Recent Results from Daya Bay

Matt Kramer
Lawrence Berkeley National Laboratory
On behalf of the Daya Bay collaboration

SLAC FPD seminar, Feb 21, 2023

Outline

- Overview of the Daya Bay Experiment
- Oscillation analysis with full dataset
- Highlights of other results (as time allows)
  - Measurement of high-energy reactor antineutrinos
  - Search for a light sterile neutrino
  - Reactor flux, spectrum, and fuel evolution
  - Neutrinos correlated with gravitational waves
  - Seasonal variation of atmospheric muon flux

Overview of Daya Bay

Reactor antineutrino oscillation

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

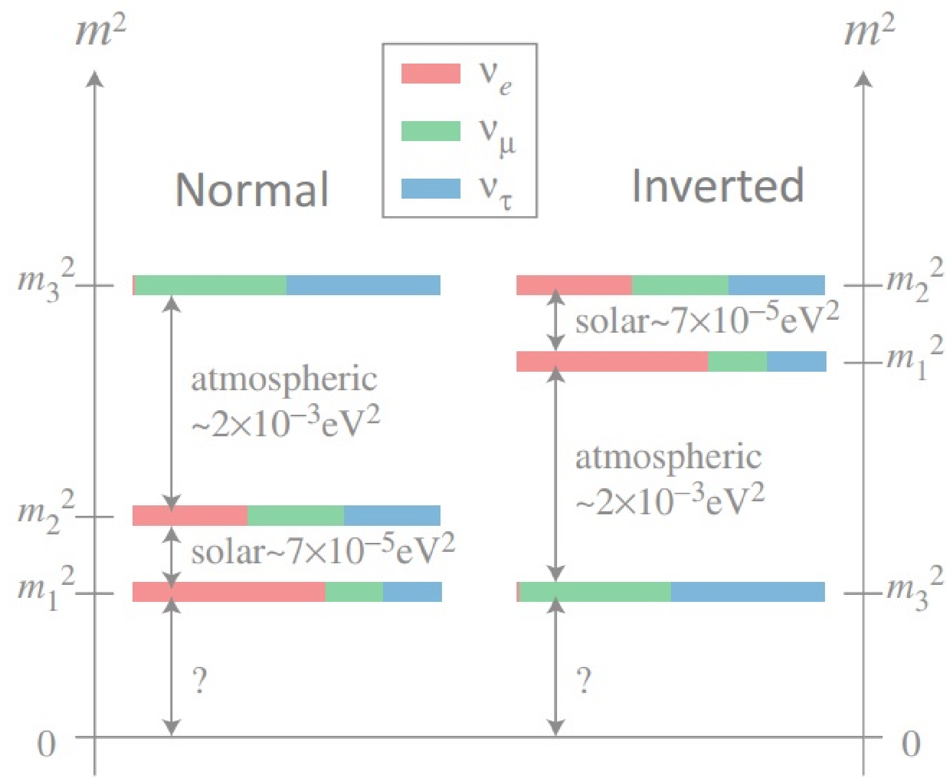
Solar / Long baseline reactor	Short baseline reactor / Long baseline accelerator	Atmospheric / Long baseline accelerator	Neutrinoless double beta decay

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

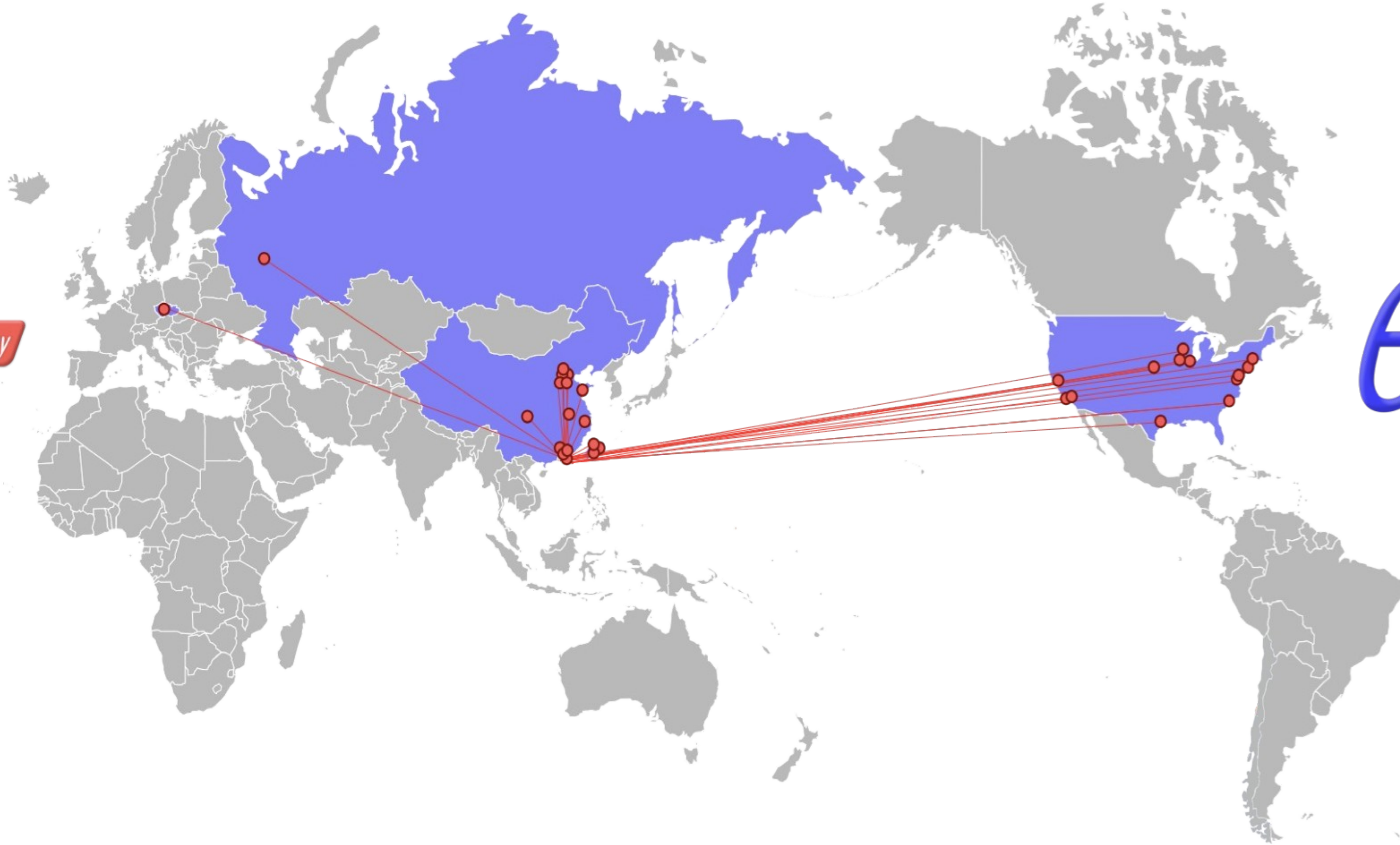
$$\begin{aligned} P_{\text{sur}} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\ &\equiv 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}\sin^2\Delta_{ee}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

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

$$|\Delta m^2_{31}| \simeq \Delta m^2_{ee} \pm 2.3\times 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{32}| \simeq \Delta m^2_{ee} \mp 5.2\times 10^{-5}\ \text{eV}^2$$



Daya Bay Collaboration



3 continents, ~200 collaborators, ~40 institutions

Daya Bay nuclear complex

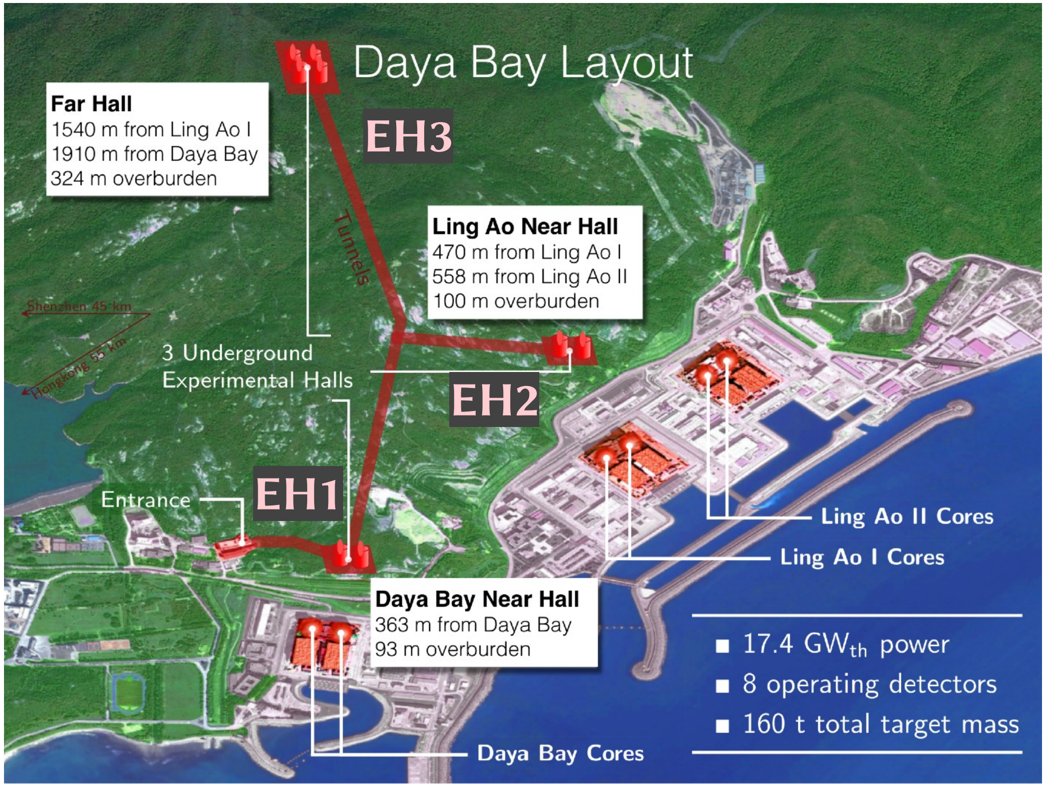
One of the world's most powerful nuclear power complexes and most intense antineutrino sources:

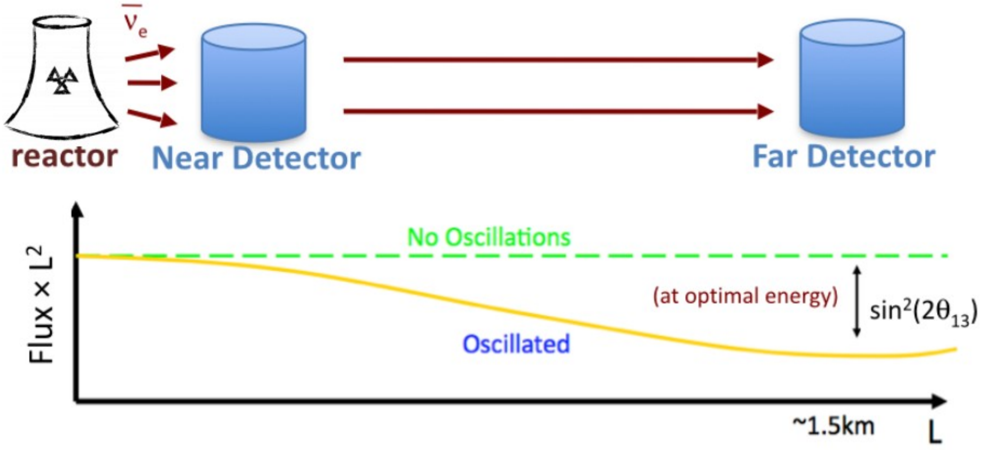
- Three plants (Daya Bay, Ling Ao I, Ling Ao II)
- Each plant: Two 2.9 GW_{th} pressurized water reactors
- Total power of 17.4 GW_{th} $\Longrightarrow$ $\mathbf{\sim 4 \times 10^{21}\ \overline{\nu}_e / s}$
- Power company provides time series data on power, burnup, fission fractions, etc.

Daya Bay experiment

Primary goal: Measure θ_{13} (and Δm^2_{ee}) via the short-baseline disappearance of reactor antineutrinos

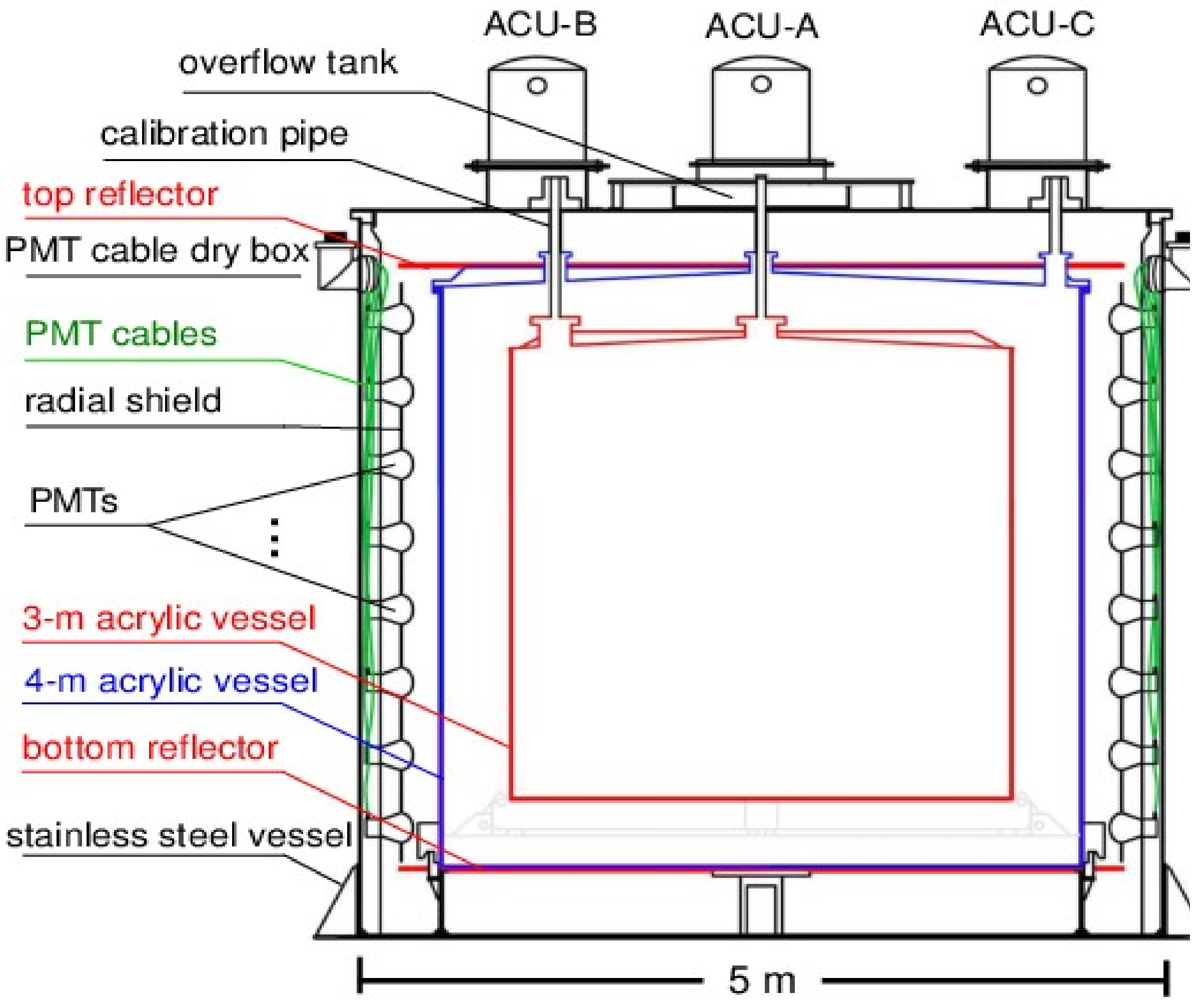
- **High statistics:** Powerful reactors, multiple large detectors
- **Low background:** Mountain overburden, radiopure materials, muon veto
- **Low systematics:** Near/far measurement essentially cancels (correlated) efficiency and reactor uncertainties
- **Optimal layout:** Far hall at disappearance maximum





*Nucl. Inst. Meth. A **811**, 133 (2016)*

Antineutrino detectors (ADs)



3 m inner acrylic vessel contains target mass: ~20 metric tons of 0.1% Gd-doped liquid scintillator

4 m outer acrylic vessel contains ~21 tons of undoped liquid scintillator to reduce inefficiency resulting from energy leakage from target

5 m stainless steel vessel contains ~40 tons of mineral oil for shielding, **192 8" PMTs** on walls for light detection

Three **Automated Calibration Units (ACUs)** on top for deployment of calibration sources

Nucl. Inst. Meth. A **773**, 8 (2015)

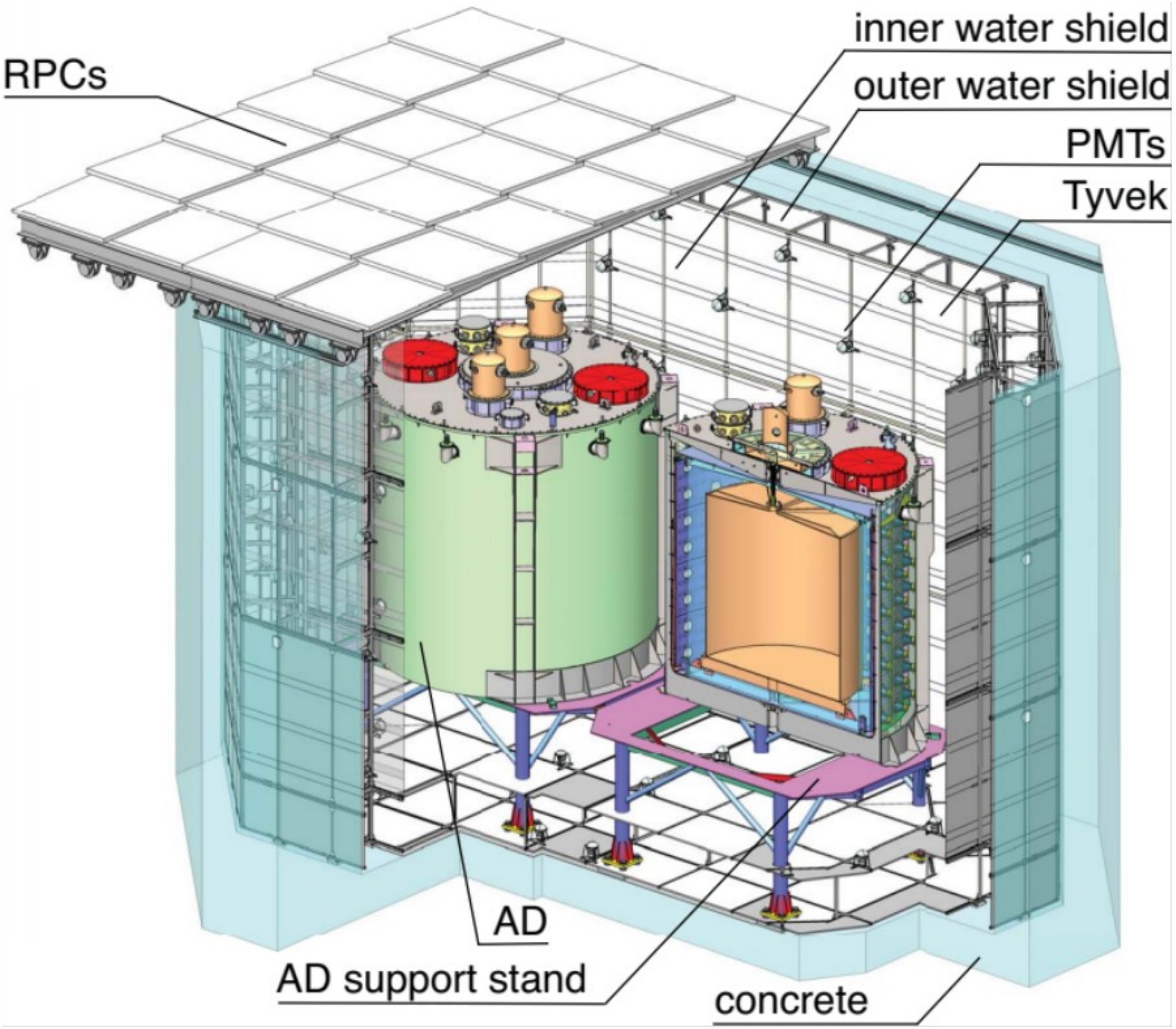
Muon system

Water pools (WPs) provide shielding against cosmic-ray muons, secondary neutrons, etc.

WPs are instrumented with PMTs, providing a muon veto system via detection of Cherenkov light

WPs are divided into inner and outer pools, optically and electronically isolated

Resistive plate chambers (RPCs) above WPs enable auxiliary studies of muons and associated backgrounds



Detecting antineutrinos

Antineutrinos are detected via
inverse β decay (IBD):

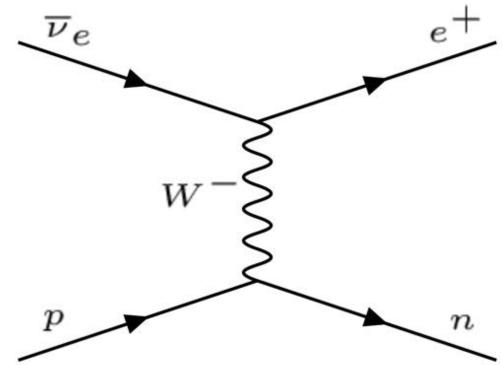
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

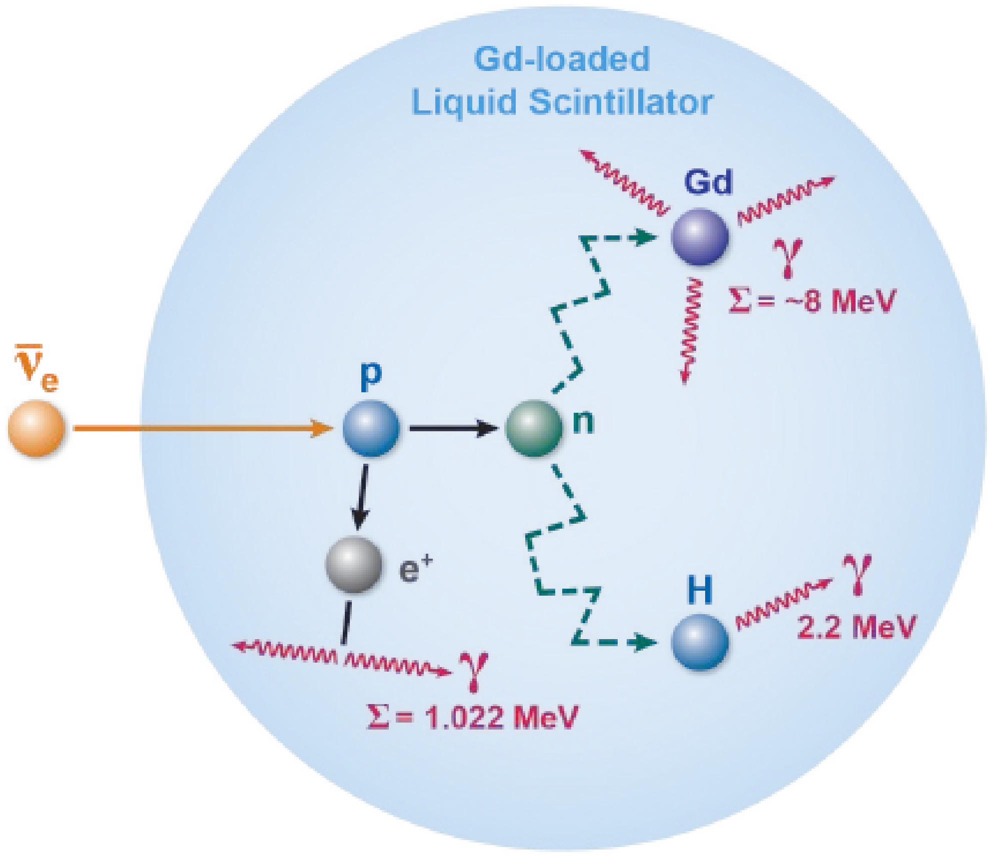
After an average of 28 μs, the neutron is captured on Gd, resulting in ~8 MeV of deexcitation gamma-rays. The coincident pulses provide a clean experimental signature, where

