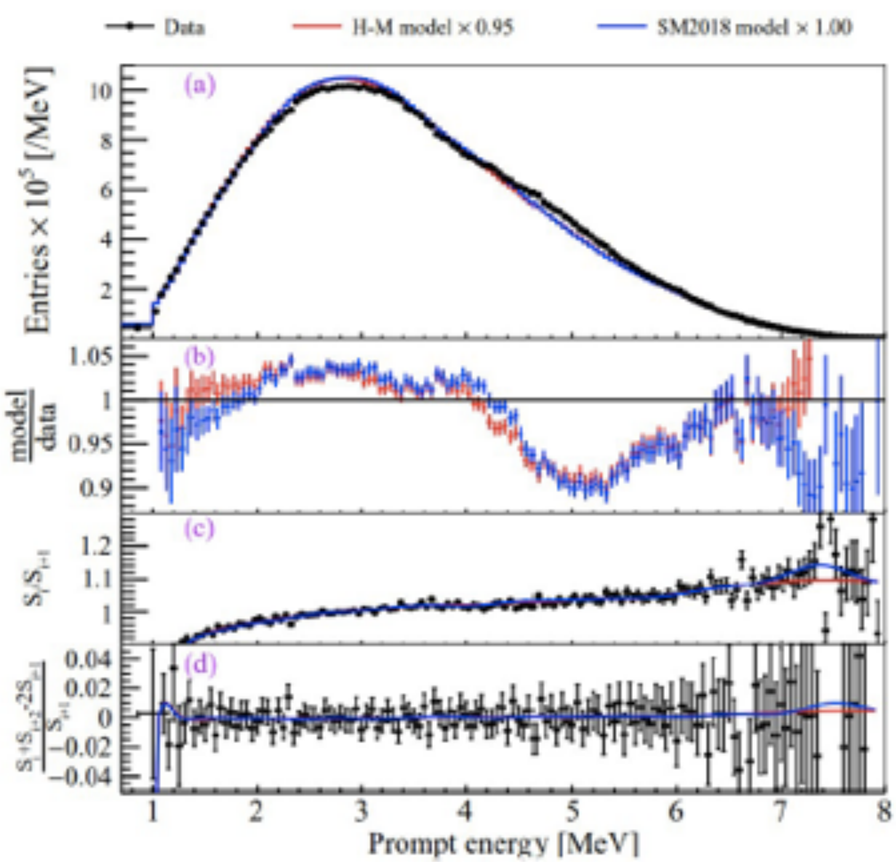
Chin. Phys. C **45**, 073001 (2021)

