Reactor neutrino oscillation (and more!) at Daya Bay

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On behalf of Daya Bay collaboration

CIPANP, Palm Springs, May 30 2018

Reactor neutrino 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

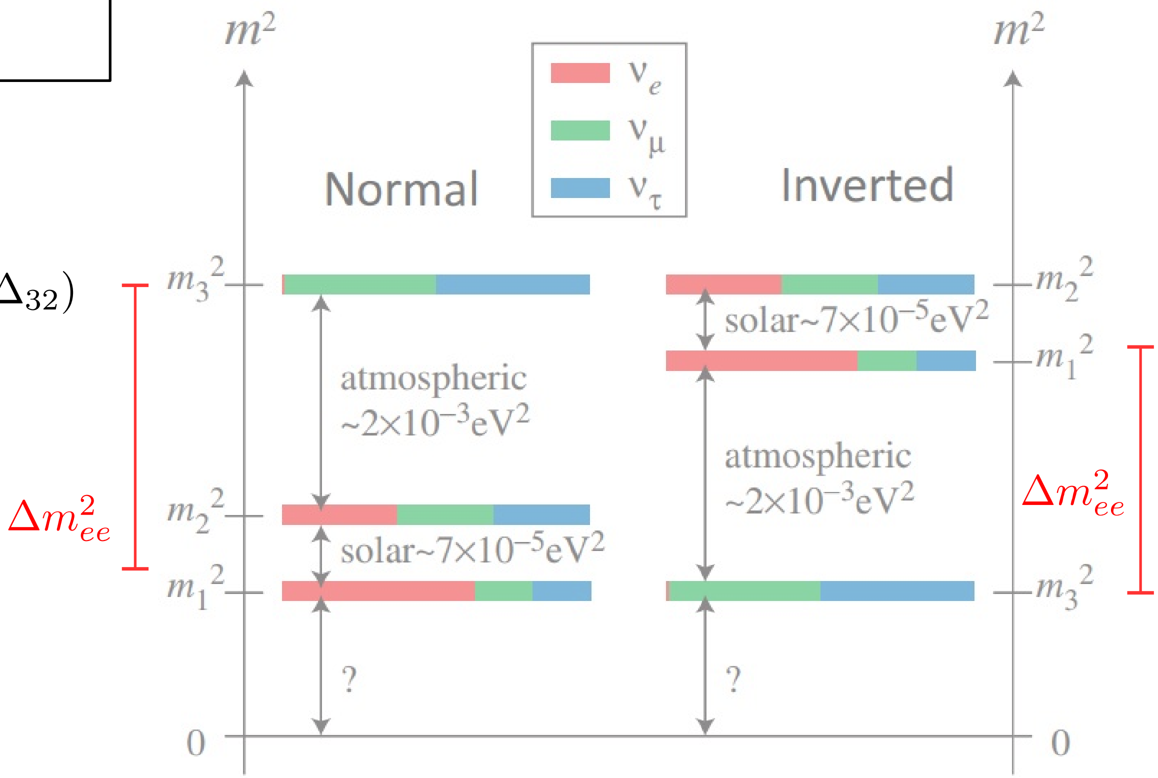
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

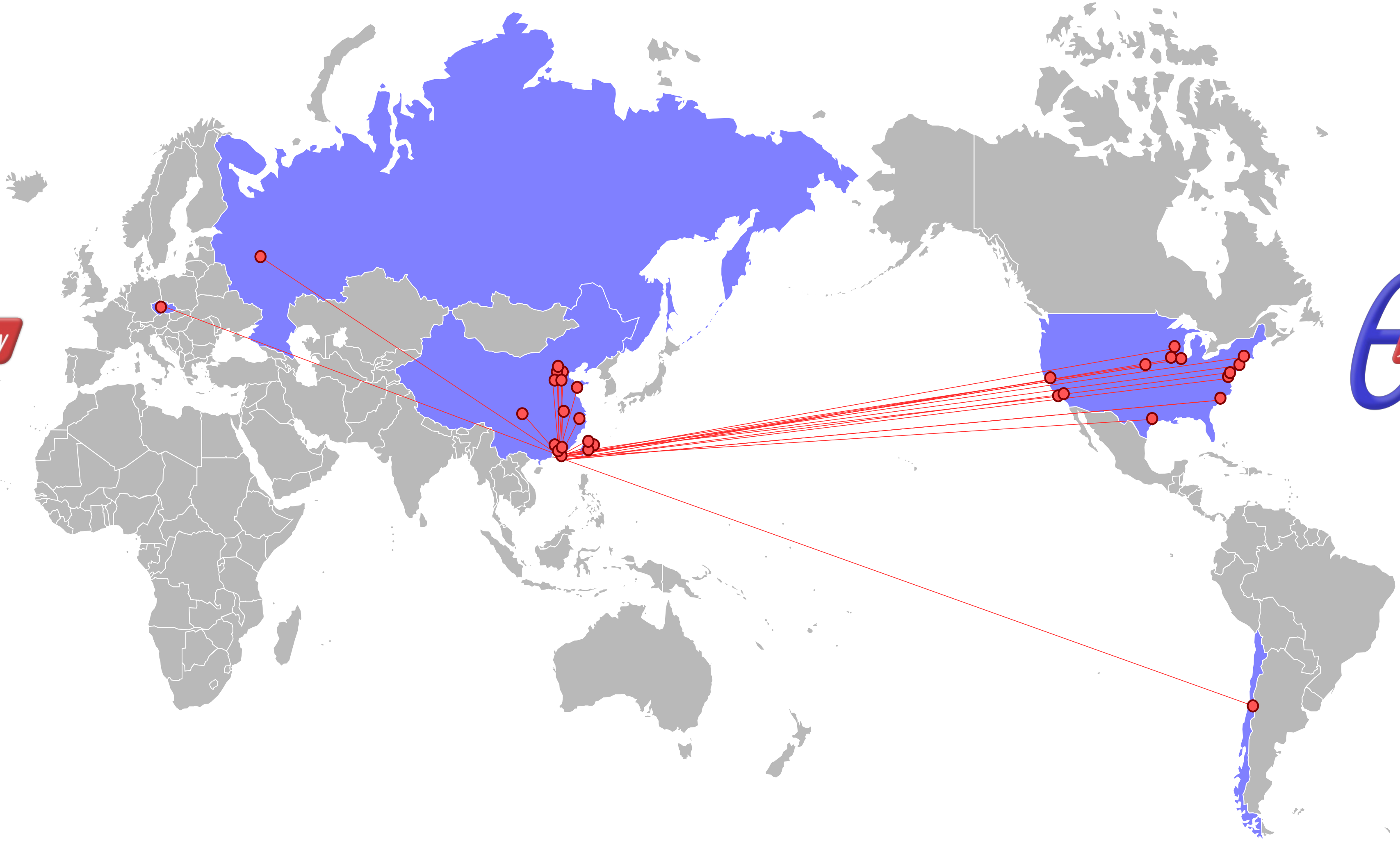
$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$