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

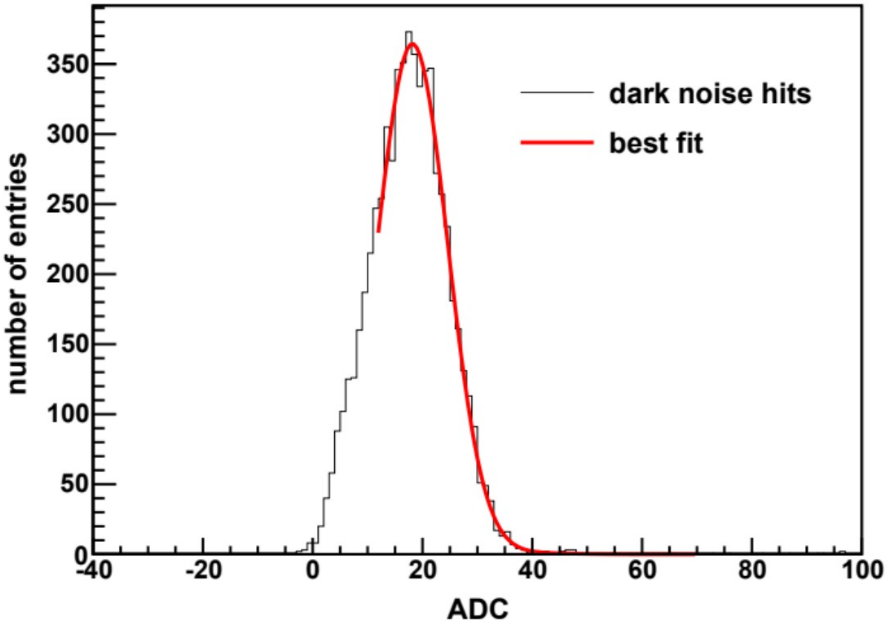
In terms of reconstructed ("prompt") energy (including annihilation γ's),

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

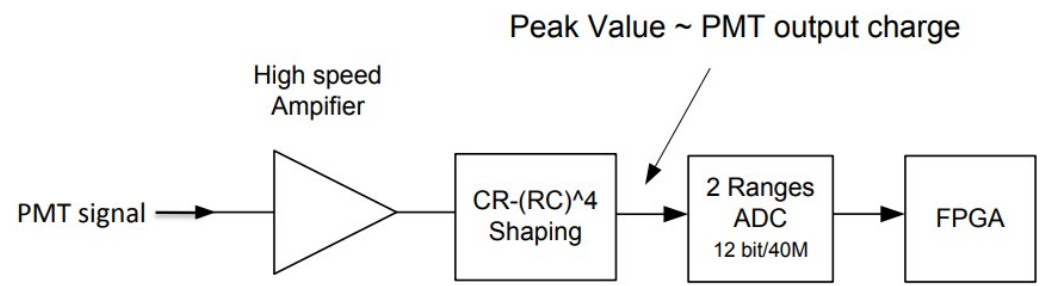




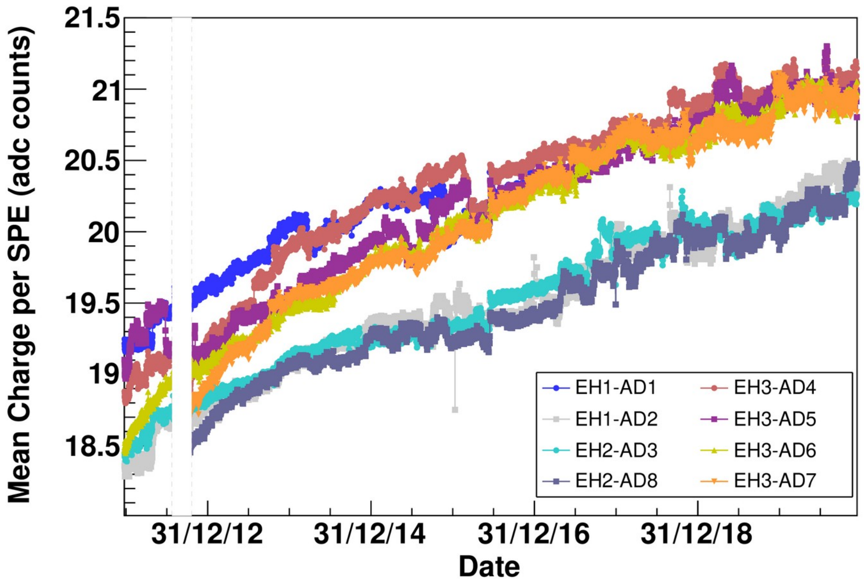
Channel calibration

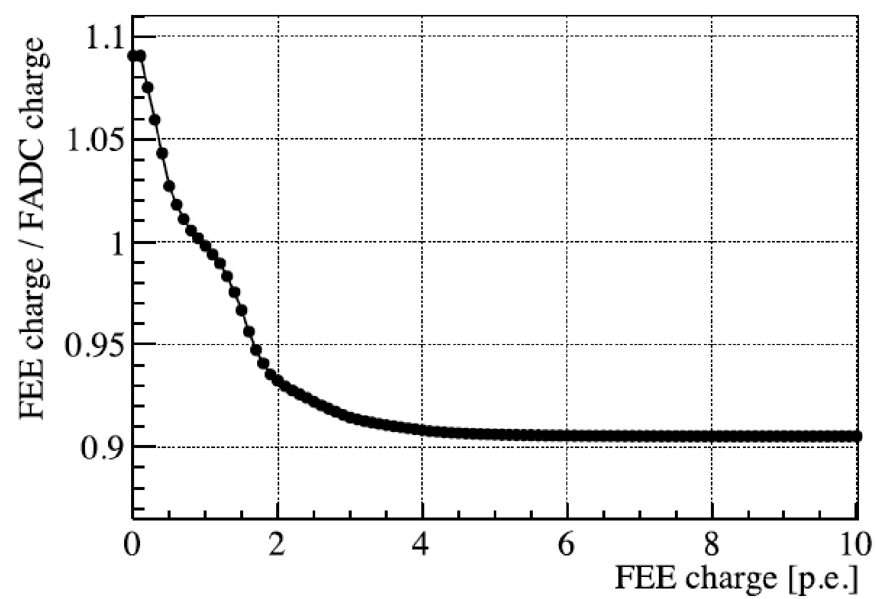


Gain (ADCs/photoelectron) measured by fitting single photoelectron peak from dark noise



Nonlinearity of front-end electronics (FEE) corrected channel-by-channel (new in this analysis)

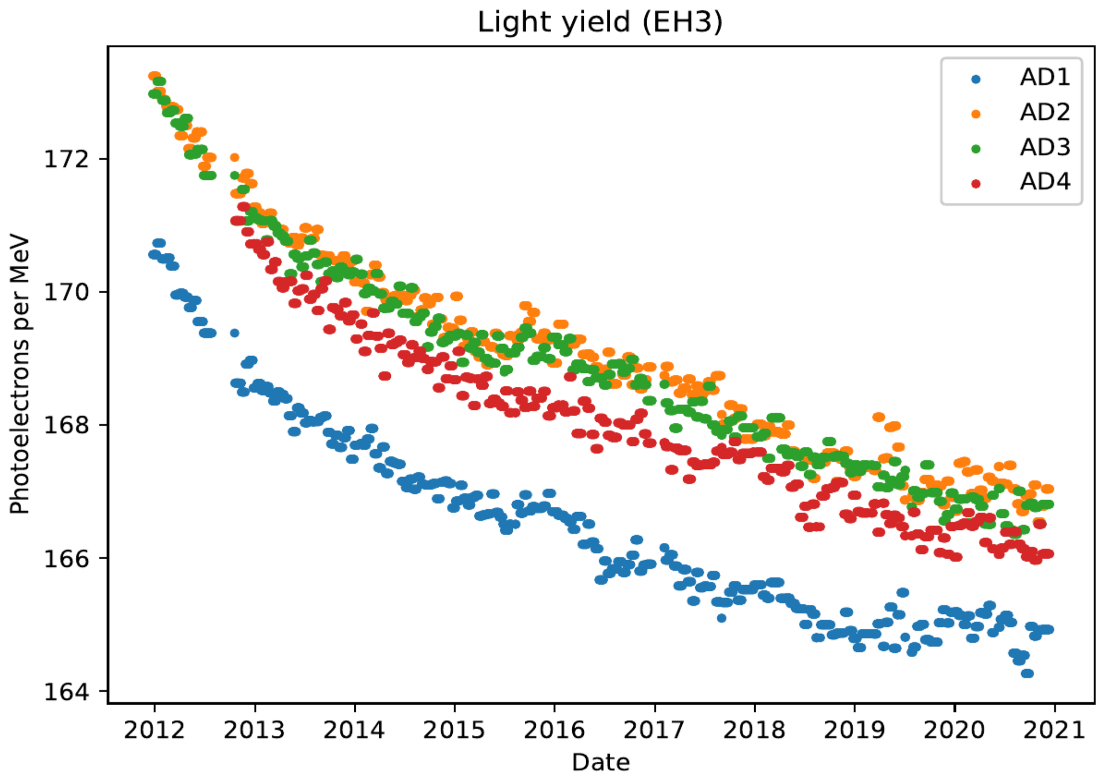


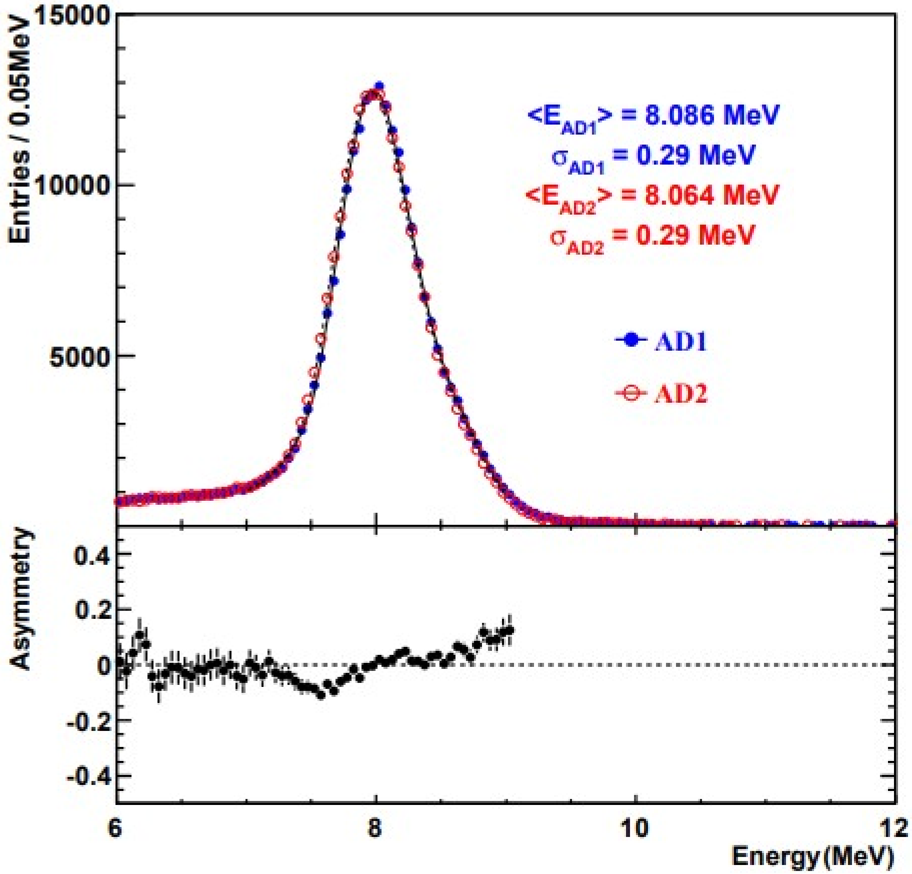


Energy scale

Energy scale (photoelectrons/MeV) determined from fit to energy spectrum of spallation neutron captures on Gd following energetic muons

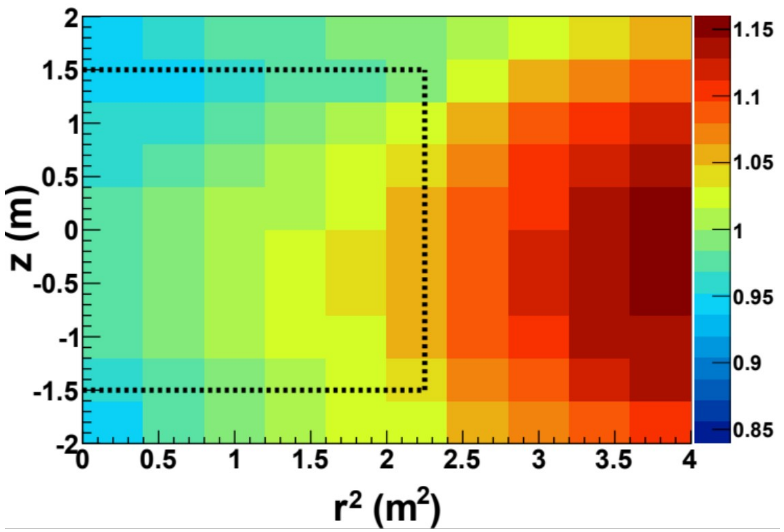
Downward trend consistent with scintillator degradation

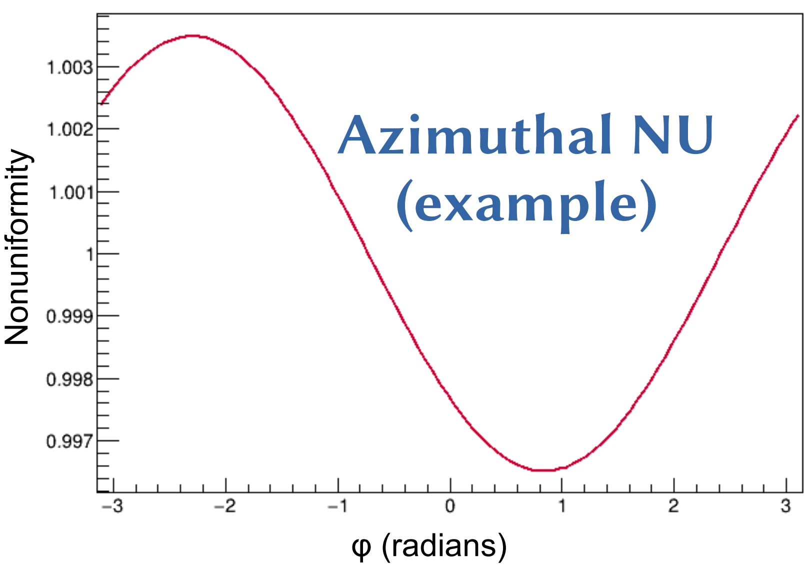




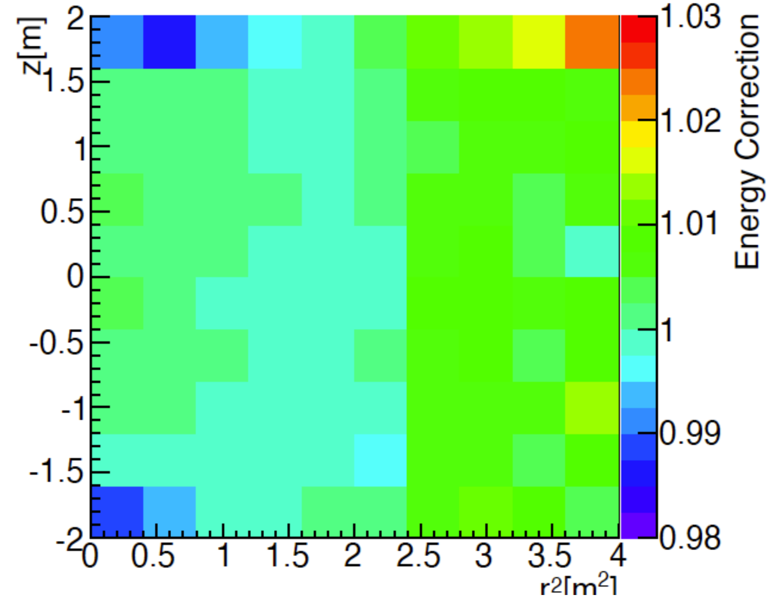
Energy nonuniformity

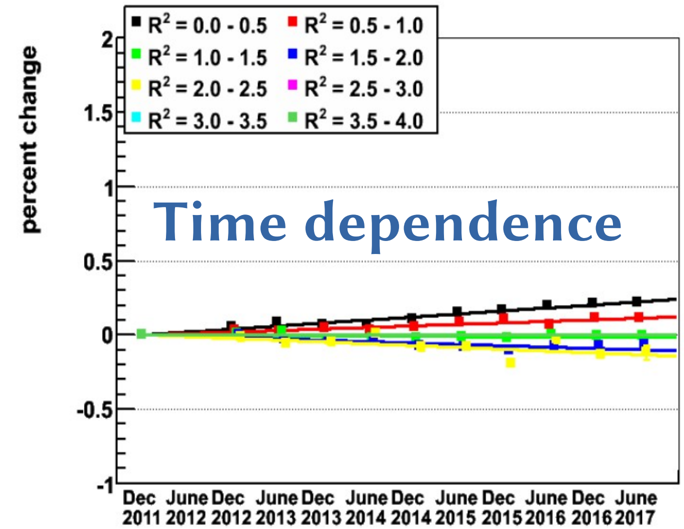
Nonuniformity from spallation neutrons





Add'l correction from improved NU measurement w/ α's (NEW)

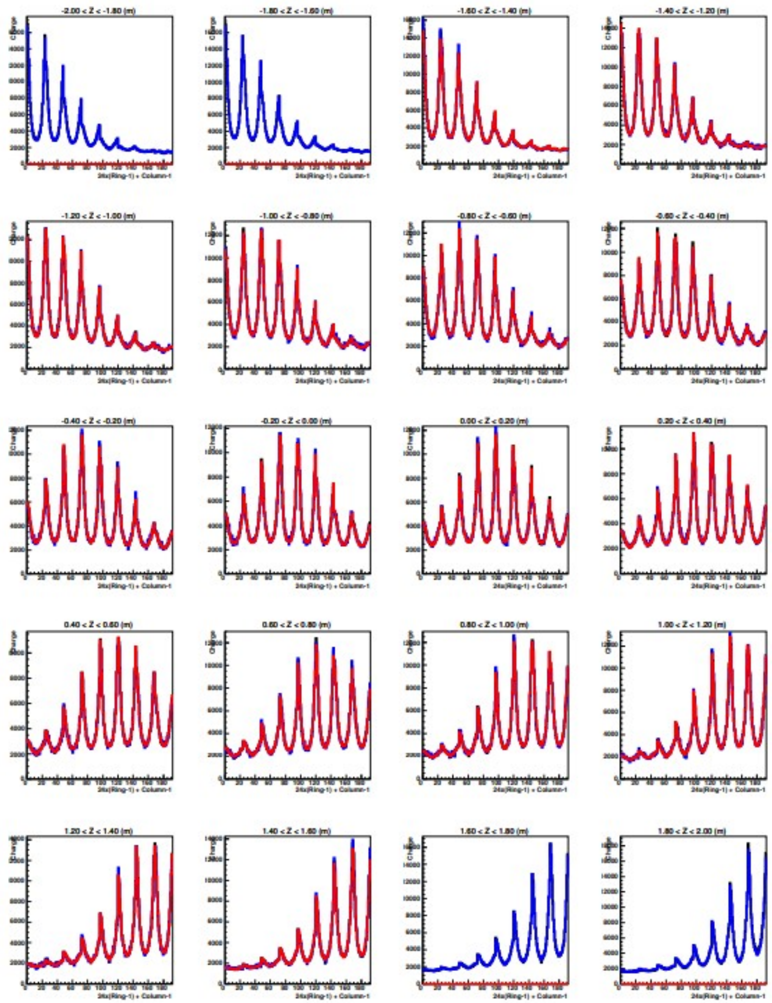




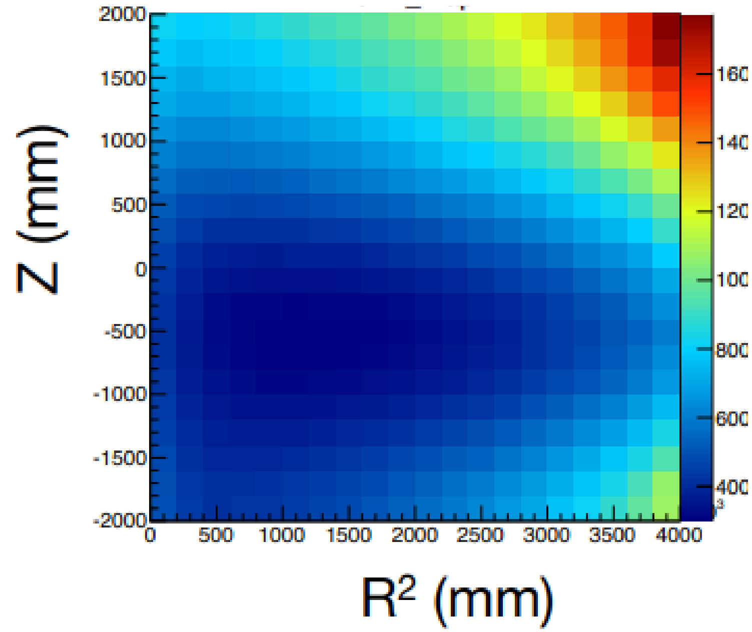
Vertex reconstruction

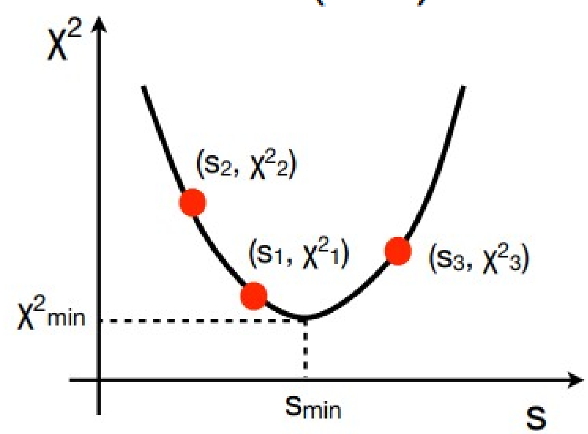
To correct for nonuniformity, need position of vertex. Use a **library of charge templates** from MC.

