大亚湾实验最新结果

凌家杰（中山大学）

第一届“粤港澳”核物理论坛
珠海，2022/07/03

The 3-neutrino Mixing

B. Pontecorvo, Z. Maki, M. Nakagawa, S. Sakata, E. Majorana

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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$

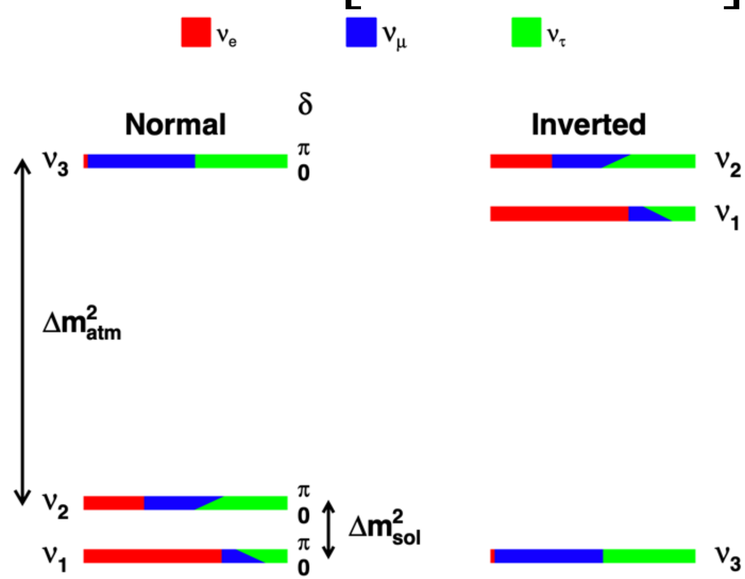
$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

Three mixing angles: θ_{23}, θ_{13}, θ_{12}

$c_{12}^2 \equiv \cos^2\theta_{12} = \frac{|U_{e1}|^2}{1-|U_{e3}|^2}$ $s_{12}^2 \equiv \sin^2\theta_{12} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2}$

$s_{13}^2 \equiv \sin^2\theta_{13} = |U_{e3}|^2$

$s_{23}^2 \equiv \sin^2\theta_{23} = \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2}$ $c_{23}^2 \equiv \cos^2\theta_{23} = \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2}$



Reactor Antineutrino Oscillation

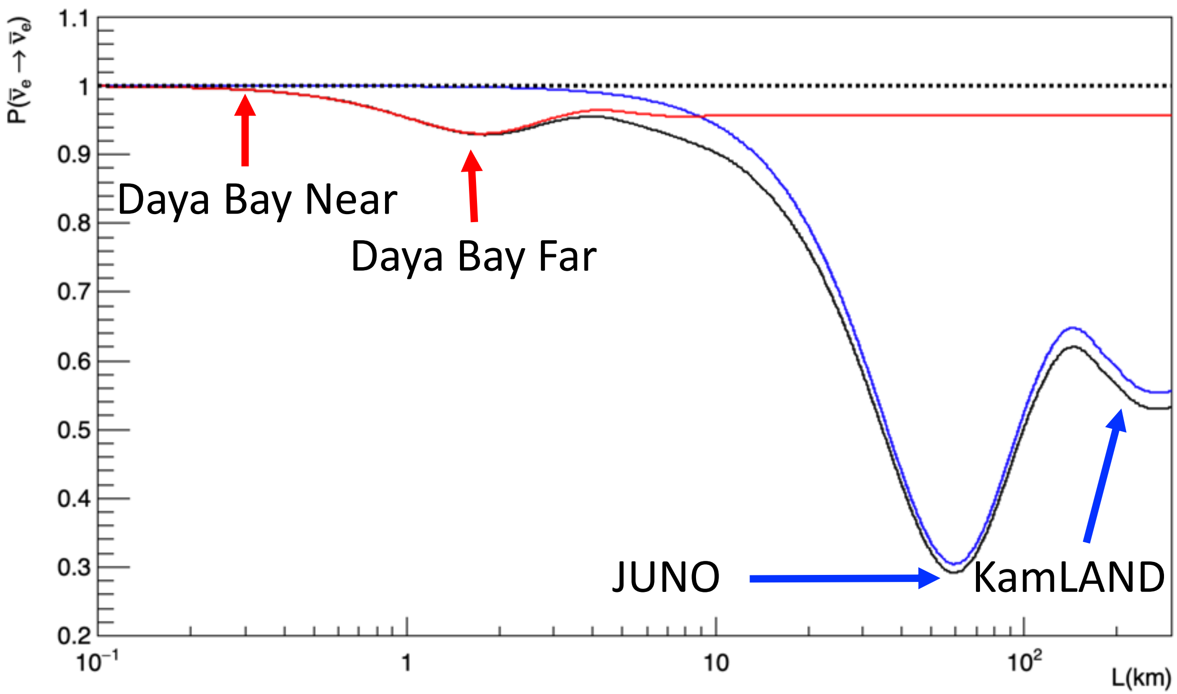
$$P_{\alpha\beta} = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i<j}^{3} Re[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}]\sin^2\Delta_{ij} + 2\sum_{i<j}^{3} Im[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}]\sin 2\Delta_{ij}$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\approx 1 - \boxed{\sin^2 2\theta_{13}\sin^2\Delta_{ee}} - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E}$$

Immune to CP violation and matter effects



Key for a precise measurement:

- ✓ **Baseline Optimization**

  $$L(\mathrm{m}) \sim \frac{\pi \cdot E\ (\mathrm{MeV})}{2.54 \cdot \Delta m^2(\mathrm{eV}^2)}$$

- ✓ **Large statistics**

  Large $\bar{\nu}_e$ flux

  Massive target mass

- ✓ **Background control**

  Large overburden

  Detector shielding

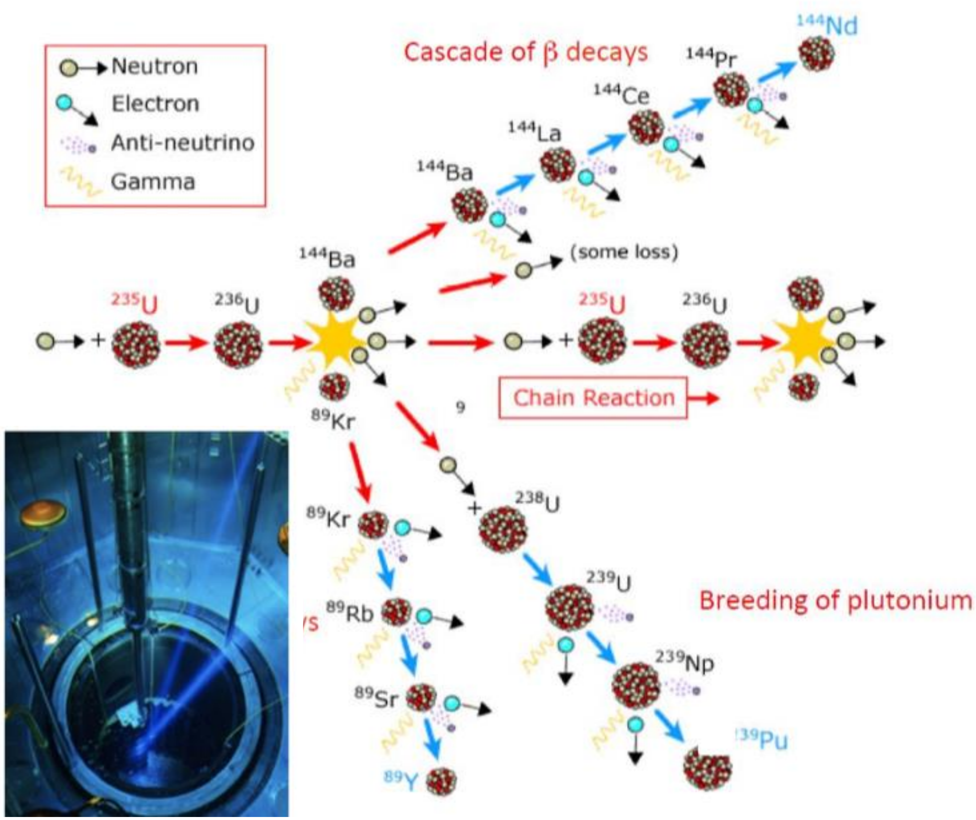
- ✓ **Systematics control**

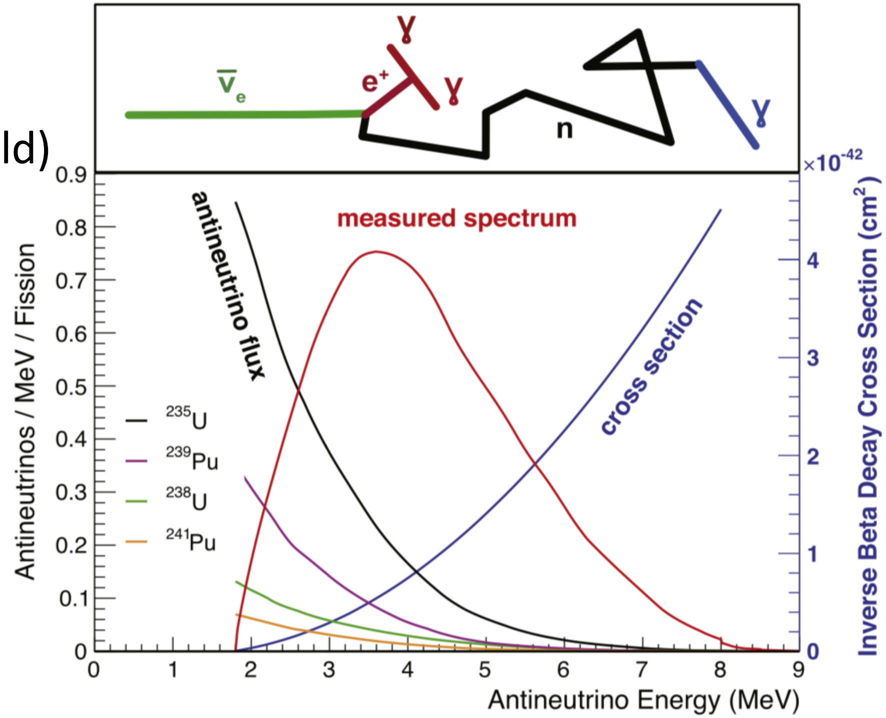
  Relative Far/Near measurement

Reactor $\bar{\nu}_e$ Production and Detection

Source: Pure $\bar{\nu}_e$ from cascade of beta decays

- ~ 200 MeV / fission
- ~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}/Sec (1/5 above IBD threshold)



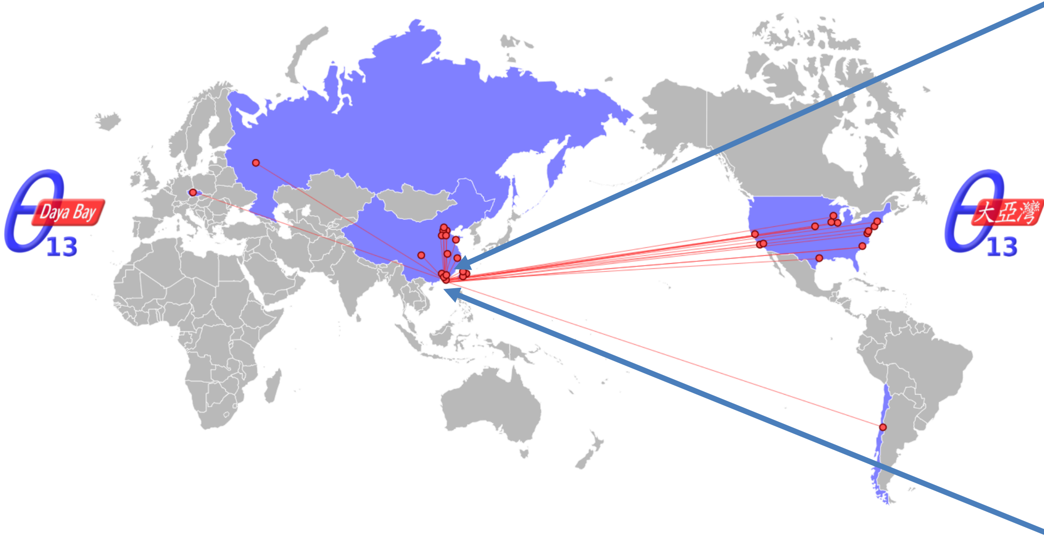


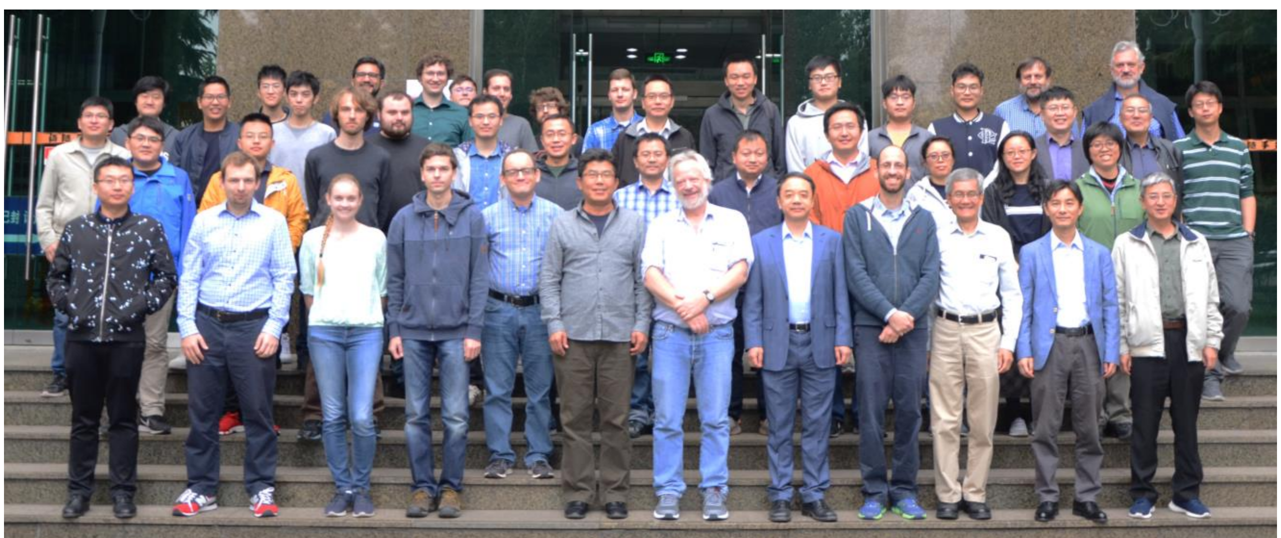
Inverse Beta decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$