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

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



Daya Bay collaboration

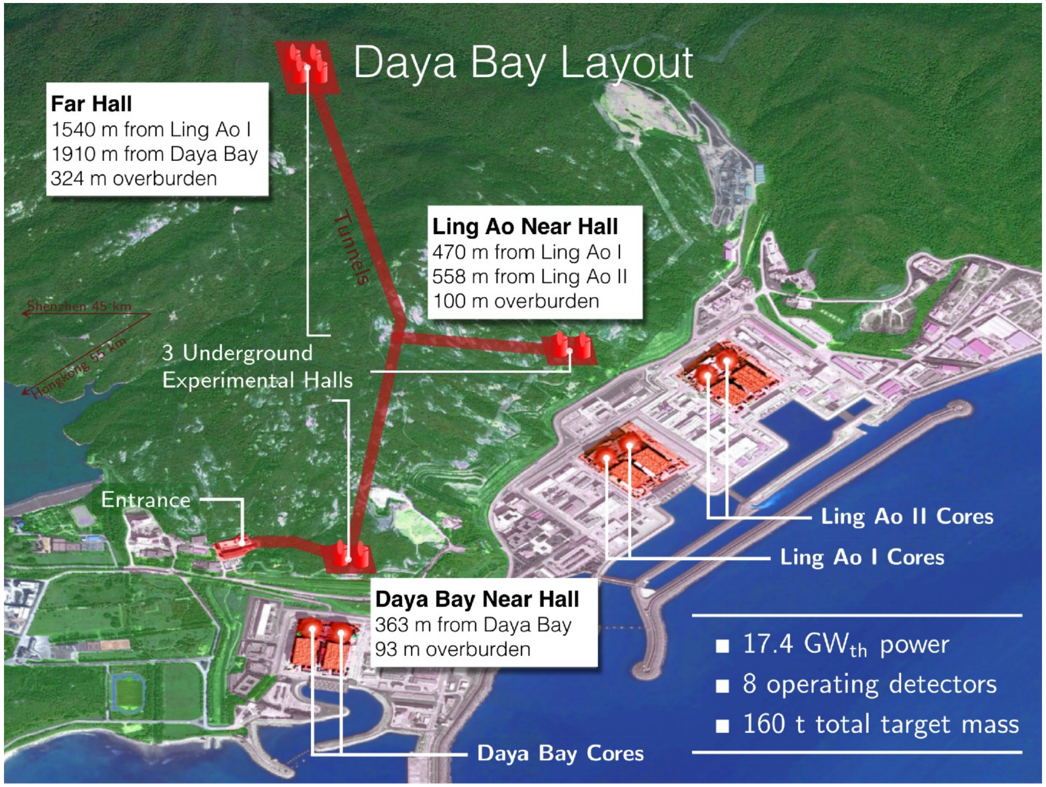


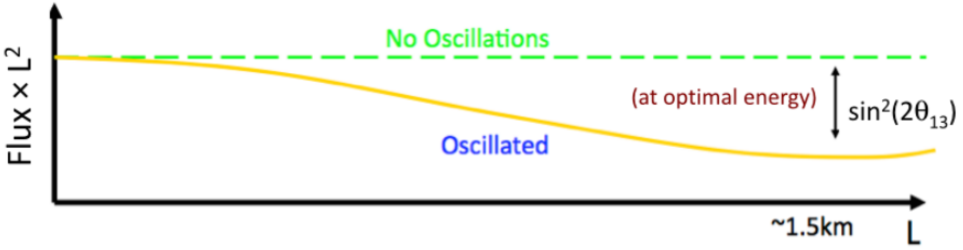
4 continents, ~200 collaborators, 42 institutions

Daya Bay experiment

An optimized design:

- **High statistics:** Powerful reactors, multiple large detectors
- **Low background:** Excellent overburden
- **Low systematics:** Near/far measurement cancels reactor and efficiency uncertainties
- **Proper placement:** Far hall at disappearance maximum





Detecting antineutrinos

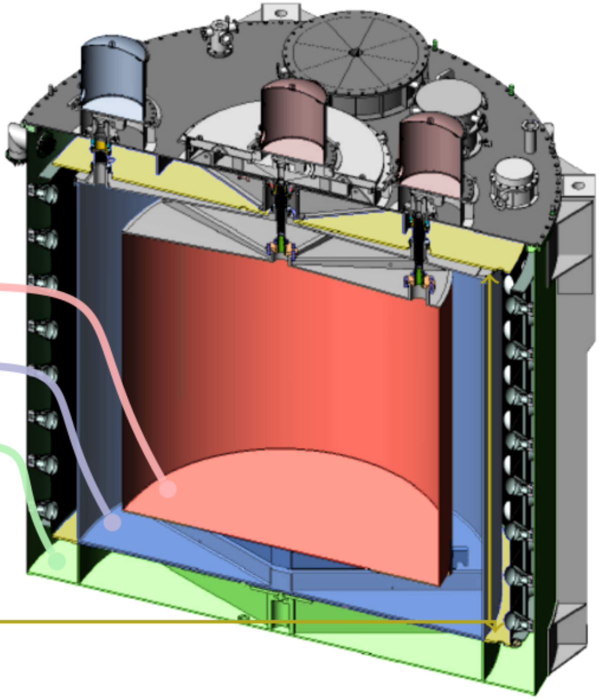
NIM A 811, 133 (2016)

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	**Mass**	**Function**
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

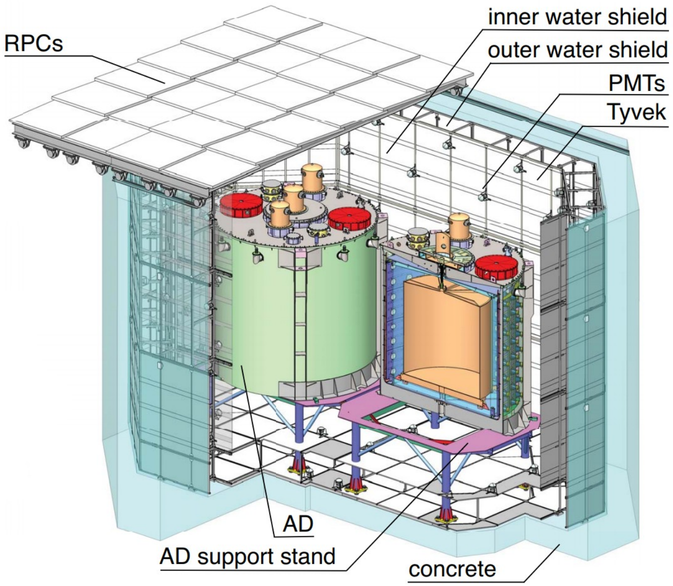
192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



NIM A 773, 8 (2015)