Some example templates



Example event: χ^2 map from comparing to templates



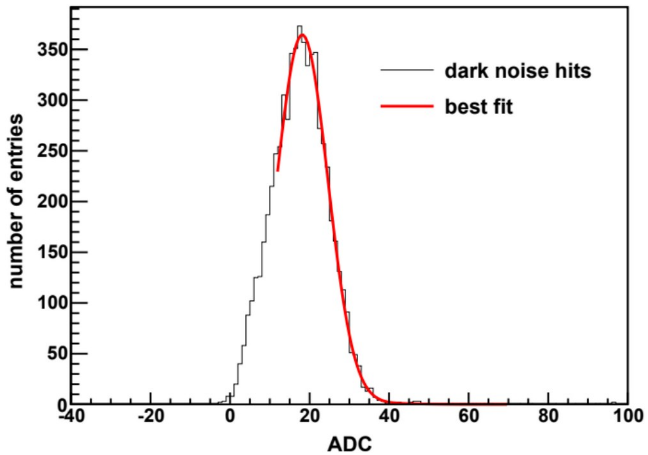


Finally, interpolate

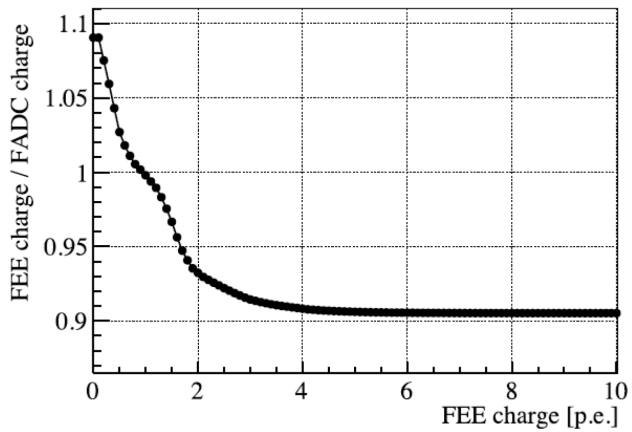
*Phys. Rev. D **95**, 072006 (2016)*

Reconstructed energy

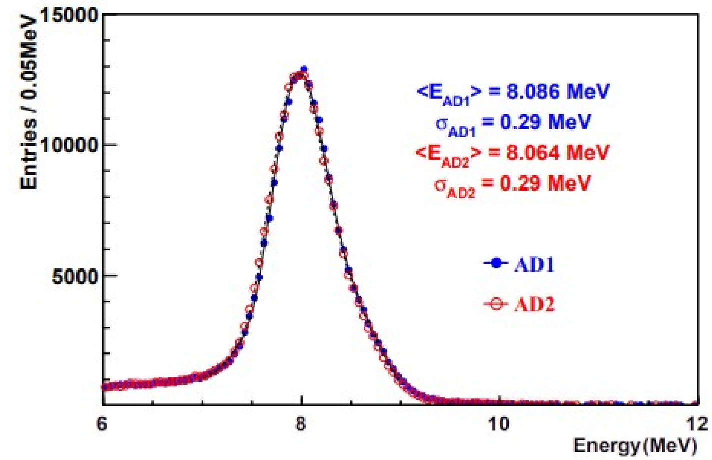
Gain calibration (ADC counts per photoelectron) from dark noise



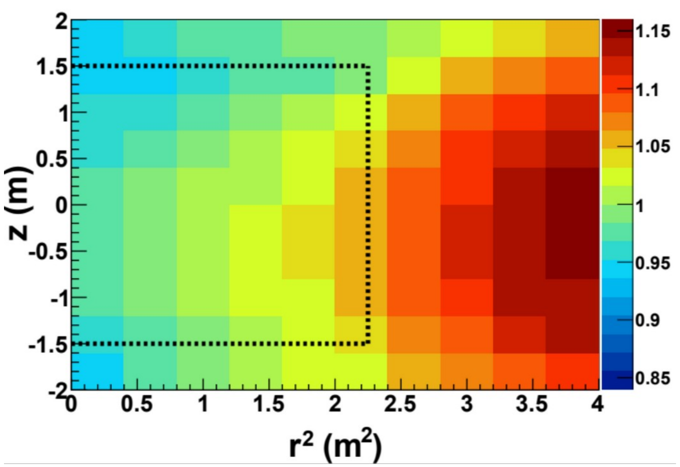
Channel-by-channel correction for **electronics nonlinearity** (NEW)



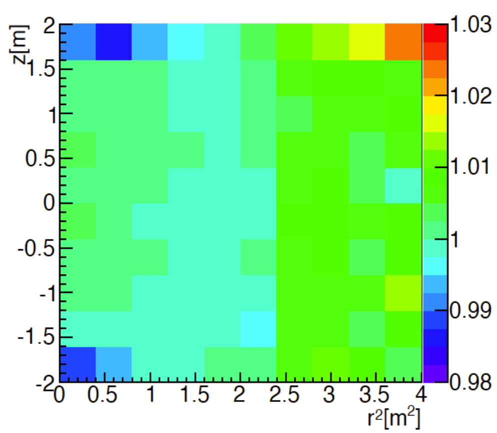
Energy scale calibration (photoelectrons per MeV) from spallation neutrons



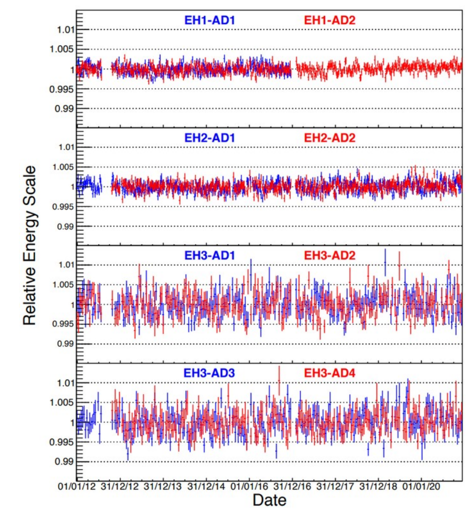
Nonuniformity correction from spallation neutrons



Additional correction based on α's (NEW)



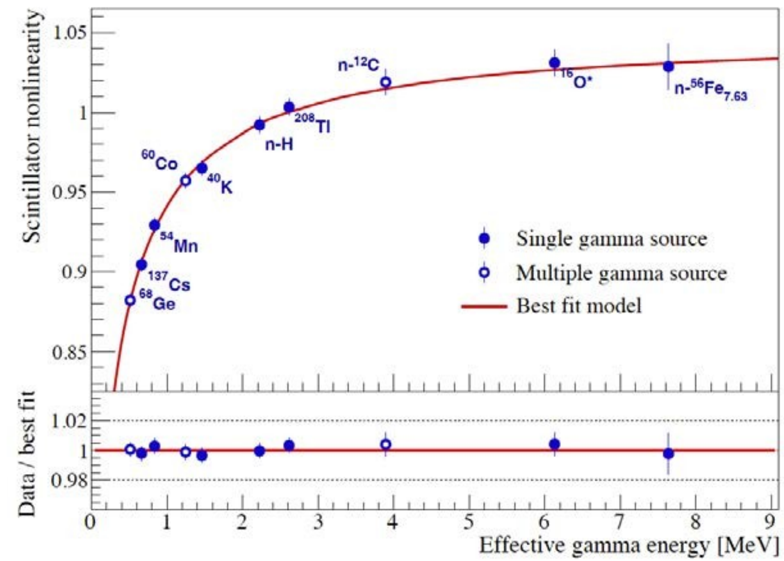
End result: Stable and consistent reconstructed energy



Nucl. Inst. Meth. A ***940***, *230 (2019)*

Antineutrino energy

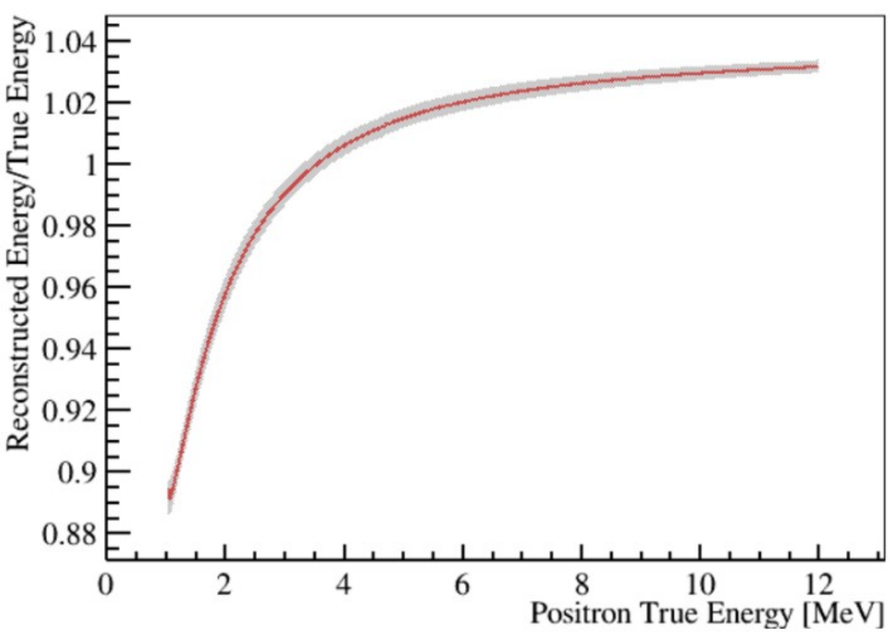
Take reconstructed energy, apply correction for scintillator nonlinearity (NL), get "true" deposited energy (e^+ ionization + annihilation)

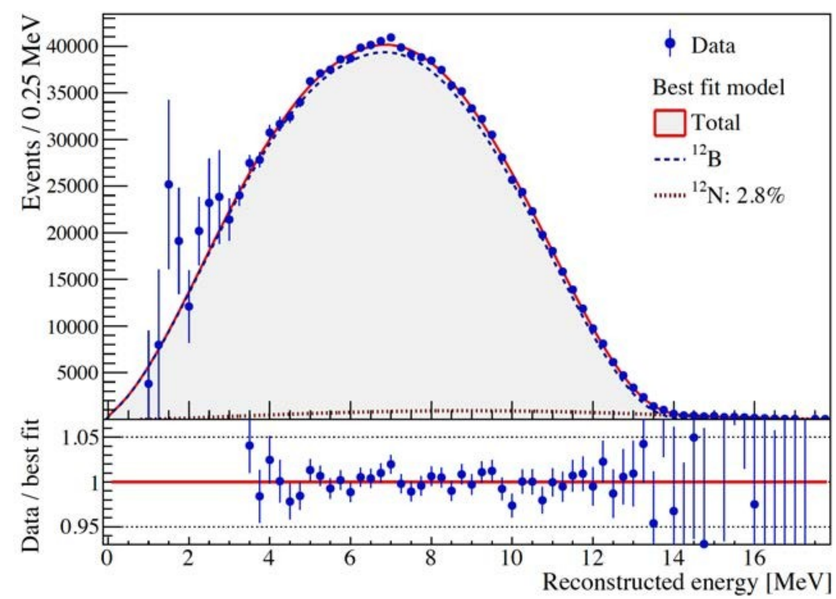


NL correction derived from calibration data, cross-checked with cosmogenic beta spectra

Antineutrino energy (for oscillation analysis) follows from kinematics:

$$E_\nu \approx E_{true} + 0.8\ \text{MeV}$$



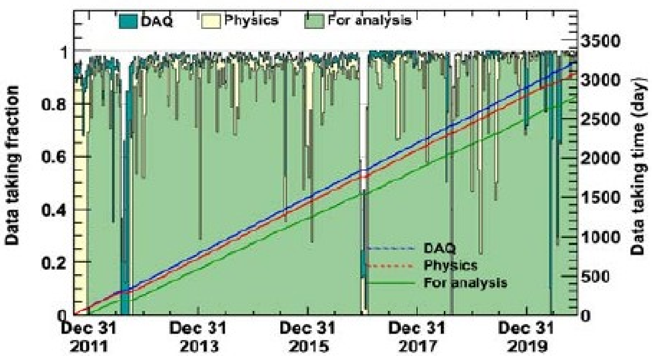


Oscillation analysis with full dataset

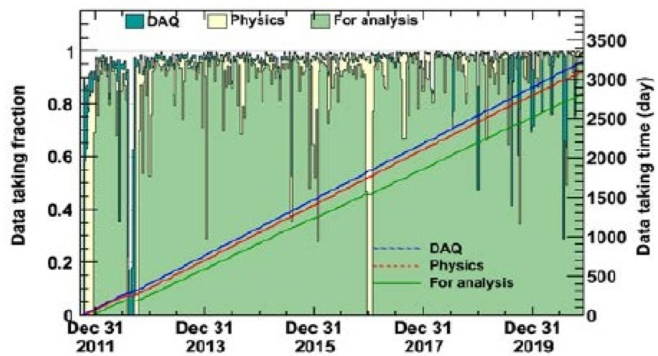
Paper accepted by PRL; arXiv:2211.14988

Full dataset!

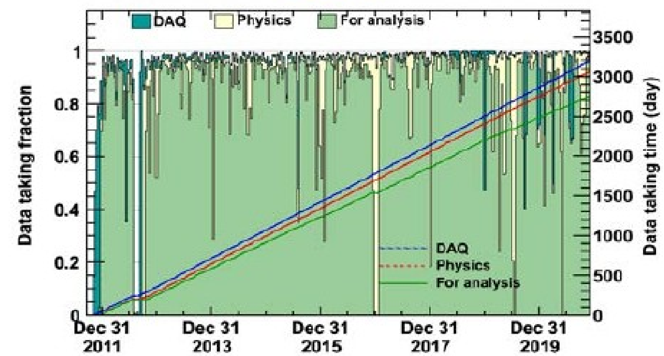
EH1



EH2



EH3



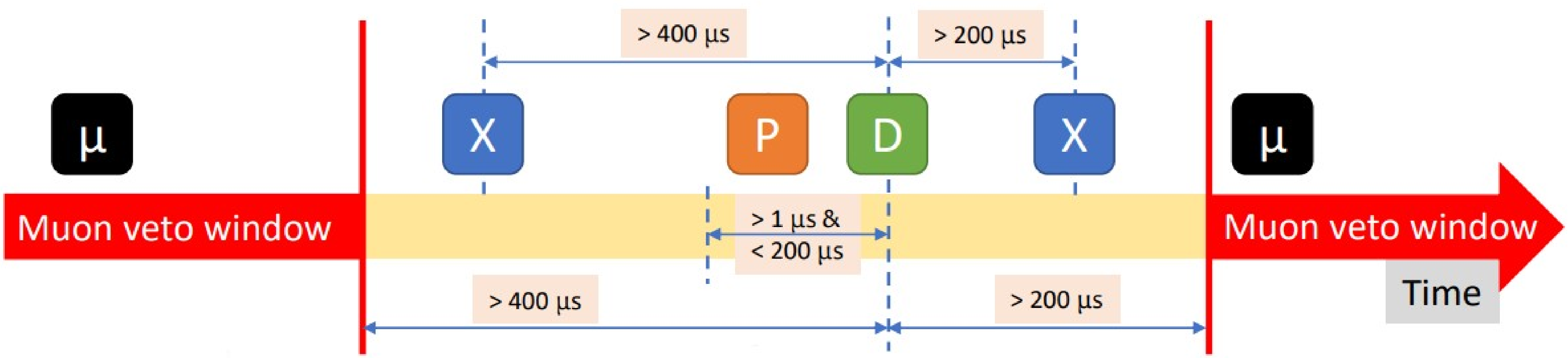
Configuration	EH1	EH2	EH3	Start date — end date	Duration (days)
6-AD	2	1	3	24 Dec 2011 — 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 — 21 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 — 12 Dec 2020	1417
Total					**3158**

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

IBD selection

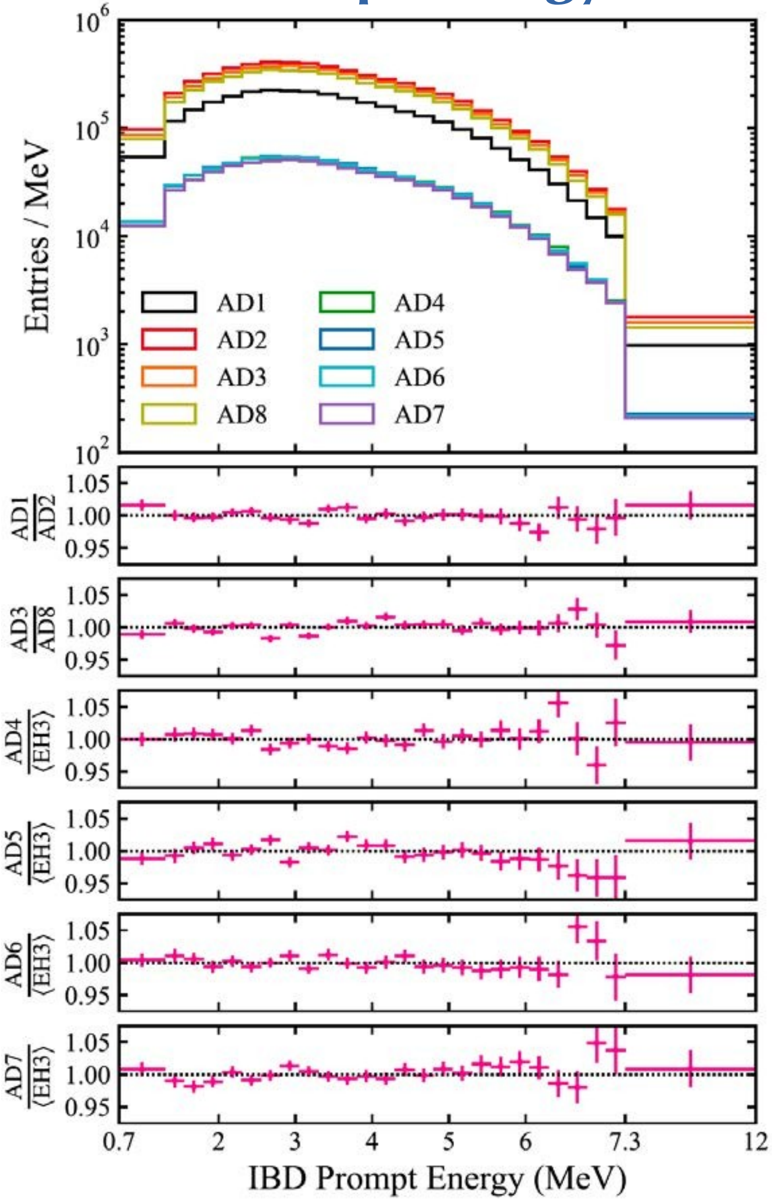
P = Prompt-like signal; D = Delayed-like signal; X = Non-muon signal

Muon veto	Water pool muon	Veto [-2 μs, 200 μs] after NHIT > **12** in OWS or IWS			
	AD muon	Veto [-2 μs, 1 ms] after > **20 MeV** signal in AD			
	AD shower	Veto [-2 μs, 0.4 s] after > **2 GeV** signal in AD			
	IWS muon veto	Veto [-2 μs, 10 μs] after **6** < NHIT ≤ **12** in IWS			(NEW)
Flasher cut		Standard, DocDB-7424	Residual, DocDB-12462		
Energy cut		0.7 ≤ P ≤ 12 MeV	6 ≤ D ≤ 12 MeV	0.7 ≤ X ≤ 20 MeV	
Decoupled Multiplicity Cut (DMC)	Full DMC for post-6AD period	Each D	One P within (-200 μs, -1 μs) && no X within (-400 μs, 200 μs)		
			Time to last muon veto window > 400 μs		
			Time to next muon veto window > 200 μs		

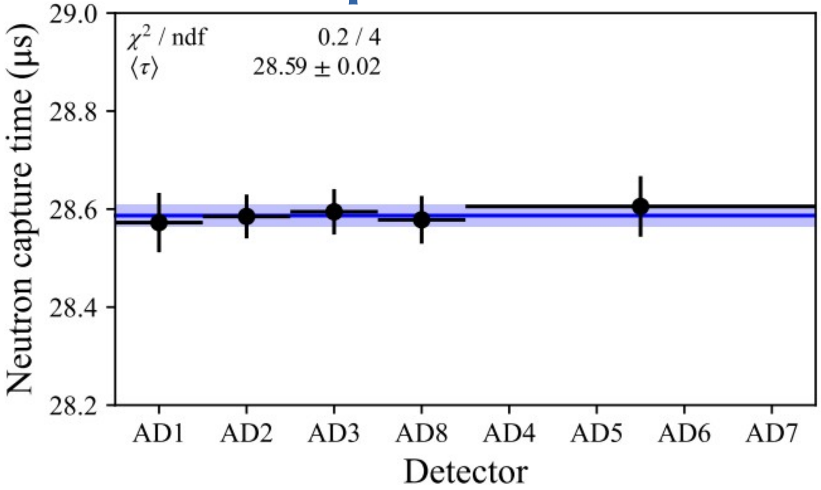


AD consistency

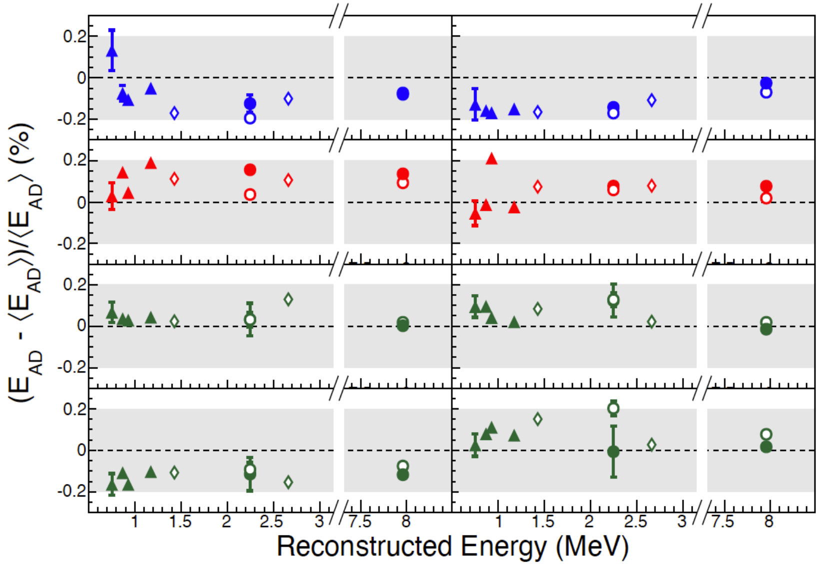
Prompt energy



Capture time



Energy scale



Efficiencies

Muon veto efficiency

$$T_\mu = T_{un-vetoed} - N_{un-vetoed} \cdot 600\mu s$$

$$\epsilon_\mu = \frac{T_\mu}{T_{before}}$$

Total time outside veto windows

# of unvetoed periods > 600 µs

Total livetime (“before” vetoing)

Decoupled multiplicity cut (DMC) efficiency

$$\epsilon_{DMC} = P\left(0; R_x \cdot 400\mu s\right) \cdot P\left(0; R_x \cdot 200\mu s\right)$$
$$= e^{-R_x \cdot 600\mu s}$$

Other efficiencies:

- Equal among ADs in Asimov case
- AD-uncorrelated uncertainties included in fit via pull terms.
- Correlated uncertainties do not affect the oscillation analysis

Description	Efficiency	Uncertainty Correlated	Uncertainty Uncorrelated
Protons per AD		0.0092	0.0003
Gd capture ratio	0.8417	0.0095	0.001
Spill-in	0.0486	0.01	0.00019
Delayed energy cut	0.9271	0.0097	0.00072
Prompt energy cut	0.9981	0.001	0.0001
Capture time cut	0.987	0.0012	0.0002
Flasher cut	0.9998	0.0001	0.00013
Total	0.802484	0.01927	0.00132

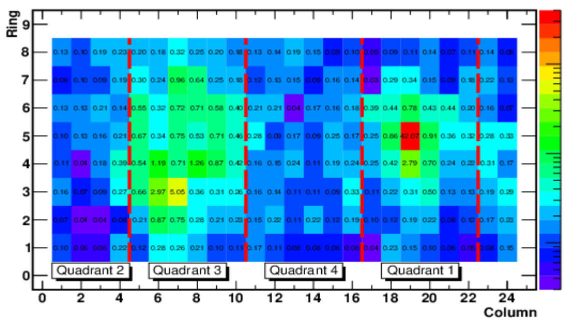
Backgrounds

Backgrounds

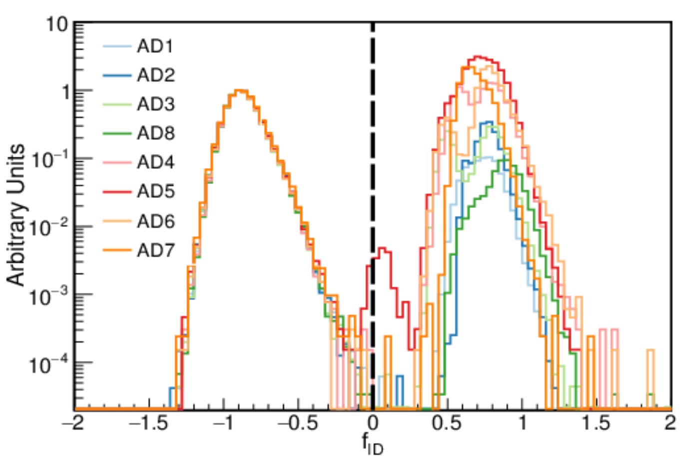
- **Flashers:** Light emission from PMTs
  - Single triggers, not pairs. Removed in order to avoid excessive rate of accidentals.
- **Accidentals** (uncorrelated pairs)
- **^{9}Li/^{8}He:** "Long-lived" (~100 ms) cosmogenic isotopes. Can emit free neutron after β decay.
- **Fast neutrons:** Ejected by muons from surroundings. Prompt signal from proton recoils.
- **"Muon-X":** Prompt signal from low-energy muons. Various delayed signals:
  - **Michel electron** from muon decay
  - **Neutron capture** from spallation
  - **Retrigger** from electronic ringing
- **^{241}Am^{13}C calibration source:** Pairs of gammas from neutron inelastic scattering followed by capture in detector materials
- **^{13}C(α,n)^{16}O:** α from natural radioactivity followed by capture of ejected neutron

Flashers (PMT light emission)

$$f_{\max} = \frac{Q_{\max}}{Q_{\mathrm{tot}}} \qquad f_{\mathrm{quad}} = \frac{Q_{q3}}{Q_{q2} + Q_{q4}}$$



$$f_{\mathrm{ID}} = \log_{10}\left[f_{\mathrm{quad}}^2 + \left(\frac{f_{\max}}{0.45}\right)^2 \right]$$

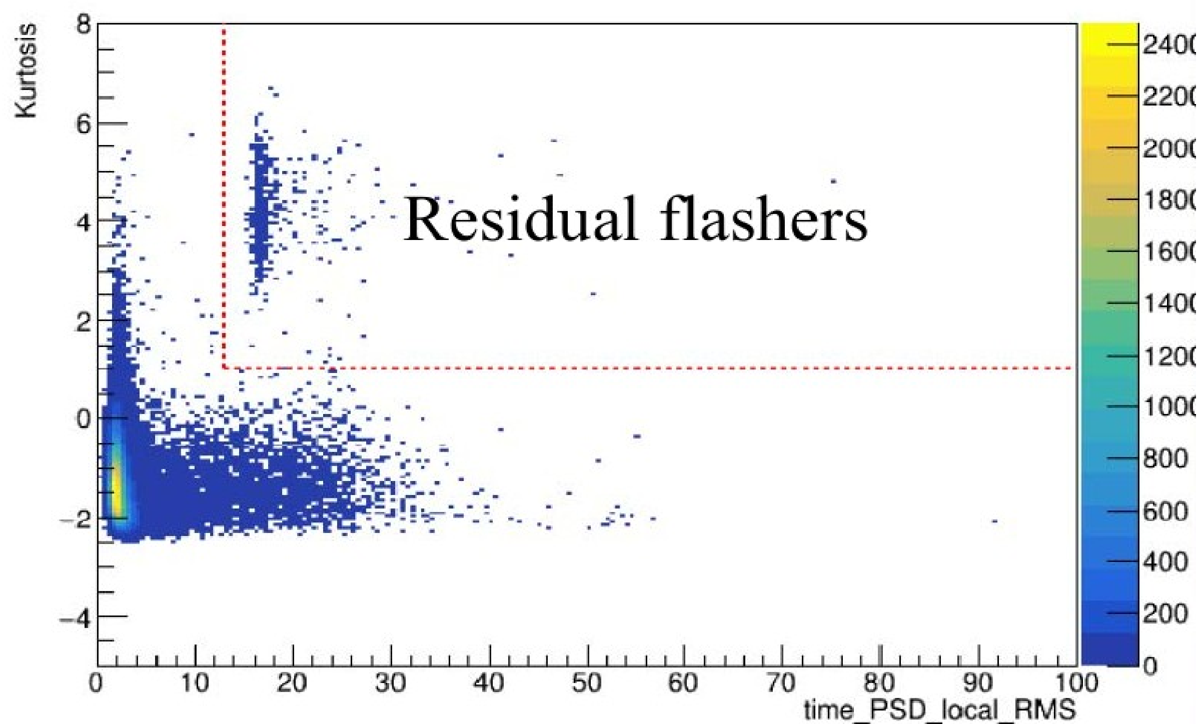


Flashers identified as events with $f_{\mathrm{ID}} > 0$.

