Latest Results from Daya Bay

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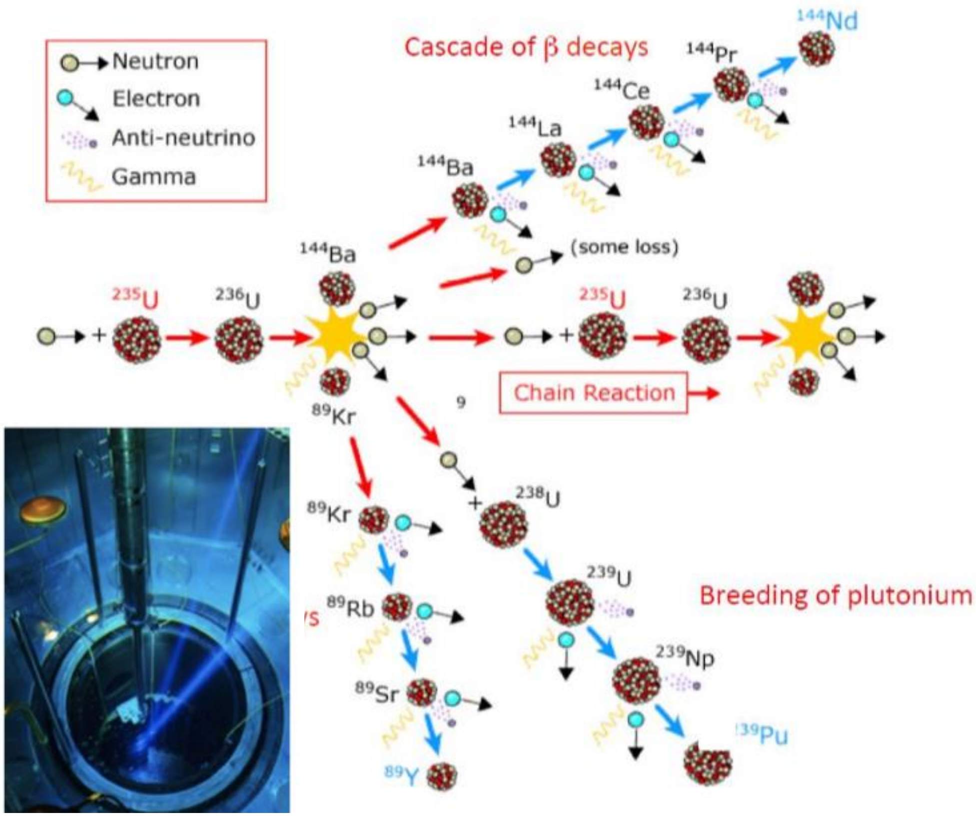
On behalf of the Daya Bay collaboration
Sun Yat-Sen University

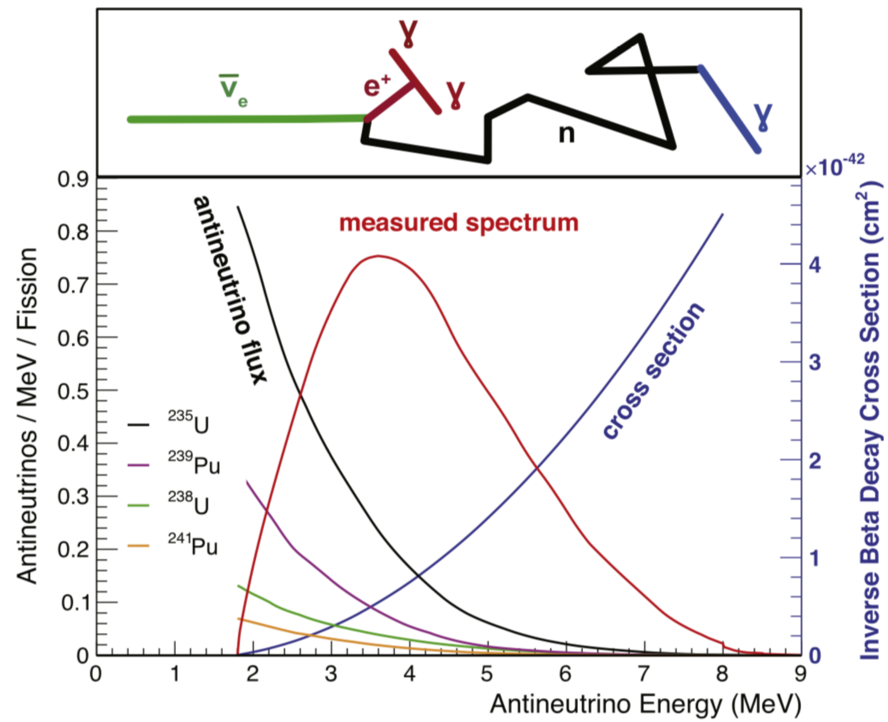
XVIII Neutrino Telescopes workshop ,
Venezia, 20 March 2018

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





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

Coincidence signals to suppress background

- Prompt: $E_p \approx E_\nu - 0.8\ MeV$
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)

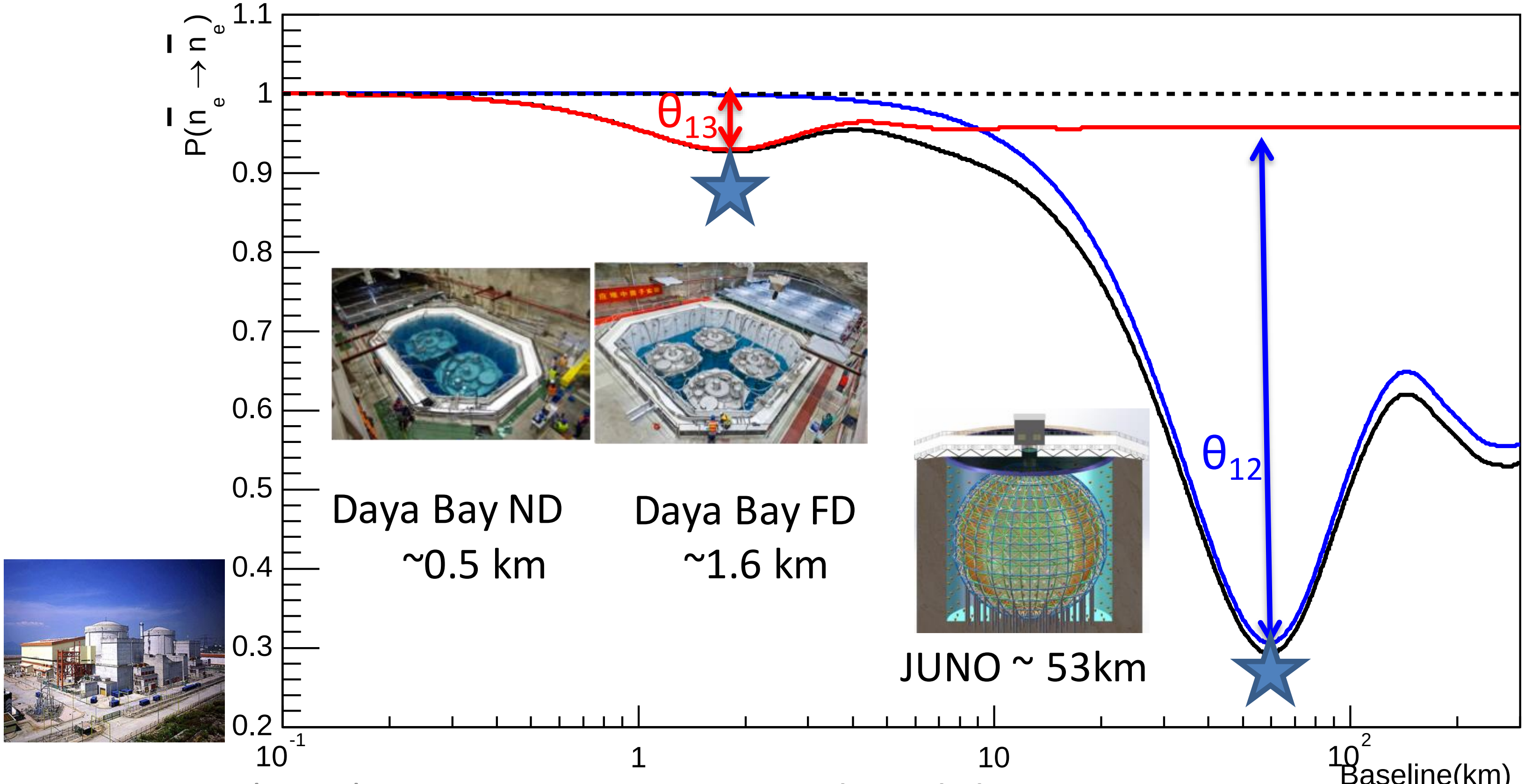
Reactor Antineutrino Oscillation

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

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

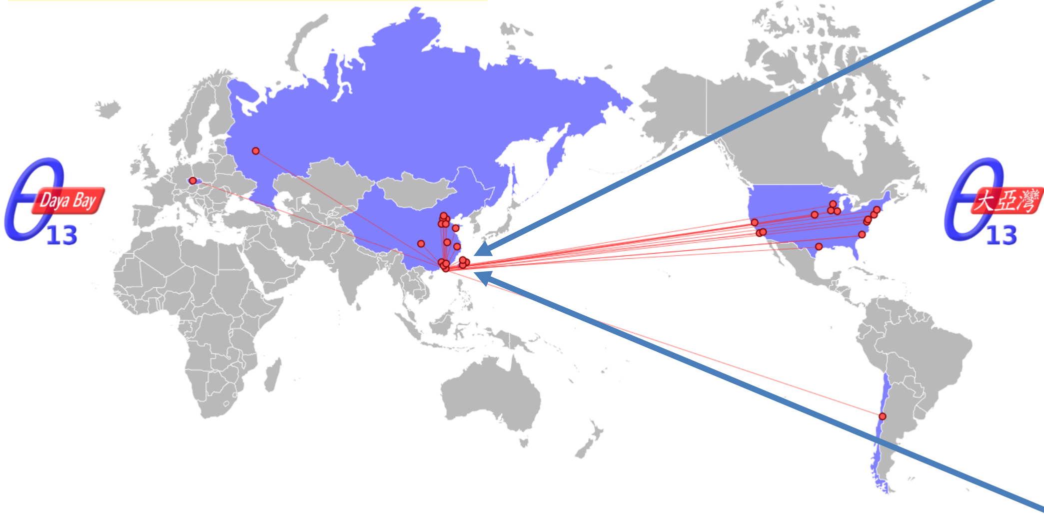
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