Coincidence signals to suppress background

- Prompt: $E_{\text{prompt}} \approx E_\nu - 0.8\ MeV$
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)

The Daya Bay Collaboration



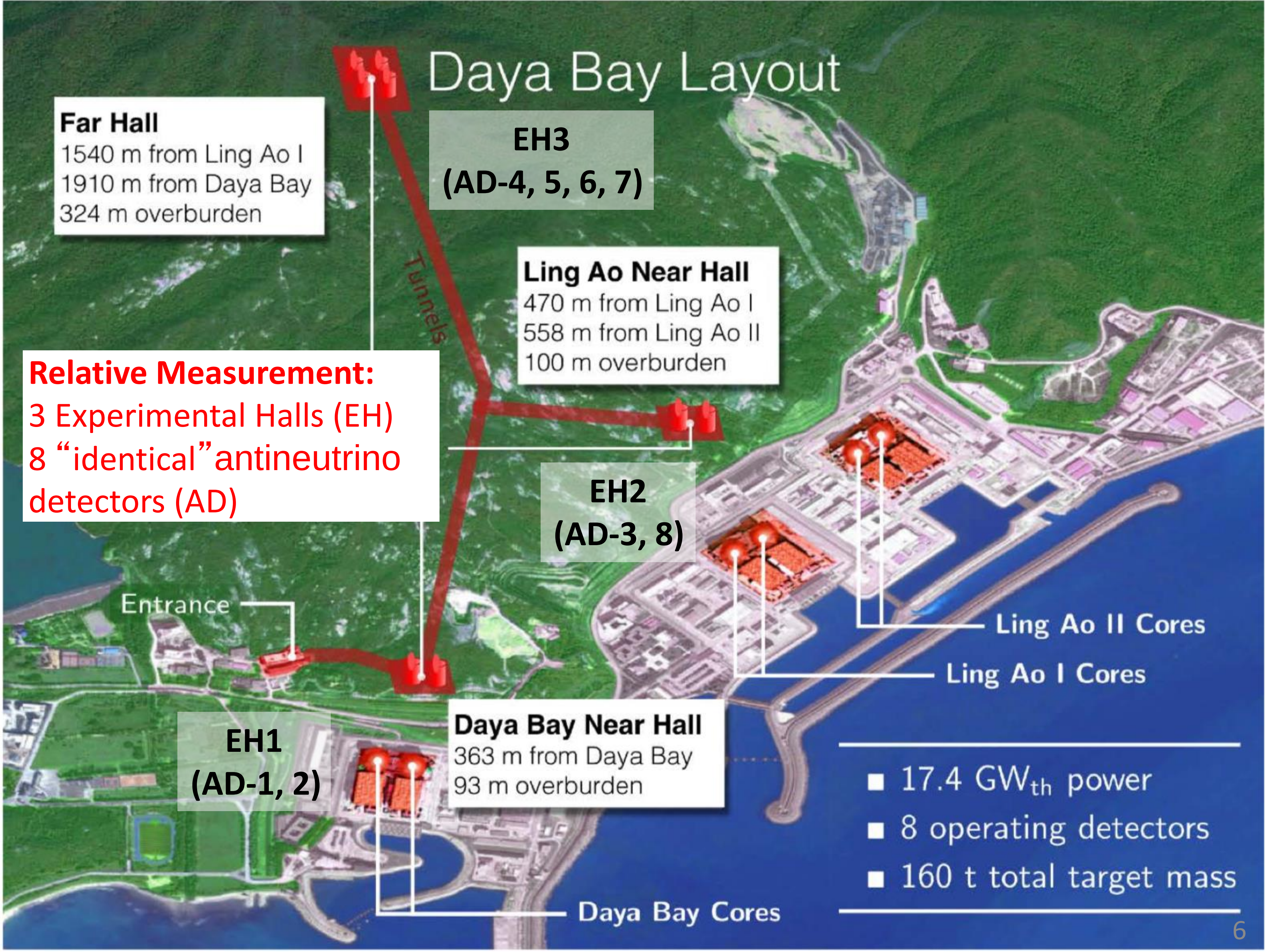


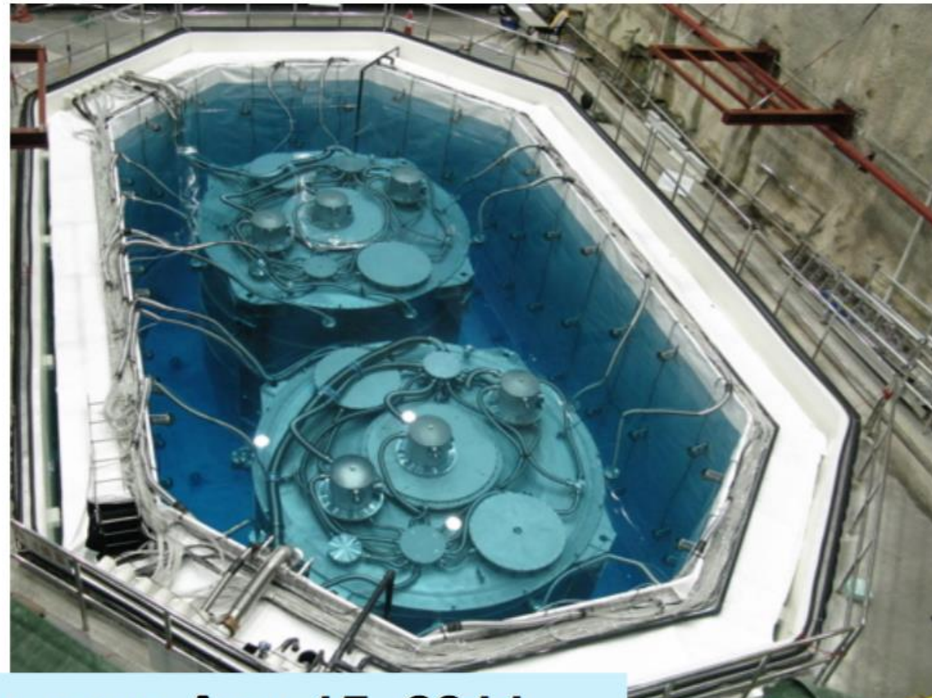
Daya Bay collaboration:

- ~200 collaborators
- ~40 institutions

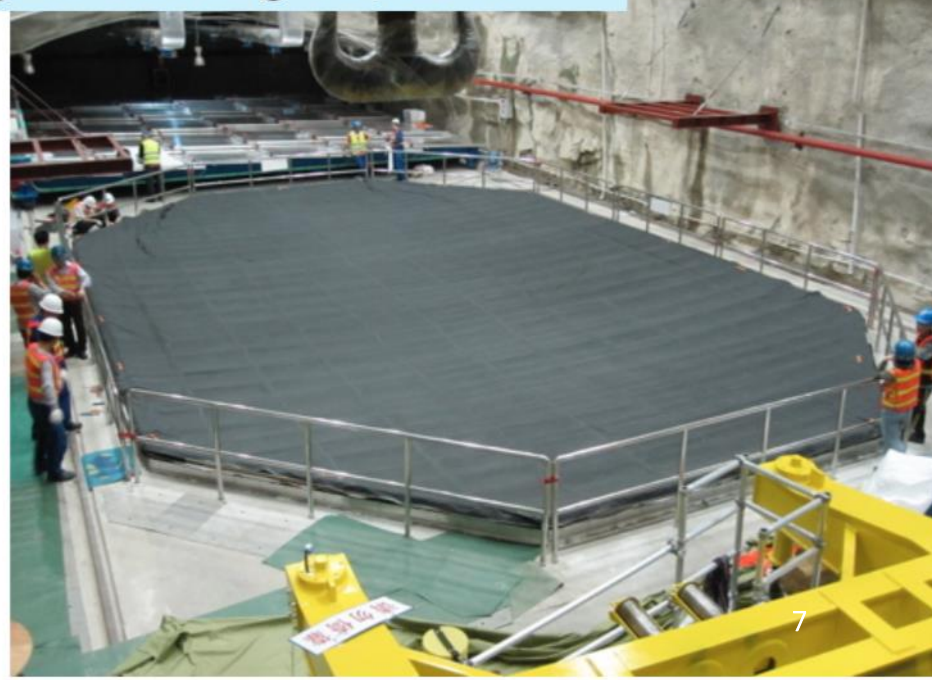
Members from SYSU:

- Jiajie Ling
- Wei Wang
- Yuenkeung Hor
- Fengpeng An
- Zhibing Li
- Honghao Zhang
- Yu Chen
- Yumei Zhang

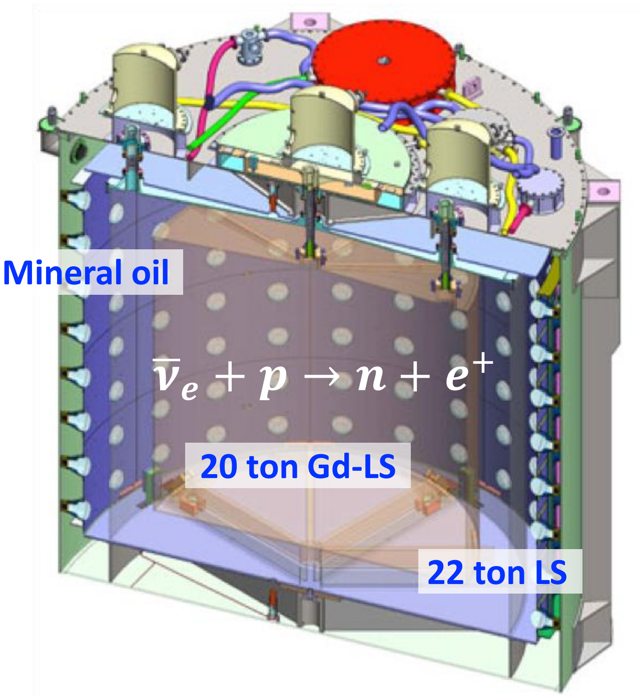

Daya Bay Layout
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
EH3
(AD-4, 5, 6, 7)
Tunnels
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
Relative Measurement:
3 Experimental Halls (EH)
8 "identical" antineutrino detectors (AD)
EH2
(AD-3, 8)
Entrance
Ling Ao II Cores
Ling Ao I Cores
EH1
(AD-1, 2)
Daya Bay Near Hall
363 m from Daya Bay
93 m overburden
17.4 GW_{th} power
8 operating detectors
160 t total target mass
Daya Bay Cores



Hall 1: Data taking began on Aug 15, 2011



Antineutrino Detector (AD) System



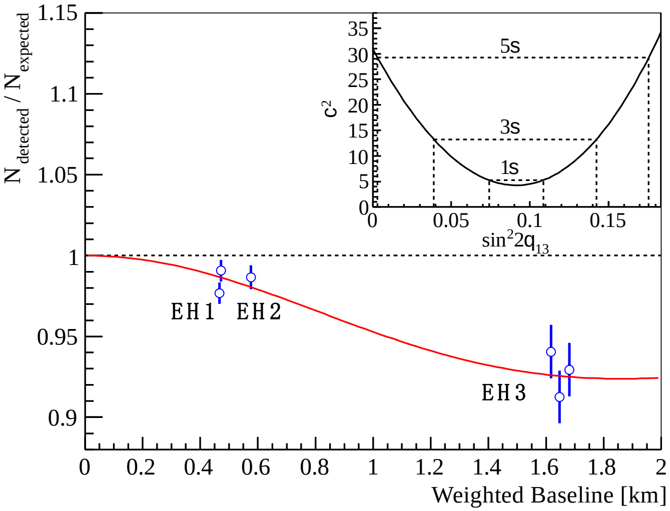
6-AD (2-1-3)
24/12/2011 – 28/07/2012
217 days

8-AD (2-2-4)
19/10/2012 – 21/12/2016
1524 days

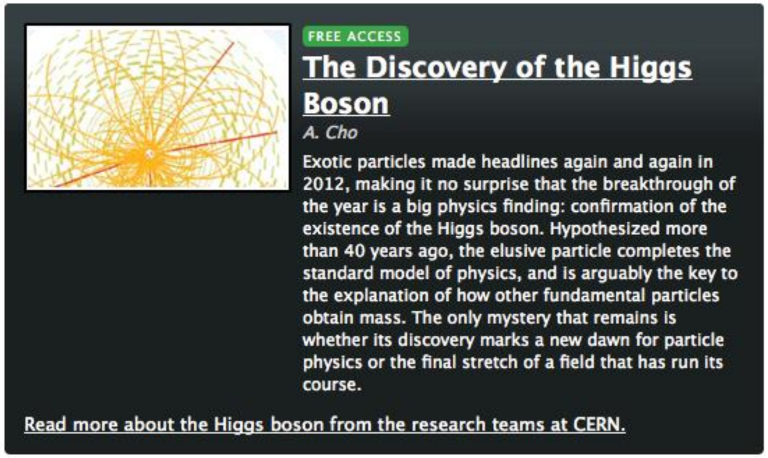
7-AD (1-2-4)
26/01/2017 – 12/12/2020
1417 days