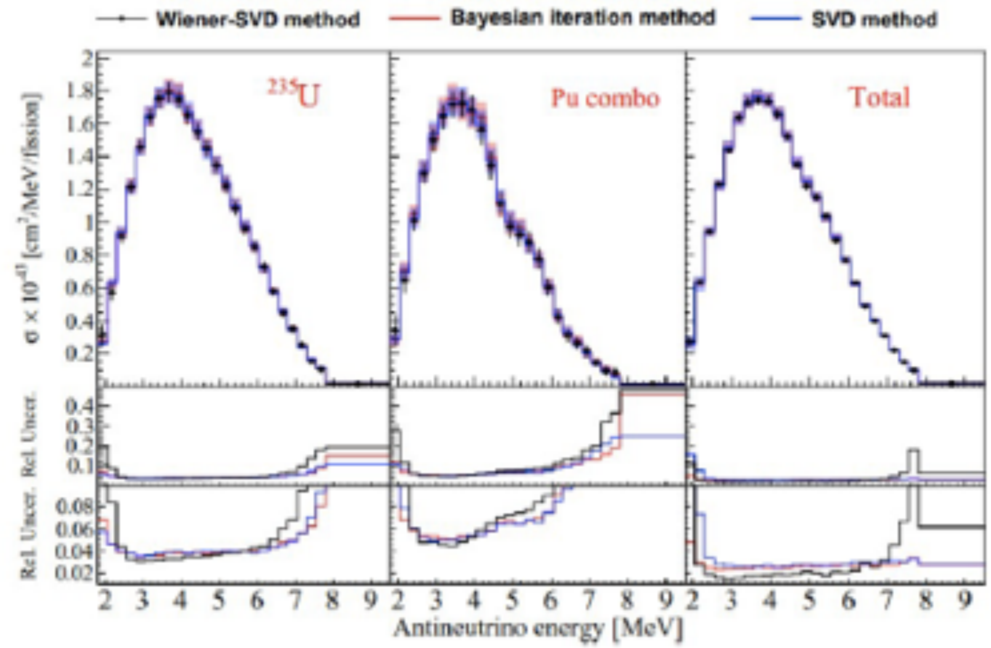
Antineutrino spectra

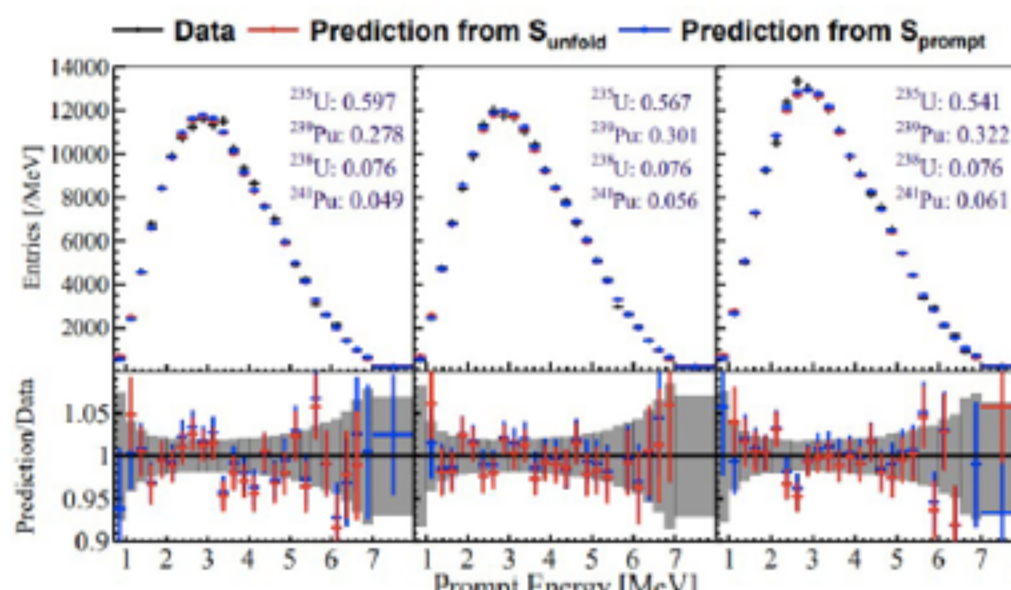
Using data at different fission fractions, extract ^{235}U and ^{239}Pu+^{241}Pu prompt spectra, unfold to $\bar{\nu}$ spectra (right)

Isotope spectra, when combined, correctly predict total prompt spectra for various fission fractions (lower right)

Comparison of prompt spectrum to model predictions confirms unresolved shape discrepancies