Additional flasher reduction using time distribution of PMT hits.

New "residual" flashers discovered in data added for this analysis, efficiently removed with new cut:

time_PSD_local_RMS > 13 && Kurtosis > 1



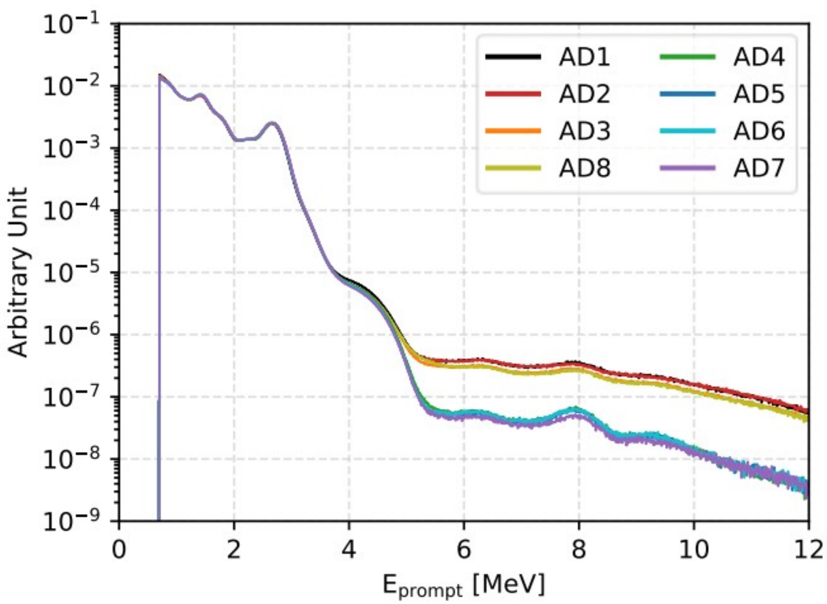
Accidentals (random pairs)

- 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

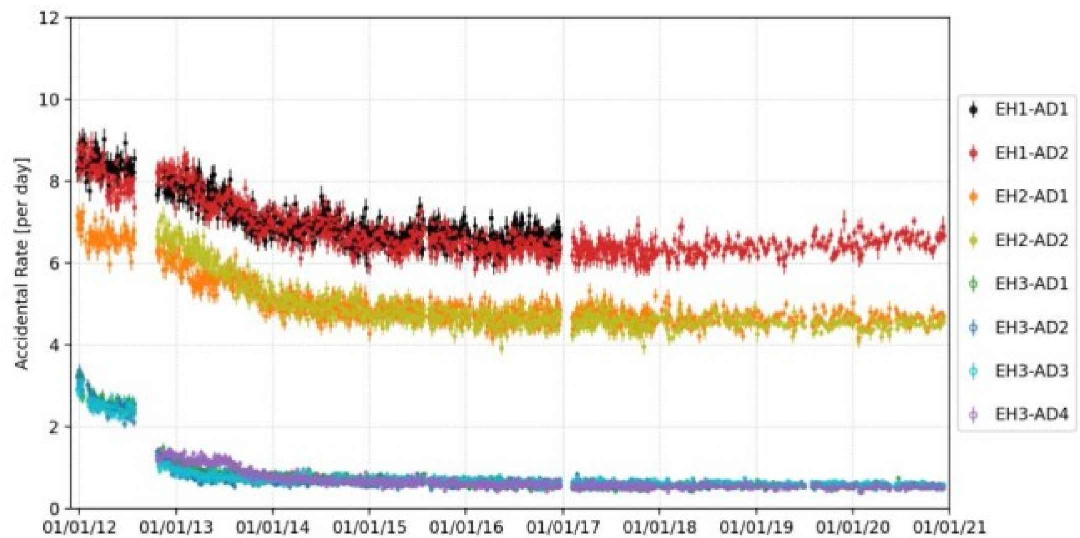
$$R_p = \frac{N_p}{T_\mu P(0, R_x \cdot 600\mu s)} = \frac{N_p}{T_\mu e^{-R_x \cdot 600\mu s}} \qquad R_d = \frac{N_d}{T_\mu P(0, R_x \cdot 600\mu s)} = \frac{N_d}{T_\mu e^{-R_x \cdot 600\mu s}}$$

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

Spectral shape (directly from singles selection)



Rate of accidentals over time



^{9}Li/^{8}He

"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.

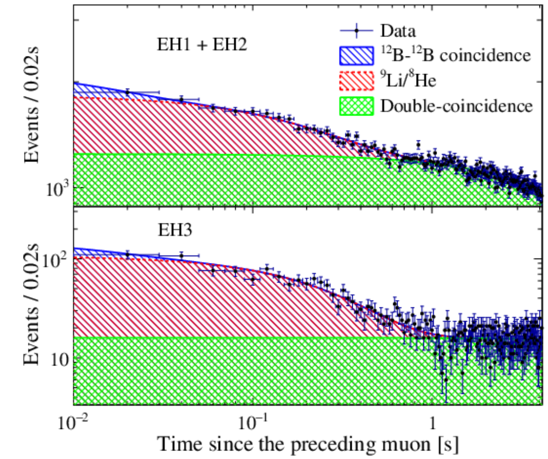
Can be statistically measured using time correlation to muons. Two methods:

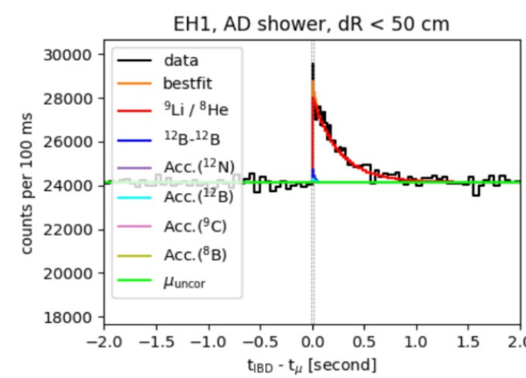
- "Time-to-last-muon": For each IBD candidates, fill a histogram with time to last muon (not necessarily parent muon), then fit:

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

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

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





^{9}Li/^{8}He (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

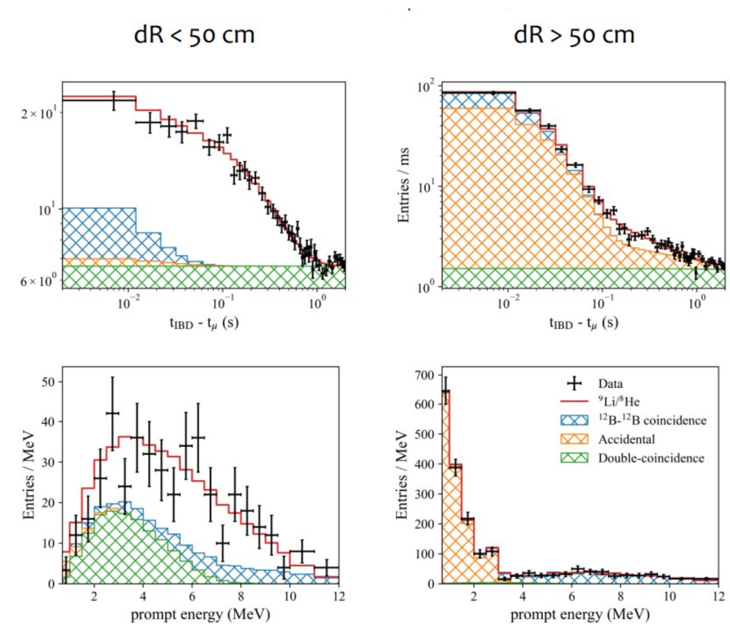
Neutron tagging efficiency leads to large uncertainty

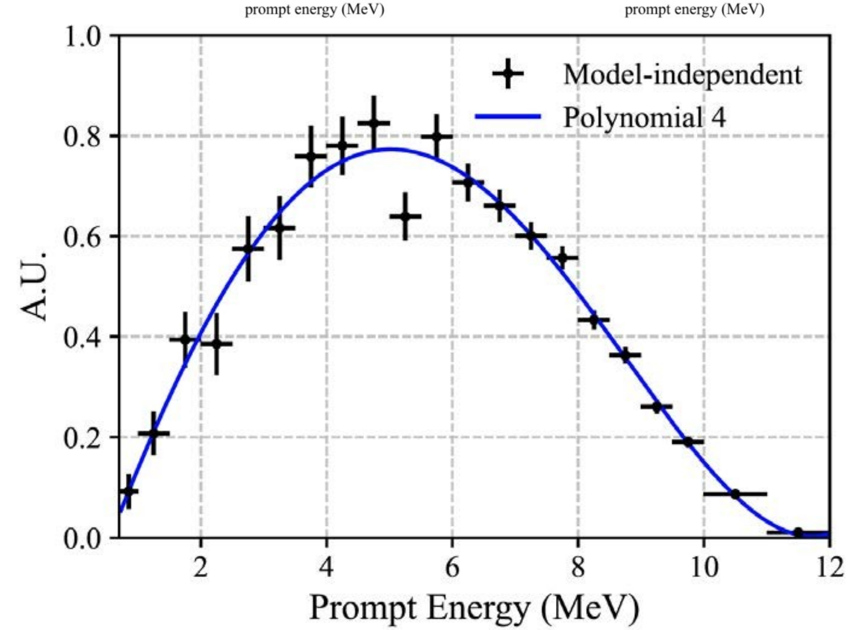
New approach: Multi-dimensional fit (time off-window):

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

Uncertainty on rates reduced by factor of ~2

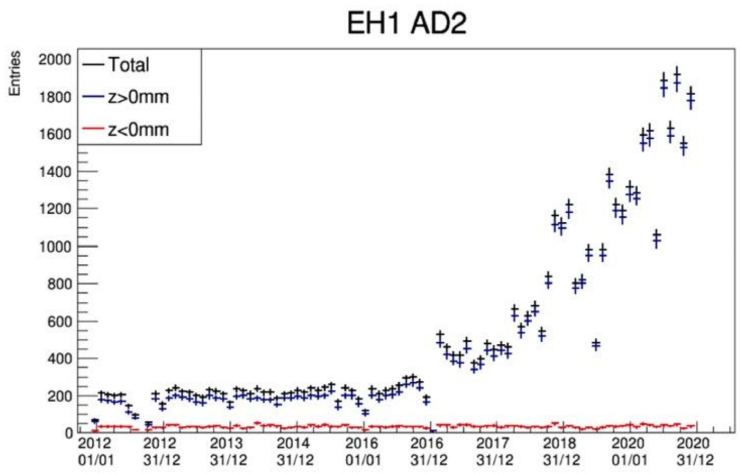
Spectrum extracted simultaneously





Fast neutrons and "muon-X"

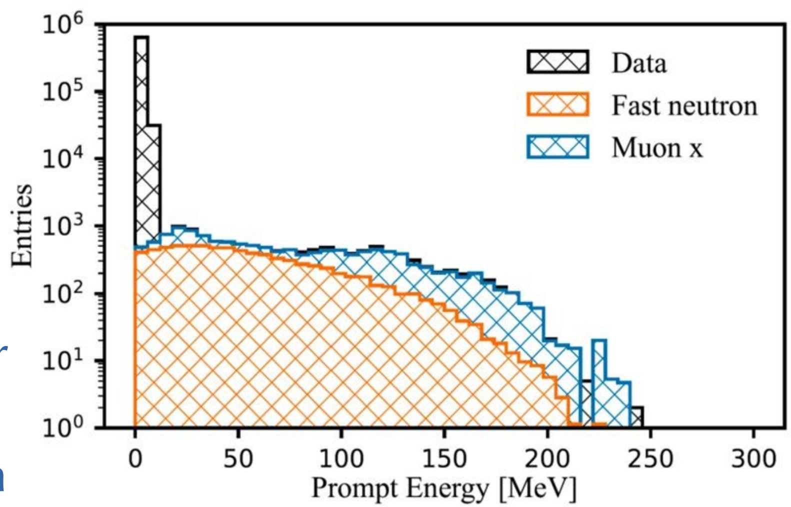
Fast neutrons: Ejected by muons from surrounding rocks and other materials
- Prompt signal: Proton recoils
- Delayed signal: Neutron capture



Muon-X: Prompt signal from low-energy muons (below veto threshold). Delayed signal from three classes:
- Muon decay: Michel electron
- Muon spallation: Neutron capture
- Muon retrigger: PMT ringing

Muon-X is a new background, caused by degradation of veto efficiency due to PMT failures in the water pools

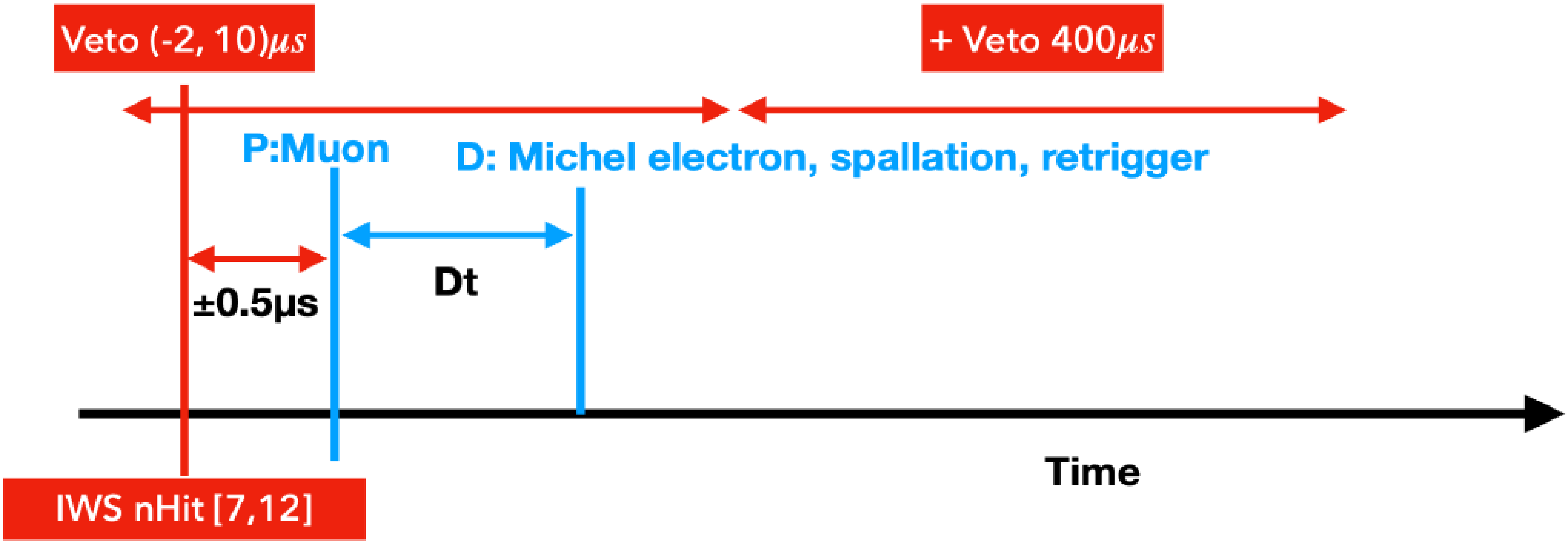
Study all of these together by using IBD sample with extended prompt energy cut (250 MeV)



Use OWS tagging to get sub-12 MeV prompt spectrum for fast neutrons, likewise IWS tagging for muon-X. Get tagging efficiency (i.e. scaling factor) from >12 MeV region

Muon-X reduction

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



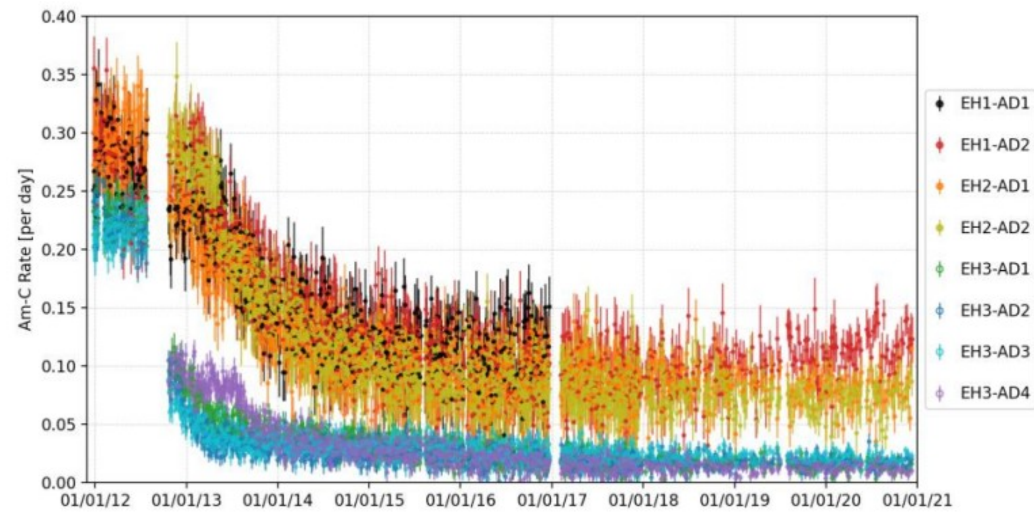
Minimal impact on muon veto efficiency

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

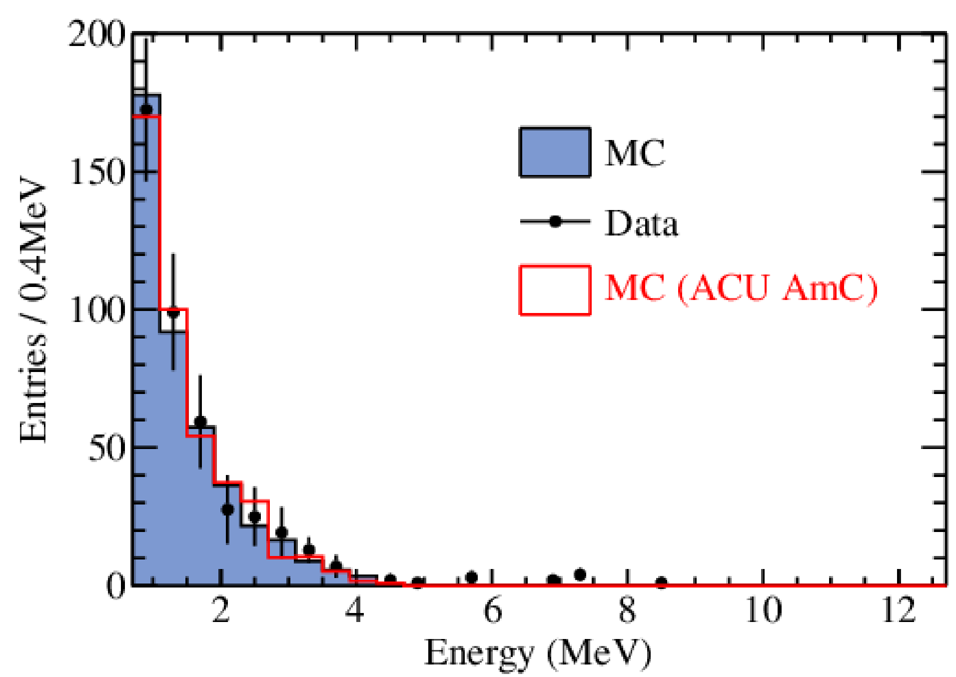


Rate is proportional to that of "neutron-like" singles in the top half of the AD:

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

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

Prompt spectrum consistent between MC and HAS data

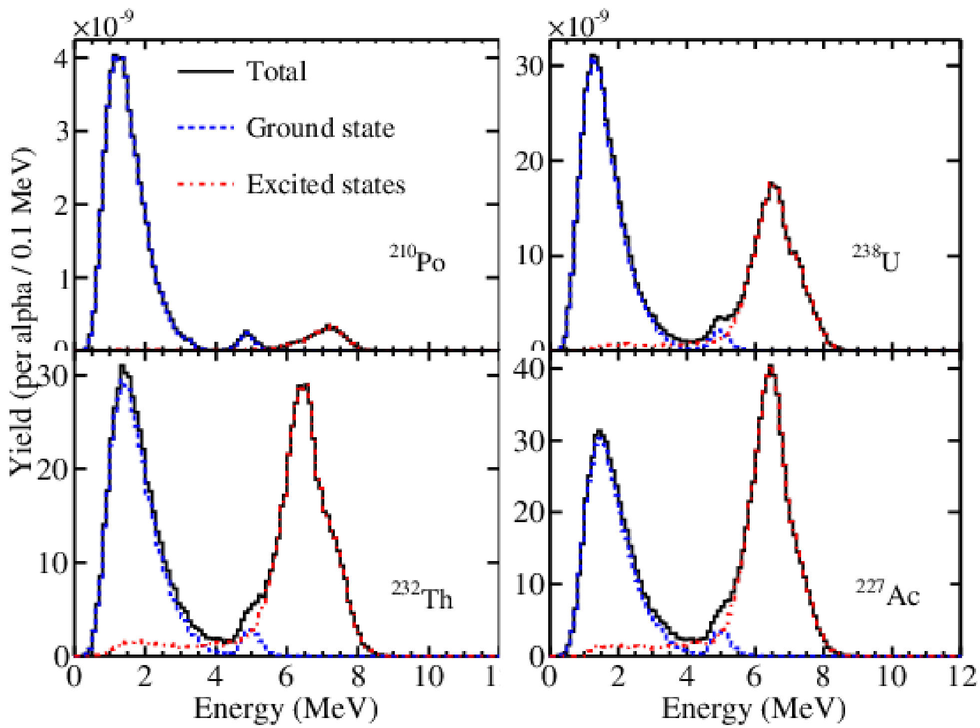


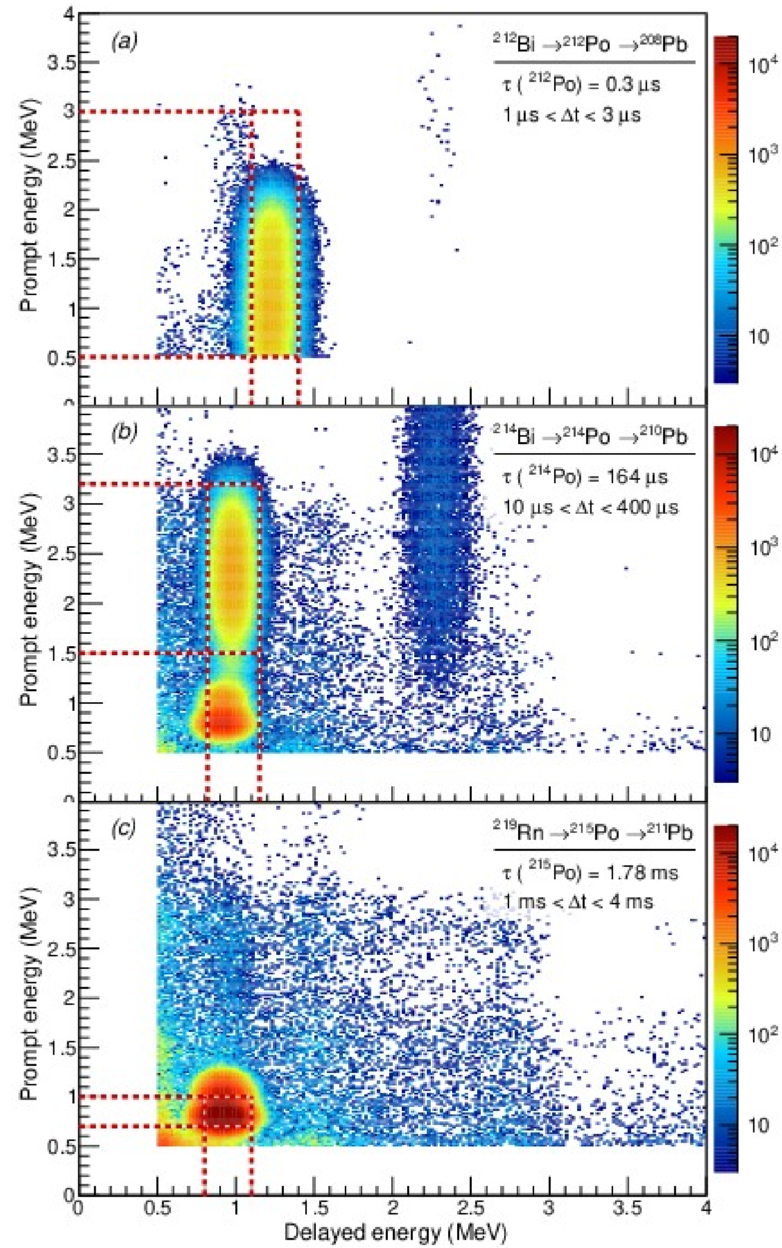
α-n reactions

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.