- AD7-8 installation
- Special calibration
- AD1 FADC installation
- AD1 GdLS→ LS
- End of operation

First Result in 2012



Daya Bay excluded θ_{13}=0 with 5.2σ with only 55 days after operation


FREE ACCESS

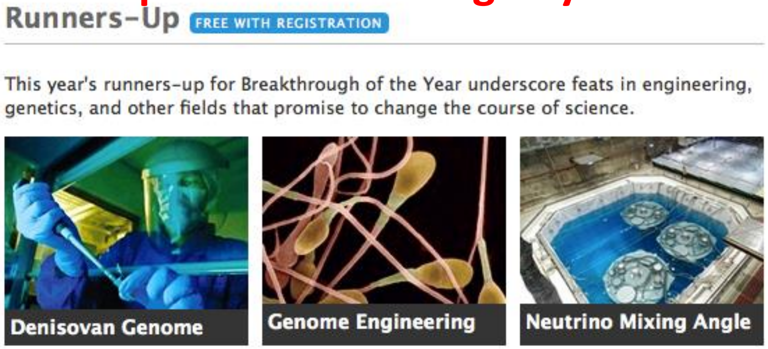
The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

2012 top 10 break-through by Science

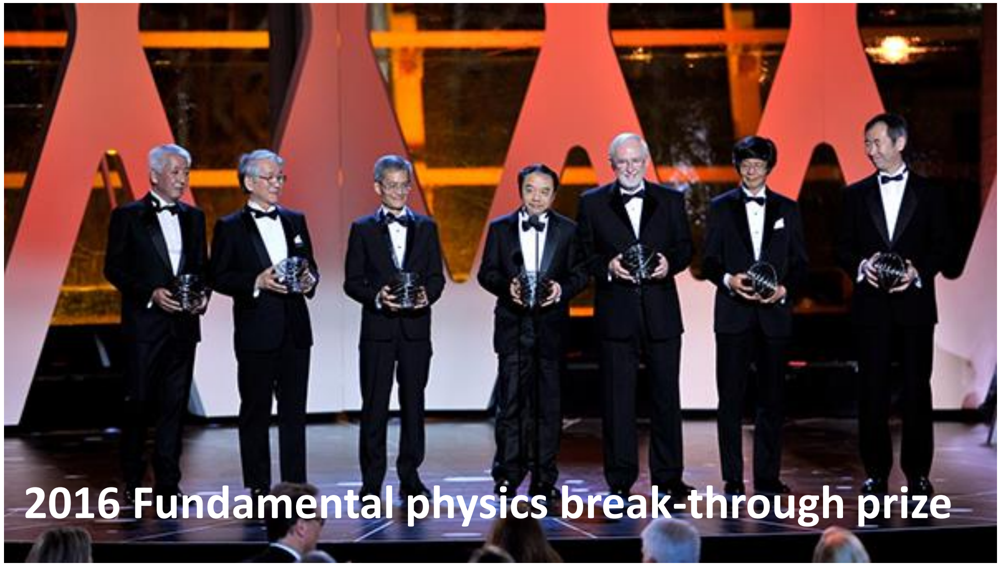

Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Denisovan Genome

Genome Engineering

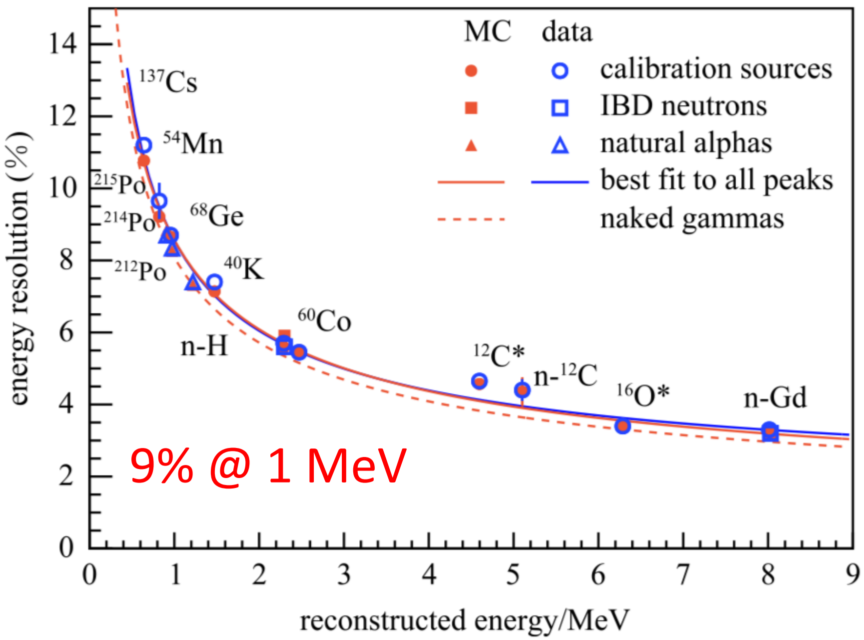
Neutrino Mixing Angle



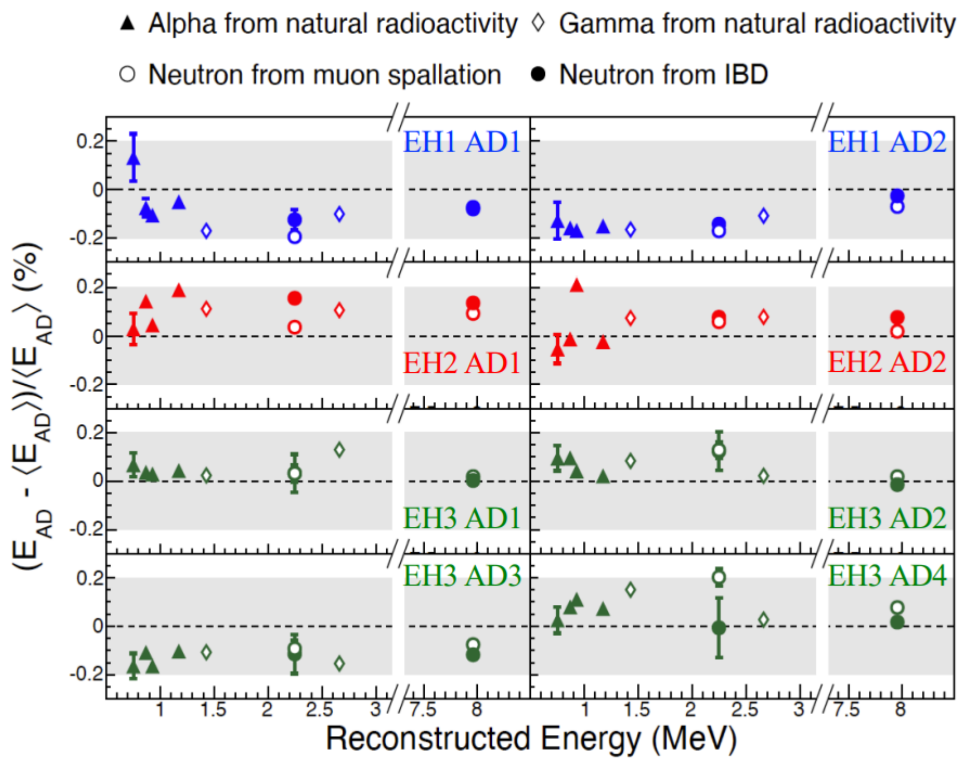
2020年12月12日 大亚湾实验停止运行

Detector Energy Response

- Rolling gain calibration using dark noise
- Weekly calibration
  - ^{68}Ge, $^{241}Am^{13}C$, ^{60}Co
  - LED diffuser ball
- Special calibration campaigns
  - ^{137}Cs, ^{54}Mn, $^{241}Am^{9}Be$, $^{239}Pu^{13}C$
- Spallation neutrons and ^{12}B
- Natural radioactivity

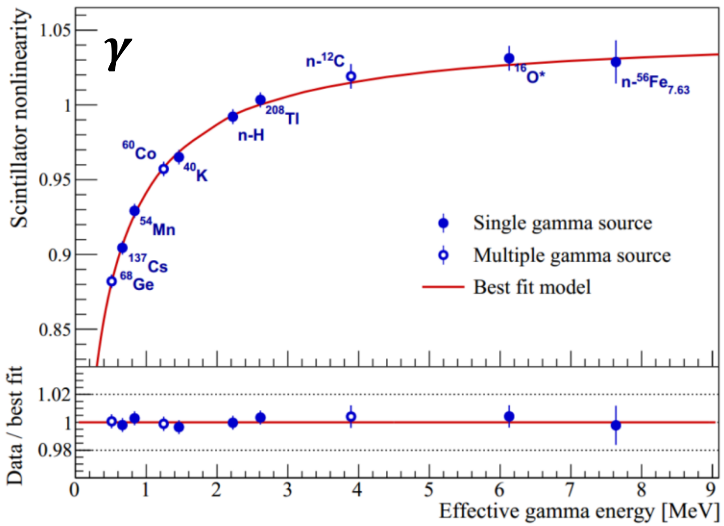


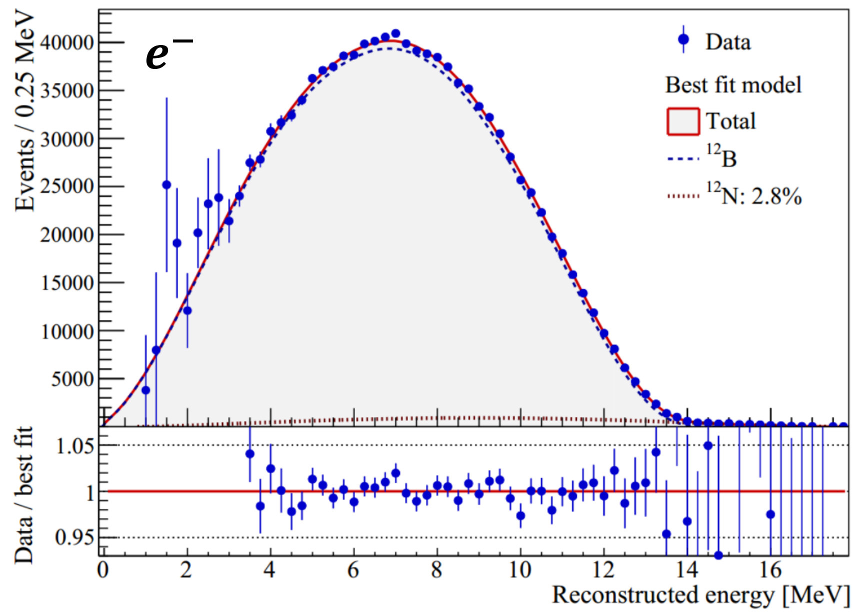
*NIM A**750** 19 (2014)*   *NIM A**797** 260 (2015)*

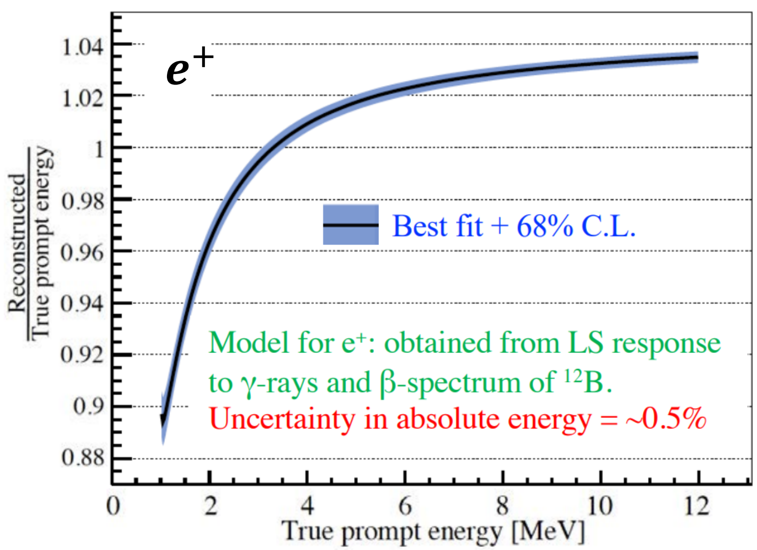


Relative detector energy scale ≲ 0.2%

Energy Nonlinearity Calibration





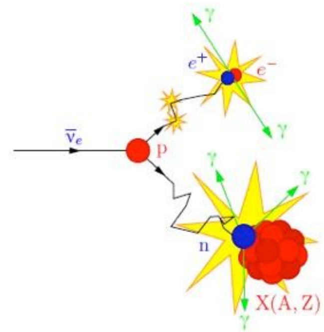


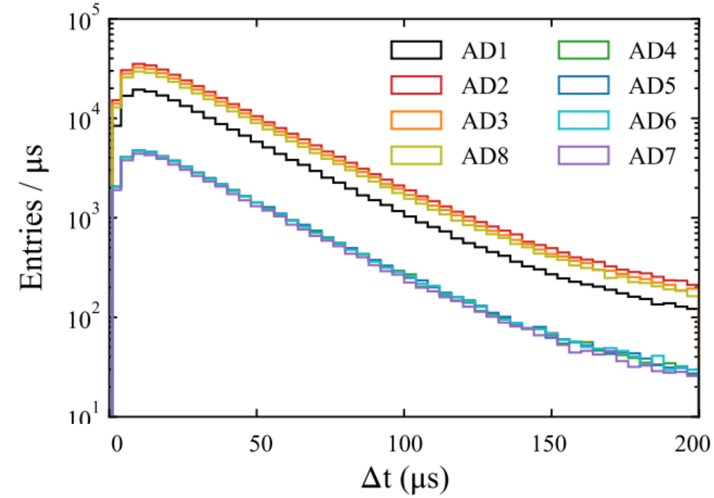
- Two major sources of energy nonlinearity:
  - Scintillator response (Birks + Cherenkov)
  - Readout electronics (FADC correction)
- Energy model for positron is derived from measured gamma and electron responses using simulation.