Immune to CP violation and matter effects



The Daya Bay Collaboration

~200 Collaborators



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

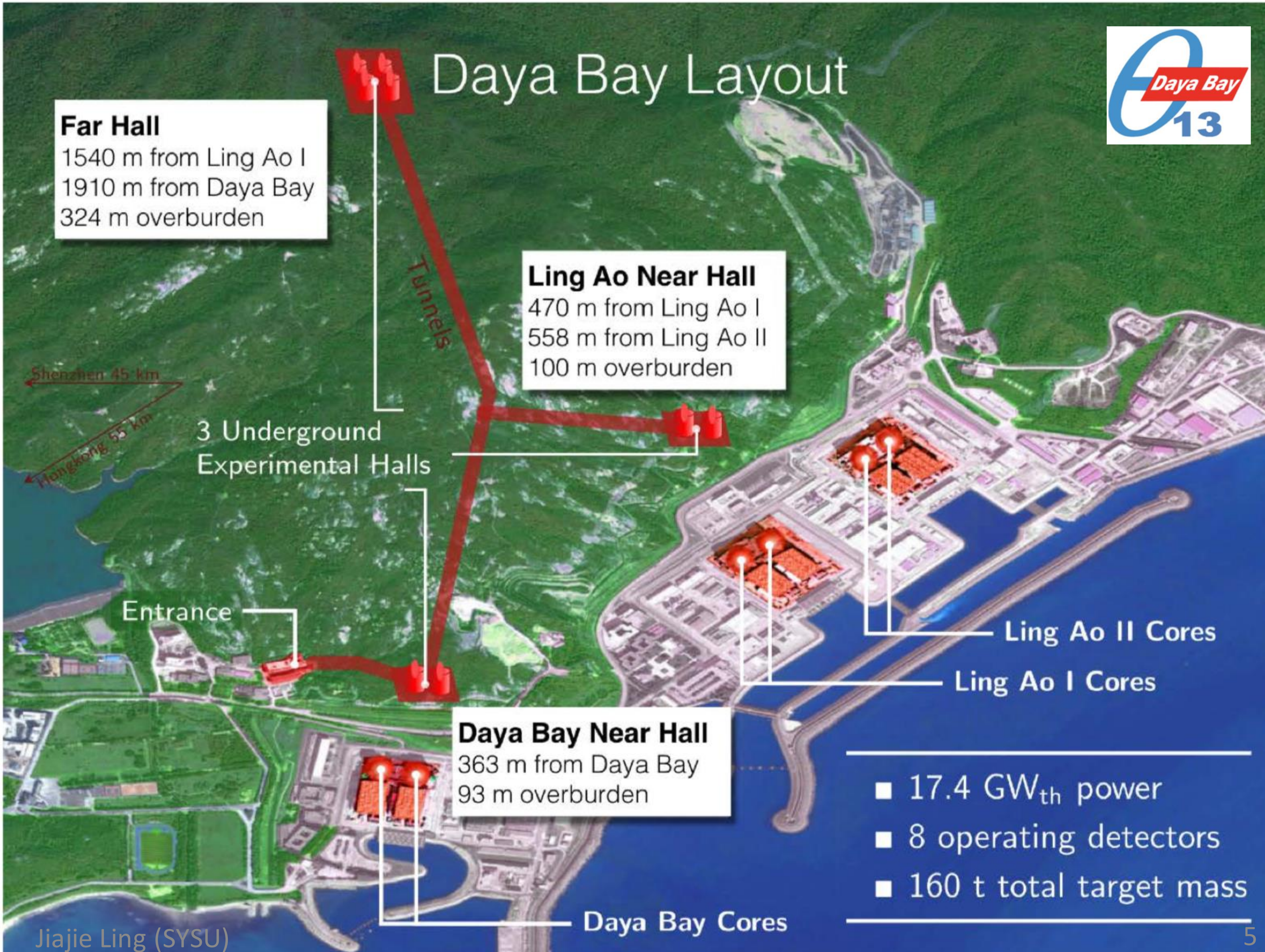
Charles University, JINR Dubna

North America (15)

Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic University of Chile


Daya Bay Layout
Daya Bay θ13
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
Tunnels
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
Shenzhen 45 km
Hongkong 55 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
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

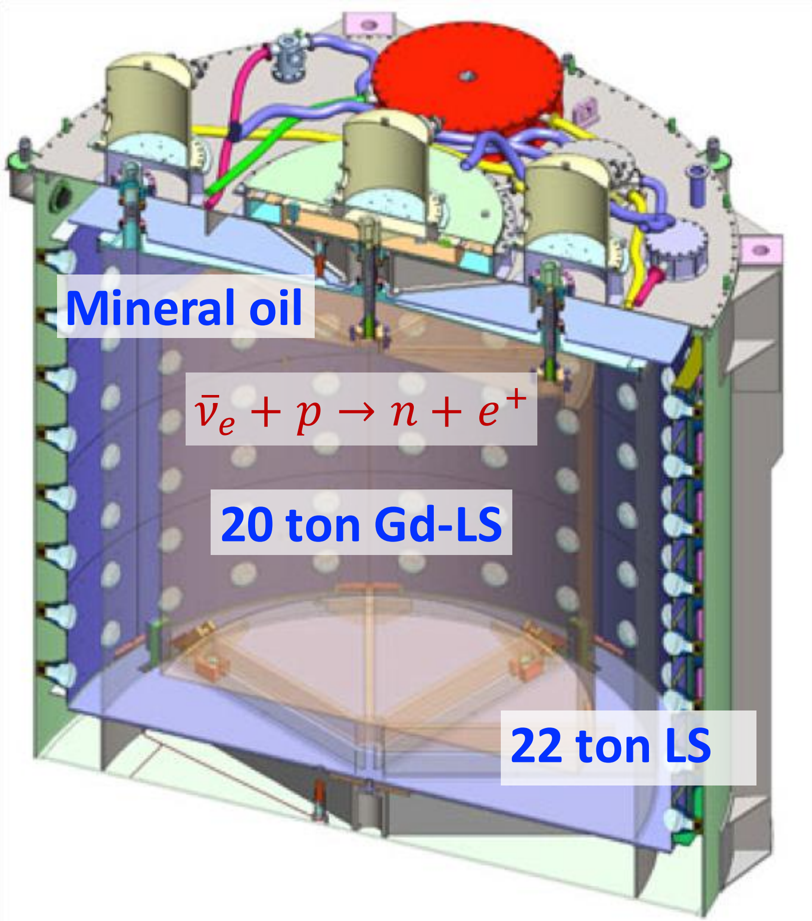
Antineutrino detectors (AD)

Relative Measurement:

- 8 "identical", 3-zone detectors

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

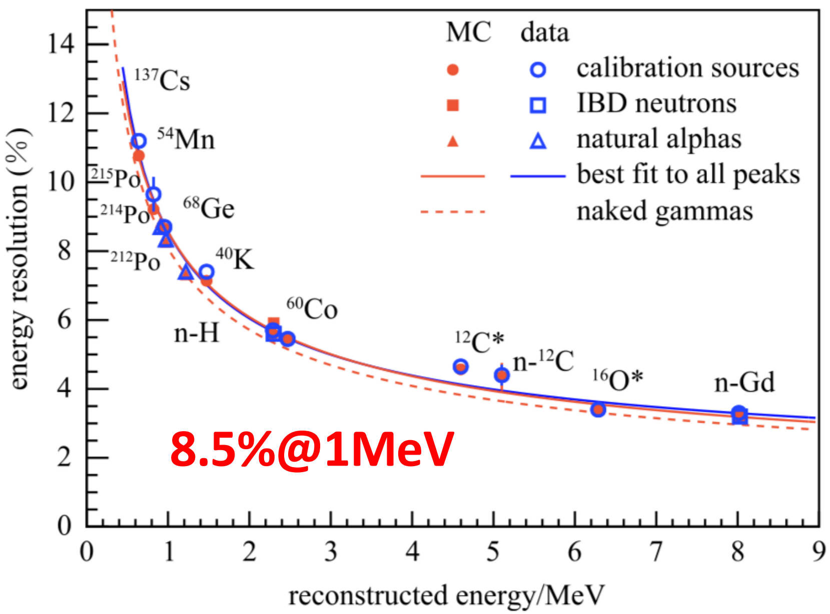
NIM A773 (2015) 8-20
NIM A811 (2016) 133-161