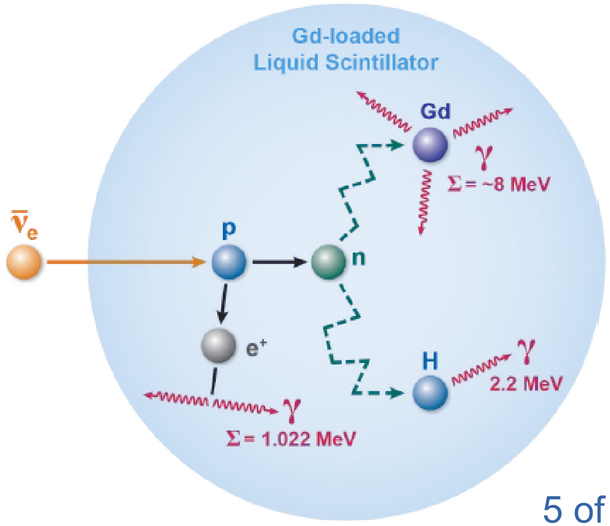
Active muon shielding



Antineutrinos are detected via **inverse β decay:**

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

The neutron is captured on Gd (H) after an average of 28 (180) μs. Coincident pulses provide a **clean experimental signature,** where $E_\nu = K_{e+} + 1.8$ MeV



Absolute energy scale

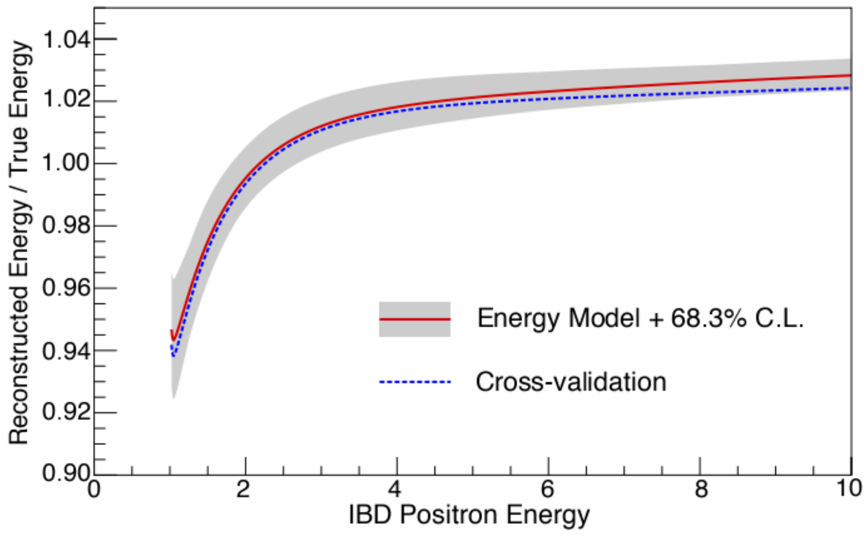
Reconstruction-level:

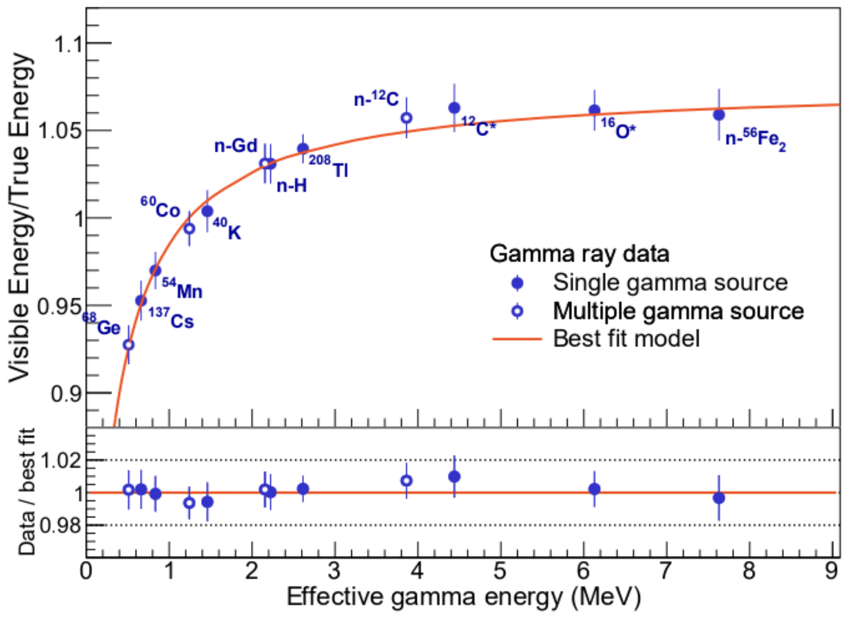
- **Regular calibration** to correct for small variations in energy scale with time
- **Nonuniformity correction** to correct for geometric variation in optical response

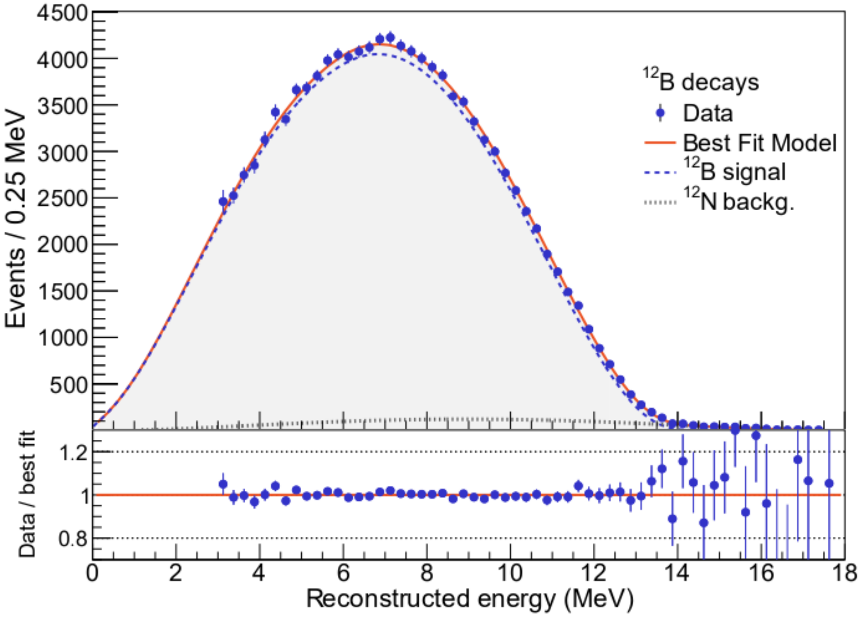
Post-reconstruction:

- **Detector response matrix:** Energy resolution, energy deposition in acrylic, etc.
- **Nonlinearity model:** Final conversion of reconstructed to positron energy; corrects for scintillator and electronics nonlinearity
  - Calibrated with gamma sources; many cross-checks