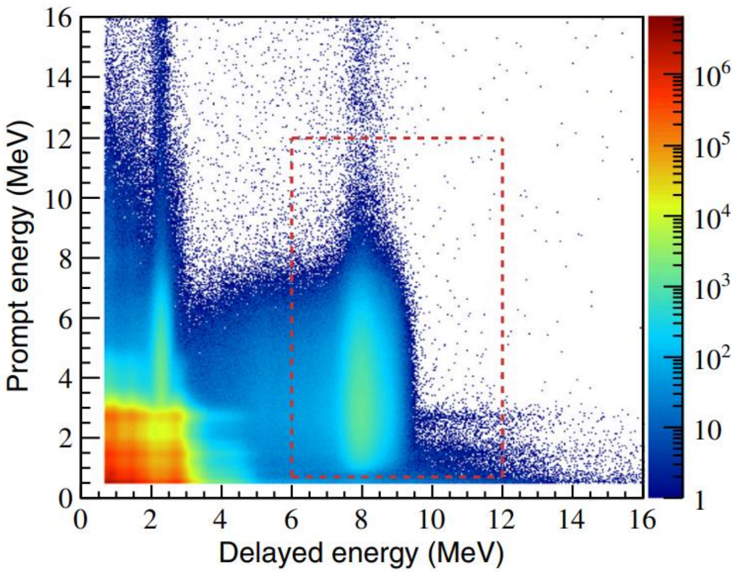
~0.5% absolute energy uncertainty

IBD Pair Selection

- Remove flashing PMT events
- Veto muon events
- Prompt and delayed energy:
  - 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 signal pairs



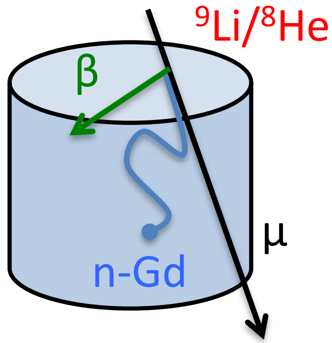


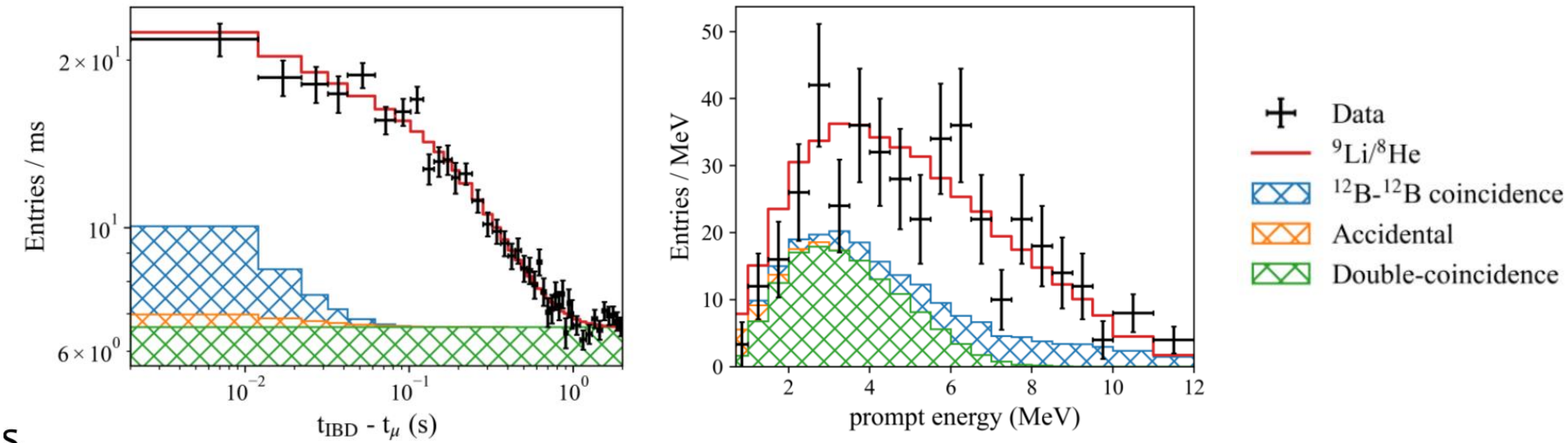


	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill in	104.9%	1.00%	0.02%
Live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

Backgrounds: $^{9}Li/^{8}He$

- Cosmogenic isotopes: $^{9}Li/\,^{8}He$:
  - $\beta - n$ decay
  - $\tau_{Li} = 257.2$ ms, $\tau_{He} = 171.7$ ms
- 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





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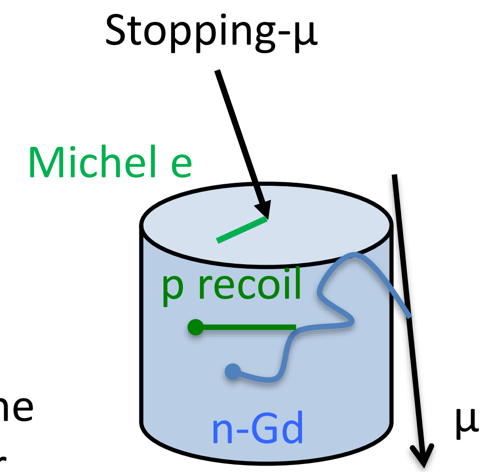
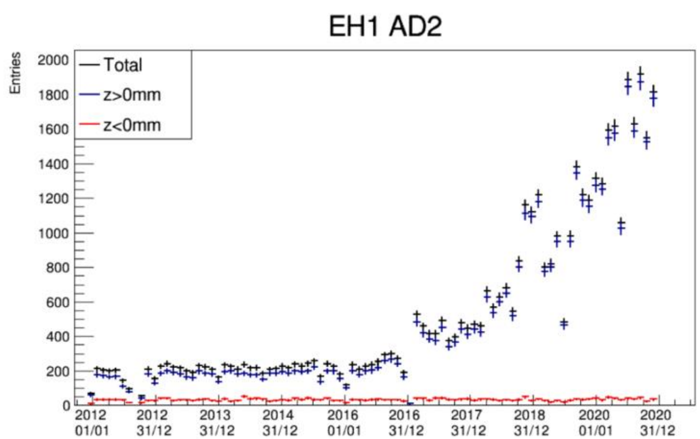
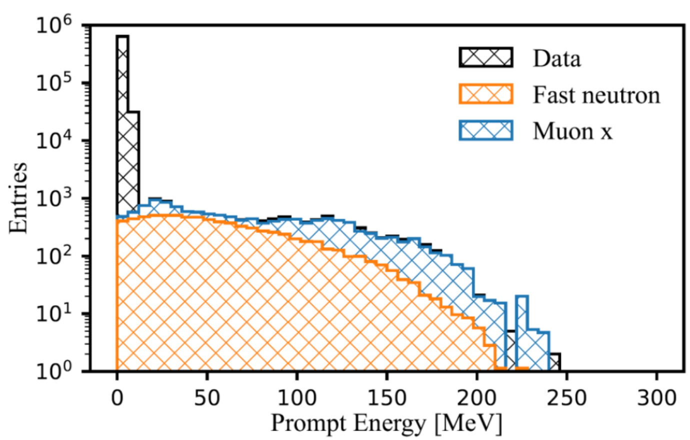
Backgrounds: Fast Neutron and Muon-X

- Fast spallation neutrons generated outside of the water pool
- Gradual failure of PMTs or high-voltage channels in the water veto system
  - Reduction of muon detection efficiency in water pool
  - Muon decays and spallation (muon-x) on top of ADs
- Lower the hit multiplicity of PMTs (nHit) in IWS from 12 to 6 to tag muon-x backgrounds
  - Reject more than 80% muon decays with < 0.1% loss of livetime
  - Extend cut on E_{Prompt} from 12 MeV to 250 MeV spectrum for fast neutron and muon-x