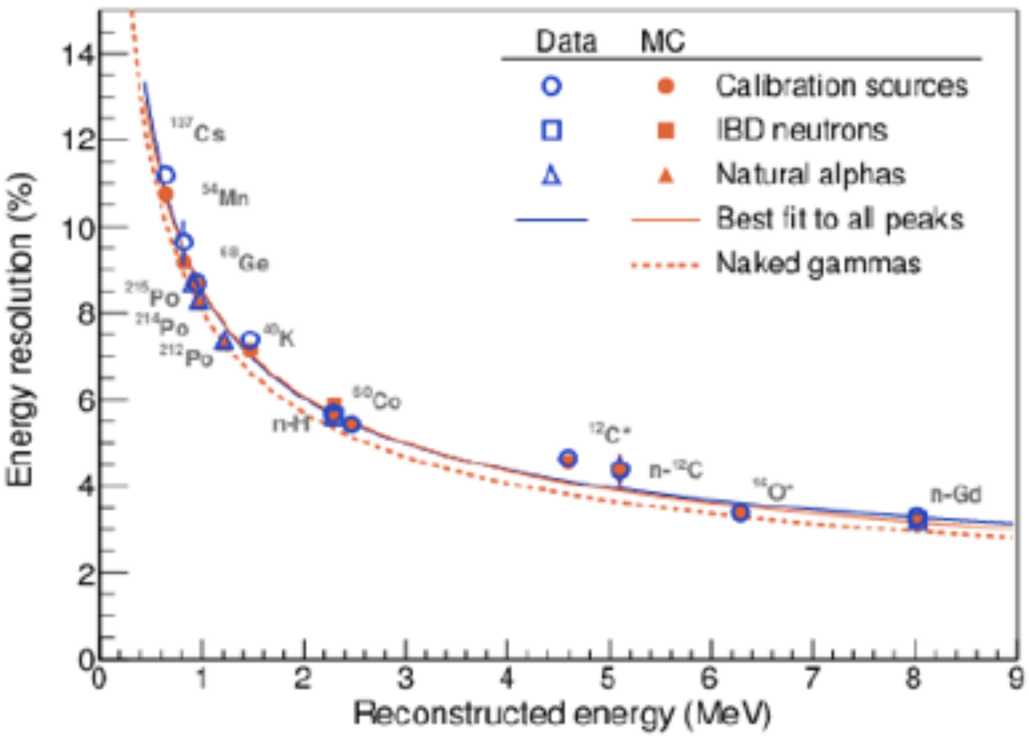


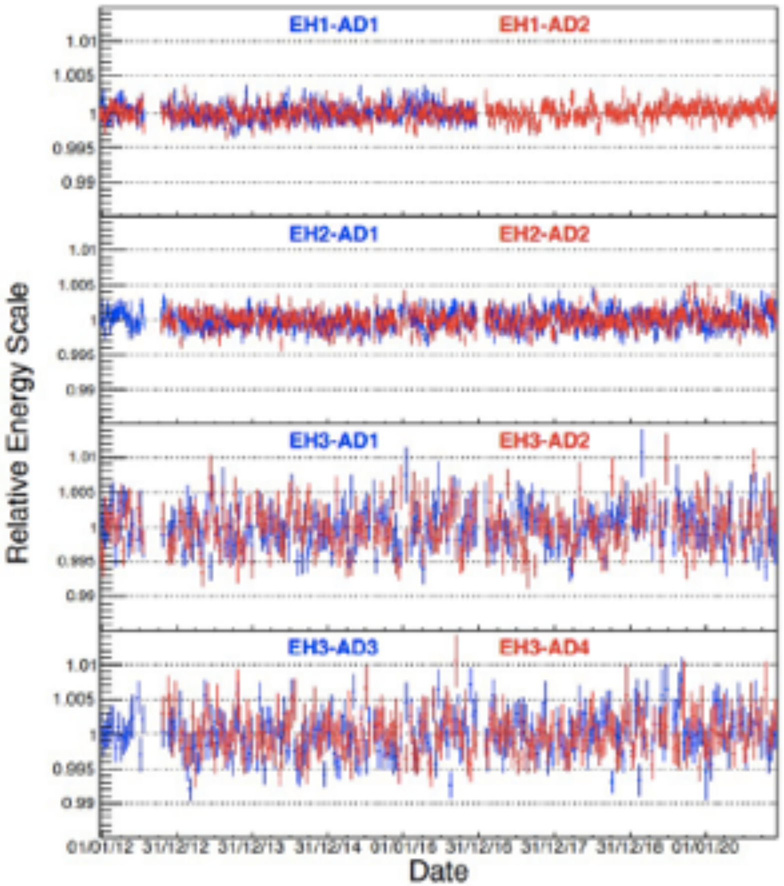


Reconstructed energy

The *visible energy* (# of photoelectrons) becomes the *reconstructed energy* after applying the space- and time-dependent corrections for detector nonuniformity

The reconstructed energy includes corrections for nonlinearity of the electronics (applied during hit charge calculation), but *no correction for scintillator nonlinearity* (that's next!)