Uncertainty ~ 1%





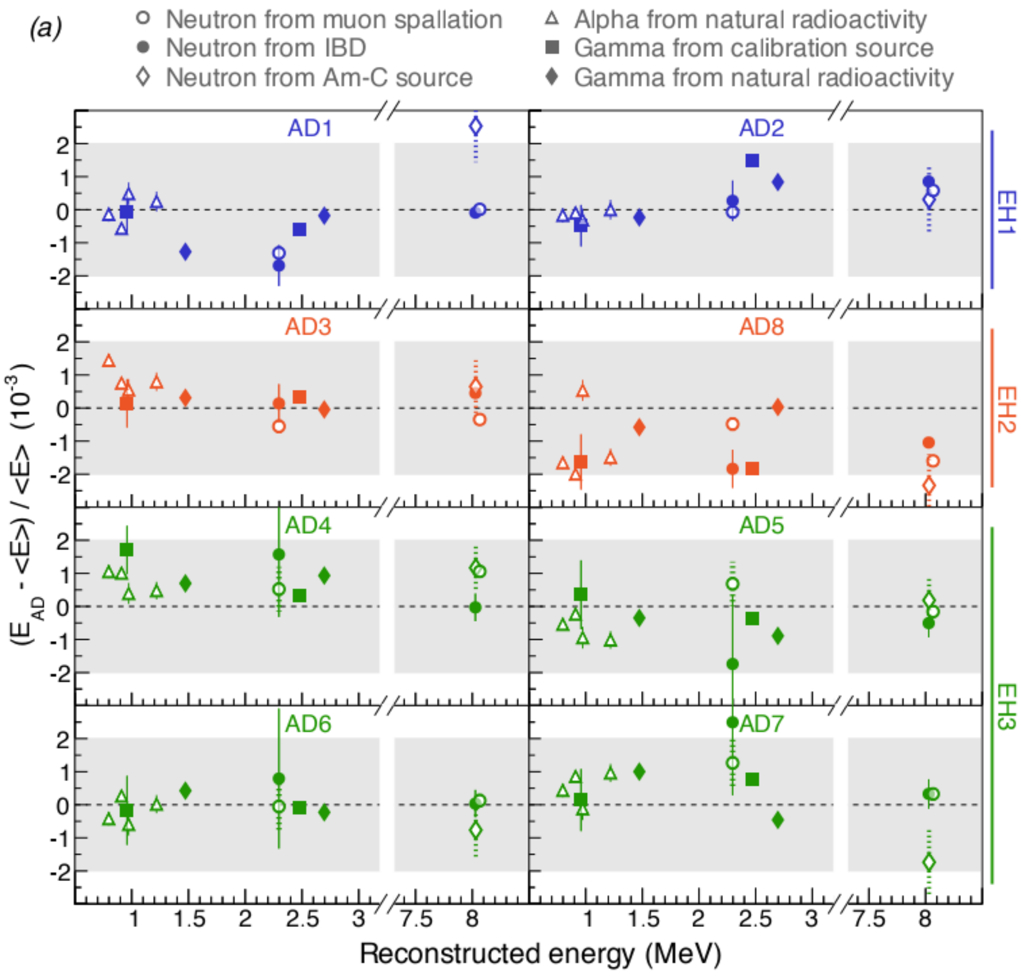


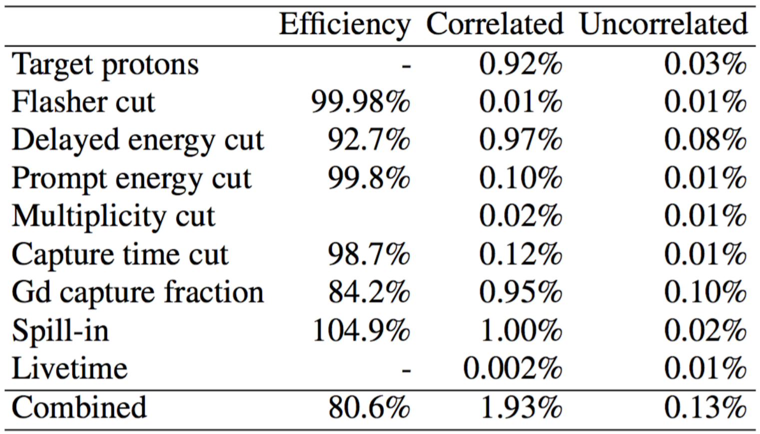
Consistent detectors

Relative energy scale uncertainty less than 0.2%

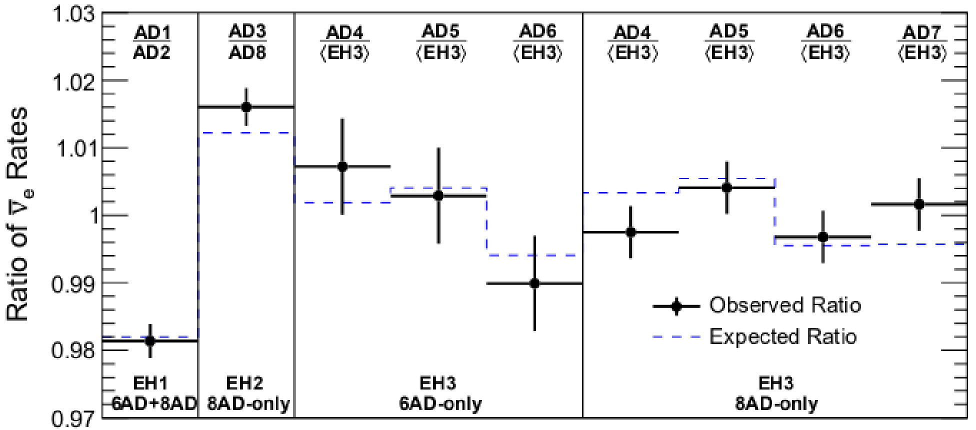
Relative efficiency constrained to within 0.13%

Neutrino rate ratios consistent with expectations

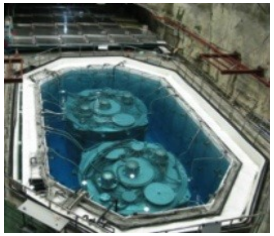




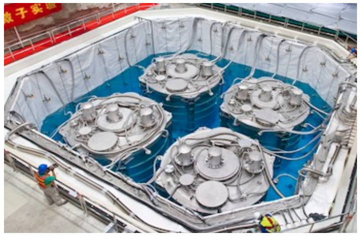
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime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