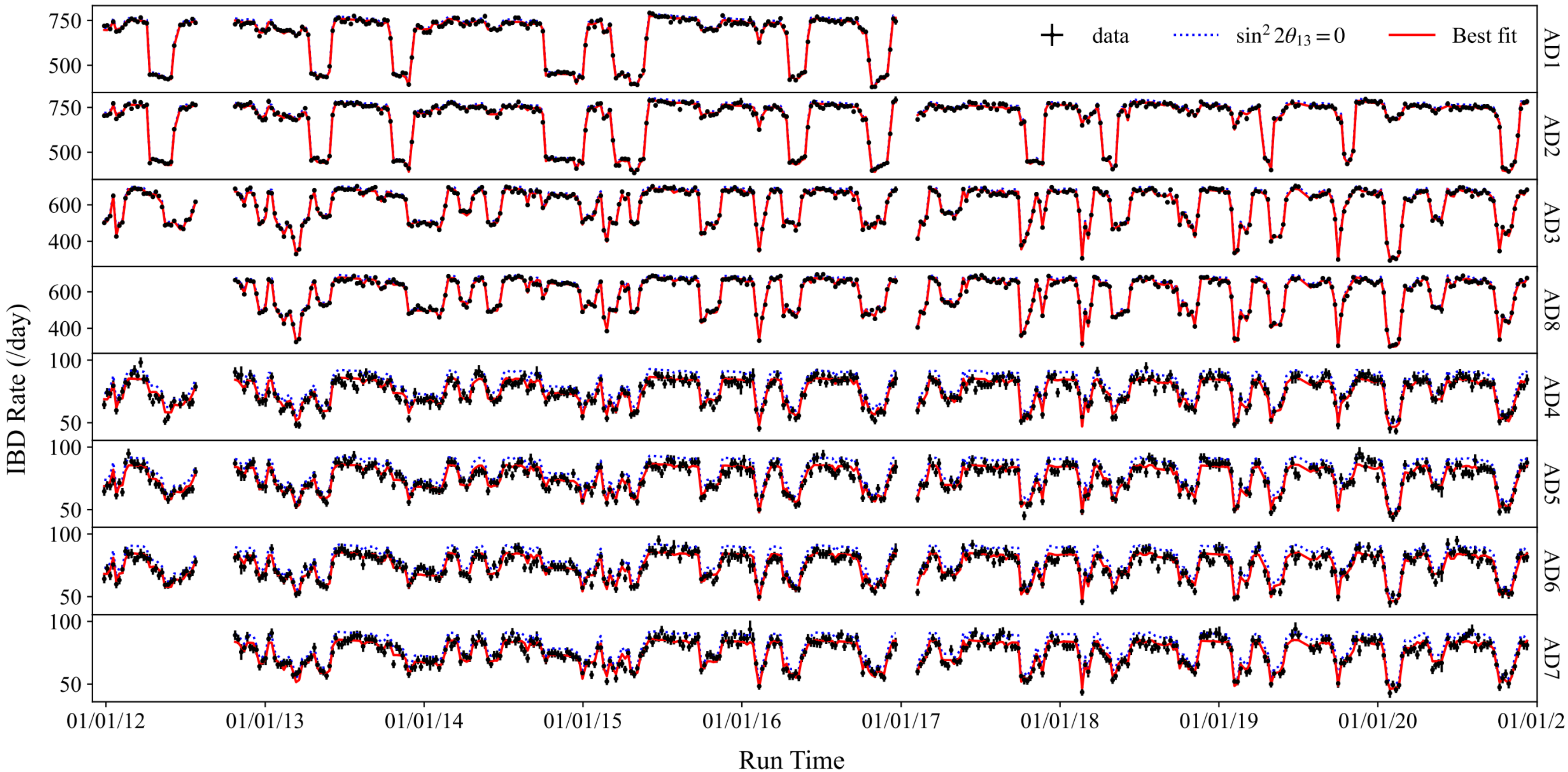
IWS nHit > 6



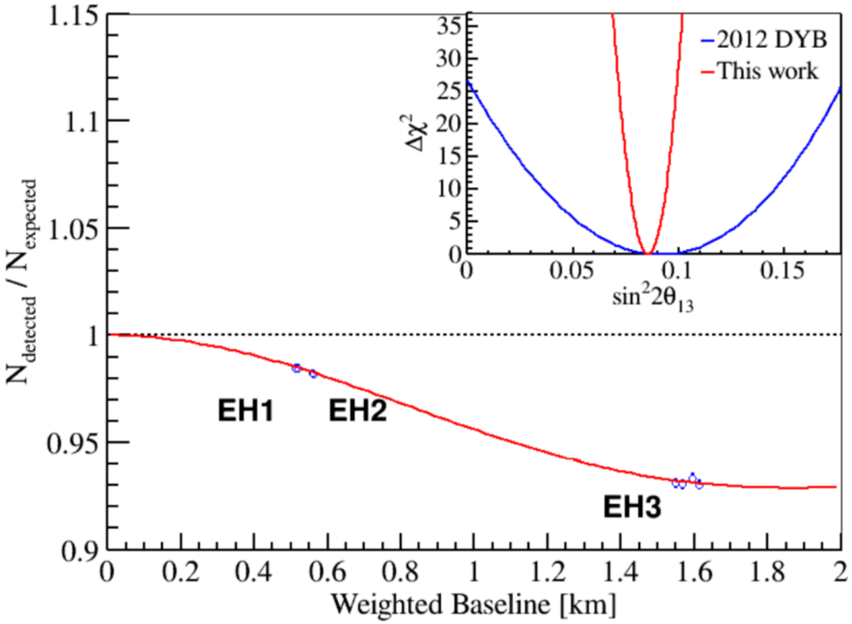
5.5 Million nGd IBD Candidates

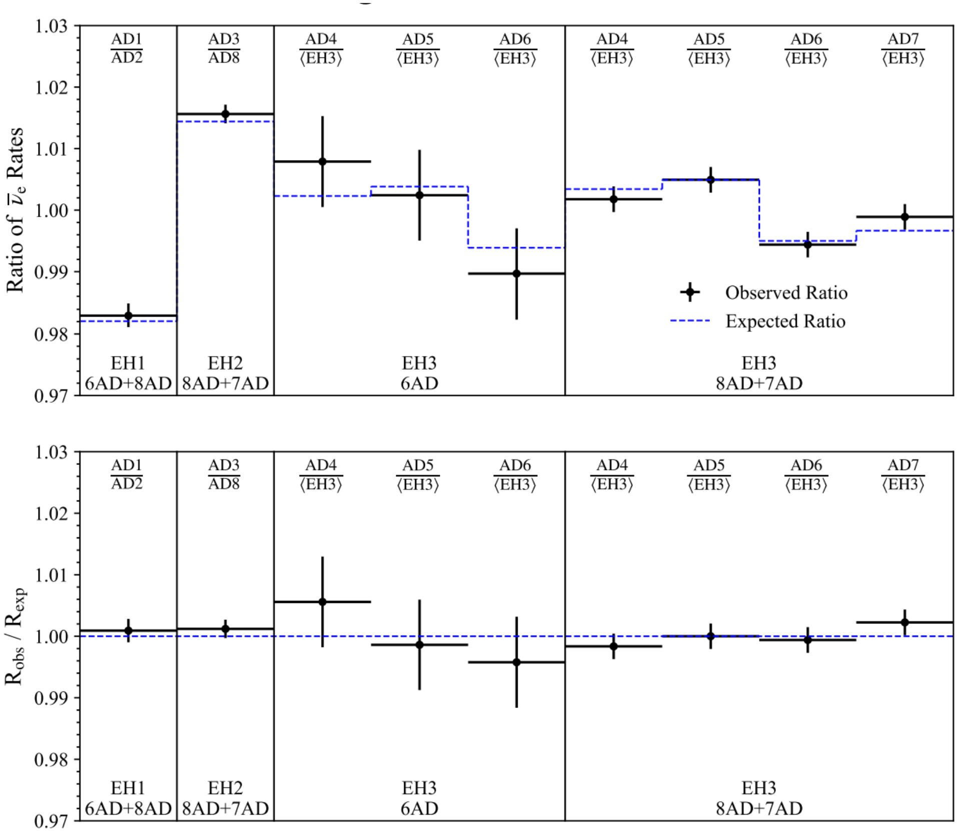
- 24/12/2011 – 12/12/2020 (3158 days)
  - ~2700 days of good data
- World largest IBD data sample
  - 5.5 M IBDs

Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
IBD candidates	2,236,810	2,544,894	764,414



Rate-only Oscillation Results

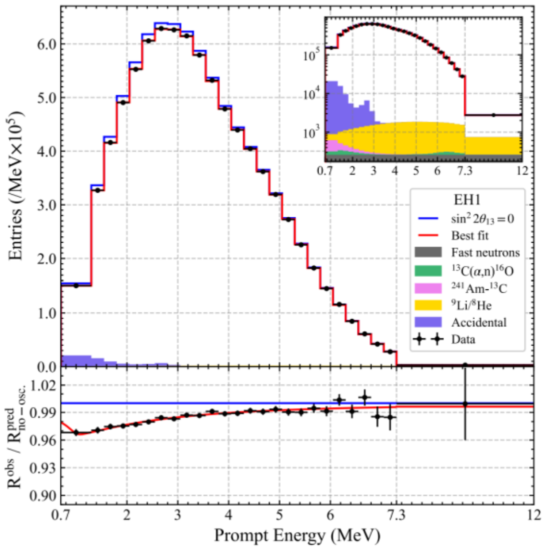


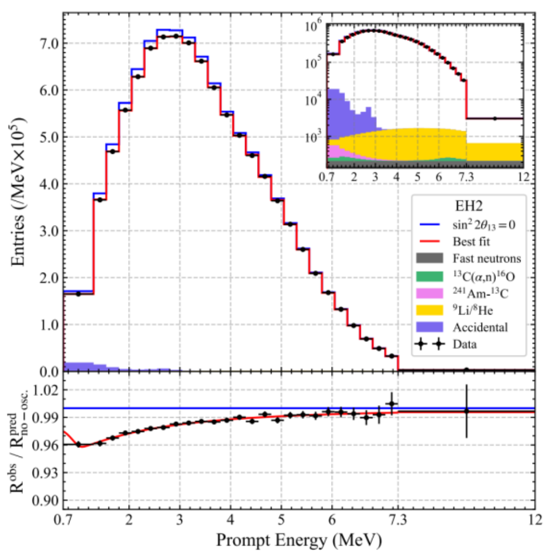


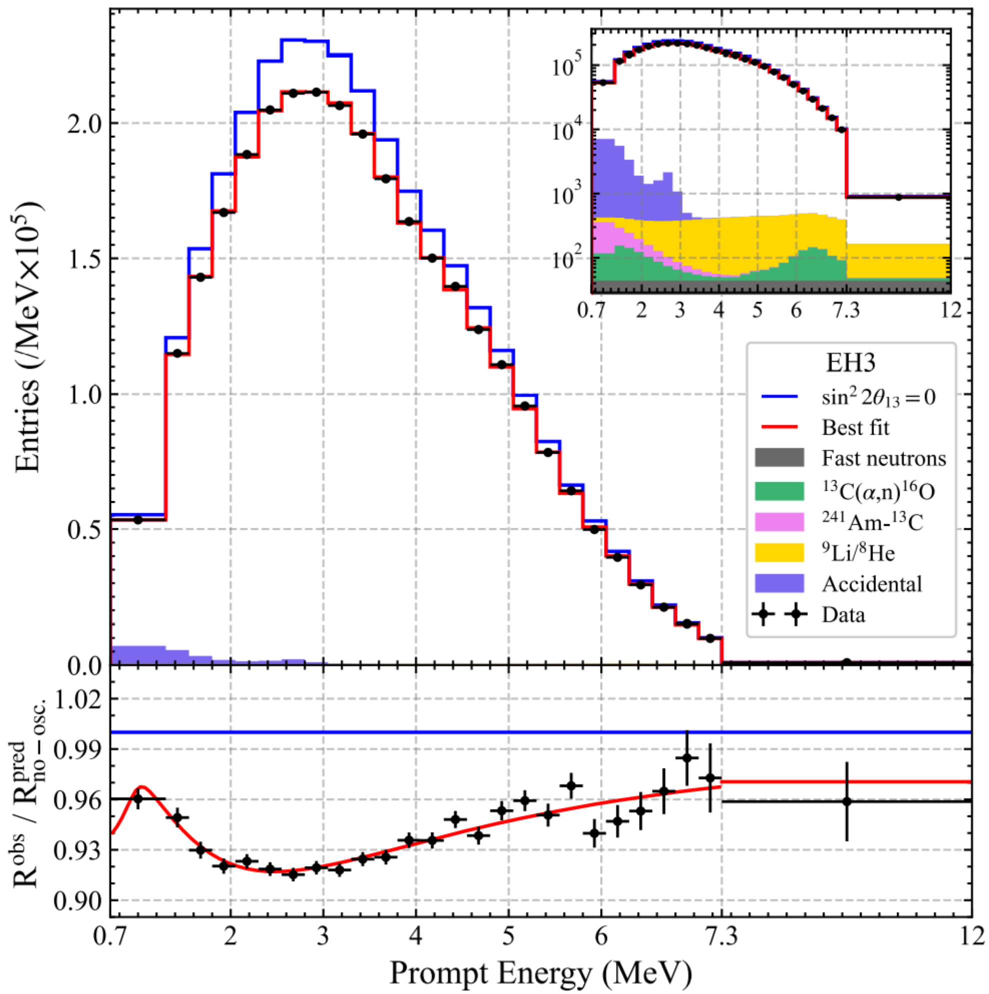
$sin^2 2\theta_{13} = 0.0854 \pm 0.0027$

χ^2/NDF = 17.3 / 19

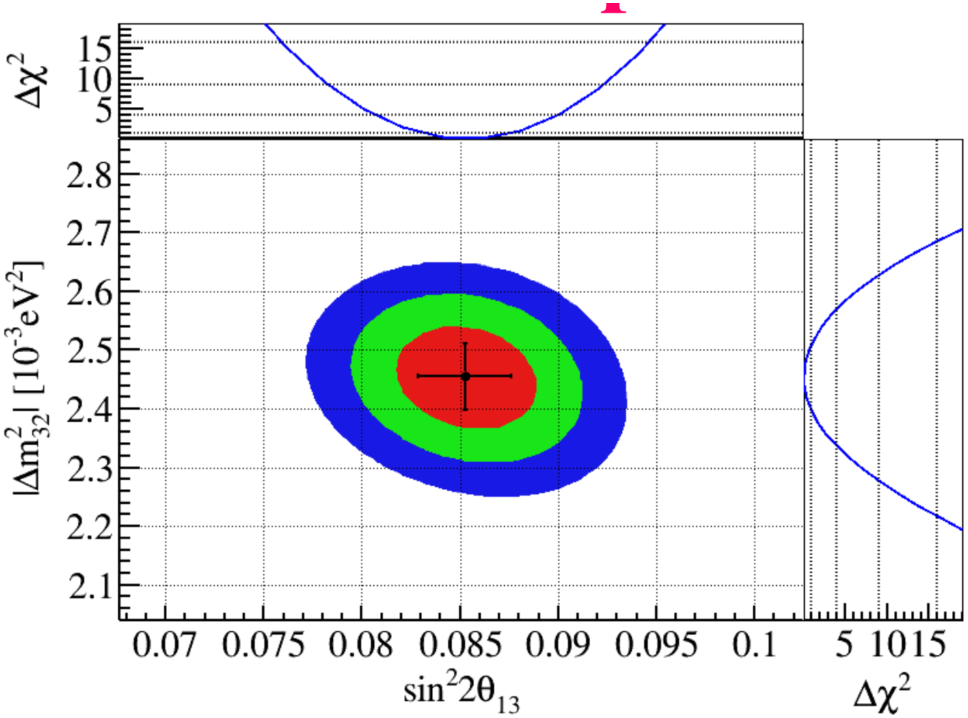
Prompt Energy Spectra

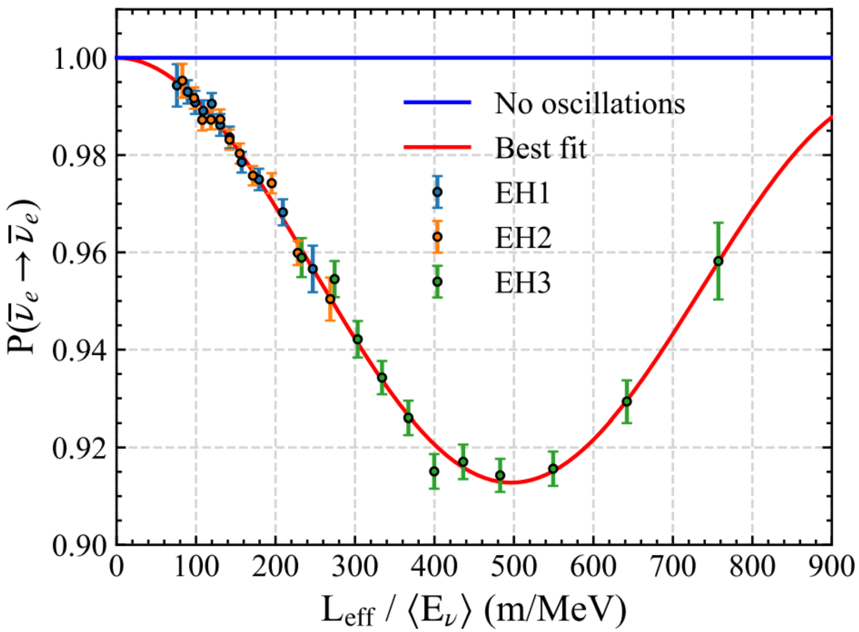






Rate+Spectra Oscillation Results





Best-fit results: χ^2/ndf = 559/518

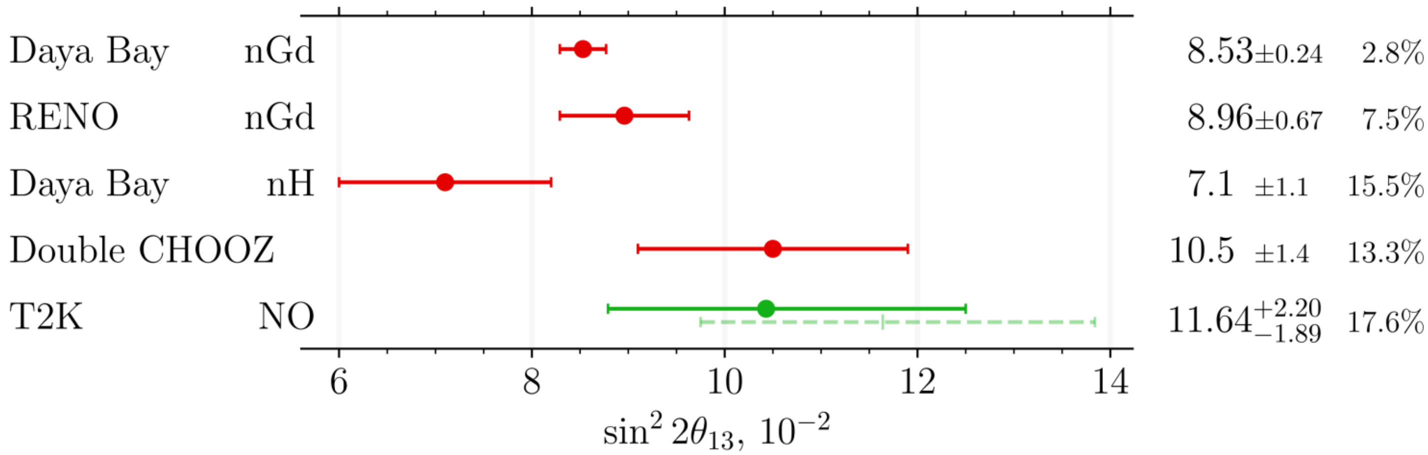
$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