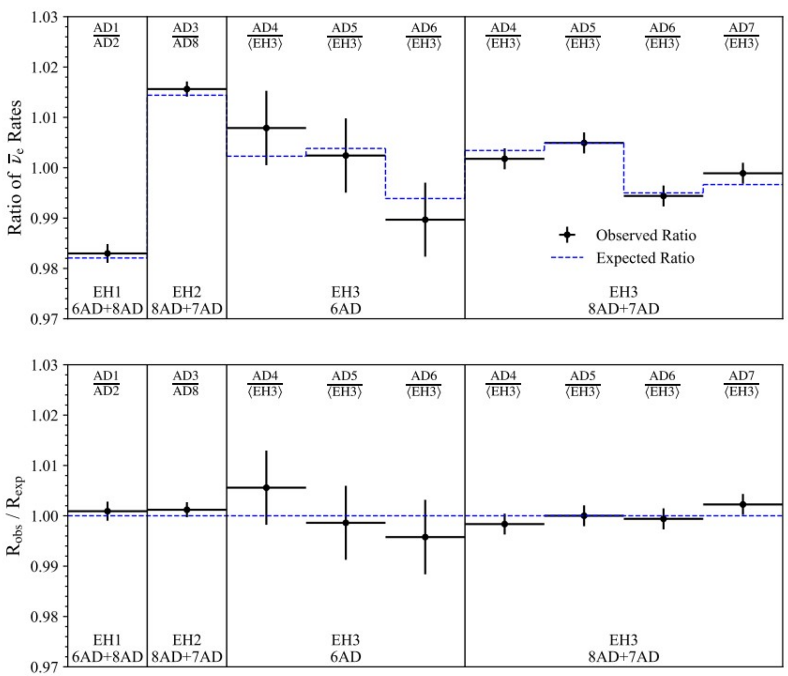


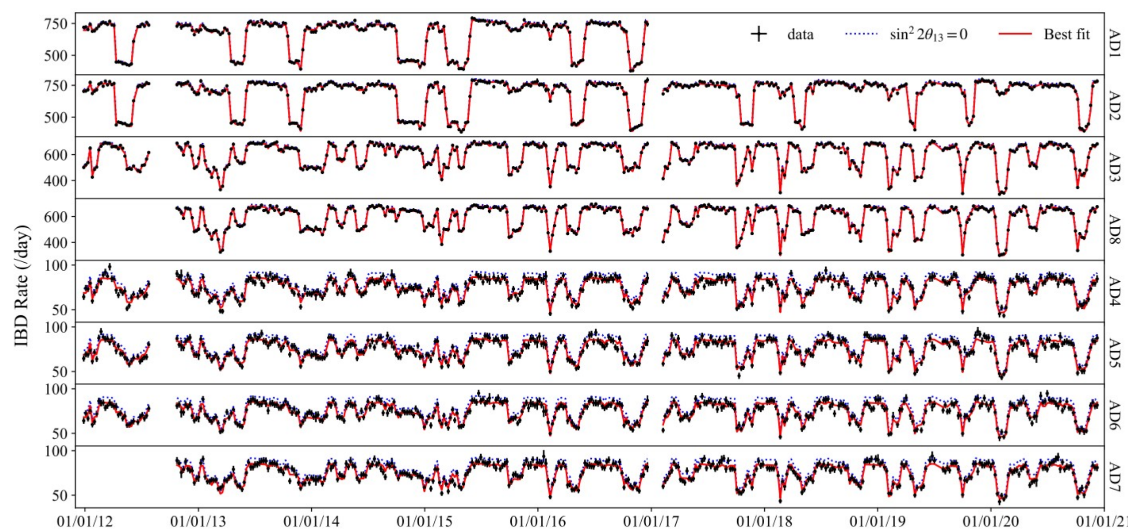
Oscillation analysis

IBD rates

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513
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 n + 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}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{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
$\overline{\nu}_e$ rate [day^{-1}]	657.2 ± 1.1	685.1 ± 1.0	599.5 ± 0.8	591.7 ± 0.8	75.0 ± 0.2	75.2 ± 0.2	74.4 ± 0.2	74.9 ± 0.2

Backgrounds at sub-2% level!





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)

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

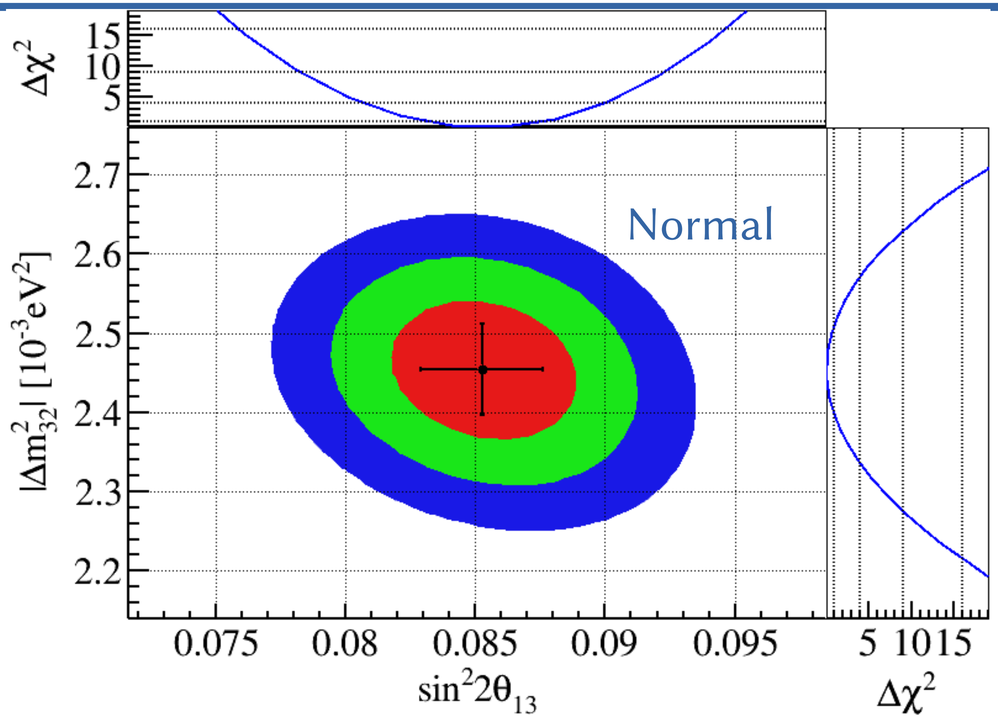
ε_l = Nonlinearity pulls
ε_d^{IAV} = Energy leakage pulls
ε_R = Correlated reactor flux pull
ε_r (ε_r^n, ε_r^s, ε_r^f,) = Uncorr. reactor flux pulls (non-equilibrium, spent fuel, fission frac.)
η = Background rate/shape pulls

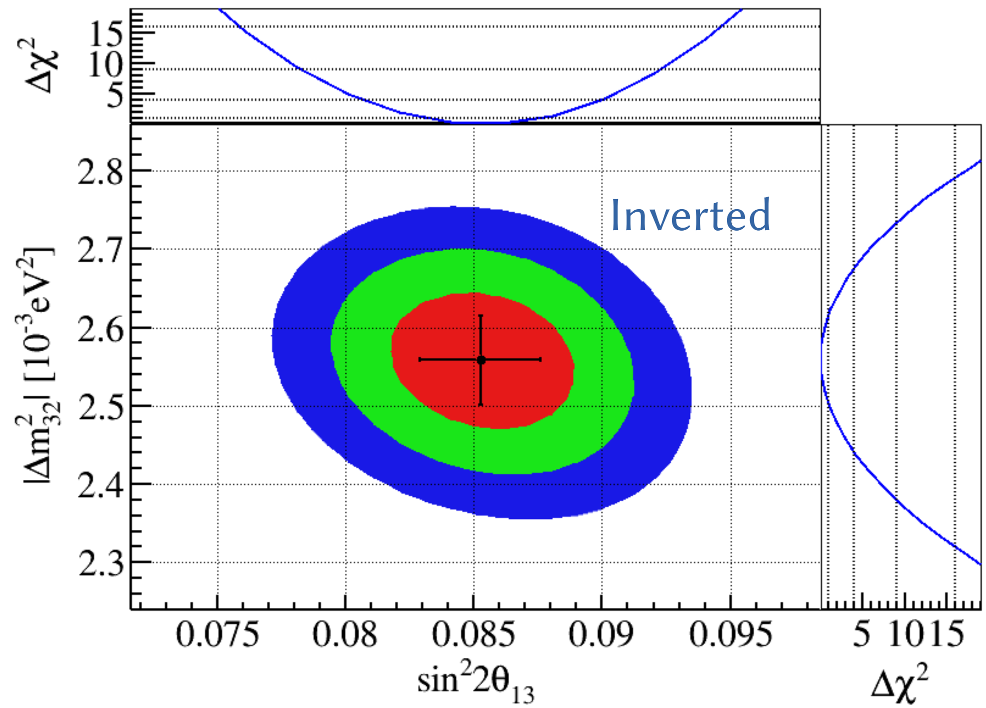
χ^2 expression

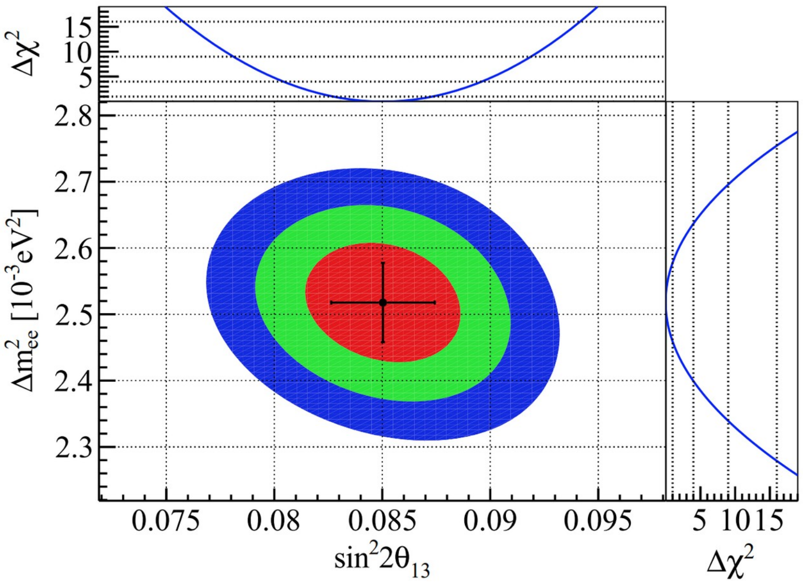
$$\chi^2 = \min_{\gamma} \sum_{d=1}^{6}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i} + \sum_{d=1}^{8}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i} + \sum_{d=1}^{7}\sum_{i=1}^{29} \frac{[M_d^i - F_d^i]^2}{F_d^i}$$
$$+ \sum_{d=1}^{8} \left[(\frac{\varepsilon_d}{\sigma_d})^2 + (\frac{\eta_d^{acc}}{\sigma_d^{acc}})^2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

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)



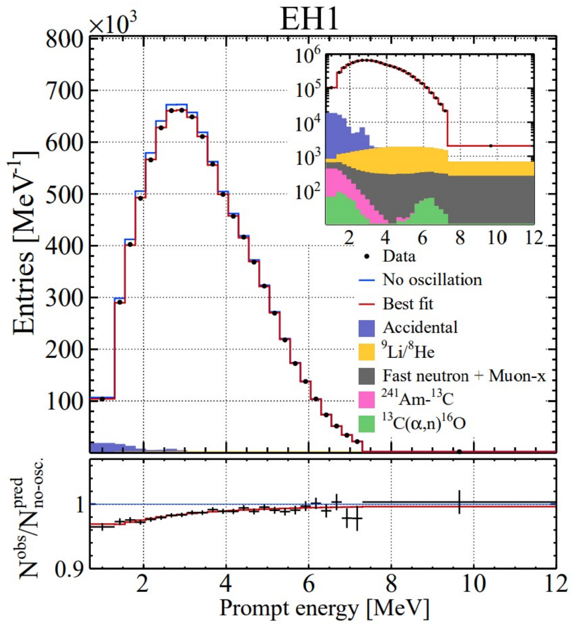


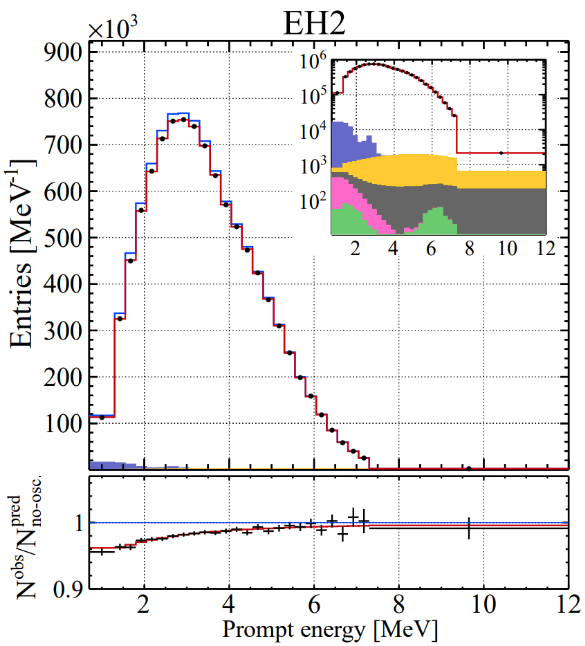


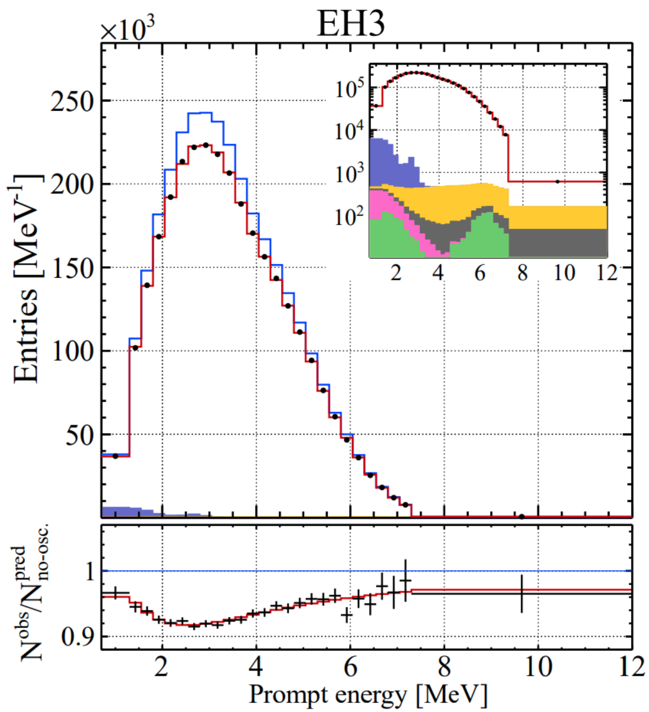
χ^2/ndf: 559/517

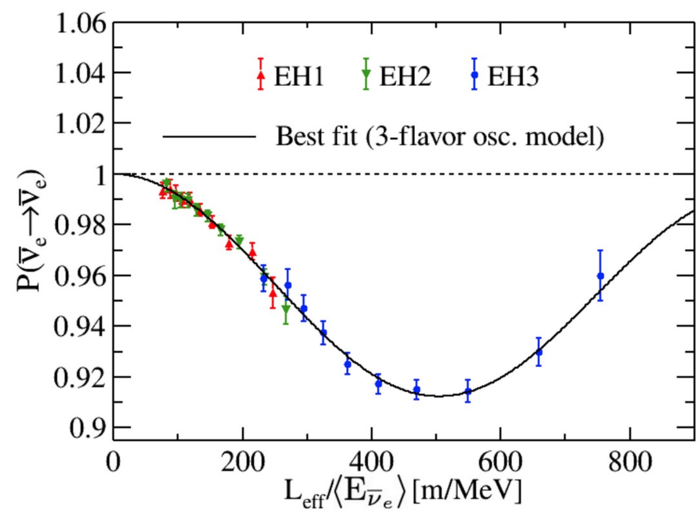
Mass order	$\sin^2 2\theta_{13}$	Δm^2 (10^{-3} eV^2)
Normal, Δm^2_{32}	0.0851 ± 0.0024	2.466 ± 0.0060
Inverted, Δm^2_{32}	0.0851 ± 0.0024	-2.571 ± 0.0060
Δm^2_{ee}	0.0852 ± 0.0024	2.519 ± 0.0060

Prompt spectra; L/E profile

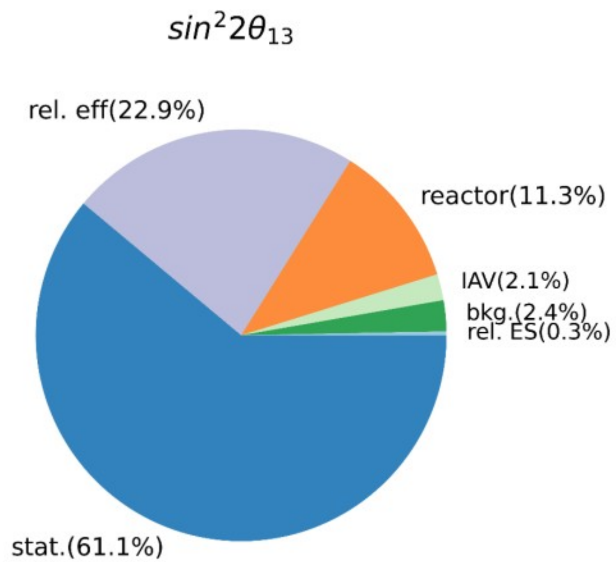


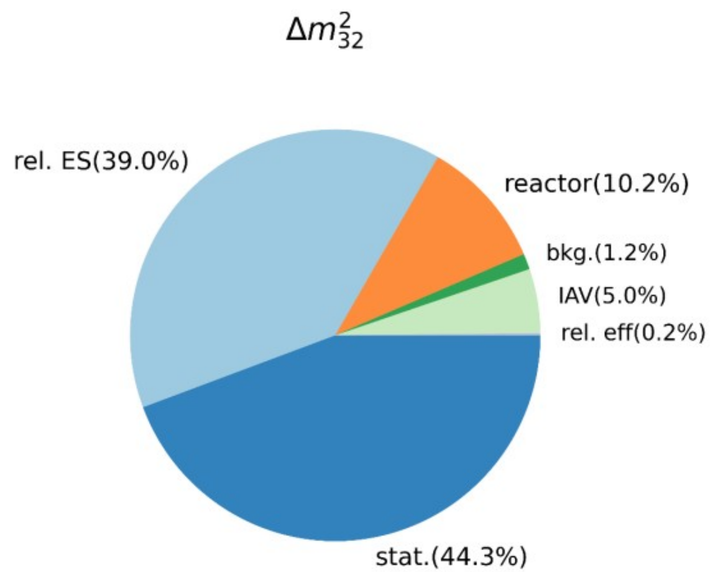




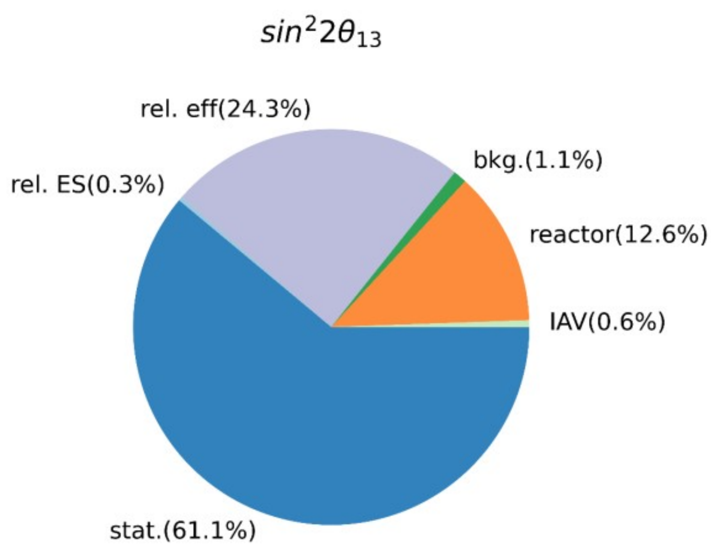


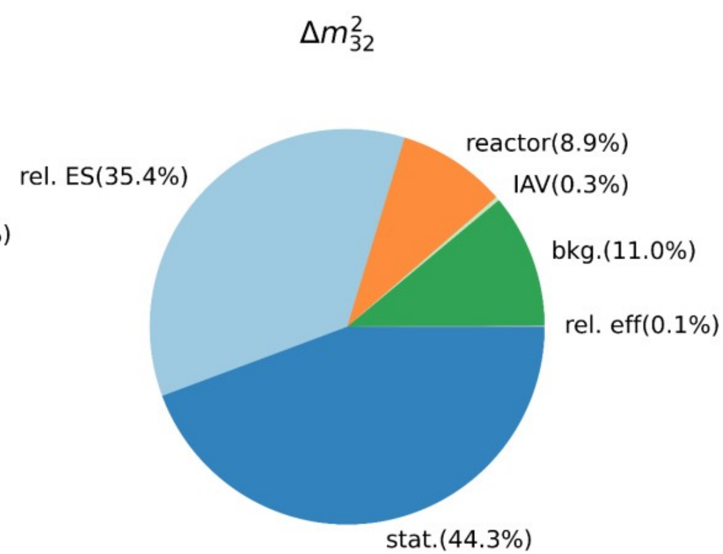
Error budget





Adding each systematic to stat-only Asimov fit





Removing each systematic from full-syst Asimov fit

Wrapping up

More physics from Daya Bay

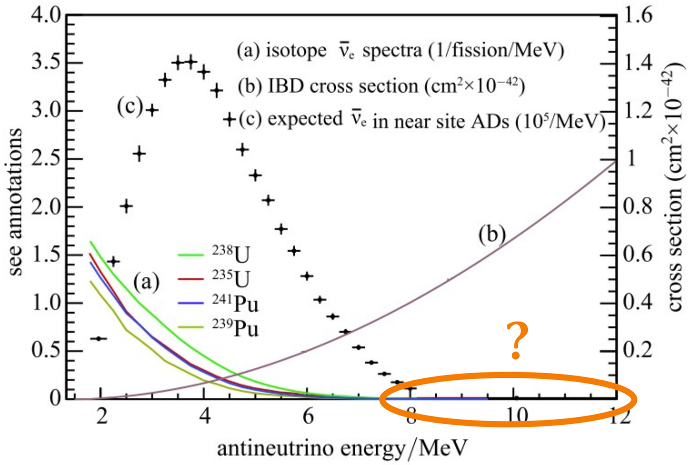
- Some highlights:
  - Measurement of high-energy reactor antineutrinos
  - Search for events associated with gravitational waves
  - Fuel evolution measurement
  - Unfolded antineutrino spectra
  - Joint measurement of antineutrino spectra w/ PROSPECT
  - Joint sterile neutrino search w/ MINOS/MINOS+
  - Measurement of seasonal variation of muon flux
  - Oscillation analysis using neutron capture on hydrogen
- See bonus slides!
- http://dayabay.ihep.ac.cn/twiki/bin/view/Public/DybPublications

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
- Many other significant recent results
- Some upcoming results
  - Spectral oscillation analysis with neutron capture on hydrogen
  - Updated sterile neutrino search
  - Updated fuel evolution measurement