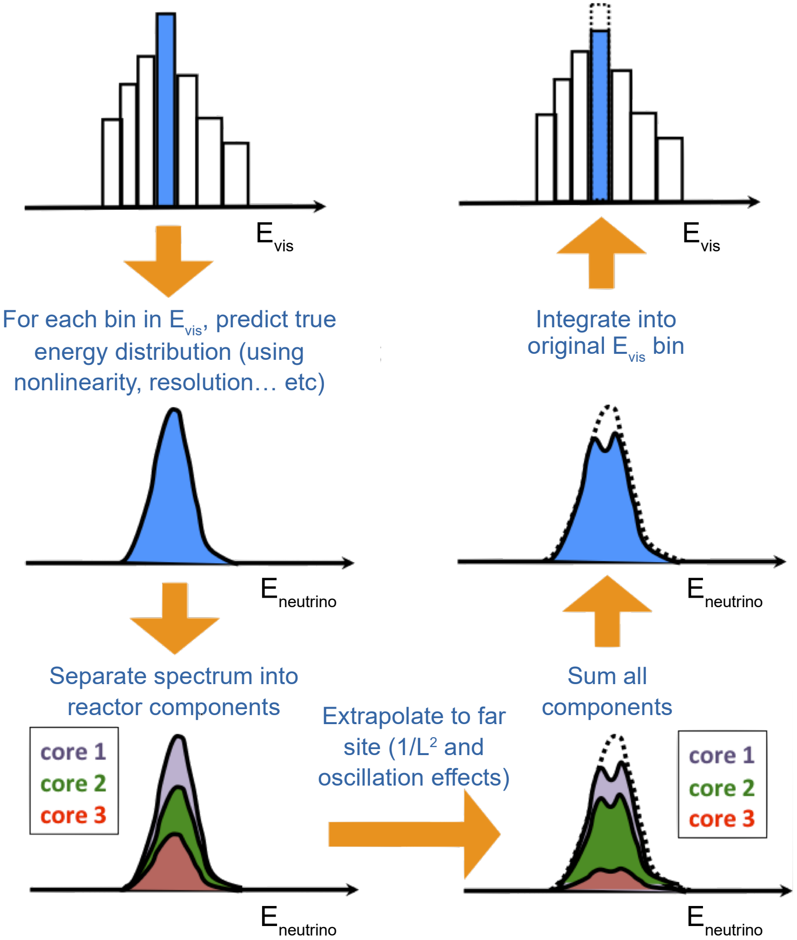
Near/far analysis



Observed near-site data
(bg. and eff. corrected)



Predicted
far-site data



For each bin in E_{vis}, predict true energy distribution (using nonlinearity, resolution… etc)

Separate spectrum into reactor components

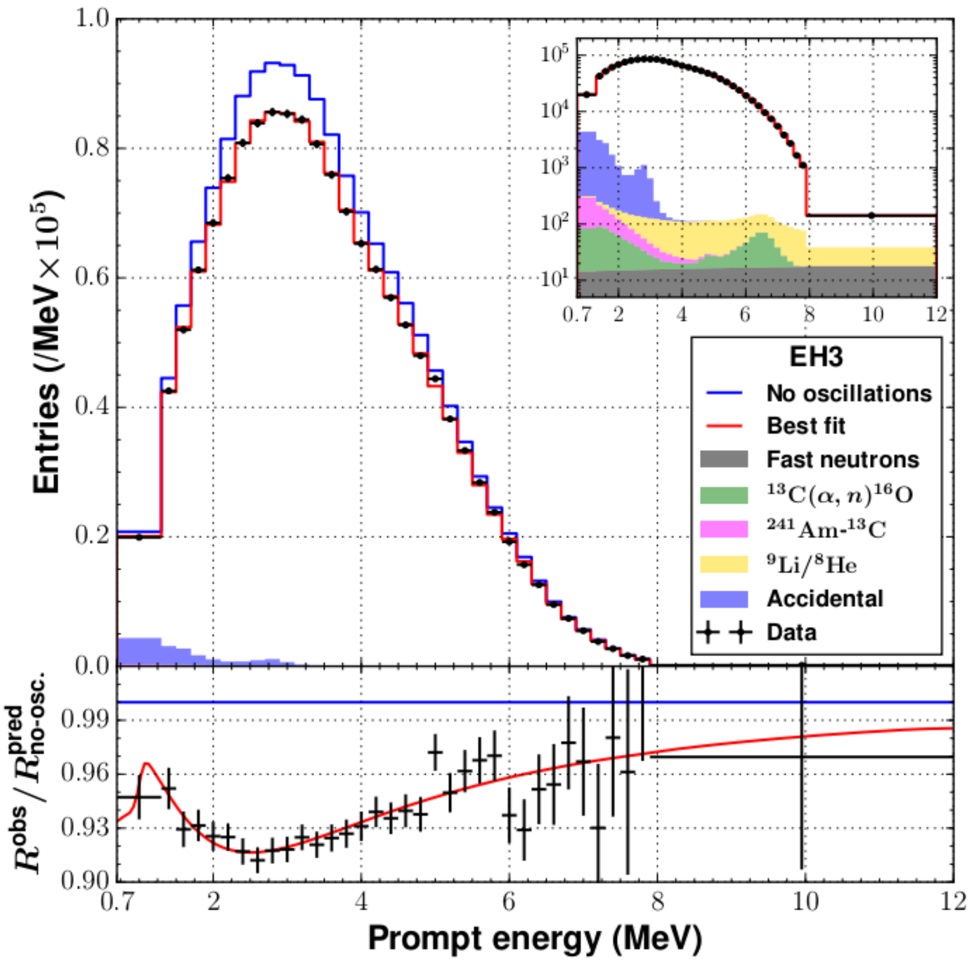
Extrapolate to far site ($1/L^2$ and oscillation effects)

Sum all components

Integrate into original E_{vis} bin

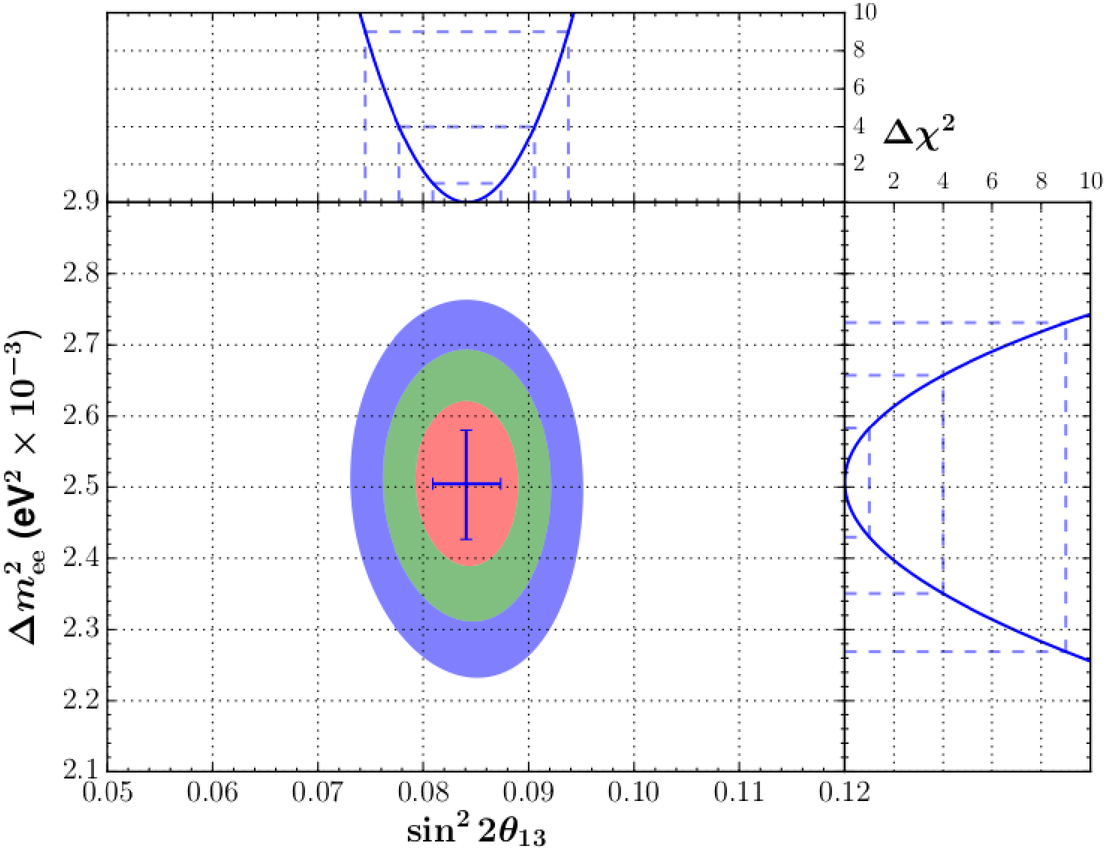
As shown previously, 8 ADs are *functionally identical.*