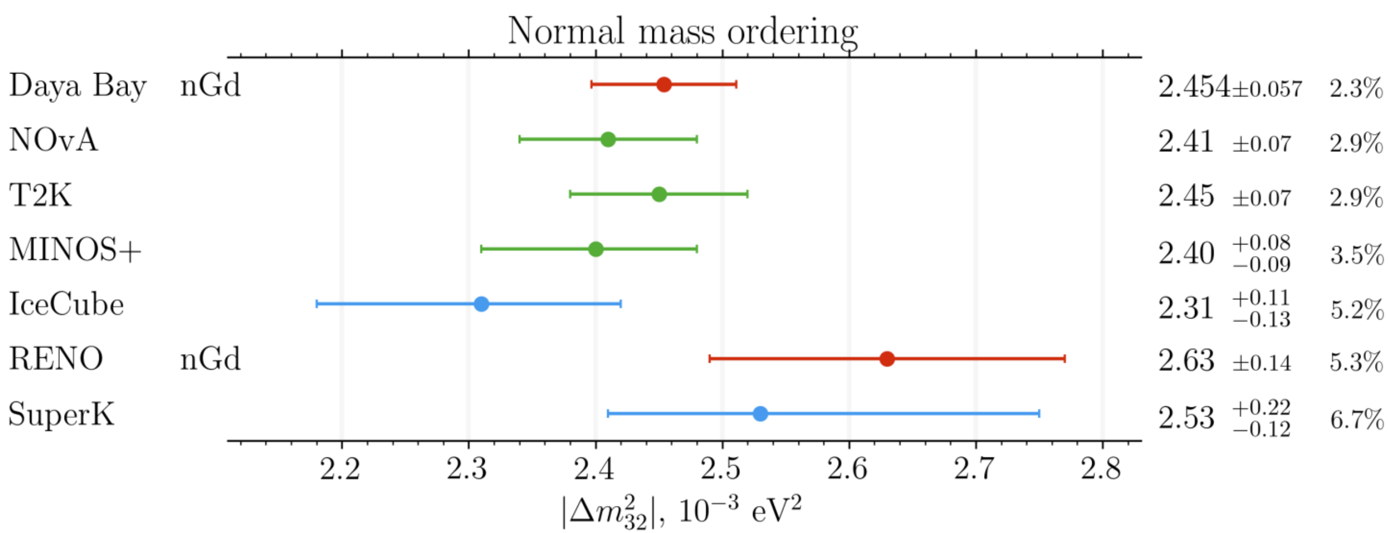
Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

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

(2.3% precision)

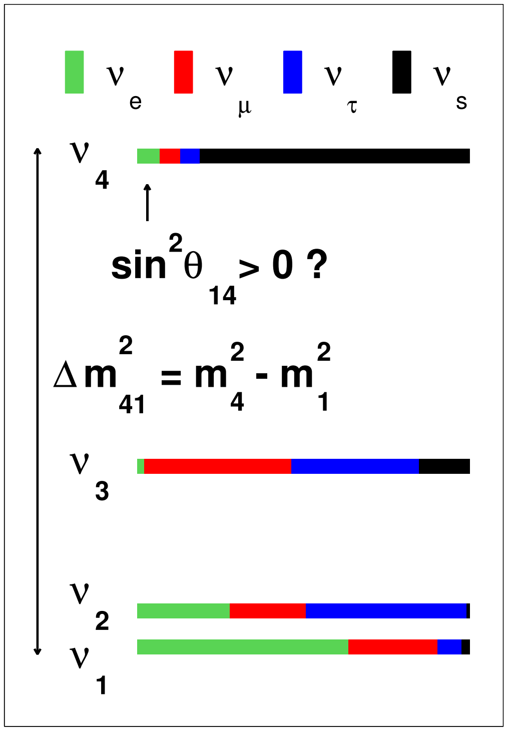
Precision Measurements

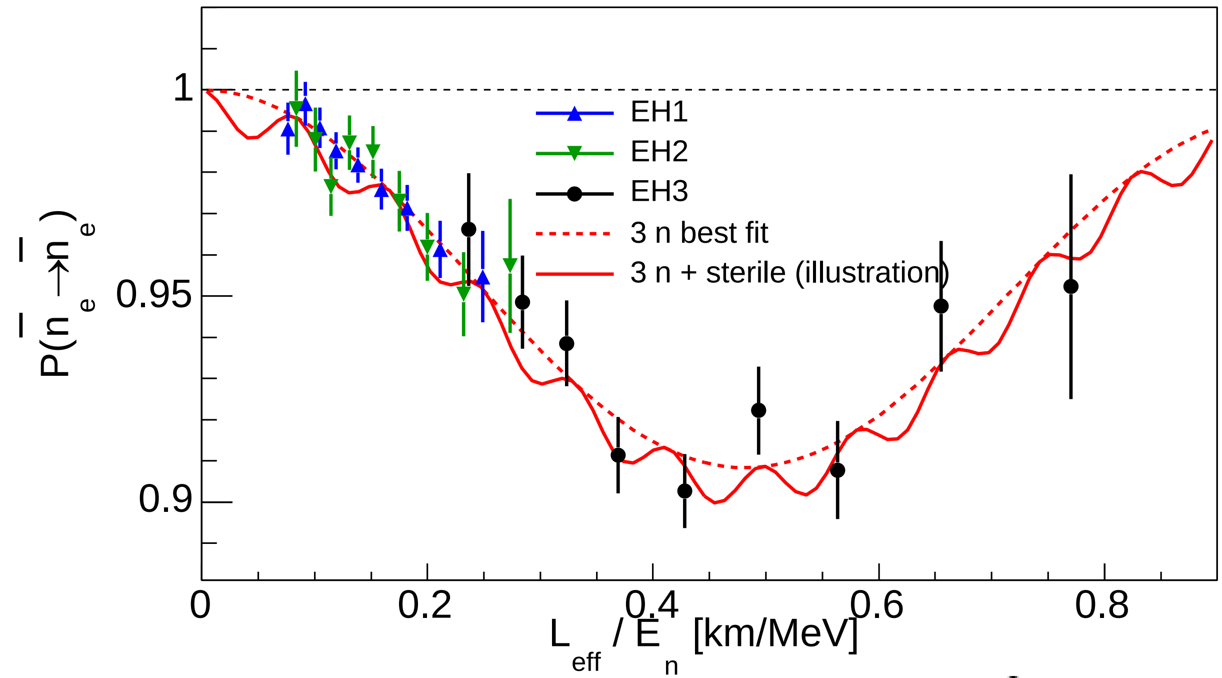




World most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$

light sterile neutrino oscillation



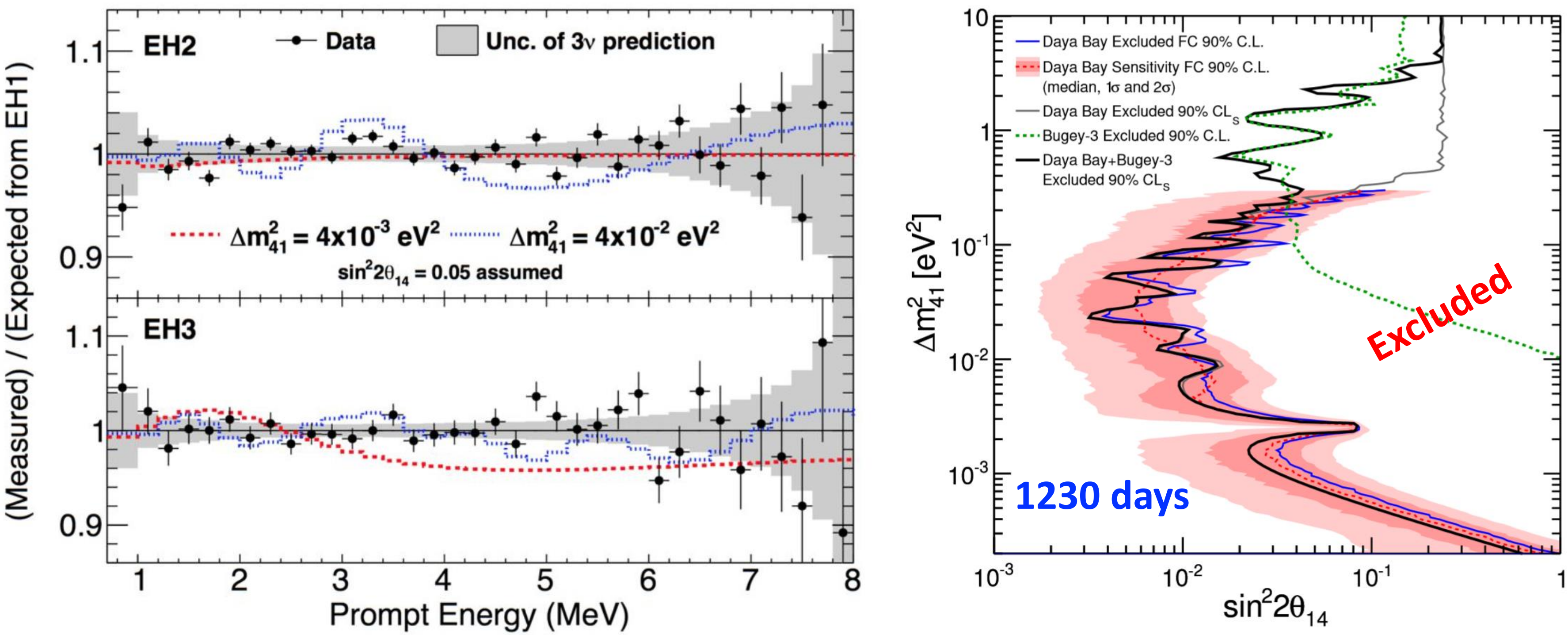


$$P(\bar{n}_e \rightarrow \bar{n}_e) @ 1 - \cos^4 q_{14} \sin^2 2q_{13} \sin^2\left(\frac{Dm_{ee}^2 L}{4E_n}\right) - \sin^2 2q_{14} \sin^2\left(\frac{Dm_{41}^2 E}{4E_n}\right)$$

- A minimum extension of the 3-ν model: 3(active) + 1(sterile)-ν model
- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

Sterile Neutrino Search

PRL 125, 071801 (2020)



- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

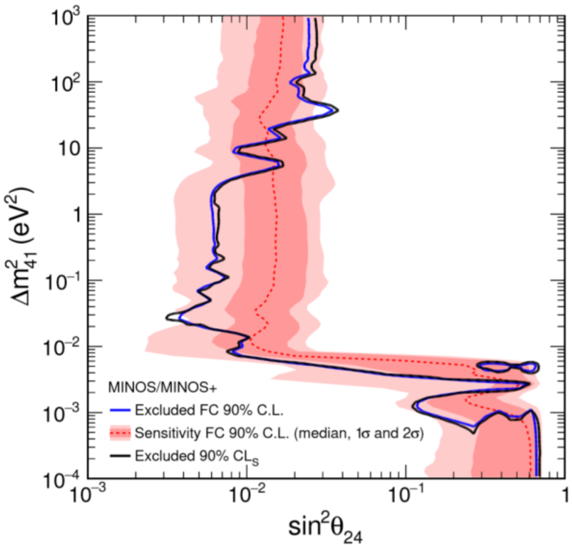
The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV^2)

Joint Sterile Neutrino Searches

*PRL **122** 091803 (2019)*

PRL 125, 071801 (2020)

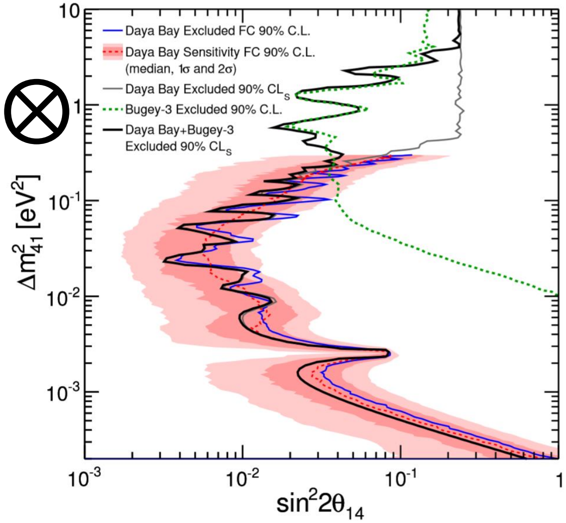
MINOS/MINOS+



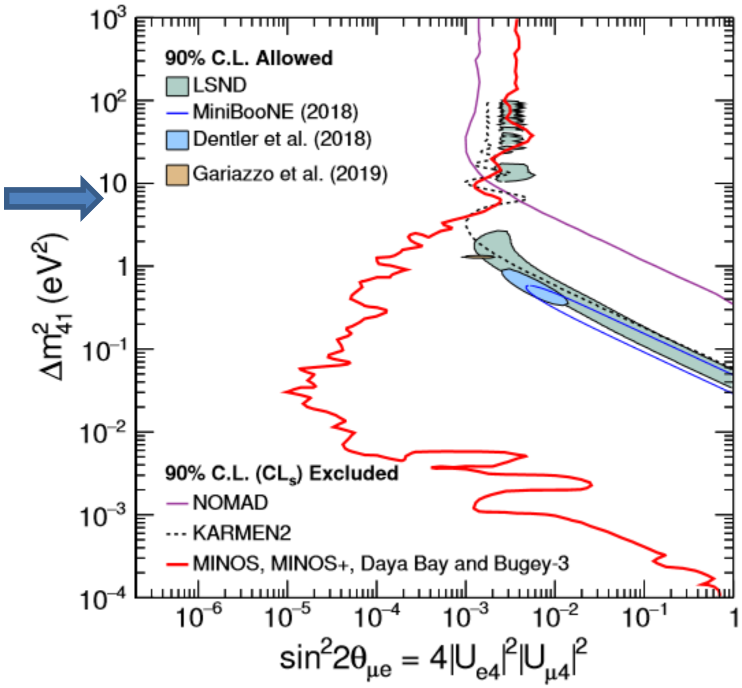
$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$