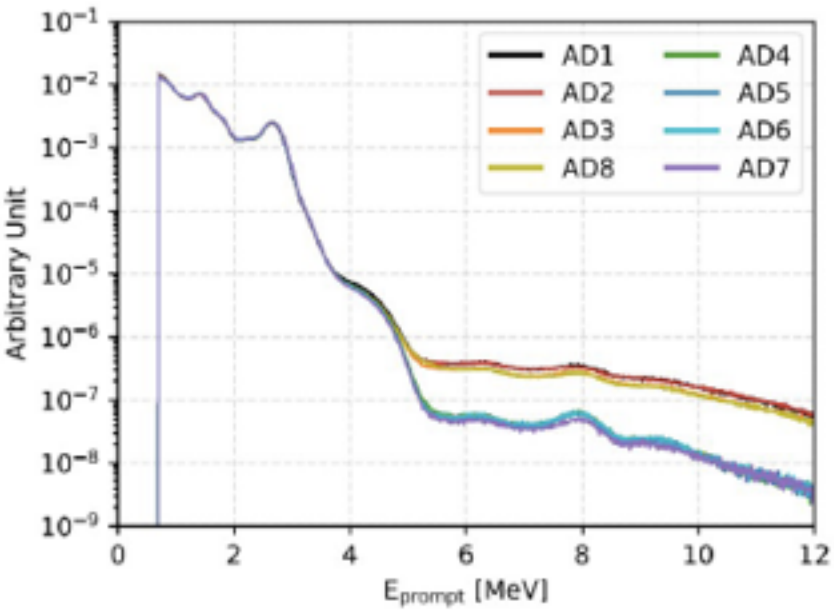
Accidentals (random pairs)

- Rate is calculated using rates of "prompt-like" and "delayed-like" isolated triggers ("singles")
- Singles are selected analogously to IBDs, but requiring one trigger rather than two

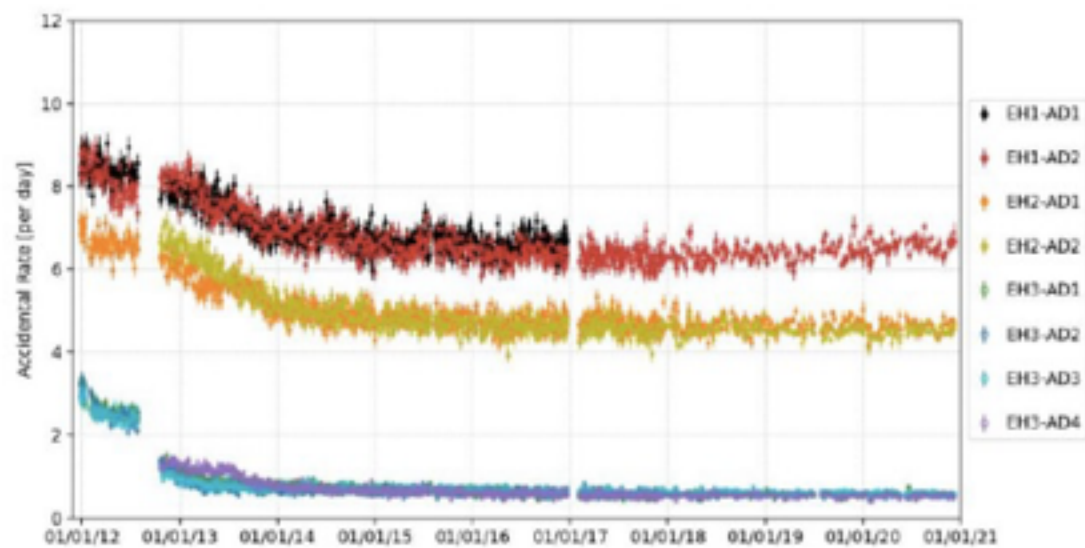
$$R_p = \frac{N_p}{T_\mu P(0, R_x \cdot 600\mu s)} = \frac{N_p}{T_\mu e^{-R_x \cdot 600\mu s}} \qquad R_d = \frac{N_d}{T_\mu P(0, R_x \cdot 600\mu s)} = \frac{N_d}{T_\mu e^{-R_x \cdot 600\mu s}}$$