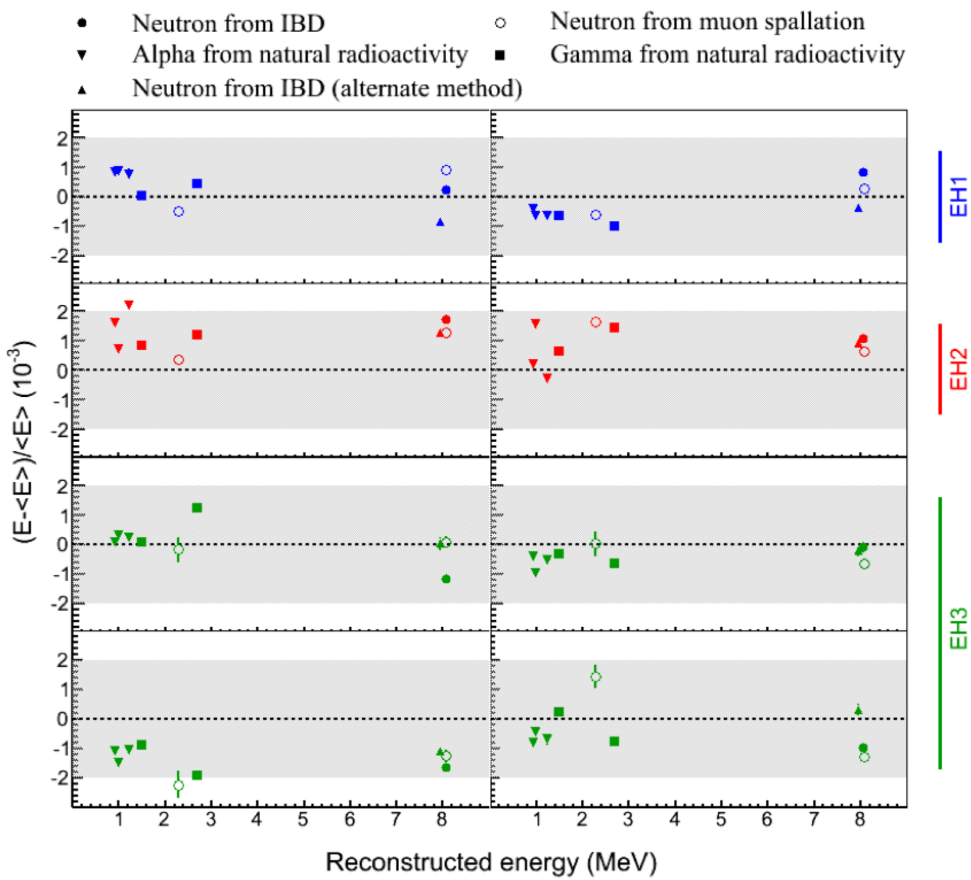
Detector Energy Response

- Weekly calibration
  - ^{68}Ge, ^{241}Am^{13}C, ^{60}Co
  - LED diffuser ball
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Spallation neutrons
- Natural radioactivity