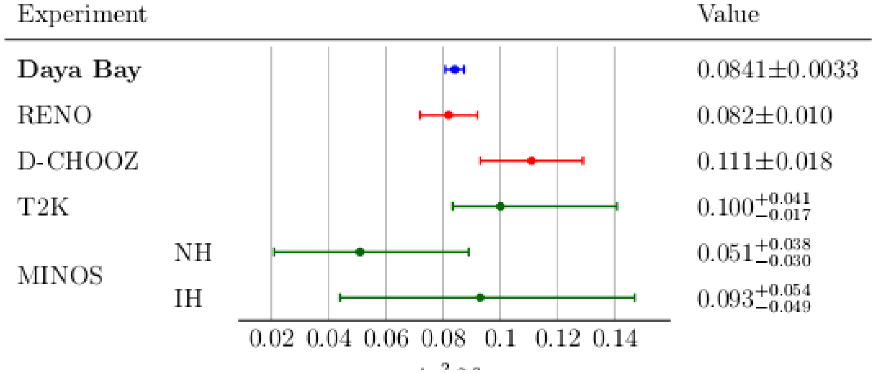
Thus, from using near site data to predict the far site spectrum, we get **cancellation of detection efficiency uncertainties,** as well as of reactor systematics.



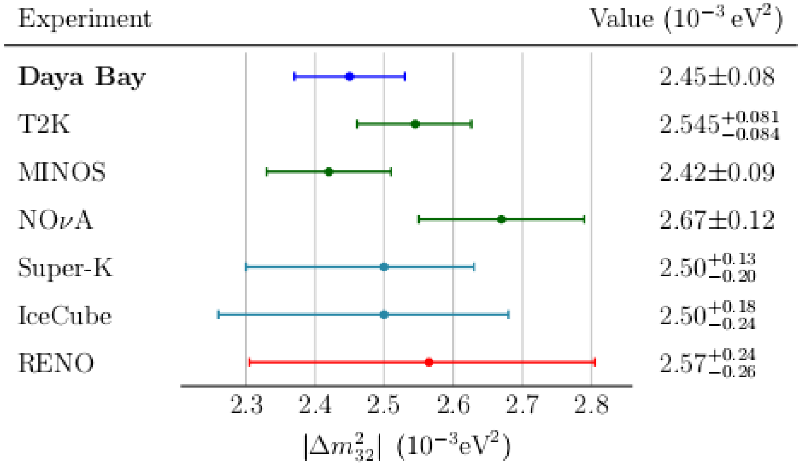
3ν oscillation results

PRD 95, 07006 (2016)





Experiment		Value
Daya Bay		0.0841±0.0033
RENO		0.082±0.010
D-CHOOZ		0.111±0.018
T2K		$0.100^{+0.041}_{-0.017}$
MINOS	NH	$0.051^{+0.038}_{-0.030}$
	IH	$0.093^{+0.054}_{-0.049}$



Experiment	Value (10^{-3} eV^2)
Daya Bay	2.45±0.08
T2K	$2.545^{+0.081}_{-0.084}$
MINOS	2.42±0.09
NOνA	2.67±0.12
Super-K	$2.50^{+0.13}_{-0.20}$
IceCube	$2.50^{+0.18}_{-0.24}$
RENO	$2.57^{+0.24}_{-0.26}$

World's most precise measurement of θ_{13}, Δm^2_{ee} (1230 days of data; 2.5 million neutrinos!)

Based on spectral shape as well as relative rates; allows extraction of Δm^2_{ee}

Background rate < 2% in all halls (→ ~0.3% uncertainty in IBD rate)

nH measurement

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

Comparable statistics thanks to Gd-free LS region

Challenging endeavor:

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

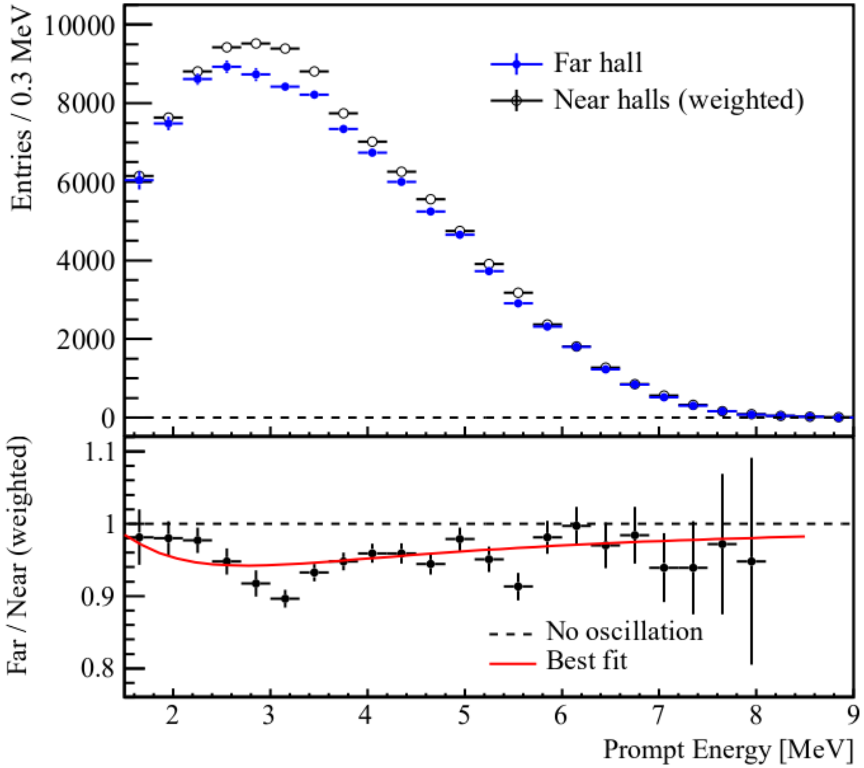
$\sin^2 2\theta_{13}$ measurements:

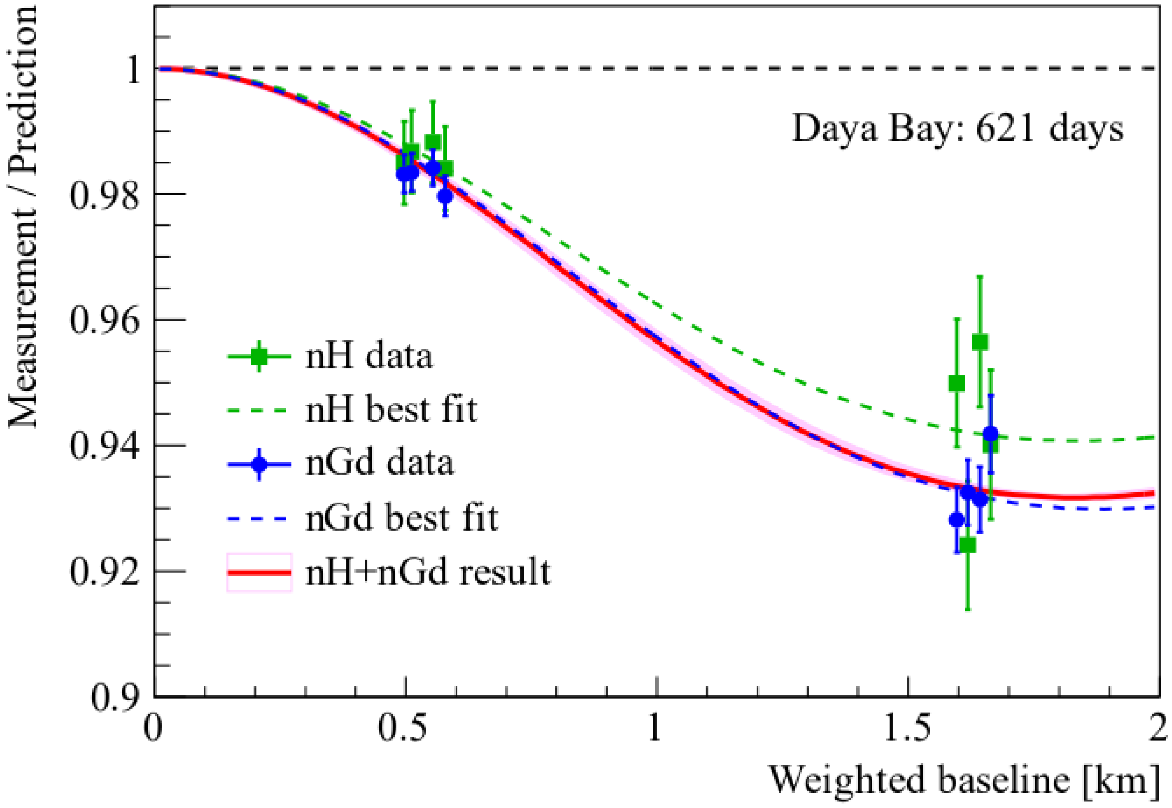
nGd: 0.084 ± 0.005

nH: 0.071 ± 0.011

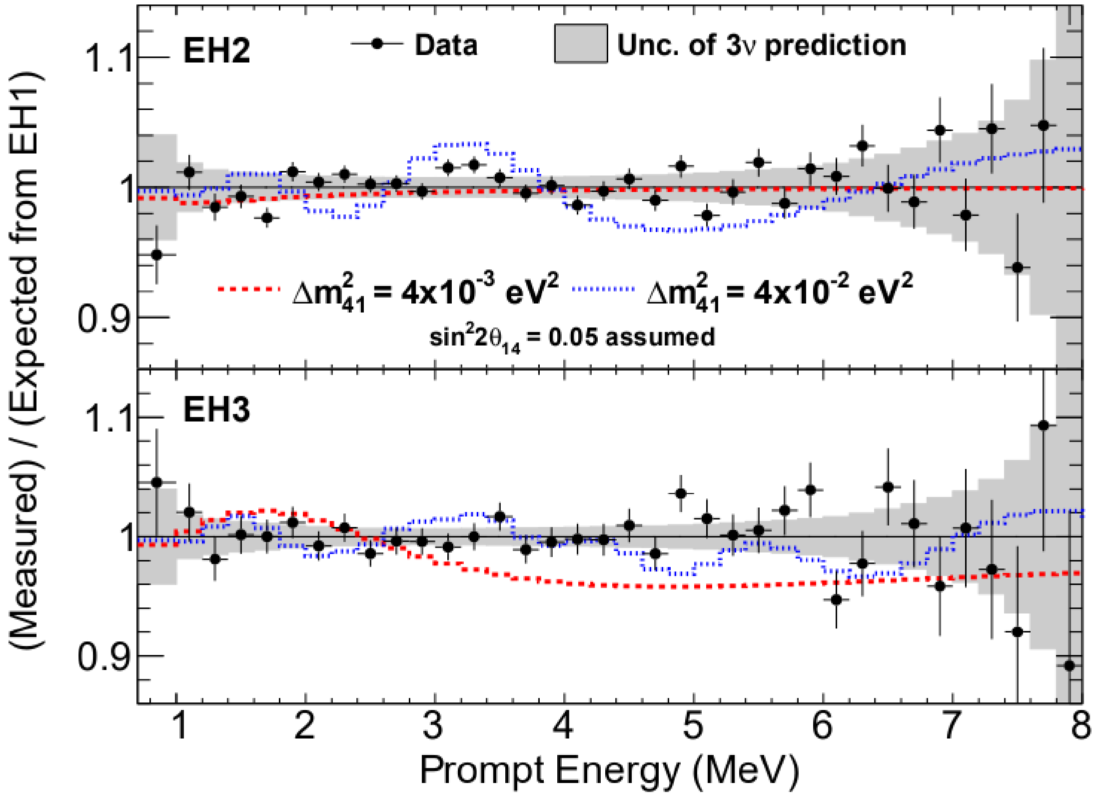
Comb.: 0.082 ± 0.004

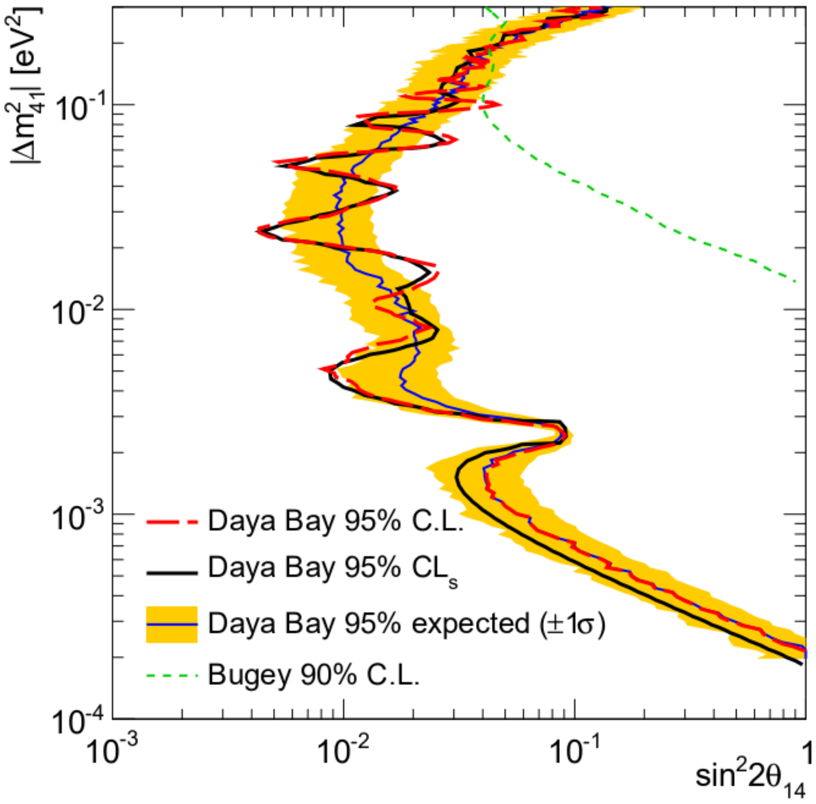
PRD 93, 072011 (2016)