$$\begin{aligned} R_{acc} &= P(0, 201\mu s \cdot R_x) P(0, 199\mu s \cdot (R_x - R_p)) P(1, 199\mu s \cdot R_p) R_d P(0, 200\mu s \cdot R_x) \\ &= 199\mu s \cdot R_p \cdot R_d \cdot e^{-600\mu s \cdot R_x}, \end{aligned}$$

Spectral shape (directly from singles selection)

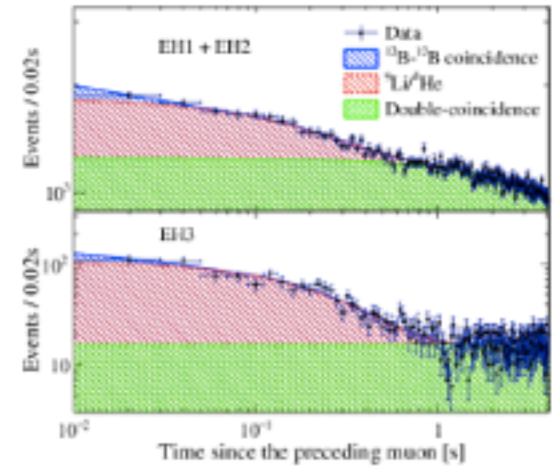


Rate of accidentals over time



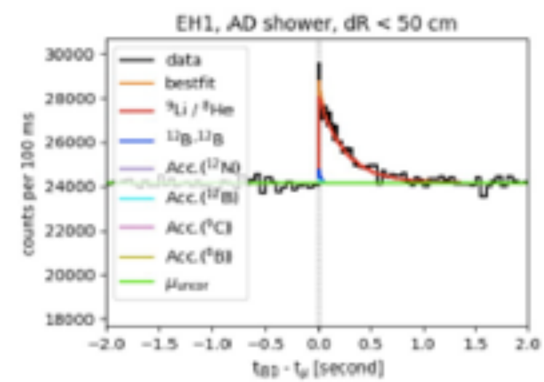
$^9Li/^8He$

"Long-lived" ($\tau^{Li}_{1/2}$ = 178.3 ms, $\tau^{He}_{1/2}$ = 119.1 ms) isotopes produced by energetic muons. Daughters from β decay can break up, releasing a free neutron.



β decay (Q_{Li} = 13.6 MeV, Q_{Li} = 13.6 MeV) gives prompt signal, neutron capture gives delayed signal, mimicking an IBD.

Can be statistically measured using time correlation to muons. Two methods:



- "Time-to-last-muon": For each IBD candidates, fill a histogram with time to last muon (not necessarily parent muon), then fit:

$$f(t) = N_{\mathrm{Li/He}}(r\cdot\lambda_{\mathrm{Li}}\cdot e^{-\lambda_{\mathrm{Li}}t}+(1-r)\cdot\lambda_{\mathrm{He}}\cdot e^{-\lambda_{\mathrm{He}}t})+N_{\mathrm{IBD}}\cdot R_\mu\cdot e^{-R_\mu t}+N_{\mathrm{BB}}\cdot\lambda_{\mathrm{BB}}\cdot e^{-R_{\mathrm{BB}}t}$$

- "Time off-window method": For each muon, fill a histogram with time difference to all nearby IBD candidates, then fit:

$$f(t) = N_{\mathrm{Li/He}}(\frac{r}{\tau_{\mathrm{Li}}}\cdot e^{-t/\tau_{\mathrm{Li}}}+\frac{1-r}{\tau_{\mathrm{He}}}\cdot e^{-t/\tau_{\mathrm{He}}})+N_{\mathrm{BB}}\cdot\frac{2}{\tau_{\mathrm{B}}}\cdot e^{-2t/\tau_{\mathrm{B}}}+C.$$