Bonus:
Other recent results

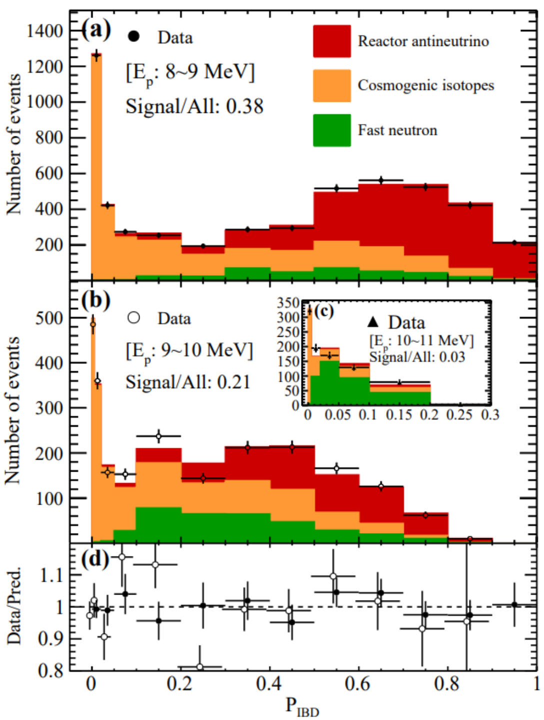
High-energy reactor $\bar{\nu}$

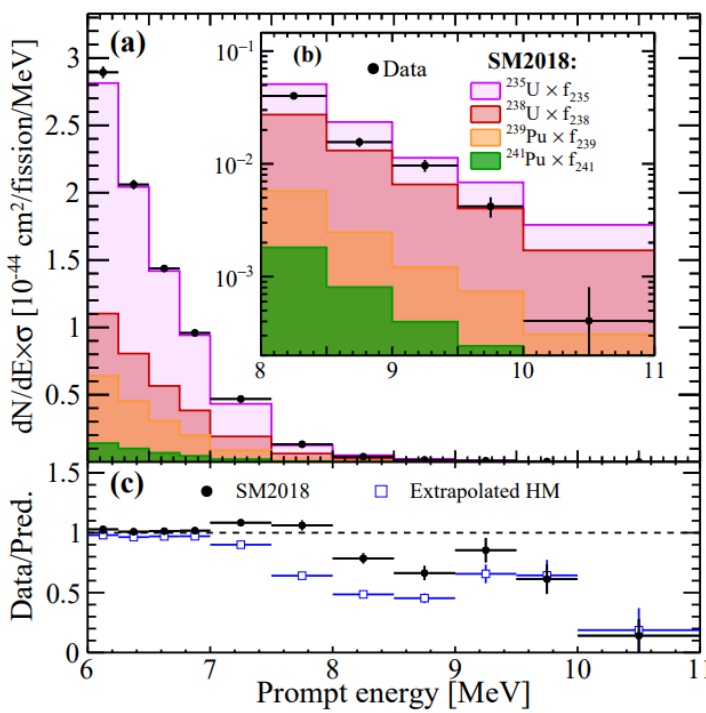


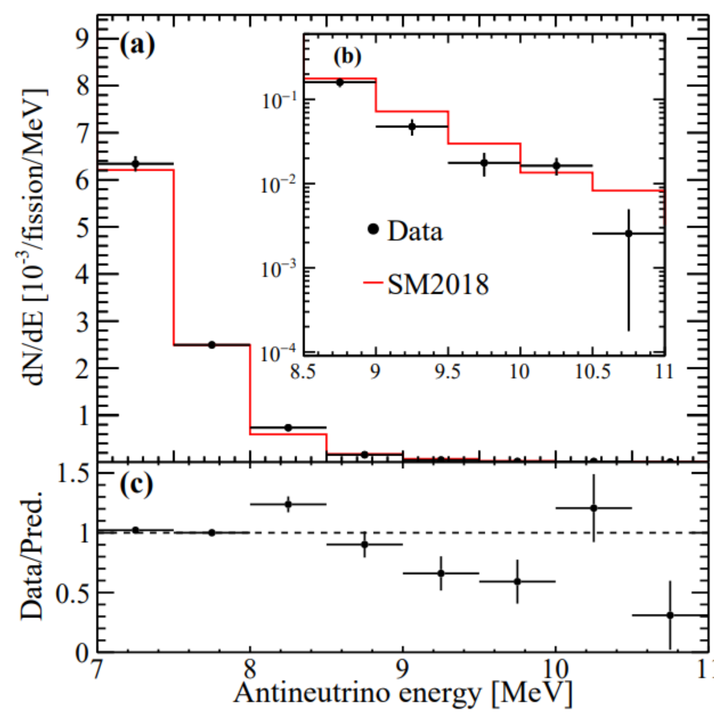
High-energy reactor antineutrinos (HERA): **Tiny signal above 8 MeV,** but useful for benchmarking nuclear models and characterizing backgrounds for future measurements (diffuse νSNB, etc.)

Multivariate analysis to statistically discriminate HERA from μ-induced bkg:

- 6.2σ observation of HERA above 10 MeV
- Statistical discriminator validated with Monte Carlo
- Comparisons to SM2018 and Huber-Mueller predictions
- Unfolded HERA antinuetrino spectrum



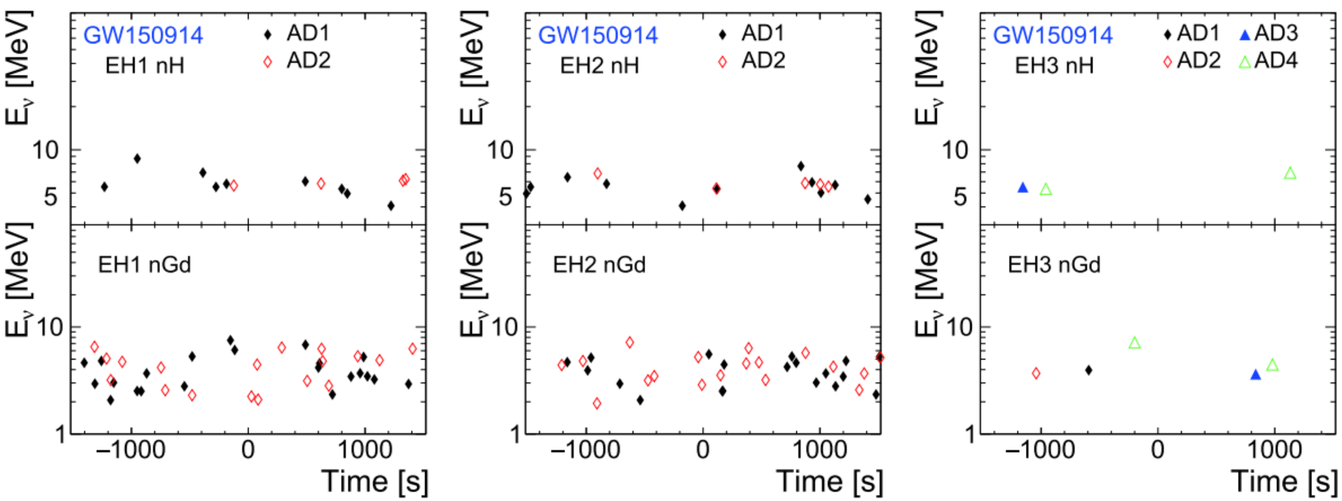




Chin. Phys. C **45**, 055001 (2021)

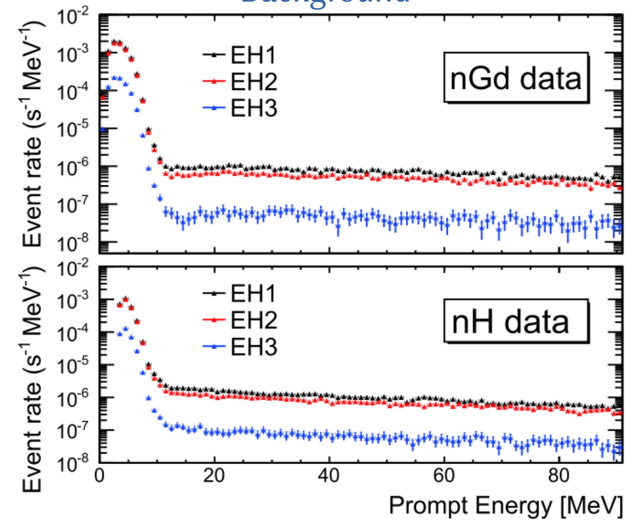
Gravitational waves

Search for IBD candidates within fixed time windows around GW events



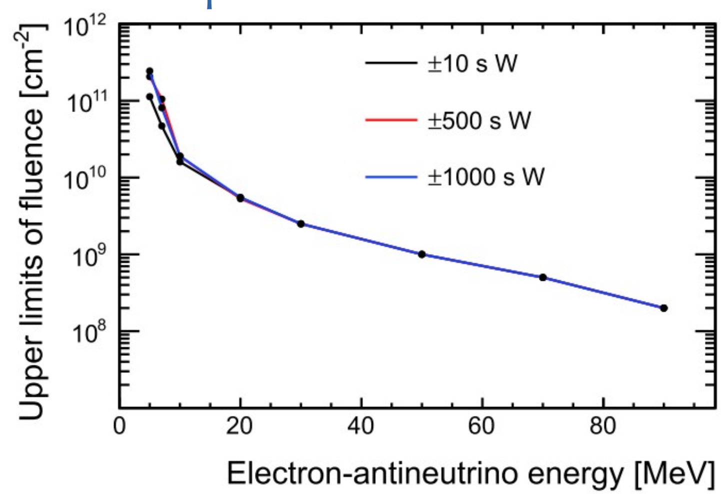
Compare to predicted background.
No significant excess for any GW.

Background



Convert results into upper limits on antineutrino fluence, both overall and for individual GWs, assuming both monochromatic and Fermi-Dirac spectra

GW event	Φ_{FD} /($\times10^{10}$ cm^{-2})	L_{GW}/($\times10^{60}$ erg)
GW150914	0.30	1.23
GW151012	0.79	23.3
GW151226	0.82	3.86
GW170104	0.97	18.3
GW170608	0.42	1.18
GW170814	0.73	5.18
GW170817	0.85	0.03



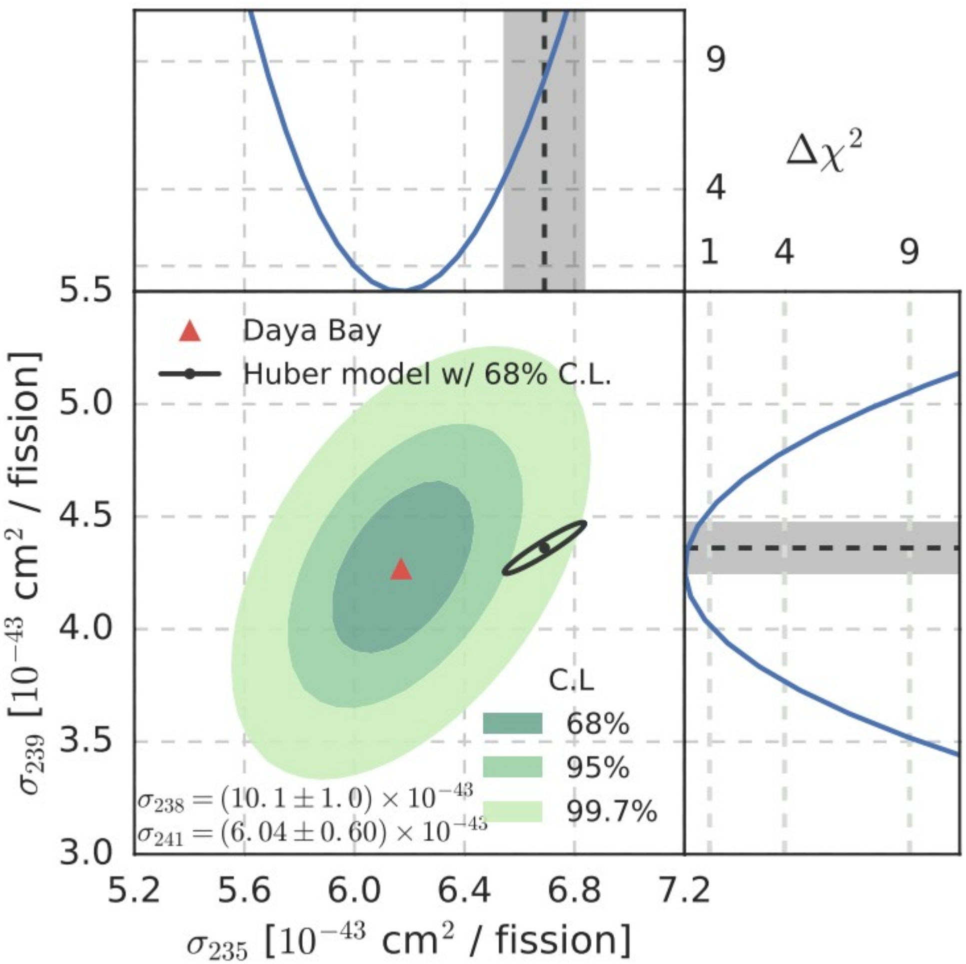
Phys. Rev. Lett. ***118***, *251801 (2017)*

Fuel evolution

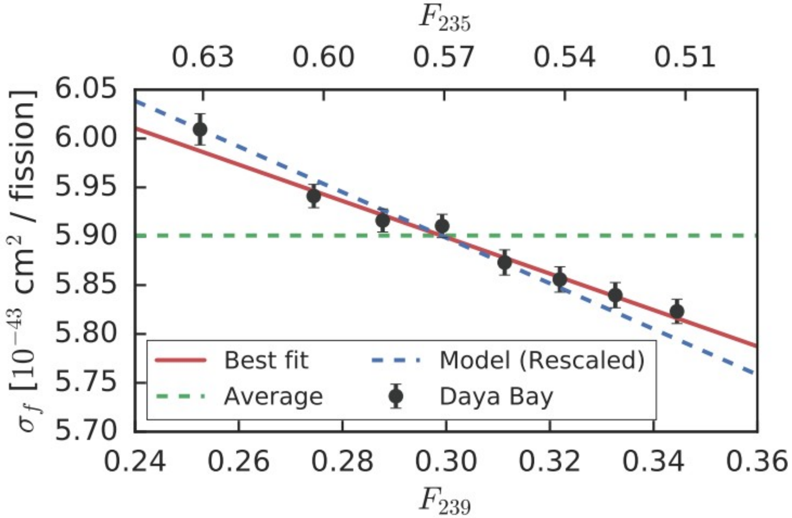
Use data at different fission fractions to:

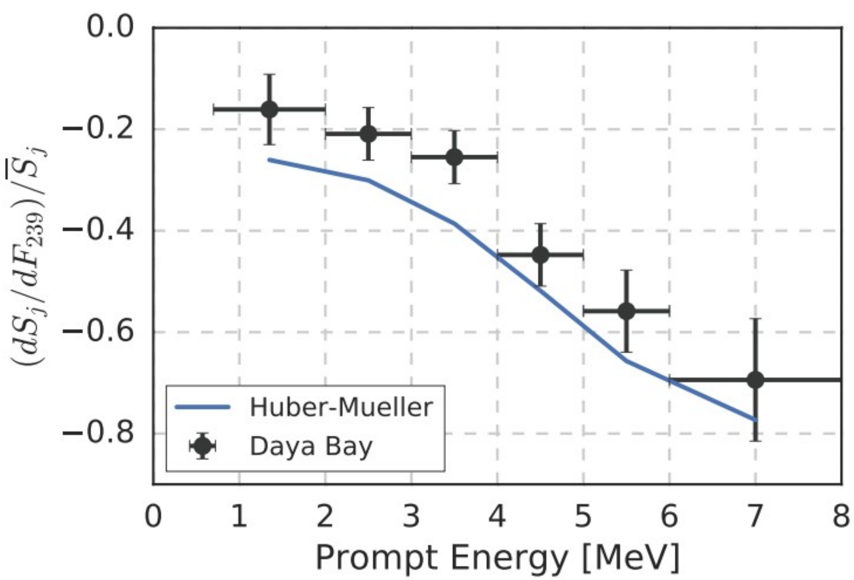
- Study overall yield as a function of ^{239}Pu fraction
- Extract individual ^{235}U and ^{239}Pu antineutrino yields
- Compare shape evolution to prediction

Results suggest model/data flux disagreement is largely due to ^{235}U



Slope inconsistent with H-M prediction at 3σ





Shape evolution generally consistent with H-M

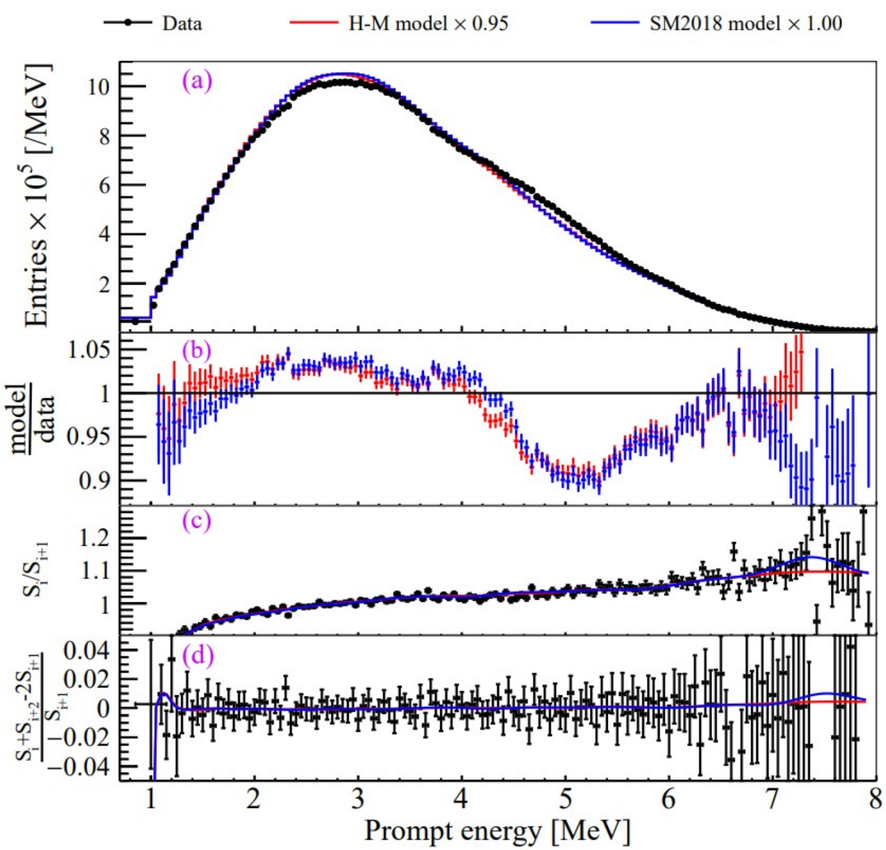
Chin. Phys. C **45**, 073001 (2021)

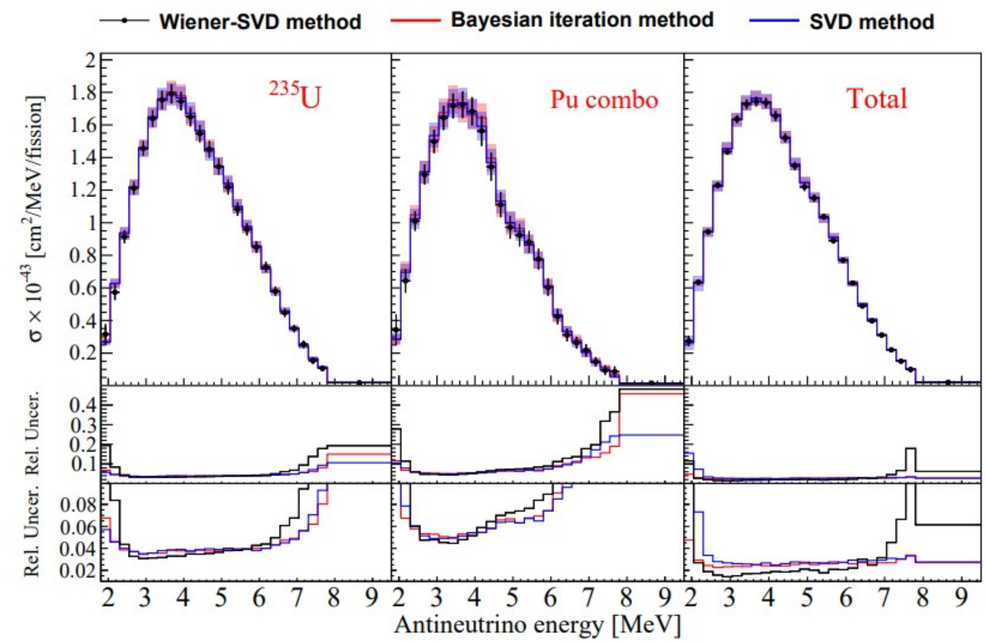
Antineutrino spectra

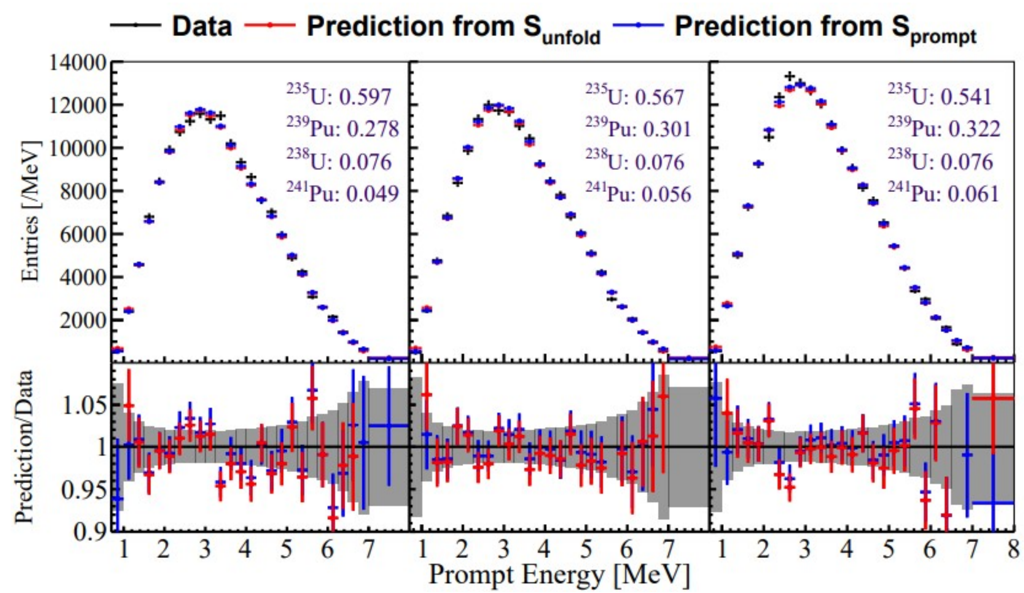
Using data at different fission fractions, extract ^{235}U and $^{239}Pu+^{241}Pu$ prompt spectra, unfold to $\bar{\nu}$ spectra (right)

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



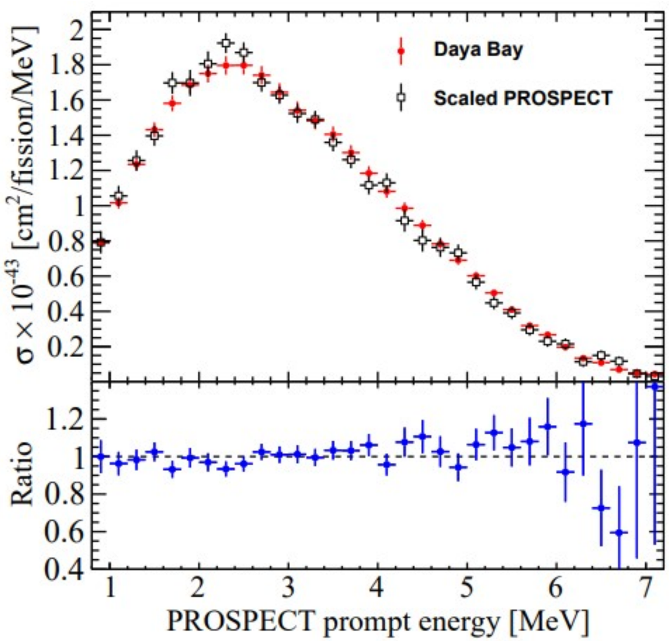




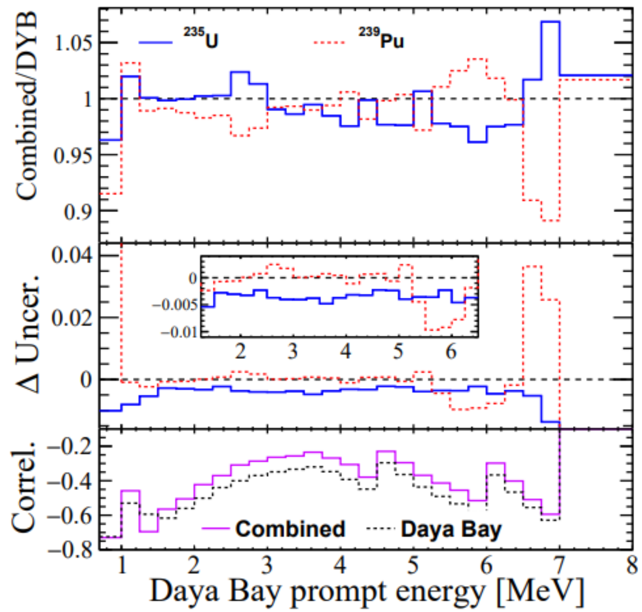
Phys. Rev. Lett. ***128***, *081801 (2022)*