NIMA750 (2014) *NIMA797 (2015)*

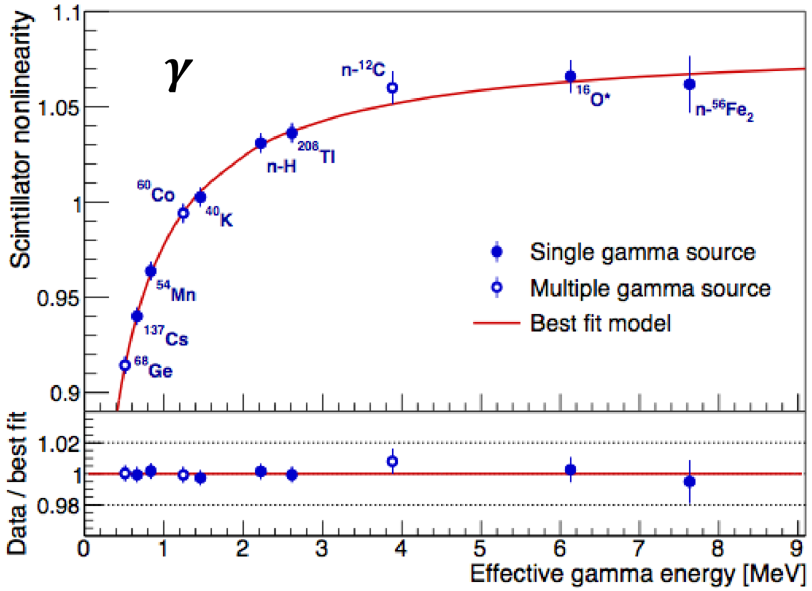


8.5%@1MeV

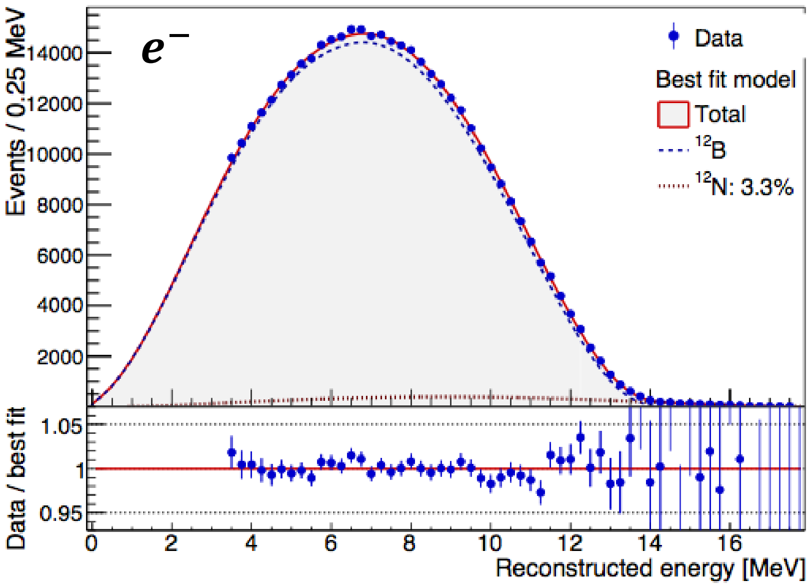


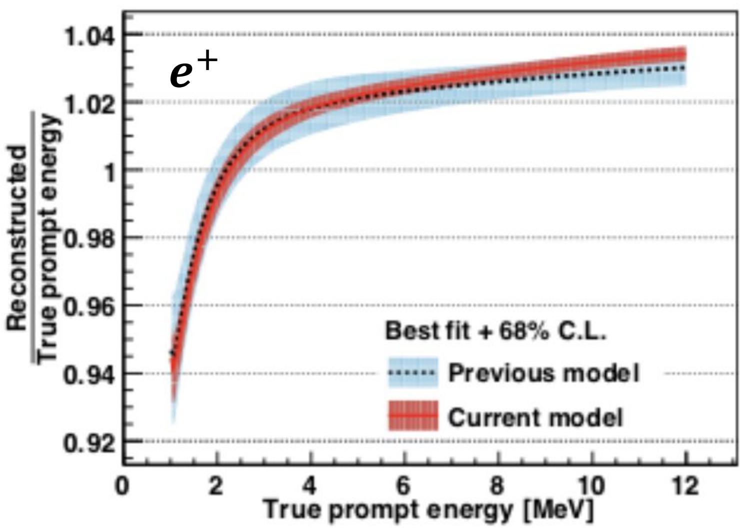
Relative detector energy scale < 0.2%

Energy Non-linearity Calibration



arXiv: 1902.08241





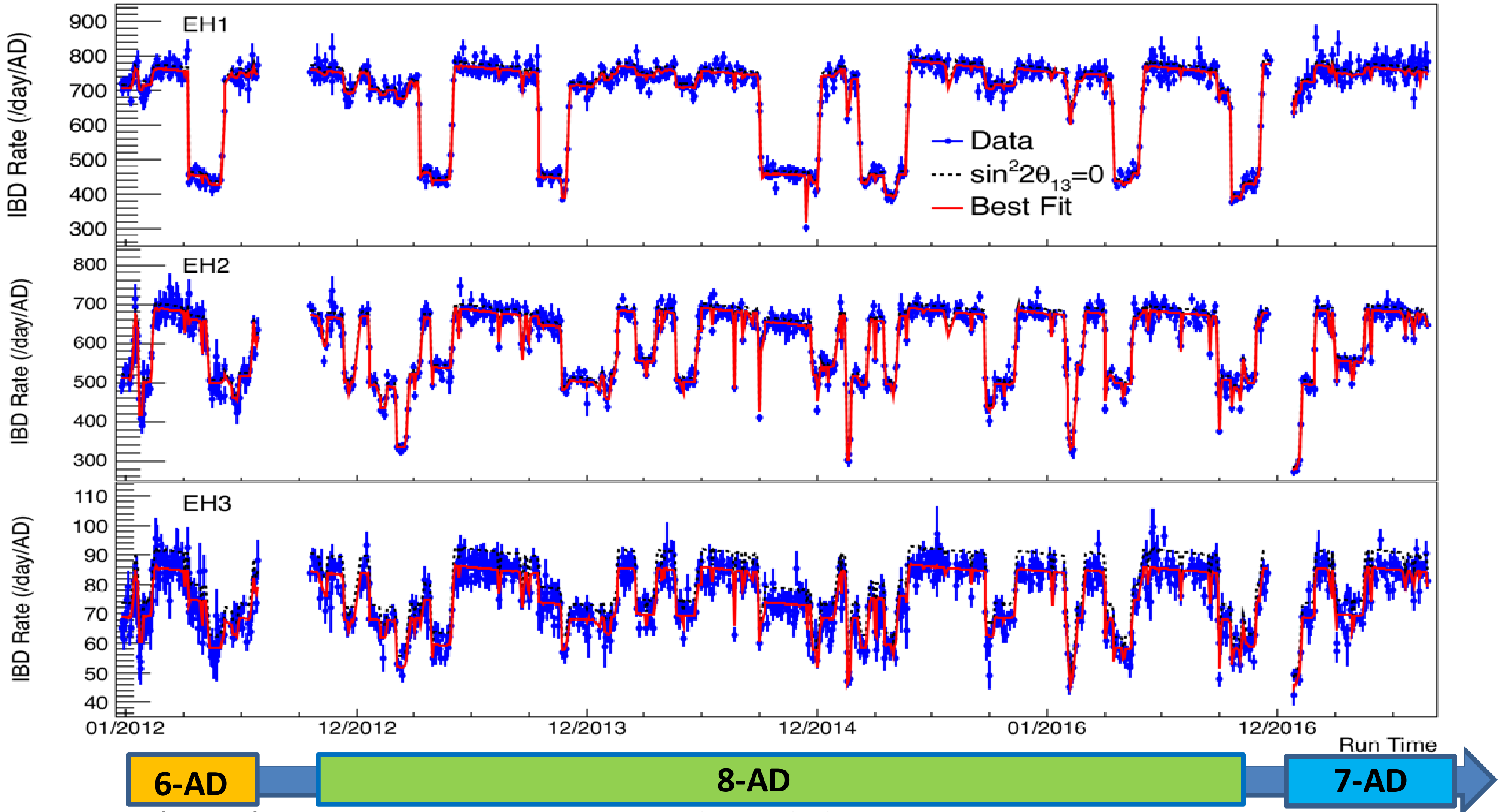
- Two major sources of non-linearity:
  - Scintillator response (Birks + Cerenkov)
  - Readout electronics (FADC correction)
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~0.5% absolute energy uncertainty

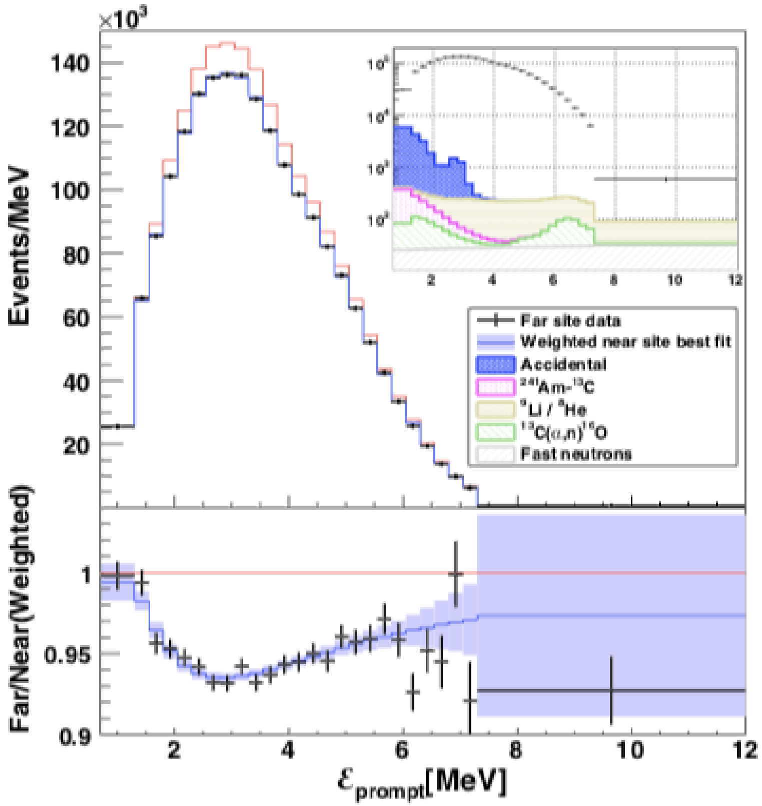
~ 4M IBD Candidates

2011/12/24 – 2017/08/30 (1958 days)

Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
IBD candidates	1,794,417	1,673,907	495,421

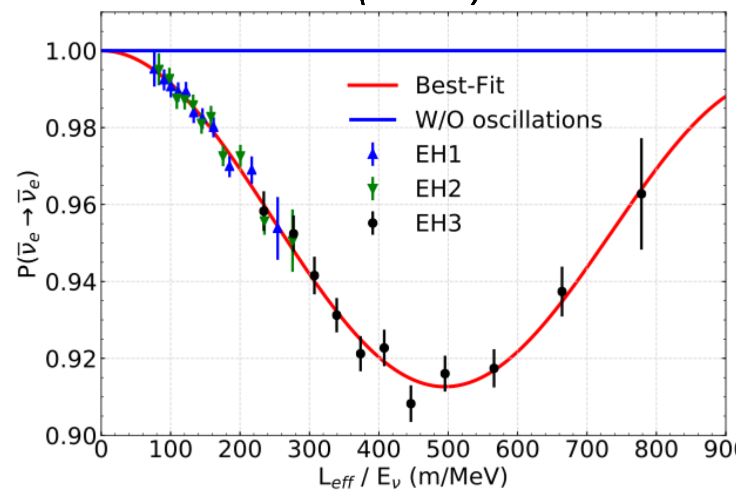


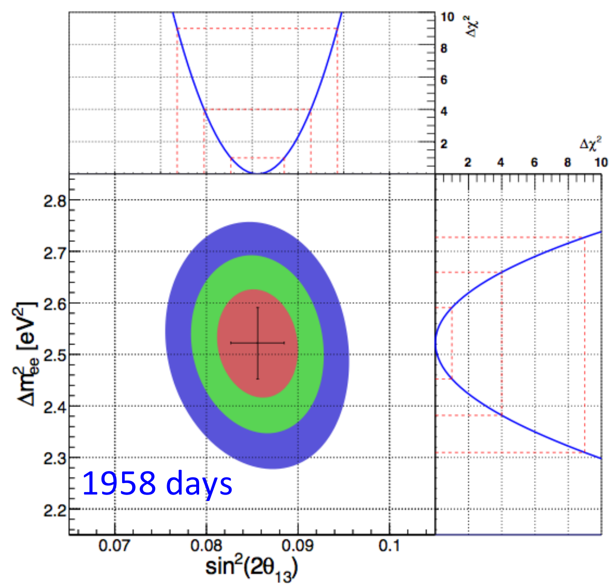
nGd Oscillation Results



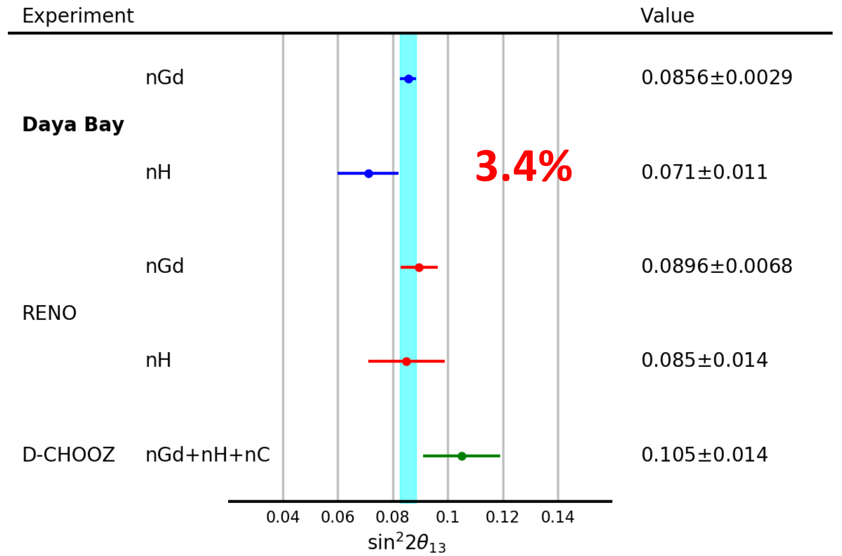
$$sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} eV^2$$
$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3} eV^2 \text{ (NO)}$$
$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3} eV^2 \text{ (IO)}$$