$^9Li/^8He$ (cont'd)

Problem: High muon rate at low muon energies ⟶ can't get a good fit

Traditional solution is "neutron tagging": Only consider muons with a coincident neutron capture

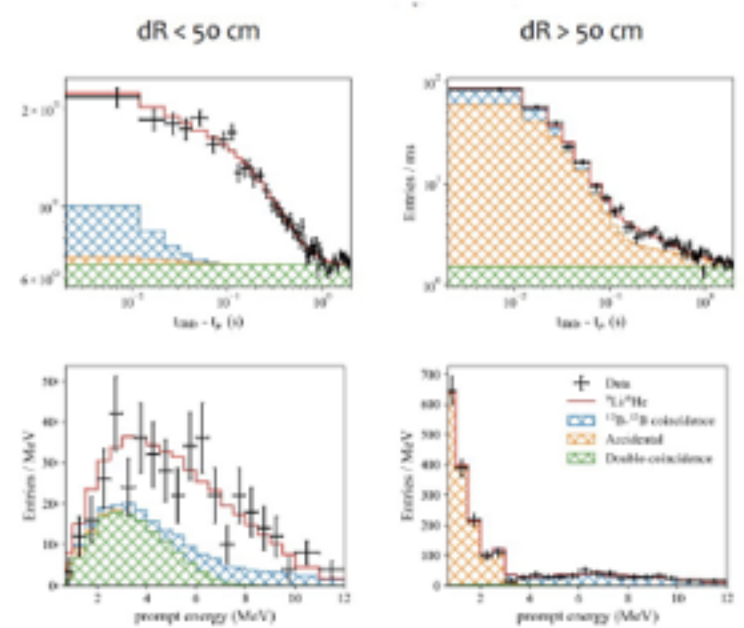
Neutron tagging efficiency leads to large uncertainty

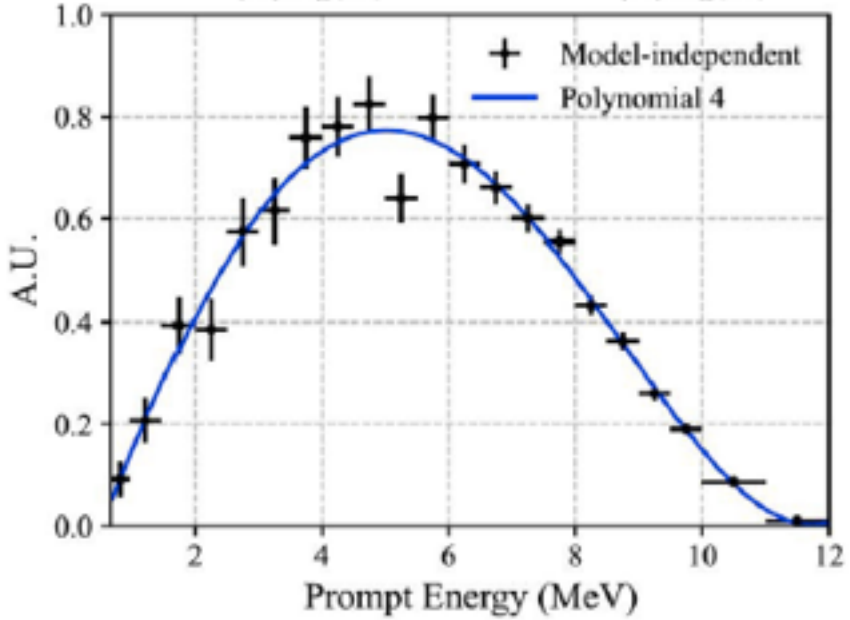
New approach: Multi-dimensional fit (time off-window):

- Time since muon
- Prompt energy
- Prompt-delayed distance (dR)
- Muon energy ("AD" or "shower")