Joint spectra with PROSPECT

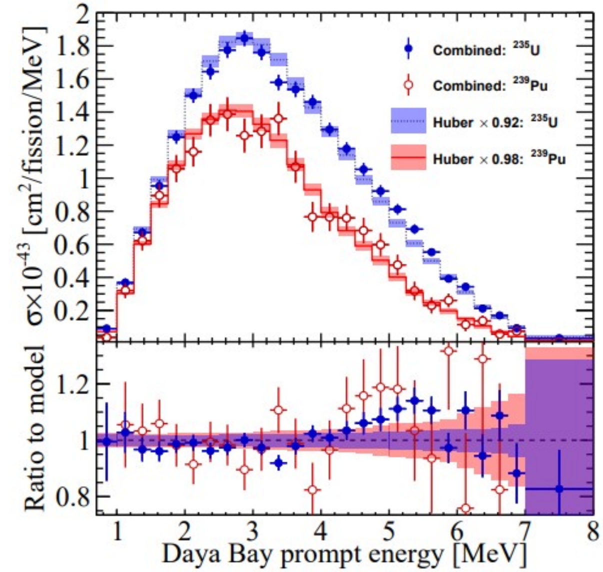
After energy response "translation", Daya Bay and PROSPECT prompt spectra are in agreement

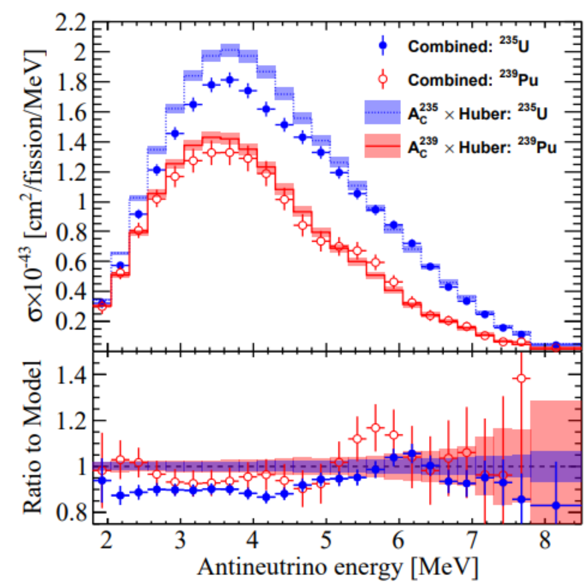


Combined ^{235}U spectrum's uncertainty is reduced from 3.5% to 3% around 3 MeV; anticorrelation of ^{235}U and ^{239}Pu reduced



Comparison to Huber-Mueller spectral shape





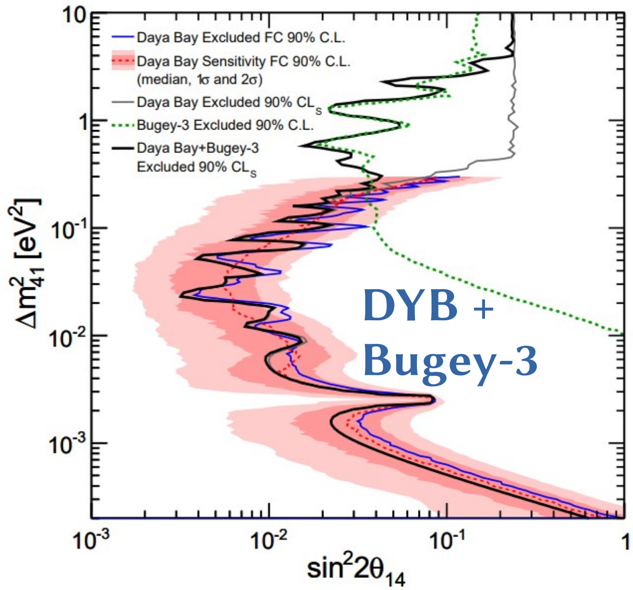
Both Daya Bay (LEU) and PROSPECT (HEU) can extract ^{235}U, ^{239}Pu spectra from their data

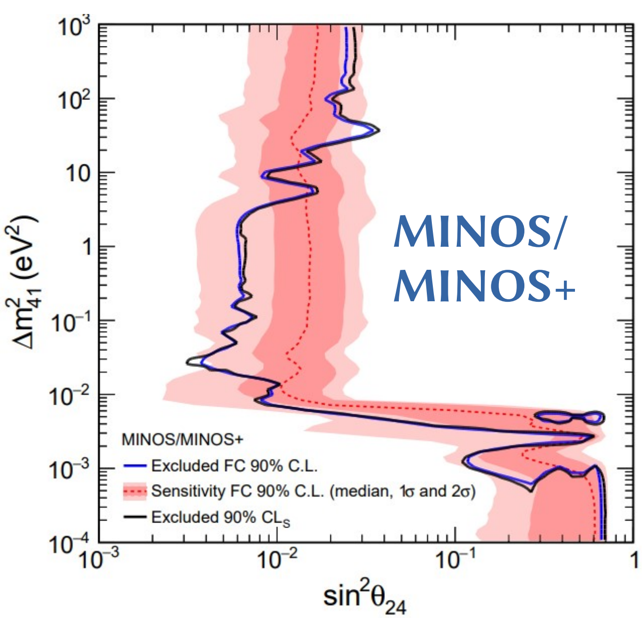
Combined spectra can be obtained by using PROSPECT's spectra as constraint in Daya Bay's fit

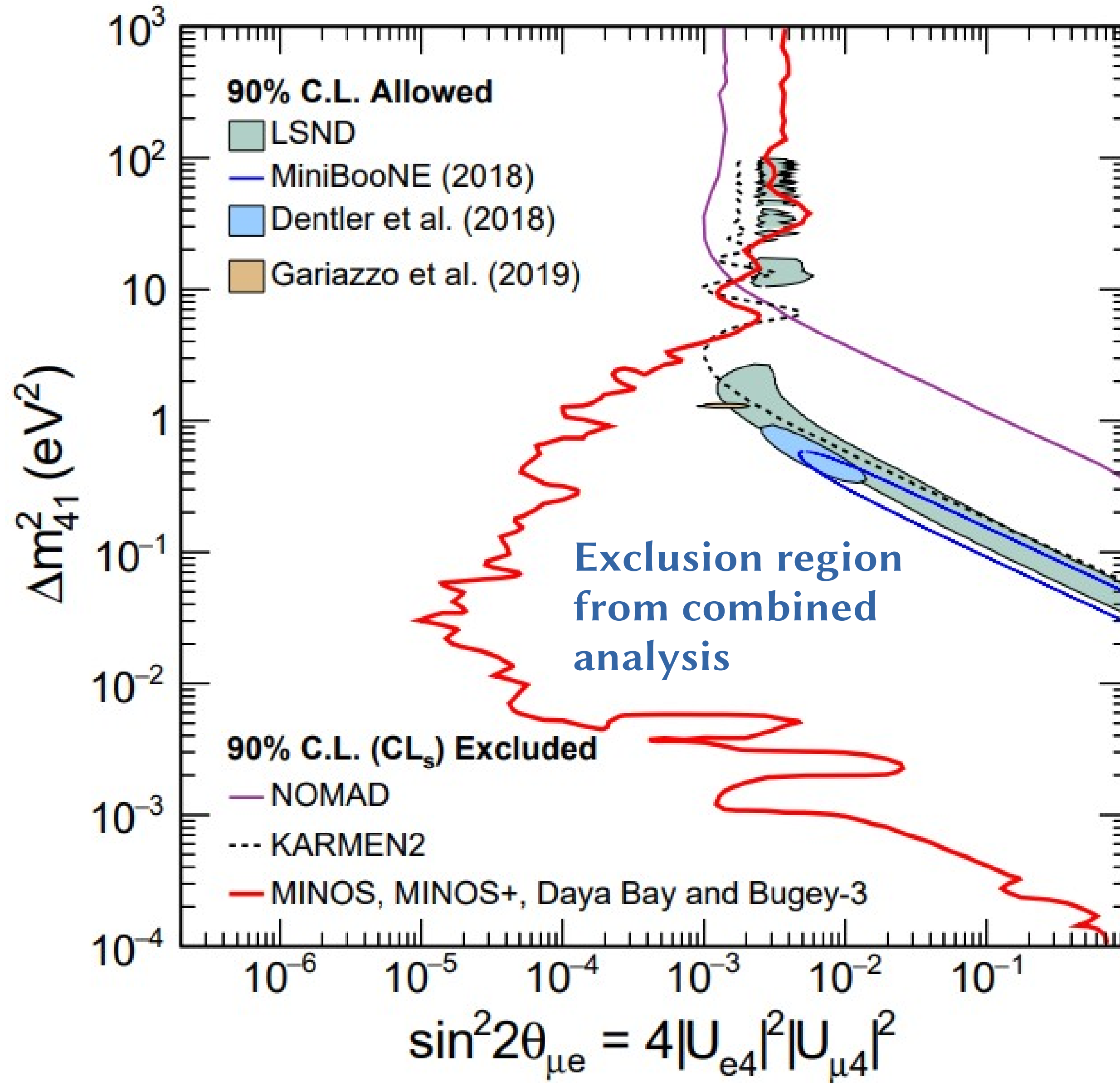
Antineutrino spectra are obtained by unfolding the prompt spectra of ^{235}U and ^{239}Pu

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

Joint sterile search w/ MINOS(+)

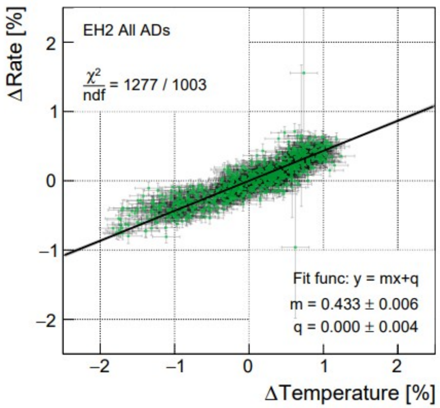


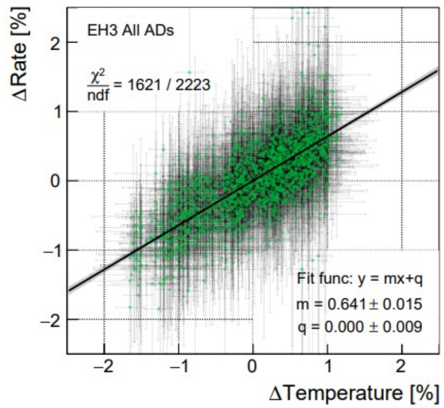




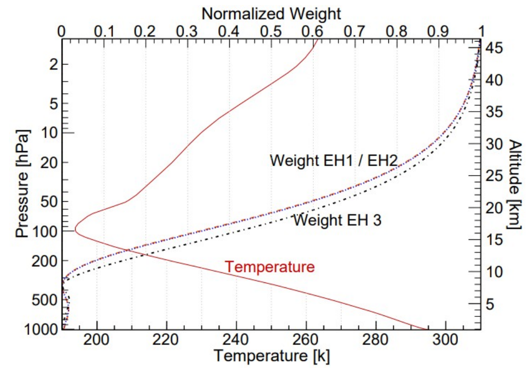
J. Cosmology and Astroparticle Phys. **1**, 1 (2018)

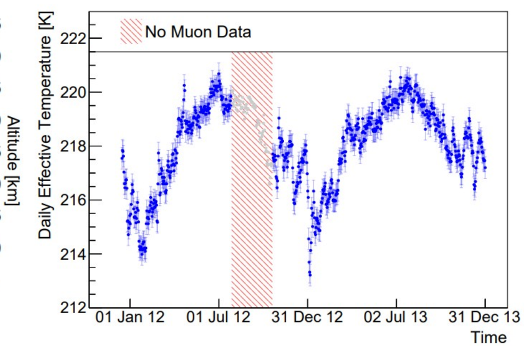
Muon modulation

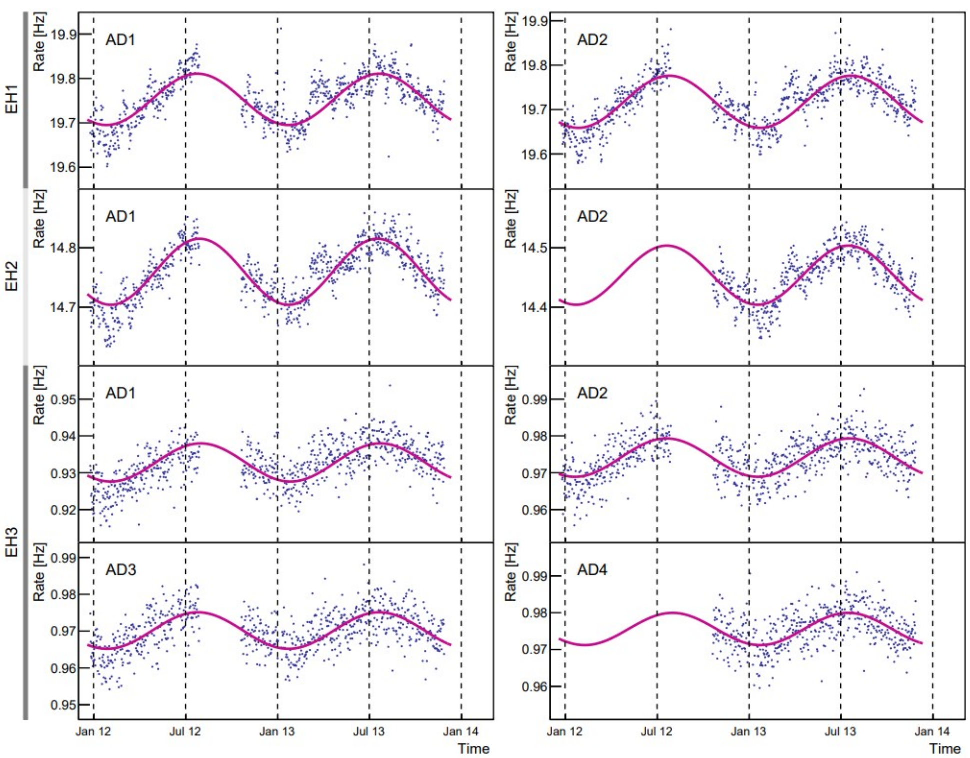


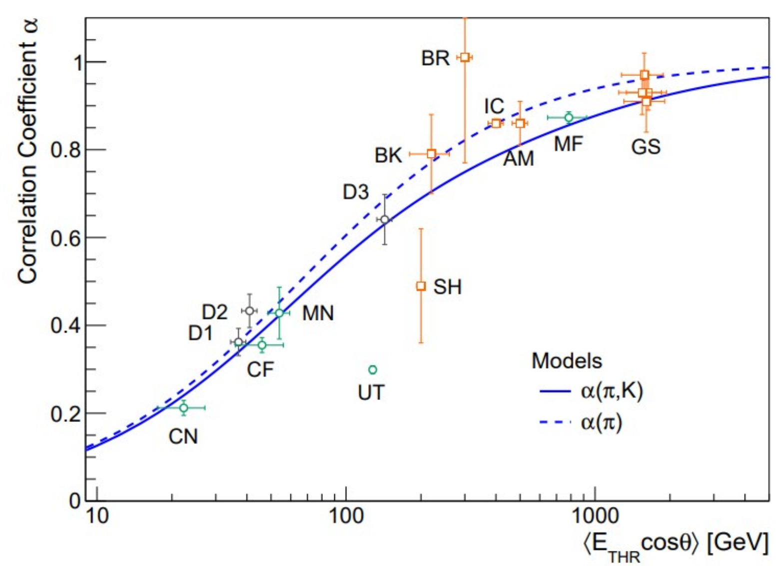


Annual modulation of muon flux agrees with predicted correlation of flux to atmospheric temperature









nH analysis

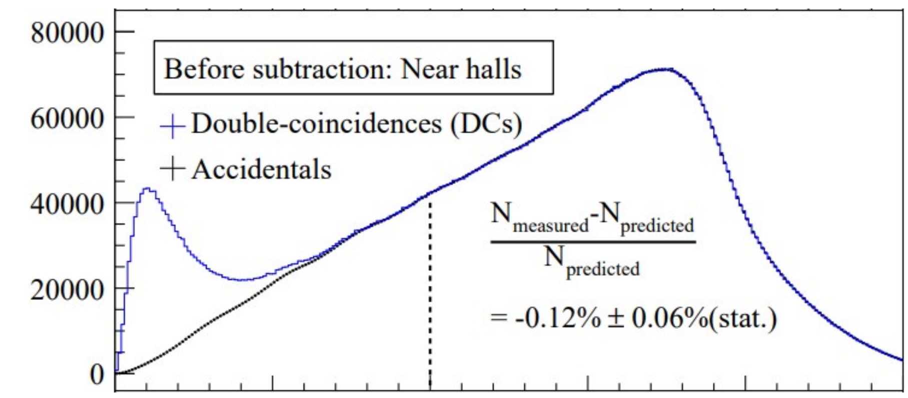
Independent rate-only analysis using nH capture (2.2 MeV)

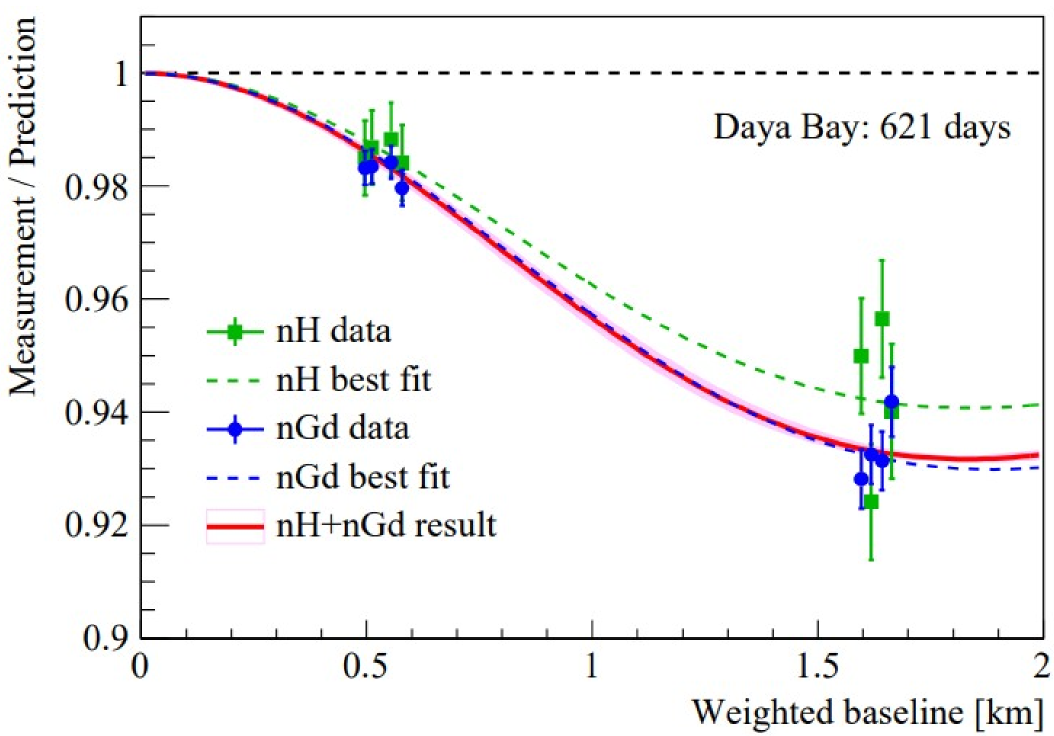
Comparable statistics thanks to Gd-free LS region

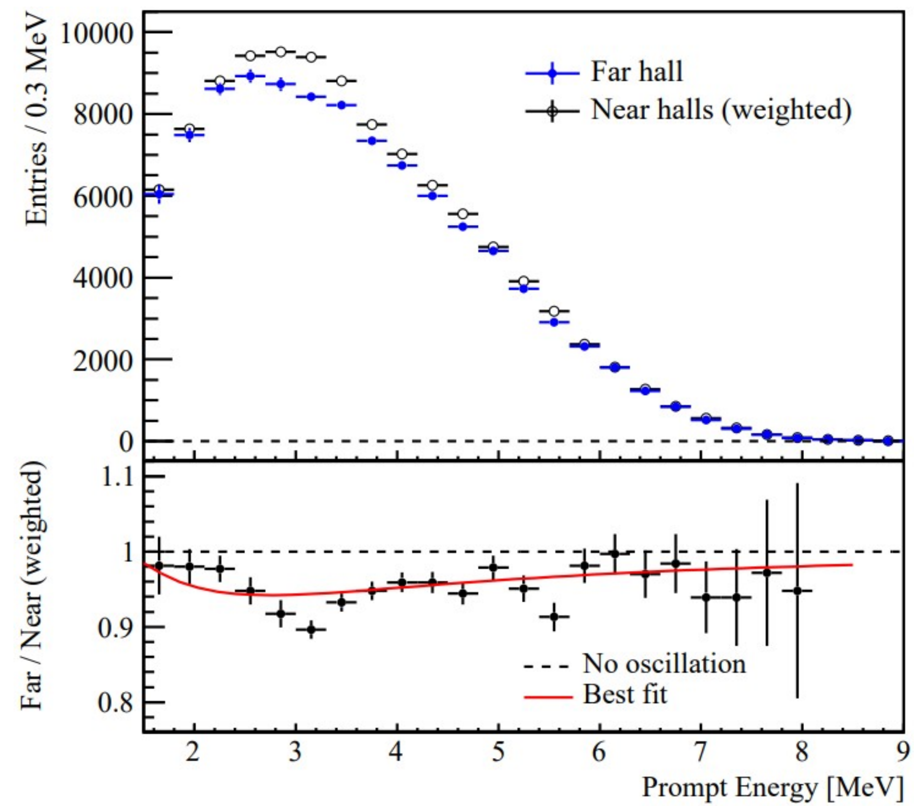
Challenges:

- Large accidental background (low energy of nH capture)
- Efficiency uncertainties in LS region

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







Bonus: Details of high-energy $\bar{\nu}$ analysis

Phys. Rev. Lett. ***129,*** *041801*

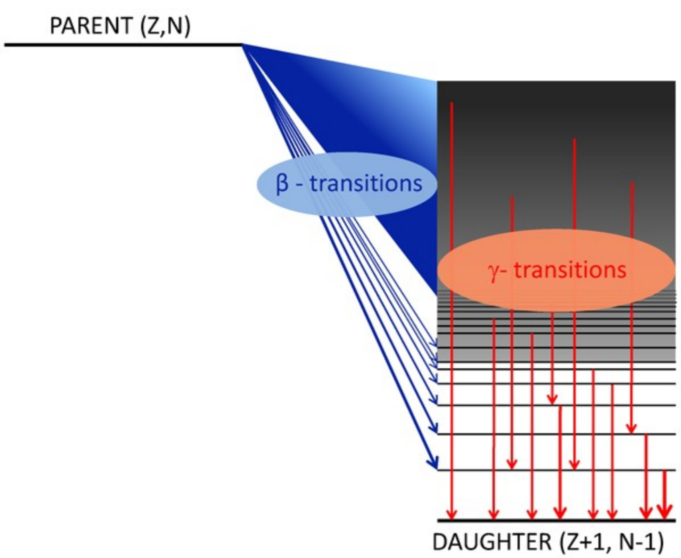
High-energy reactor $\bar{\nu}$

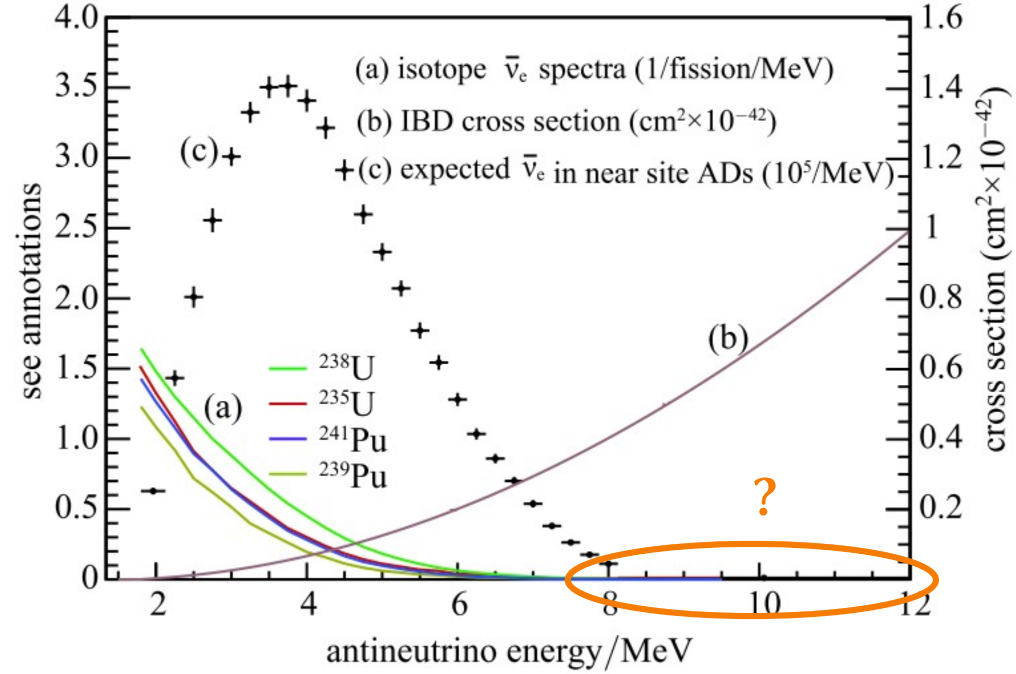
Why study high-energy reactor antineutrinos **(HERA)** having **prompt energy > 8 MeV**?