$\otimes$

Daya Bay + Bugey-3



$|U_{e4}|^2 = \sin^2\theta_{14}$

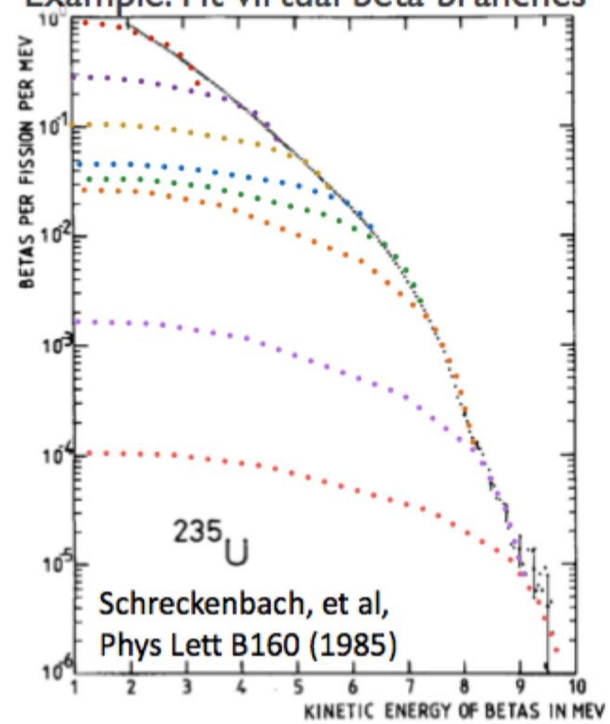


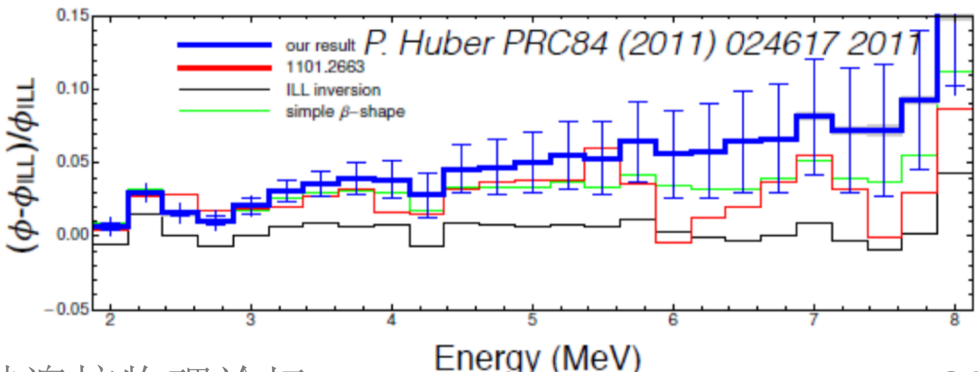
- The combined results can exclude the LSND and MiniBooNE signal region at $\Delta m^2_{41} < 5$ eV^2 at 90% C.L.

Reactor $\bar{\nu}_e$ Flux Prediction

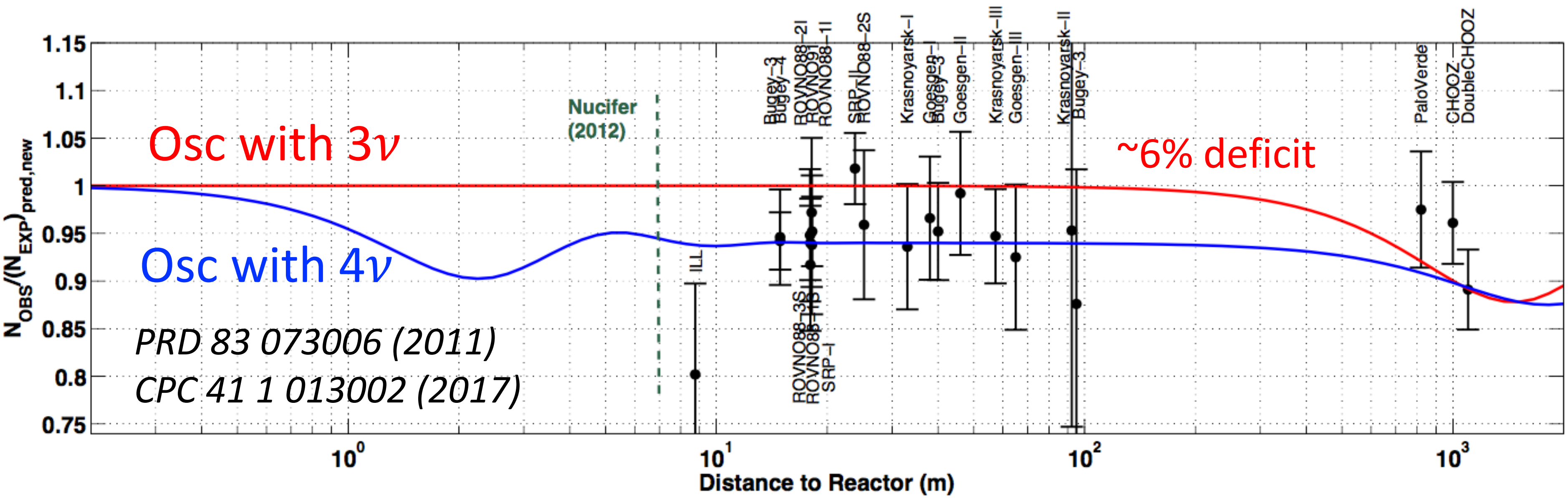
- Summation (ab initio) method
  - > 6000 decay branches
  - Missing data in the nuclear database
  - ~30% forbidden decays
  - ~ 10% uncertainty
- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to $\bar{\nu}_e$ with >30 virtual β-decay branches
  - Old: ILL + Vogel (^{238}U) model (1980s)
  - New: Huber + Mueller (^{238}U) model (2011)
  - ~ 2.4% uncertainty

Example: Fit virtual beta branches



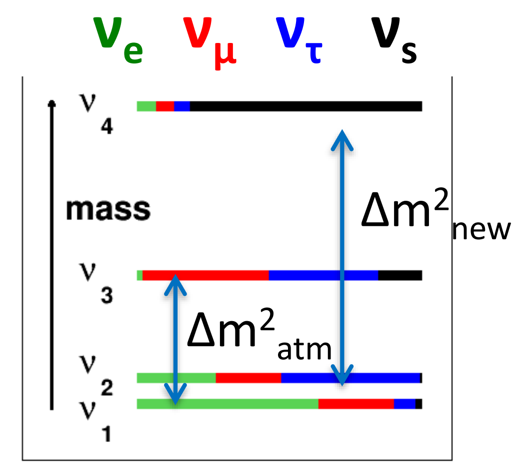


Reactor Antineutrino Anomaly (RAA)



The measured $\bar{\nu}_e$ flux at 10-100 m from reactor cores is ~6% below the theoretical calculation

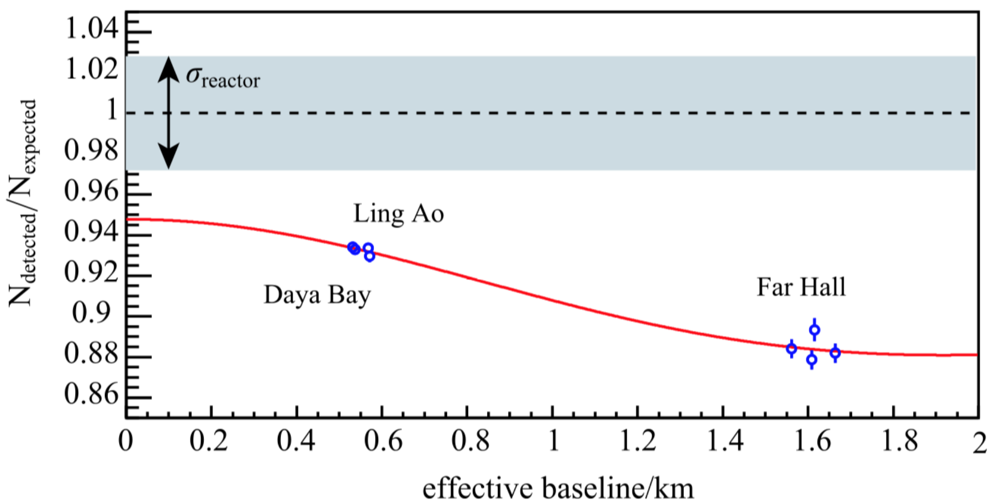
- Theoretical reactor $\bar{\nu}_e$ flux modelling?
  - Systematic uncertainty underestimation (2%→5%)
- Sterile neutrinos ($\bar{\nu}_e \rightarrow \bar{\nu}_s$)?
  - High frequency oscillation (Δm^2_{new}~ 1-10 eV^2) at baseline of few meters



3 (active)+1(sterile)-υ model

Reactor $\bar{\nu}_e$ Flux and Spectrum

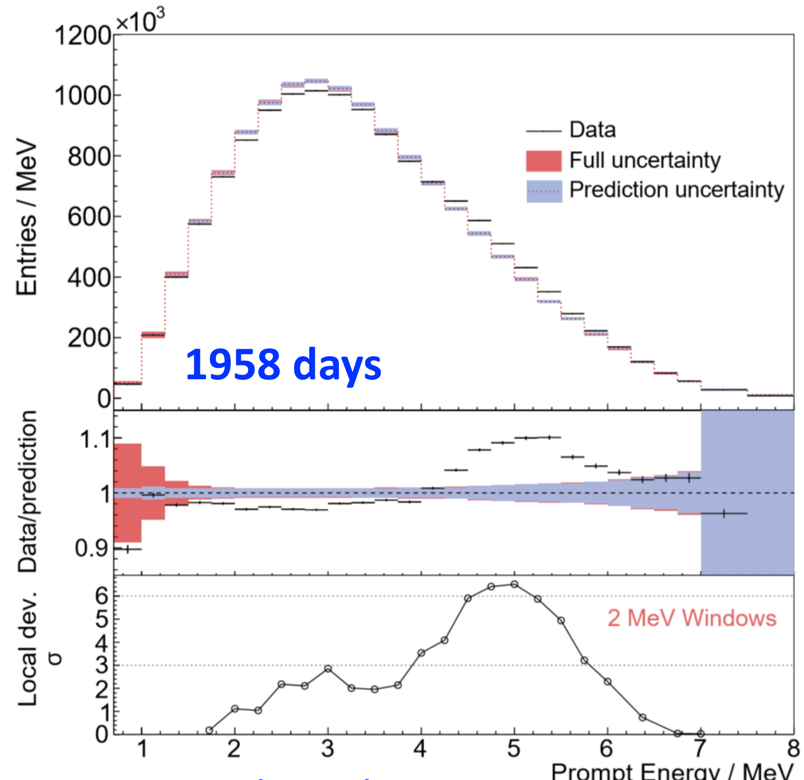
*PRD **100** 052004 (2019)*



$$R = \frac{data}{Model\ (Huber + Mueller)}$$

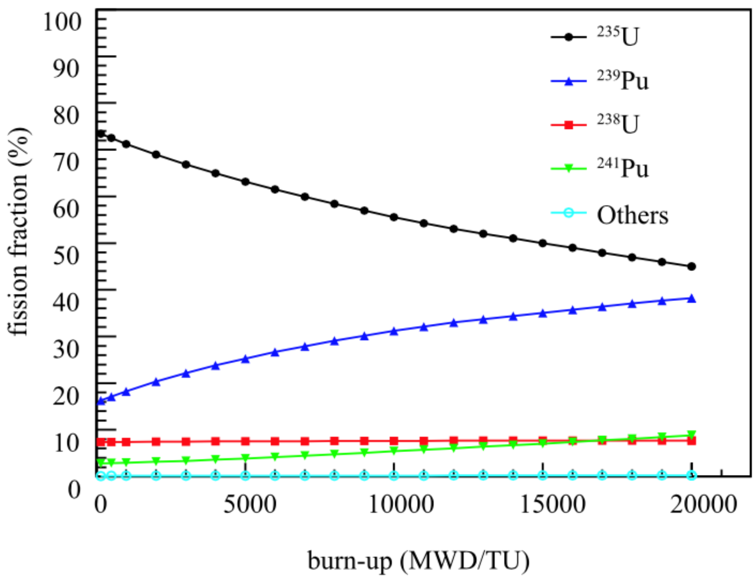
$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