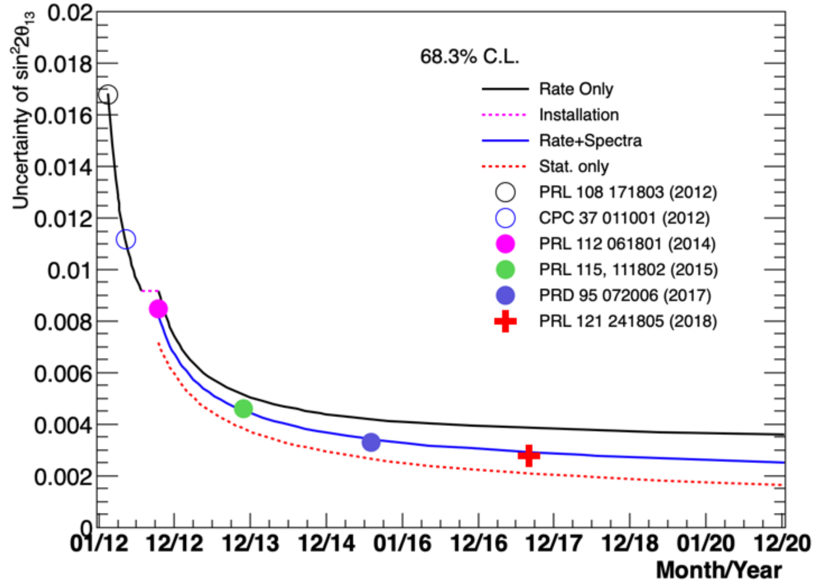
PRL 121 (2018) 241805

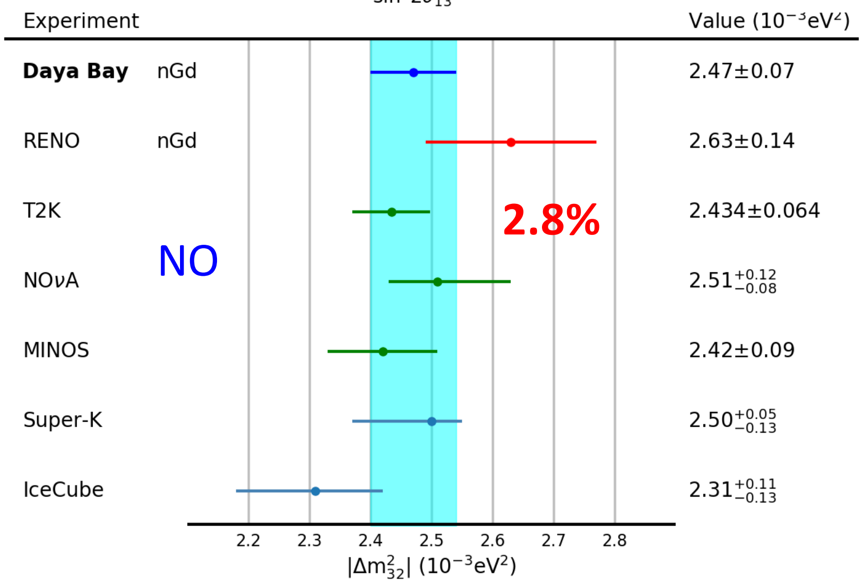


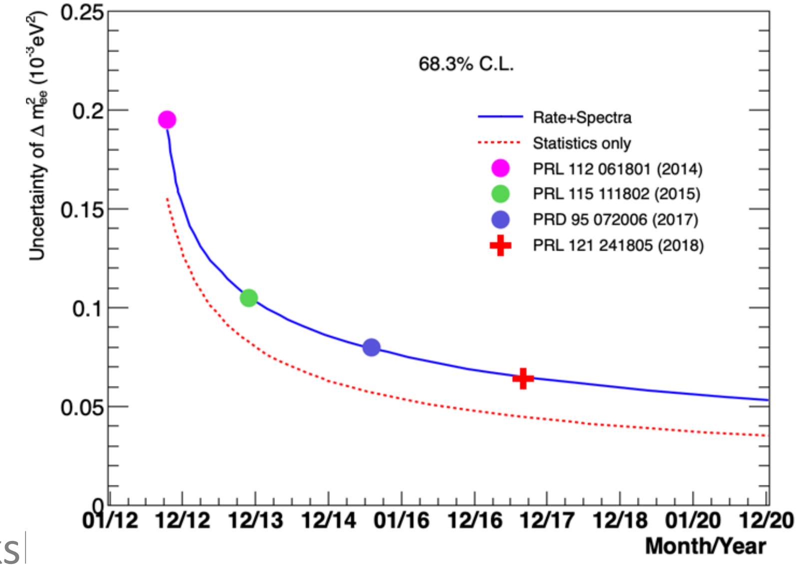


Precision Measurements

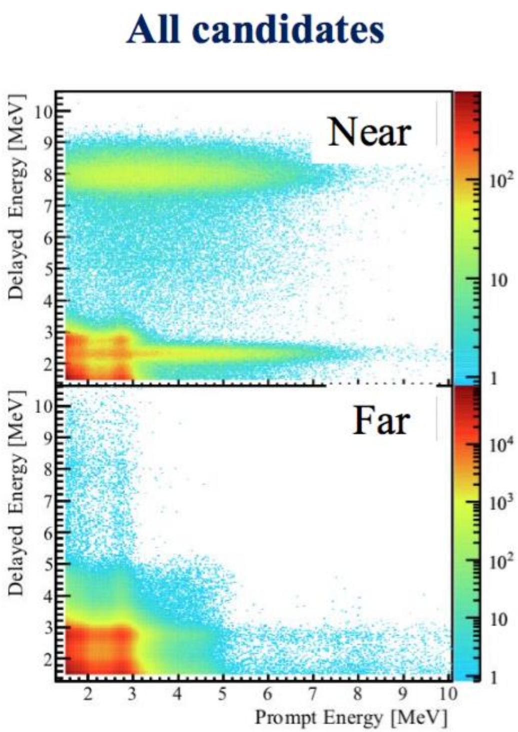


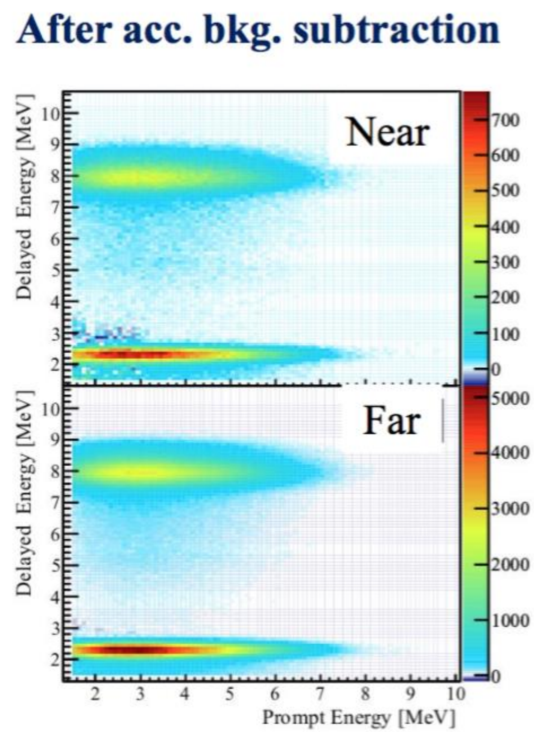


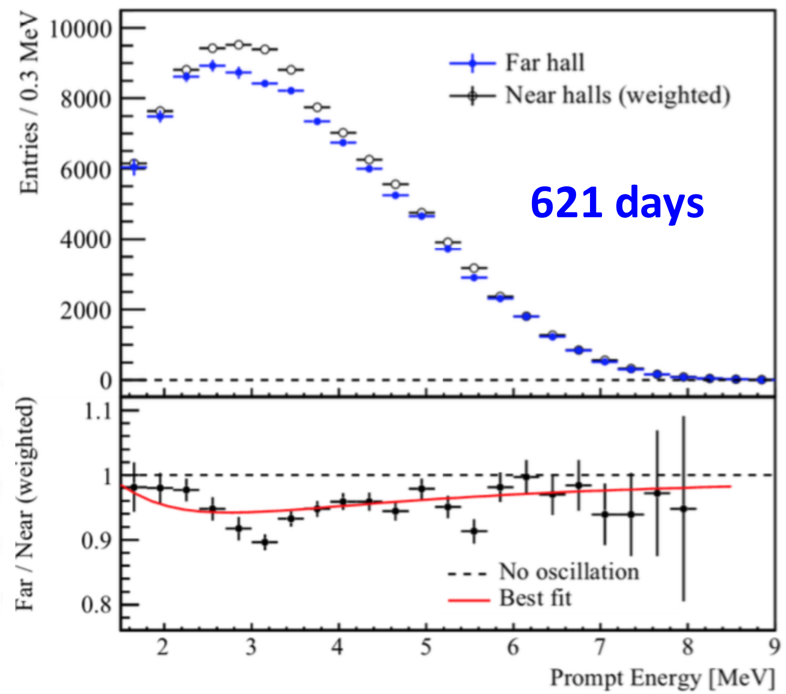




$\sin^2 2\theta_{13}$ from nH-Capture







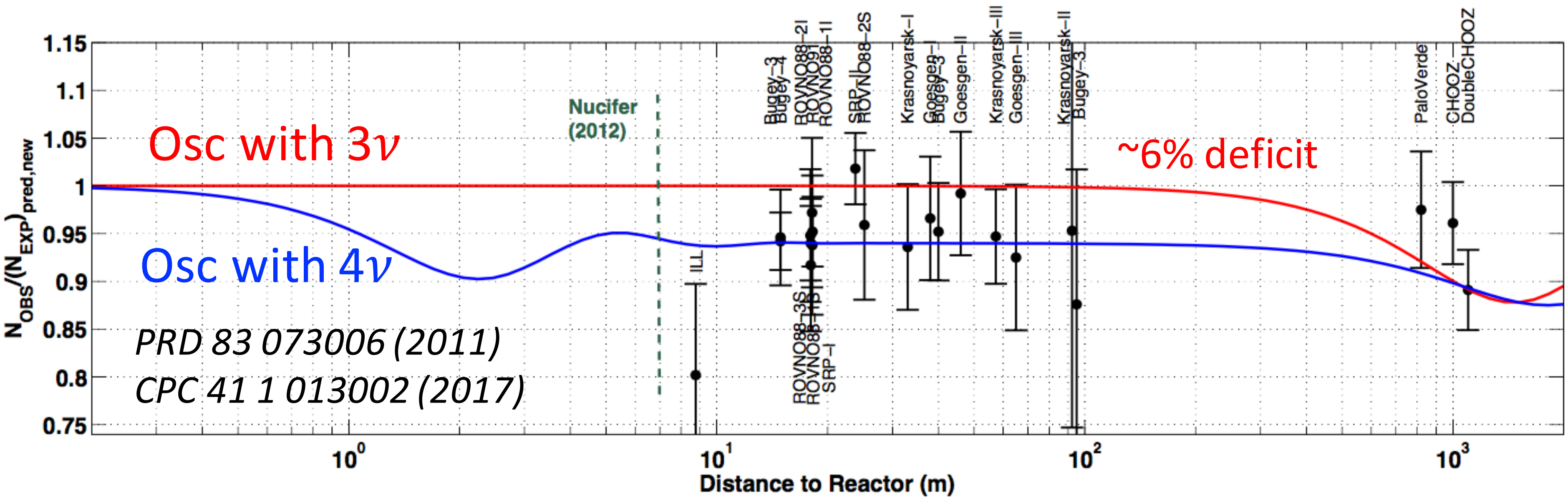
Phys. Rev. D 93, 072011 (2016)

- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging: 12% (54%) accidental background at near (far) site

Rate Only analysis: $\boldsymbol{sin^2 2\theta_{13} = 0.071 \pm 0.011}$

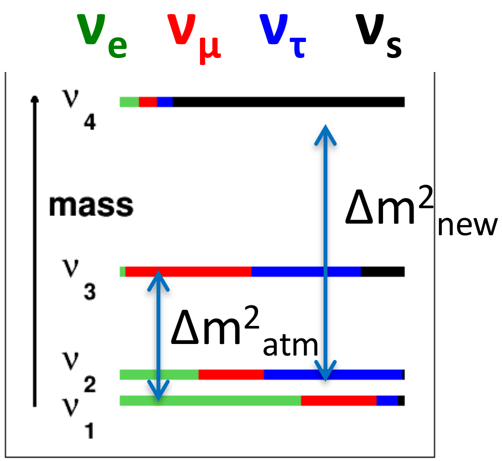
Updated rate + spectra nH analysis results are coming soon

Reactor Antineutrino Anomaly (RAA)



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

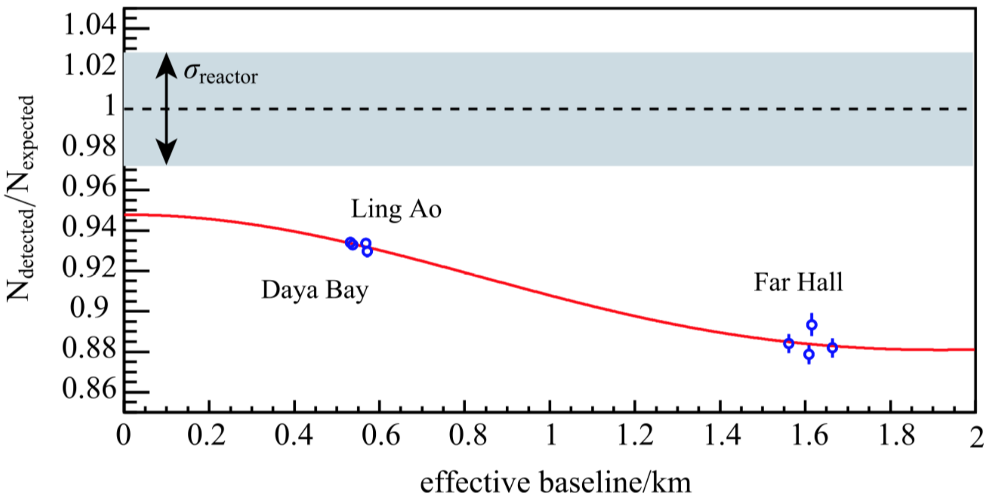
- Theoretical reactor $\bar{\nu}_e$ flux modelling?
  - Systematic uncertainty underestimation (2%→5%)
- Sterile neutrinos ($\bar{\nu}_e \rightarrow \bar{\nu}_s$)?
  - High frequency oscillation (Δm^2_{new}~ 1-10 eV^2) at baseline of few meters

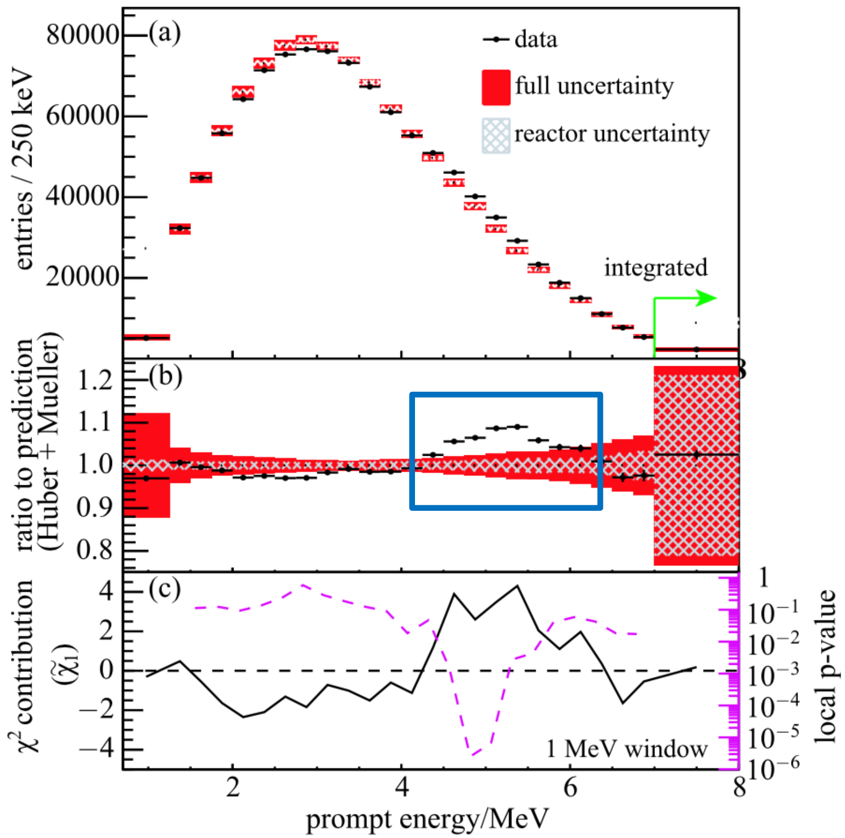


3 (active)+1(sterile)-υ model

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

arXiv:1808.10836 *CPC 41.1.013002 (2017)*





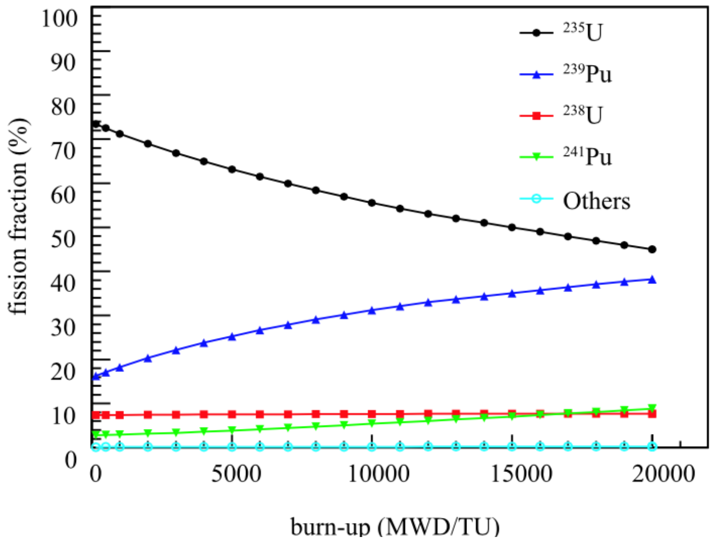
$$R = \frac{data}{Model\ (Huber + Mueller)}$$

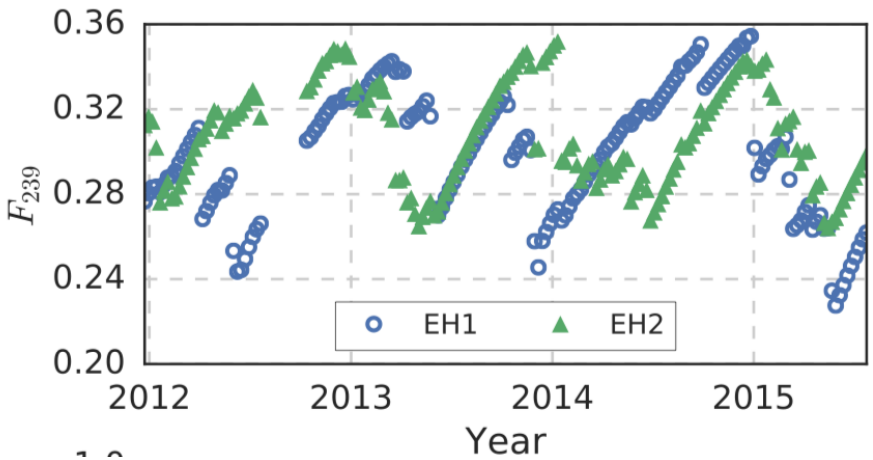
$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