Uncertainty on rates reduced by factor of ~2

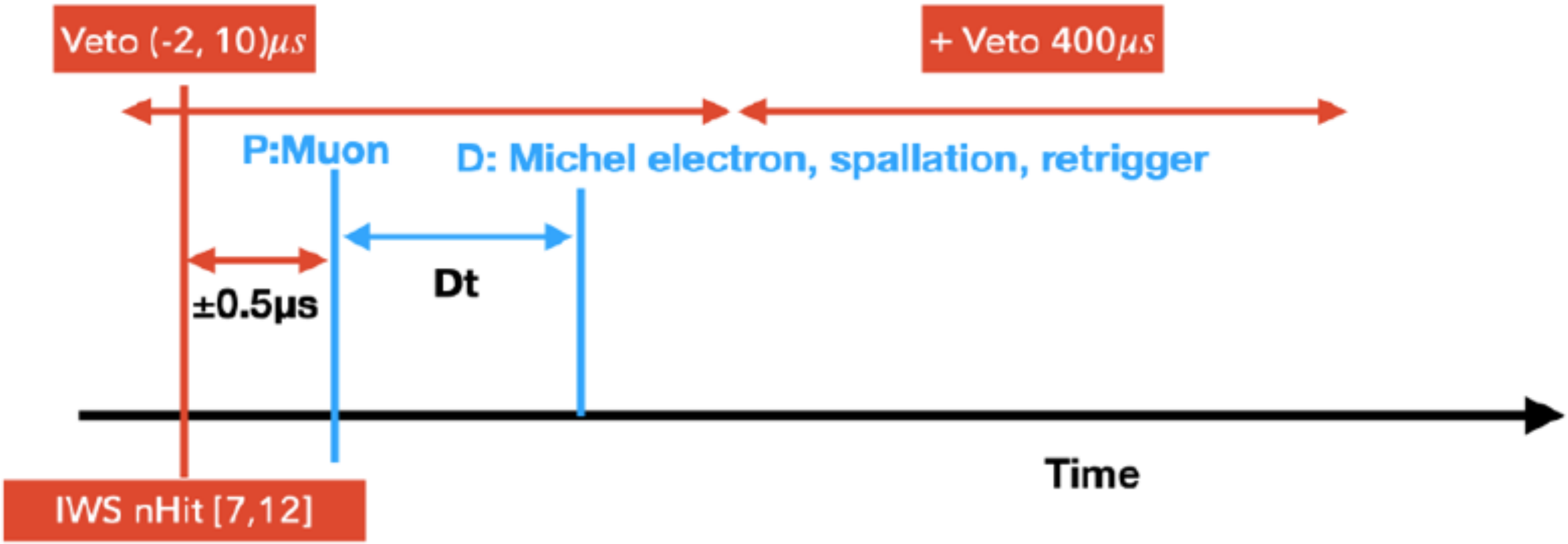
Spectrum extracted simultaneously





Muon-X reduction

Remove 80% of muon-X background by adopting new IWS veto:



Minimal impact on muon veto efficiency

AmC source

$^{241}Am^{13}C$ calibration source produces neutrons

When source is stowed, shielding keeps neutrons out of GdLS

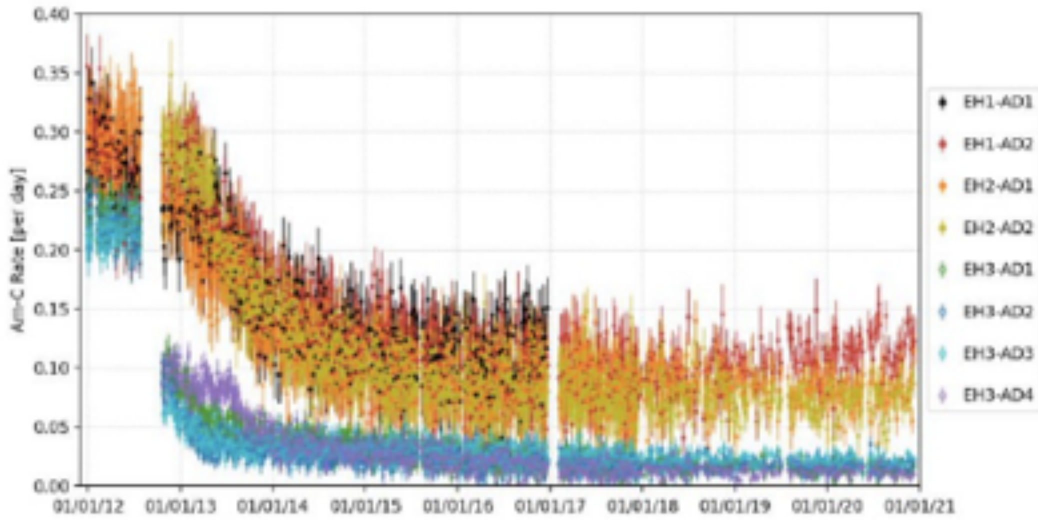
But correlated gammas can be produced by neutron inelastic scattering followed by capture in stainless steel (or Gd overflow tank), mimicking IBD signature

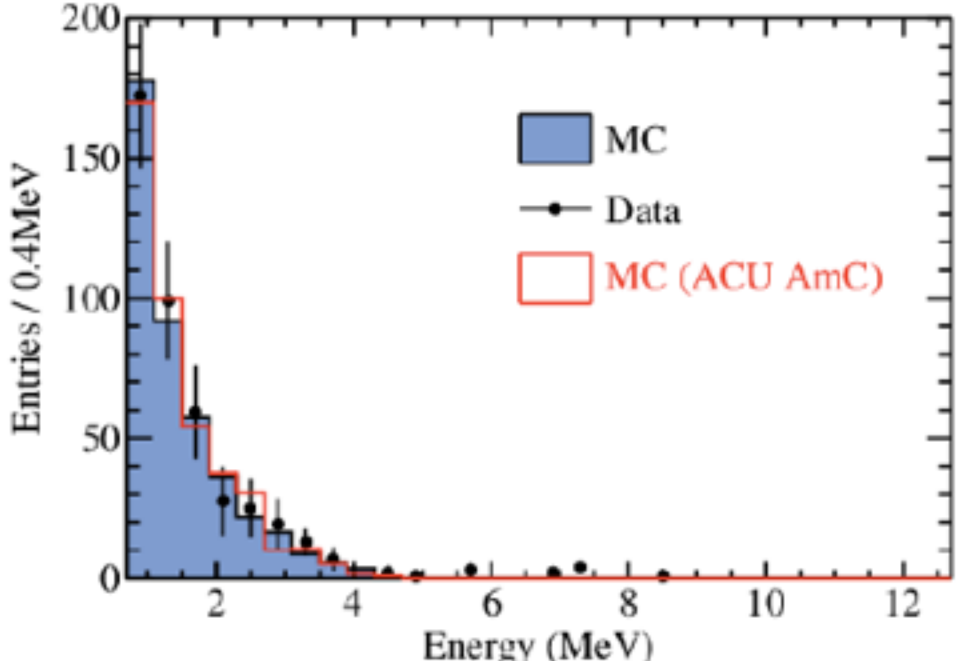
Rate is proportional to that of "neutron-like" singles in the top half of the AD:

$$R_{AmC} = R_{n-like} \cdot Y, \quad R_{n-like} = R_d^{up} - R_d^{low}$$

Factor *Y* determined using MC, benchmarked with data from a high-activity neutron source (HAS)

Prompt spectrum consistent between MC and HAS data





α-n reactions

Correlated pairs initiated by α's from decay chains (^{238}U, ^{232}Th, ^{235}U) and ^{210}Po. Reaction with ^{13}C releases a neutron.

Rates of the three chains determined by selecting Bi-Po, Rn-Po cascades. Rate of ^{210}Po from (quenched) 0.5 MeV α peak in singles spectrum.

MC used to determine rate and spectrum of the α-n background as a function of the rates of the chains/^{210}Po.