*PRL **123** 111801 (2019)*

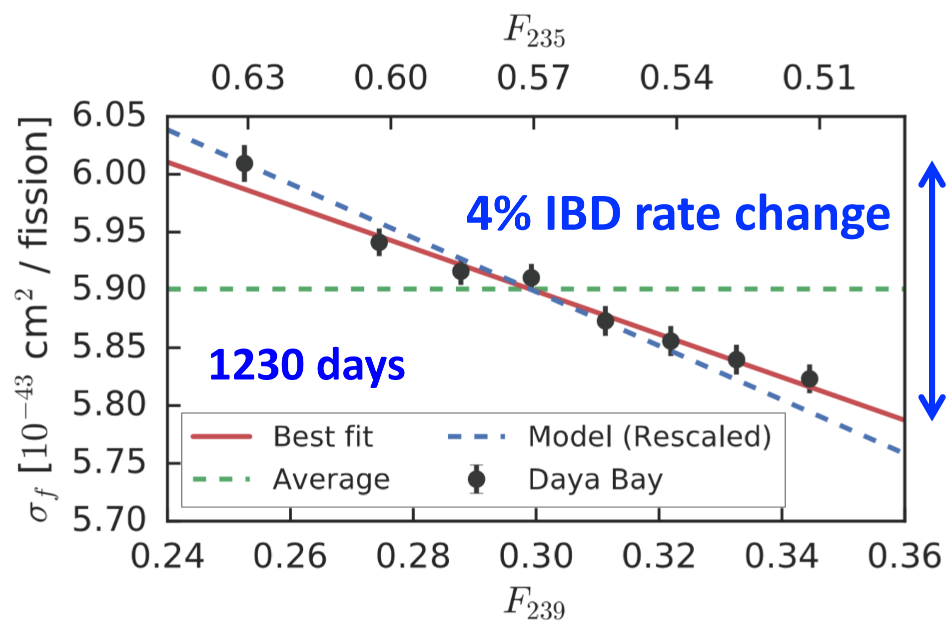


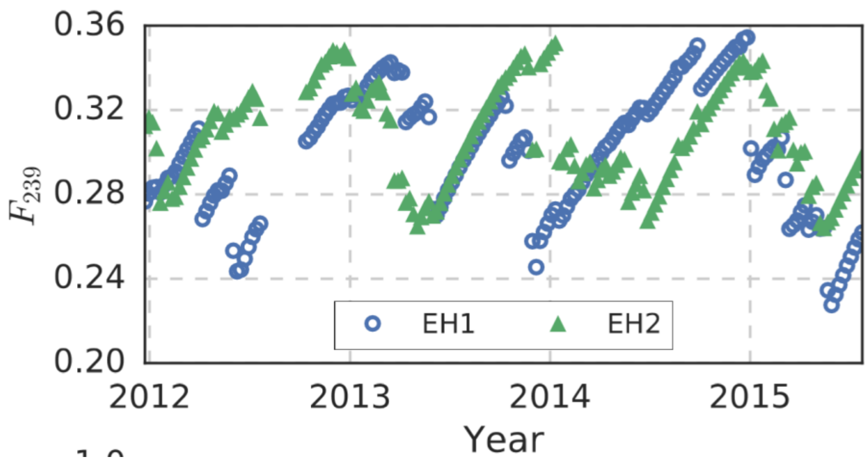
- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total >5σ deviation, especially significant deviation at 4-6 MeV region of the prompt energy (>6σ)
- No effect on far/near relative measurement for θ_{13} and Δm^2_{32}

Reactor Isotope Fuel Evolution



*PRL **118** 251801 (2017)*

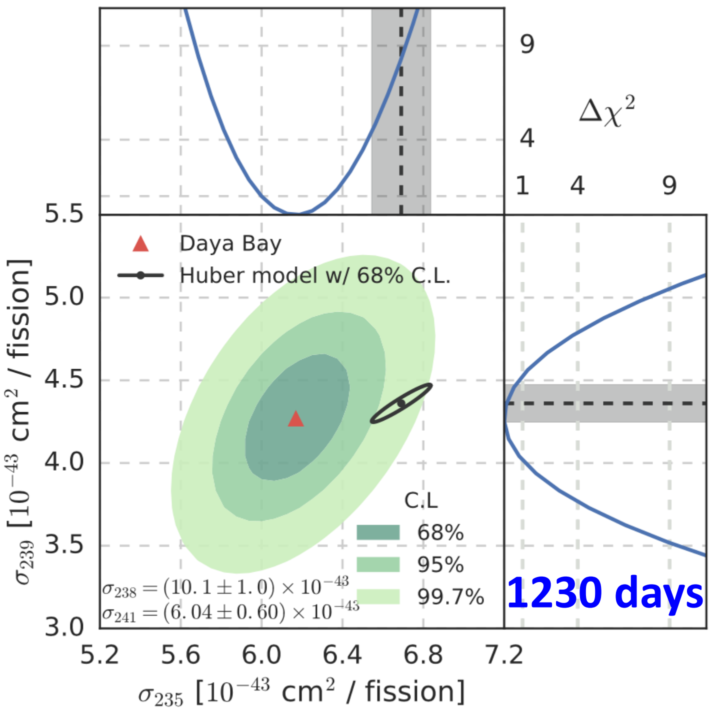




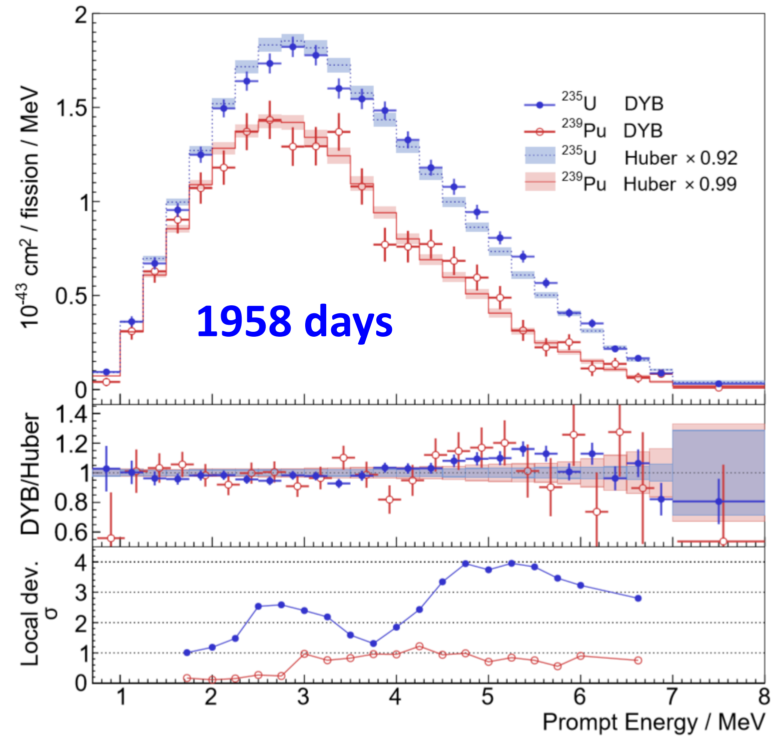
- Clear fuel-dependent evolution
- Evolution slope deviates from Huber + Mueller (H-M) model: disfavors sterile neutrino only (equal deficit) hypothesis at 2.6σ

Isotope Yields and Spectra Measurements from Fuel Evolution Study

PRL ***118*** *251801 (2017)*



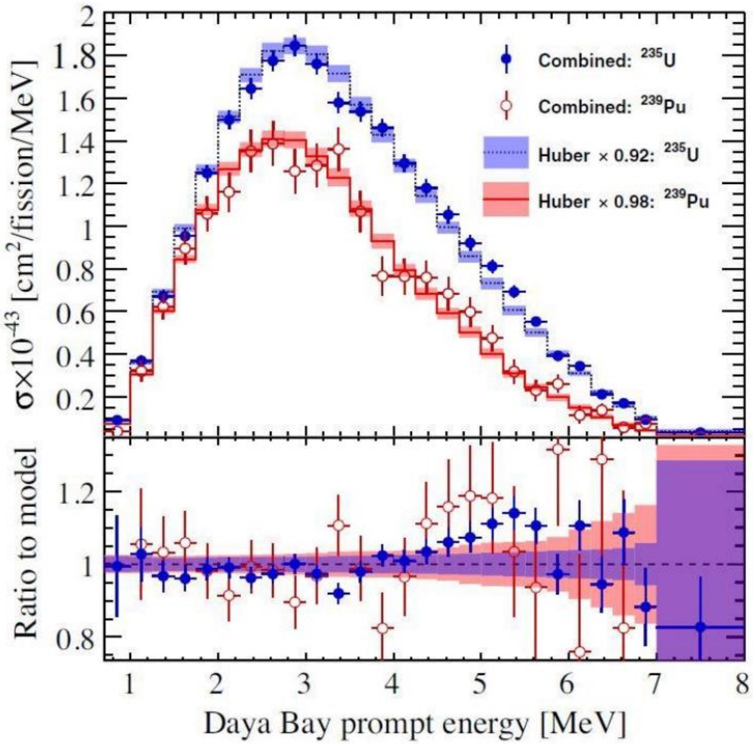
PRL ***123*** *111801 (2019)*



- Daya Bay data prefer ^{235}U to be mainly responsible for the Reactor $\bar{\nu}_e$ Anomaly
- First measurement of ^{235}U and ^{239}Pu spectra from a commercial reactor
- Consistent with bump structure at 4-6 MeV
- Local spectra deviation from prediction: ^{235}U (4σ) and ^{239}Pu (1.2σ)

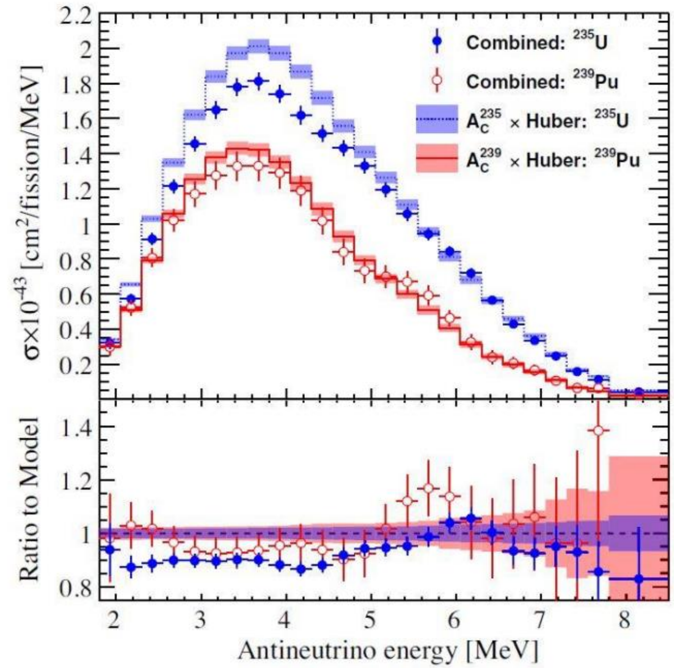
Joint analysis of Daya Bay and PROSPECT

- Compared with Daya Bay-only result, ^{235}U spectral shape err: 3.5% → 3%
- Reduce the degeneracy between ^{235}U and ^{239}Pu (by 20%).
- Central values change within 2% (consistent within uncertainties).



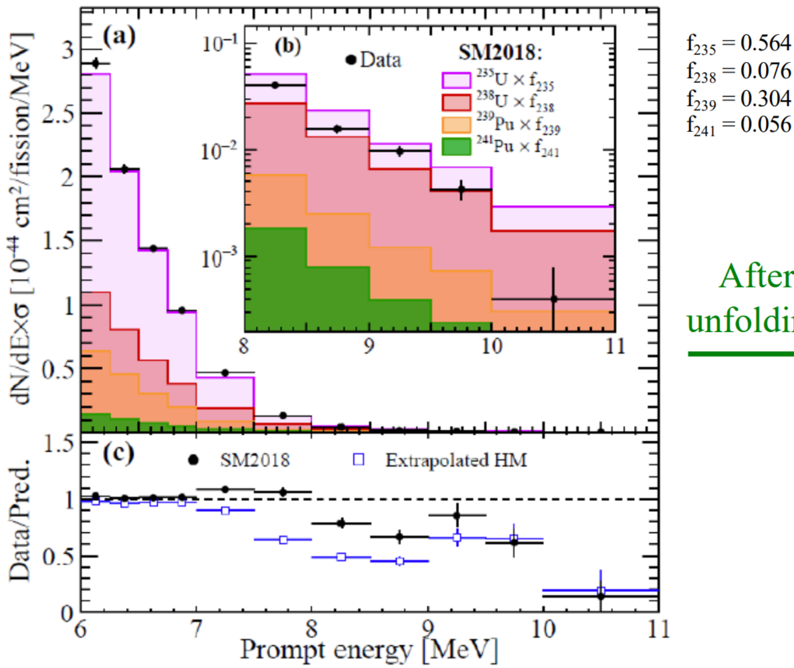
[Phys. Rev. Lett. 128, 081801 (2022)]

- Unfold the $\bar{\nu}_e$ spectrum with Wiener-SVD method
- More precise prediction for other Exps



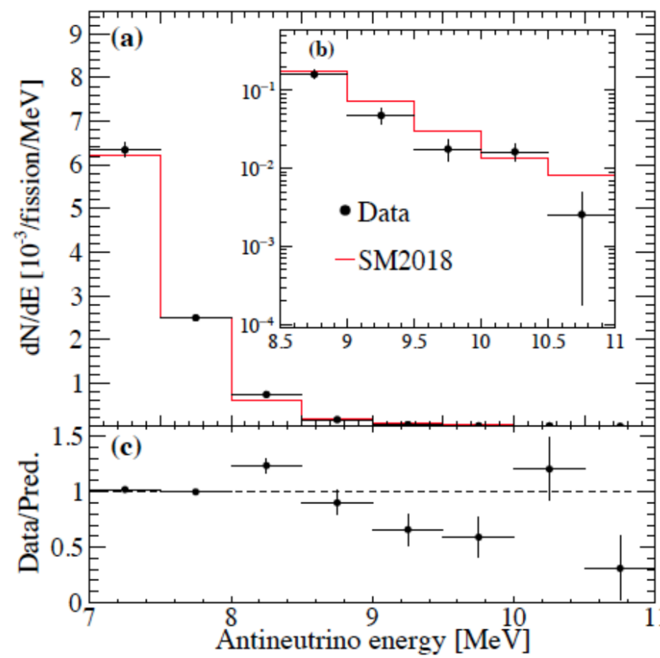
First Evidence of reactor neutrinos with Eν > 10 MeV

- 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

Summary

- Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ with 2.8% and 2.3% precision
- Set the most stringent upper limit for light sterile neutrino with $\Delta m^2_{41} < 0.2\ \mathrm{eV}^2$
  - A joint fit with MINOS/MINOS+ is able to exclude most of LSND/MiniBooNE signal region
- Reactor fuel evolution is observed
  - Reactor Antineutrino Anomaly is mainly caused by ^{235}U
  - First measurement of ^{235}U and ^{239}Pu spectra from commercial reactor
- First evidence of reactor neutrinos with energy above 10 MeV

谢谢！