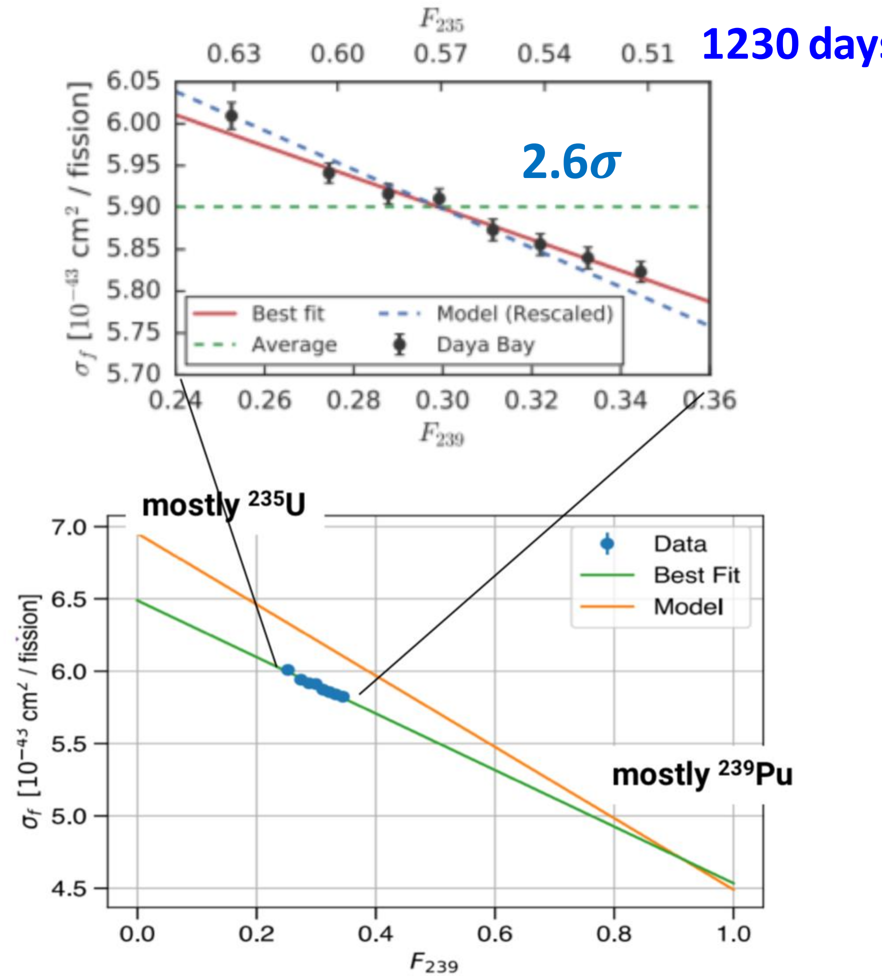
- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total 3σ deviation, especially significant deviation at 4-6 MeV region of the prompt energy
- No effect on θ_{13} and Δm^2_{ee} for far/near relative measurement

Reactor Fuel Evolution

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







- Clear fuel-dependent evolution
- Evolution slope deviates from model: disfavors equation deficit hypothesis

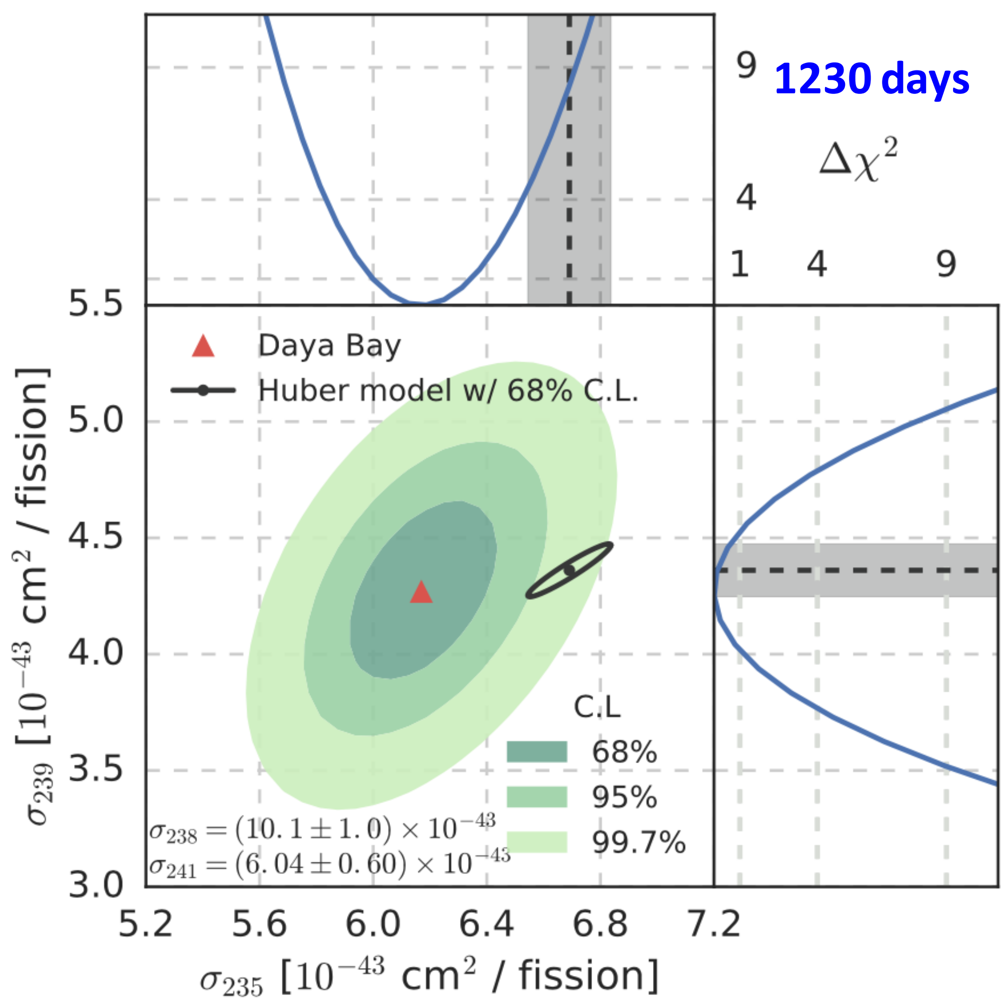
Reactor Isotope $\bar{\nu}_e$ Yield

- Combined fit of two major fission isotopes ^{235}U and ^{239}Pu by constraining ^{238}U and ^{241}Pu

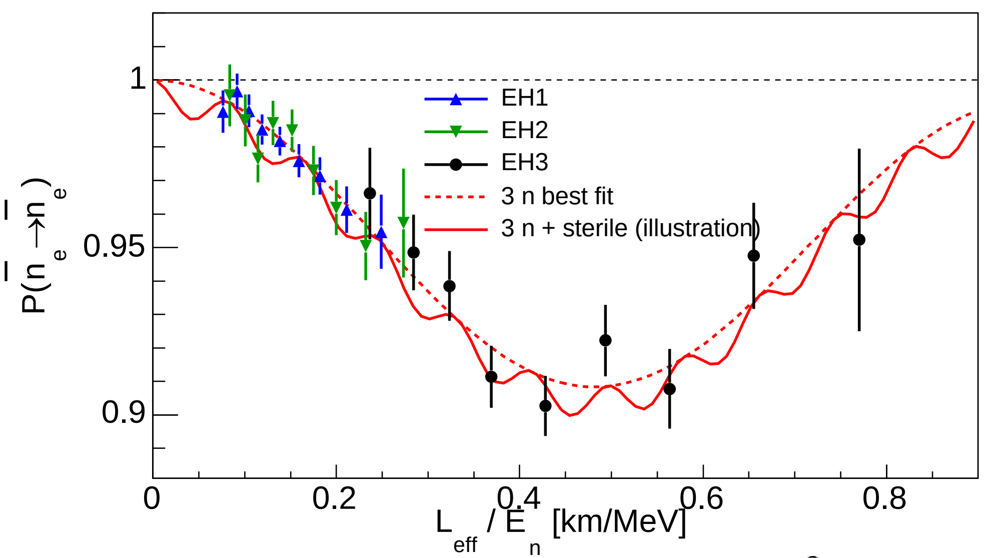
$$\chi^2 = (\sigma_f - F\sigma)^T V^{-1} (\sigma_f - F\sigma) + \sum_{^{238}U,\,^{241}Pu} \frac{(\sigma_i - \bar{\sigma}_i)^2}{\varepsilon_i^2}$$

- Daya Bay data prefer ^{235}U to be mainly responsible for the RAA
- Disfavor all isotopes with equal deficit (2.8σ) or ^{239}Pu only hypothesis (3.2σ)