- Shed light on discrepancies between data and nuclear models
- Characterize backgrounds for future experiments (diffuse νSNB, etc.)

Expected to arise from short-lived, high-Q_β isotopes (e.g. ^{88,90}Br, ^{94,96,98}Rb)

- Previous measurements biased by "pandemonium effect":





Challenge: Low rate, large contamination of cosmogenic backgrounds (isotopes, fast neutrons)

This study:

- Multivariate analysis to extract HERA prompt spectrum
- HERA $\bar{\nu}$ spectrum unfolded from prompt spectrum

Dataset

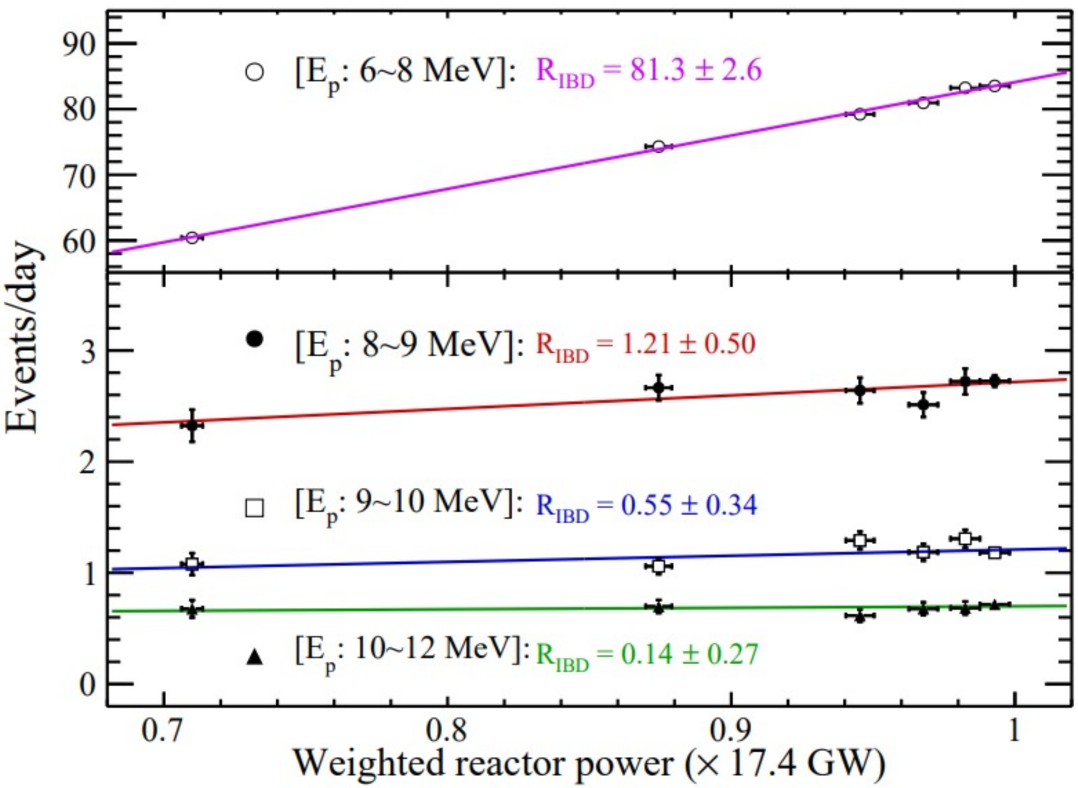
- Use 1958 days of data (Dec 24, 2011 – Aug 31, 2017)
- Standard (“A”) selection with shortened (1 ms) shower veto
  - More information for constraining cosmogenic isotope bkg.

Criterion	Selection A
Calibration	^{60}Co and ^{241}Am-^{13}C method
Reconstruction	Corrected center-of-charge
8-inch PMT light emission	Reject $f_{\rm ID} \geq 0$
2-inch PMT light emission	Reject $Q_{\rm max}$(2-inch PMTs) $>$ 100 p.e.
Prompt energy	(0.7, 12.0) MeV
Delayed energy	(6, 12.0) MeV
Prompt-delayed Δt	(1, 200) μs
Multiplicity veto *(pre)*	No signal >0.7 MeV 200 μs before prompt
Multiplicity veto *(post)*	No signal >0.7 MeV 200 μs after delayed
Water Shield muon veto	Veto (-2, 600) μs after NHIT $>$ 12 in OWS or IWS
AD muon veto	Veto (0, 1) ms after >20 MeV signal
AD shower veto	Veto ~~(0, 1) s~~ (0, 1) ms after >2.5 GeV signal

- 4M IBD candidates, ~9000 in 8-12 MeV prompt energy region

The challenge

$$R = R_{\mathrm{IBD}} P_{\mathrm{reactor}} + R_{\mathrm{bkg}}$$



- Rate in 8-12 MeV 1/20th of rate in 6-8 MeV
- $R_{\mathrm{IBD}} > 0$ at $>30\sigma$ for 6-8 MeV; $<2.5\sigma$ above 8 MeV
- Backgrounds: Cosmogenic isotopes (^{9}Li/^{8}He correlated; ^{12}B+^{12}B accidental), fast neutrons

Strategy:

- **Get the fractions of IBDs and backgrounds** in each energy bin with an unbinned fit over all events in the bin, exploiting:
  - Time to last muon
  - Vertical position
  - Reactor power
- **Get the IBD prompt spectrum** by scaling the total spectrum by the IBD fraction in each bin
- **Get the uncertainty** both from statistics and from systematics (pull term) in background model
- **Validate the model** by defining a discriminator P_{IBD}. Compare distribution to toy MC prediction.
- **Unfold the prompt spectrum** to get the antineutrino spectrum

Model PDF

In each energy bin, let r_p be the fraction of events of type p:

- Cosmogenic isotopes
- Fast neutrons
- IBDs

Then in each energy bin, we want the best fit of the vector $\mathbf{r}$ (of r_p for all three p)

For each IBD candidate, determine:

- $\mathbf{\Delta t}$, vector of time differences to most-recent muon in each of eight muon categories (four energy ranges × with/without associated neutron)
- z, vertical position of event
- w, baseline-weighted reactor power

Then define event-by-event probability distribution function (PDF), parameterized by $\mathbf{r}$:

$$F(\boldsymbol{r}; \boldsymbol{\Delta t}, z, w) = \sum_p r_p f_p(\boldsymbol{\Delta t}) h_p(z) k_p(w)$$

where f_p, h_p, and k_p are the 1D PDFs of $\mathbf{\Delta t}$, z, and w for events of type p, respectively

1D Sub-PDFs

Time-to-last-muon f(Δt):

$$f(\Delta t) = \kappa \cdot e^{-\kappa \Delta t}$$

where $\kappa = R_\mu$ for muon-uncorrelated events (IBDs and fast neutrons) and $\kappa = R_\mu + \frac{n}{\tau}$ for cosmogenic isotopes (τ = lifetime; n = 1 for $^{9}Li/^{8}He$, n = 2 for $^{12}B+^{12}B$)

- Eight muon categories in **Δt**: (four energy ranges × with/without water pool neutron)
- For lowest-energy muons *without WP neutrons* in EH1 and EH2, high muon rate leads to degenerate time constants
  - Use result for neutron-tagged muons, scaled by the neutron tagging efficiency from EH3 (validated with Geant4, constrained by pulls in fit)

Vertical position h(z):

- Uniform for IBDs and cosmogenic isotopes
- Top-dominated for fast neutrons (measured from IBD candidates in 12-20 MeV)

Weighted reactor power k(w):

- Proportional to *w* for IBDs
- Flat for cosmogenic isotopes and fast neutrons

$$F(\boldsymbol{r}; \boldsymbol{\Delta t}, z, w) = \sum_p r_p f_p(\boldsymbol{\Delta t}) h_p(z) k_p(w)$$

Fitting event type ratios

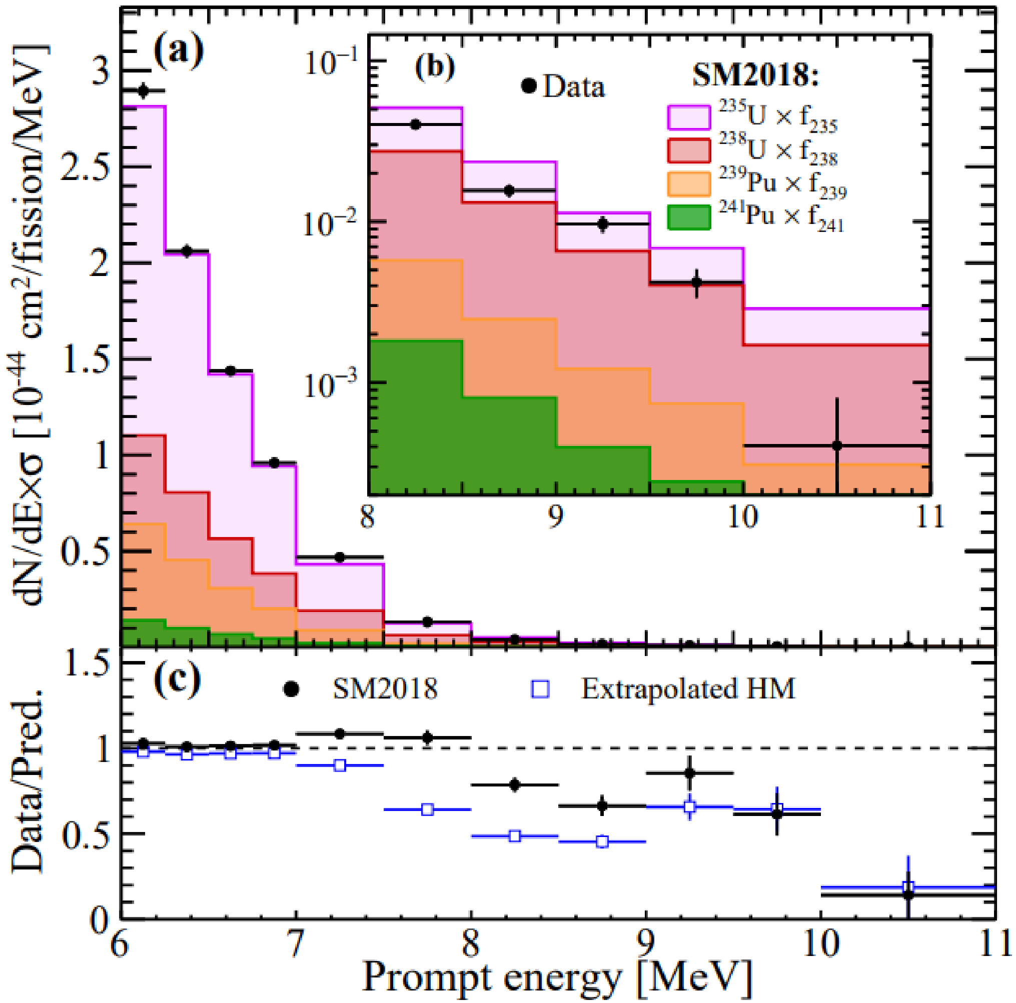
Fitting: Find **r** (for each energy bin) that minimizes

$$\chi^2(\boldsymbol{r}) = -2\sum\left[\log F(\boldsymbol{r};\boldsymbol{\Delta t},z,w)\right] + g(\boldsymbol{\epsilon})$$

where the sum runs over all IBD candidates and $g(\boldsymbol{\varepsilon})$ is the penalty for the systematic pulls $\boldsymbol{\varepsilon}$ (which modify the 1D PDFs f_p etc.)

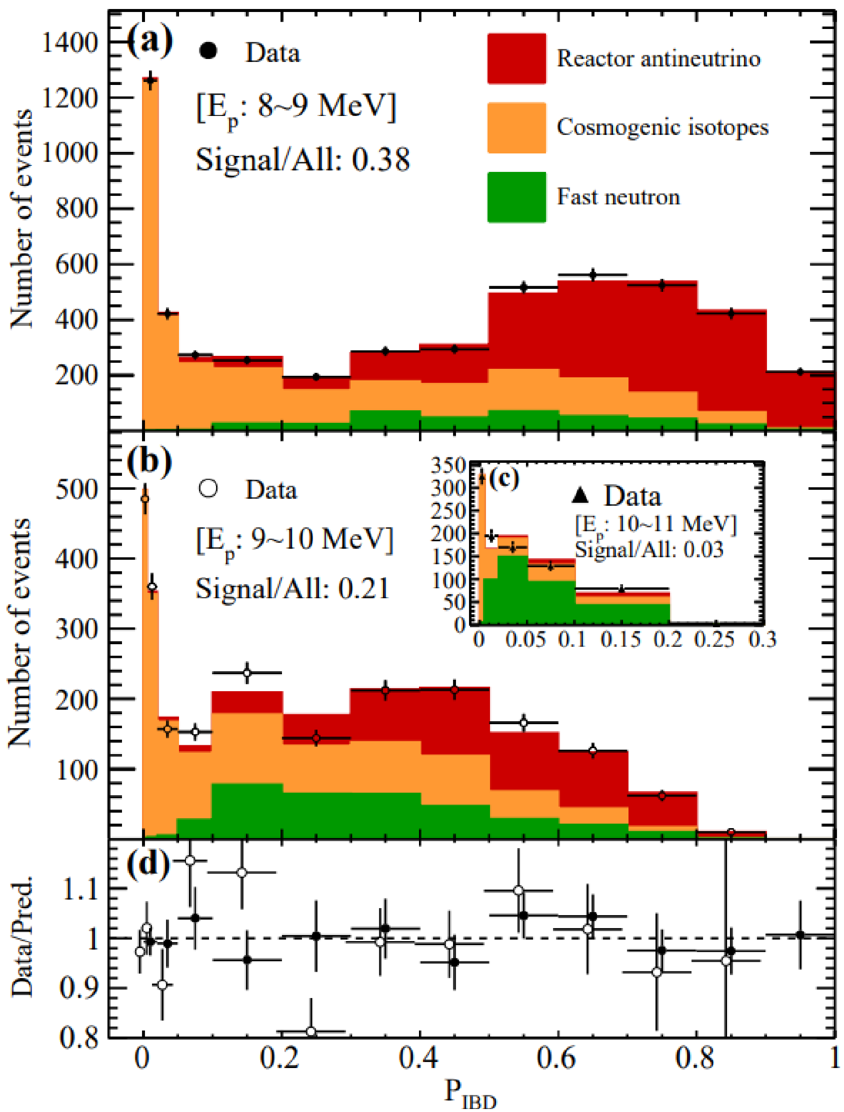
Observations:

- Measured IBD yield 3% larger than SM2018 (recent summation prediction) in 6-8 prompt MeV, but 29% smaller for 8-11 prompt MeV
- Above 10 prompt MeV, expected 5σ significance based on SM2018, but only observed 1σ
- Deficits vs SM2018 consistent with pandemonium effect
- Extrapolated Huber-Mueller model strongly disagrees with data ⟶ not recommended



Prompt spectrum $S_{\mathrm{IBD}}(E) = r_{\mathrm{IBD}}(E)\, S_{\mathrm{all}}(E)$

Validation of model



P_{IBD} shows that reactor antineutrinos can be statistically separated from backgrounds (worse at higher energy).

Define, for each event, the discriminator P_{IBD} (probability of being an IBD):

$$P_{IBD} = \frac{r_{IBD} f_{IBD}(\boldsymbol{\Delta t}) h_{IBD}(z) k_{IBD}(w)}{F(\boldsymbol{r}; \boldsymbol{\Delta t}, z, w)}$$

Use toy MC to predict P_{IBD} distribution for each event class and energy bin

Compare measured distribution to sum (over event classes) of predictions. Good agreement.

Cross check: Obtain consistent results when ignoring (one of) $\boldsymbol{\Delta t}$, z, w, or when only including a single hall

Background model contributes bulk of uncertainty:

- Below 9.5 MeV, ~60% of total uncertainty comes from isotopes
- Above 10 MeV, ~70% comes from fast neutrons
- Statistics only ~20% of total

Unfolded antineutrino spectrum

Unfold the prompt spectrum using a fitting procedure. Minimize:

$$\chi^2 = (\boldsymbol{P} - \boldsymbol{M})\mathbf{Cov}^{-1}(\boldsymbol{P} - \boldsymbol{M})^T$$

M is the measured prompt spectrum,
Cov is its covariance, and

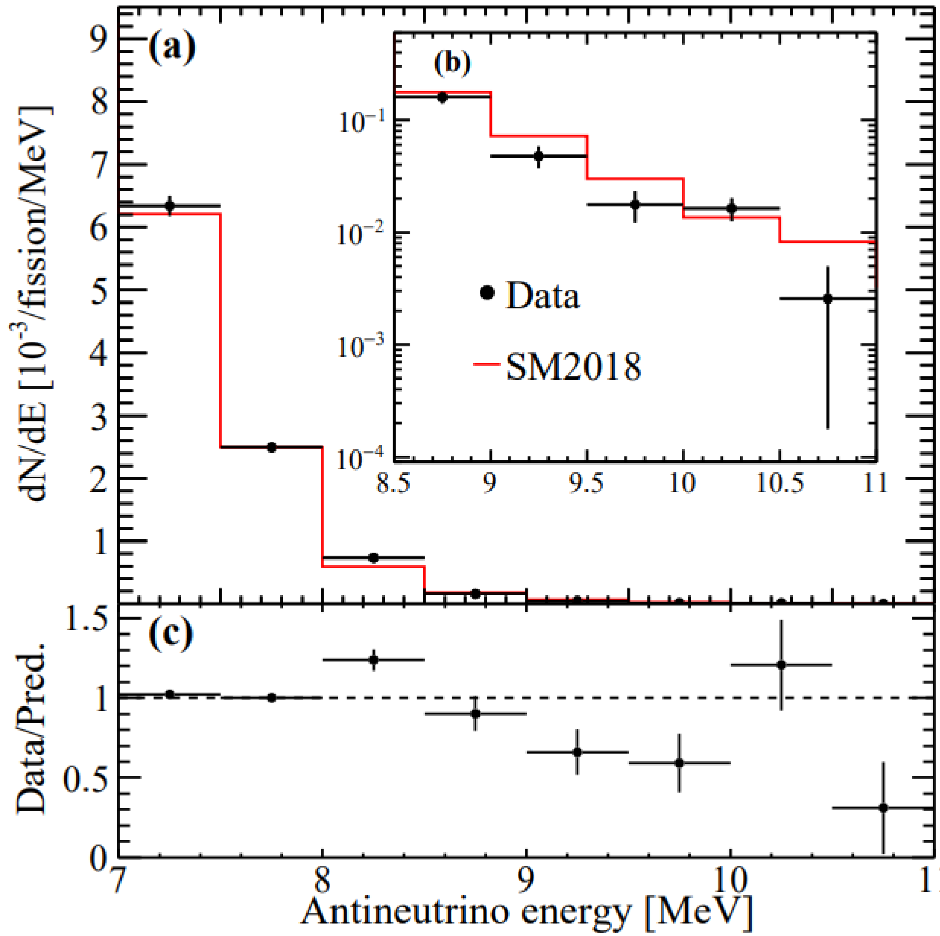
$$\boldsymbol{P} = \boldsymbol{R}\boldsymbol{S}^{\text{fit}}$$

is the predicted prompt spectrum, based on the detector response matrix **R** and the predicted antineutrino spectrum $\mathbf{S}^{\text{fit}}$ (varied in the minimization)

Unfolding procedure is equivalent to matrix inversion, but allows more statistical tests

Use wide bins to avoid large statistical fluctuations and bin-to-bin anticorrelations (common pitfall in unfolding)

Spectrum for immediate use by the community



- Assuming no HERA above (10, 10.5, 11) MeV, the χ^2 is found to be (38.3, 1.6, 0.03)
- **6.2σ rejection of no-HERA above 10 MeV**
- Above 10.5 MeV, no-HERA hypothesis not rejected

Backup

Muon veto efficiency

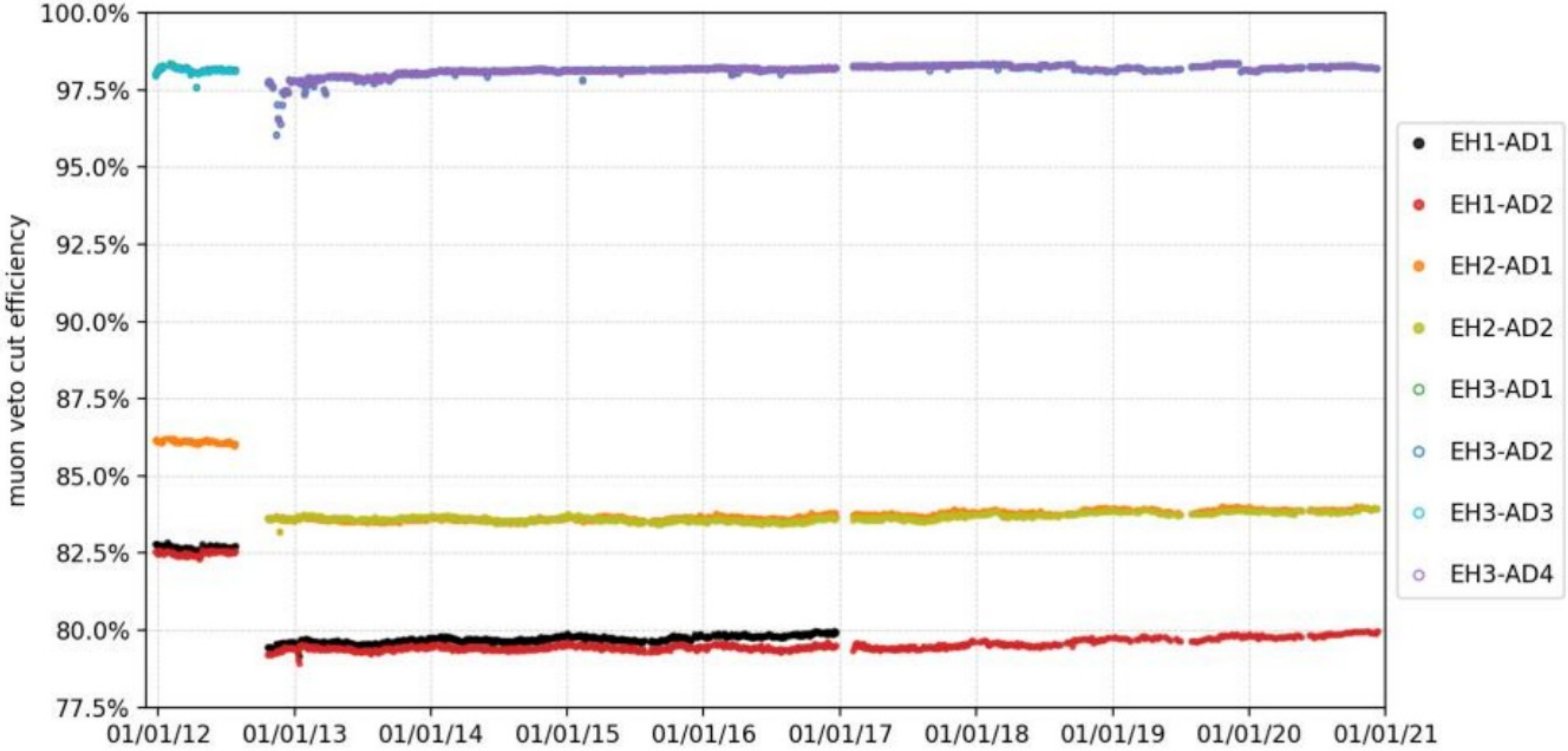
$$T_\mu = T_{un-vetoed} - N_{un-vetoed} \cdot 600\mu s$$

$$\epsilon_\mu = \frac{T_\mu}{T_{before}}$$

Total time outside veto windows

# of unvetoed periods > 600 µs

Total livetime ("before" vetoing)



Multiplicity cut efficiency

$$\epsilon_{DMC} = P\left(0; R_x \cdot 400\mu s\right) \cdot P\left(0; R_x \cdot 200\mu s\right) = e^{-R_x \cdot 600\mu s},$$