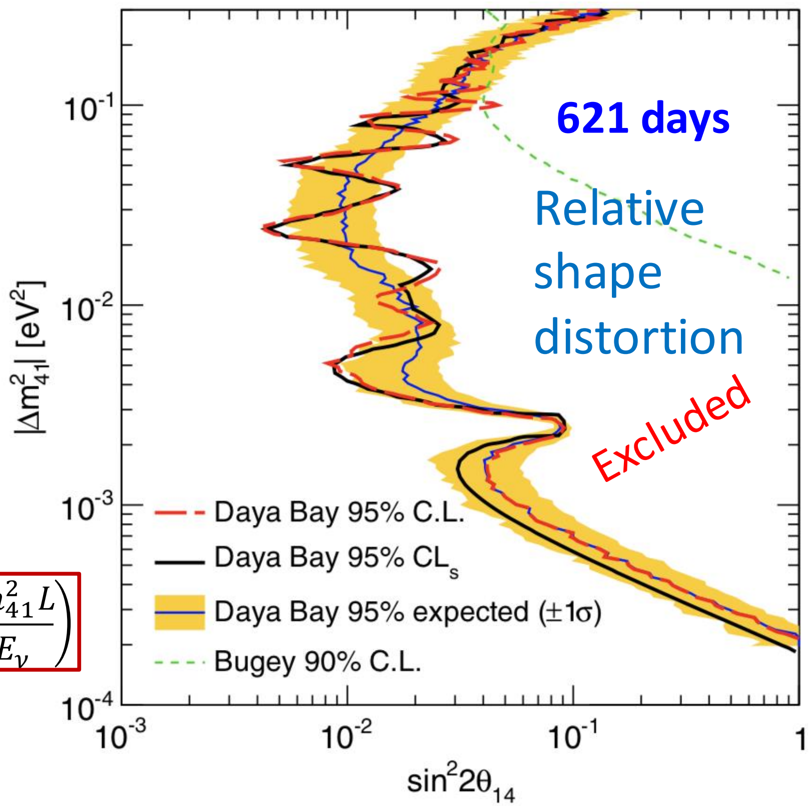
Phys. Rev. Lett. 118, 251801 (2017)



Sterile Neutrino Search



PRL 117, 151802 (2016)



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - cos^4\theta_{14} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - sin^2 2\theta_{14} sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

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

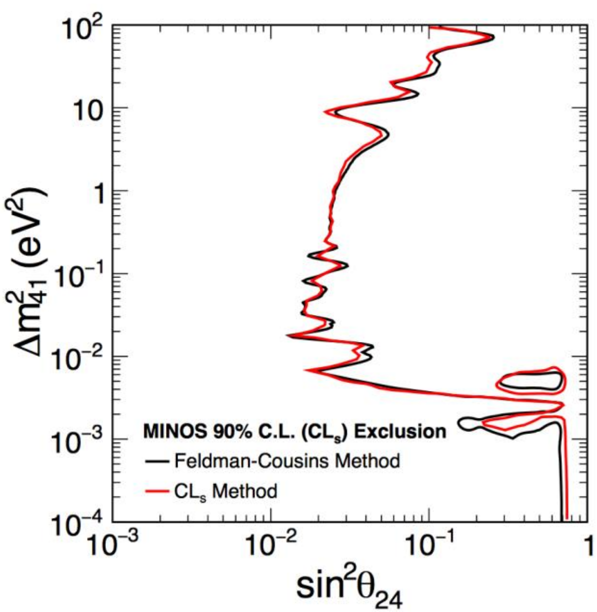
No light sterile neutrino ($\Delta m^2 < 0.2$ eV^2) signal was found

Joint Sterile neutrino Searches

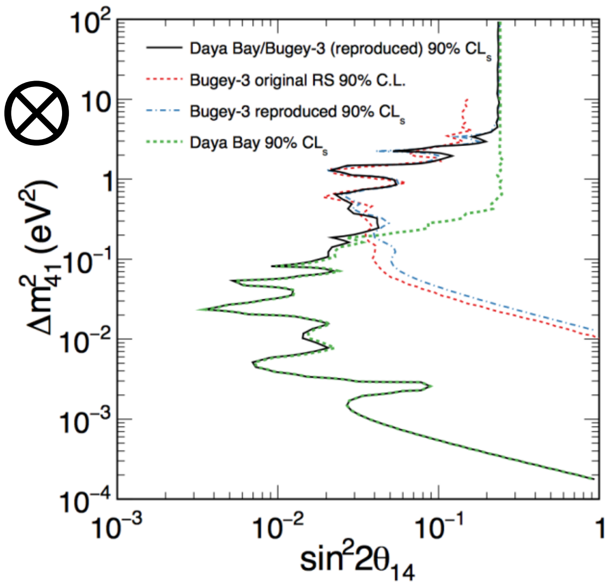
PRL 117, 151803 (2016)

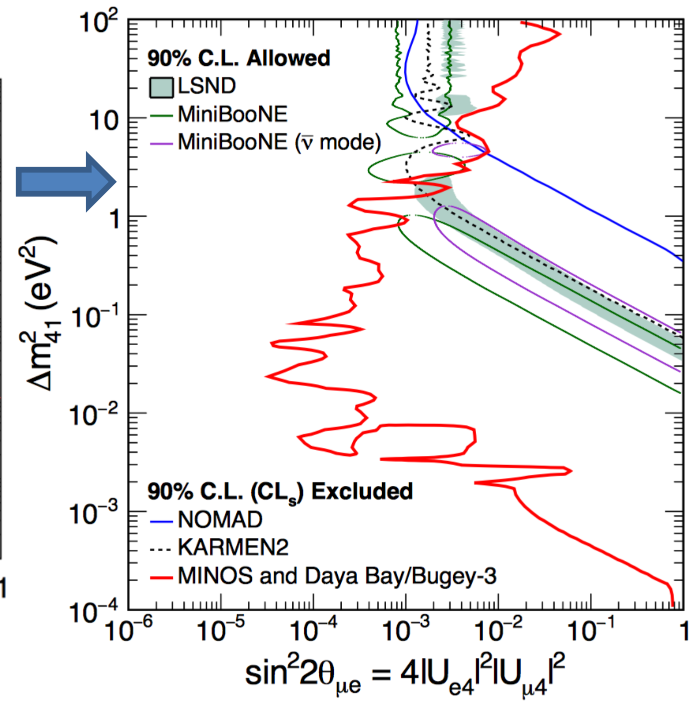
PRL 117, 151801 (2016)

MINOS



Daya Bay + Bugey-3





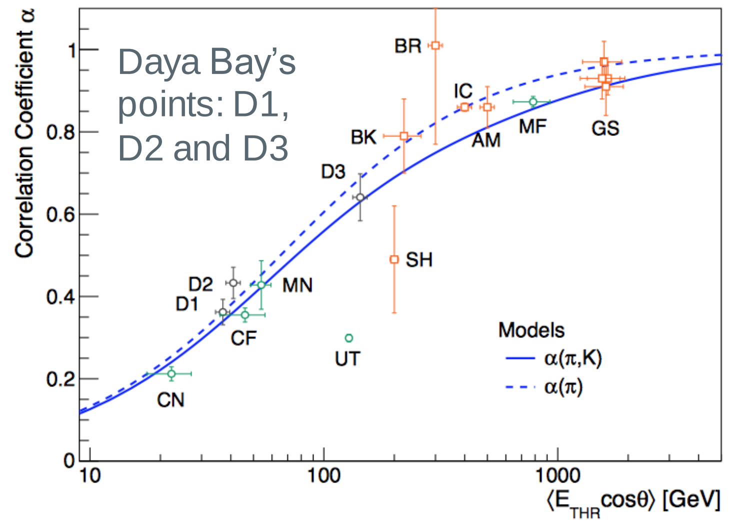
- The combined results can exclude most of the LSND and MiniBooNE region assuming 3+1 neutrino model
- Updates are expected in the near future

Cosmic-Ray Related Results

JCAP 1801 (2018)

Seasonal Variation of the Underground Cosmic Muon Flux

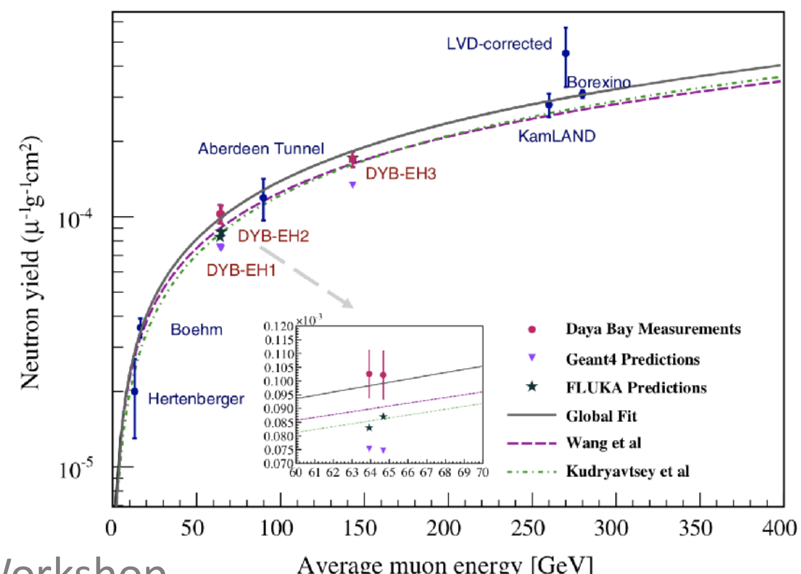
Observe a clear correlation between atmospheric temperature and variations in muon flux



PRD 97, 052009 (2018)

Cosmogenic neutron production at Daya Bay

Measurement of neutron yield in LS. Important input for underground experiments.



Summary

- Daya Bay has made the most precise measurements on
  - $\boldsymbol{sin^2 2\theta_{13} = 0.0856 \pm 0.0029}$
  - $\boldsymbol{|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}}$**eV²**
    - $\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}$eV² (NO)
    - $\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}$eV² (IO)
  - Expected to < 3%, running until 2020
- Many new and improved analyses are in preparation.

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