Sterile neutrino search





PRL 117, 151802 (2016)

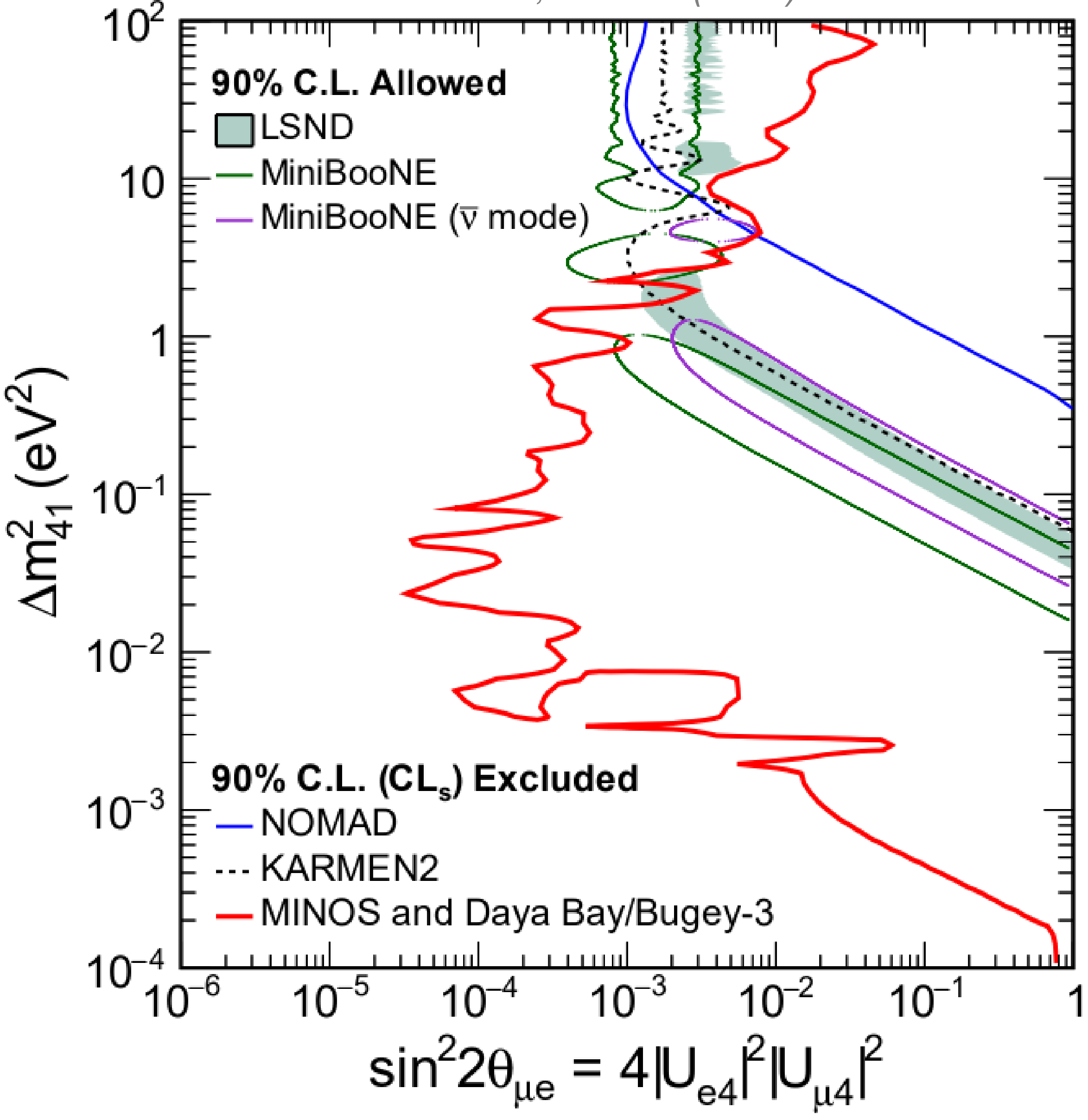
Search for an additional neutrino state by comparing spectra across different sites

Signal appears as a spectral distortion at a frequency different from that of Δm^2_{ee}

Obtain world's strongest limits on $\sin^2 2\theta_{14}$ for Δm^2_{41} in $[2\text{x}10^{-4}, 0.2]$ eV^2

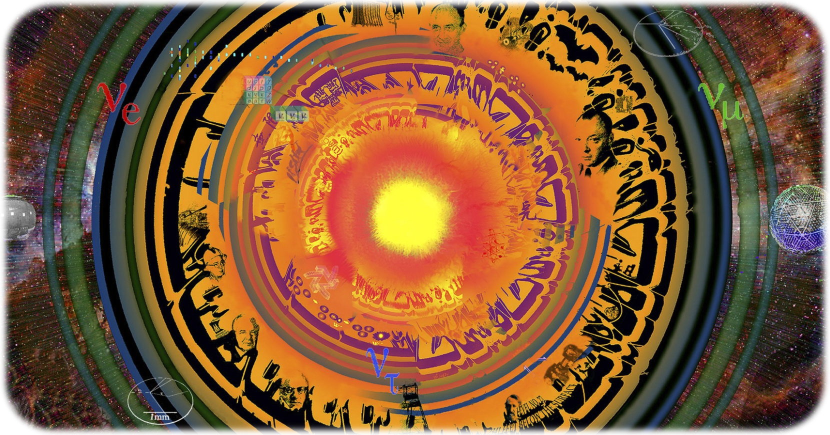
Adding MINOS/Bugey-3

PRL 117, 151801 (2016)



Synergy in combination with **MINOS** (accelerator ν_μ disappearance, $|U_{\mu 4}|^2$) and **Bugey-3** (short-baseline reactor $\bar{\nu}_e$ disappearance, $|U_{e4}|^2$):

- Stringent limits on $\sin^2 2\theta_{\mu e}$ over six orders of magnitude in Δm^2_{41}
- Exclude LSND and MiniBooNE allowed regions at 90% CL for $\Delta m^2_{41} < 0.8$ eV^2



MINOS experiment (artist's impression)

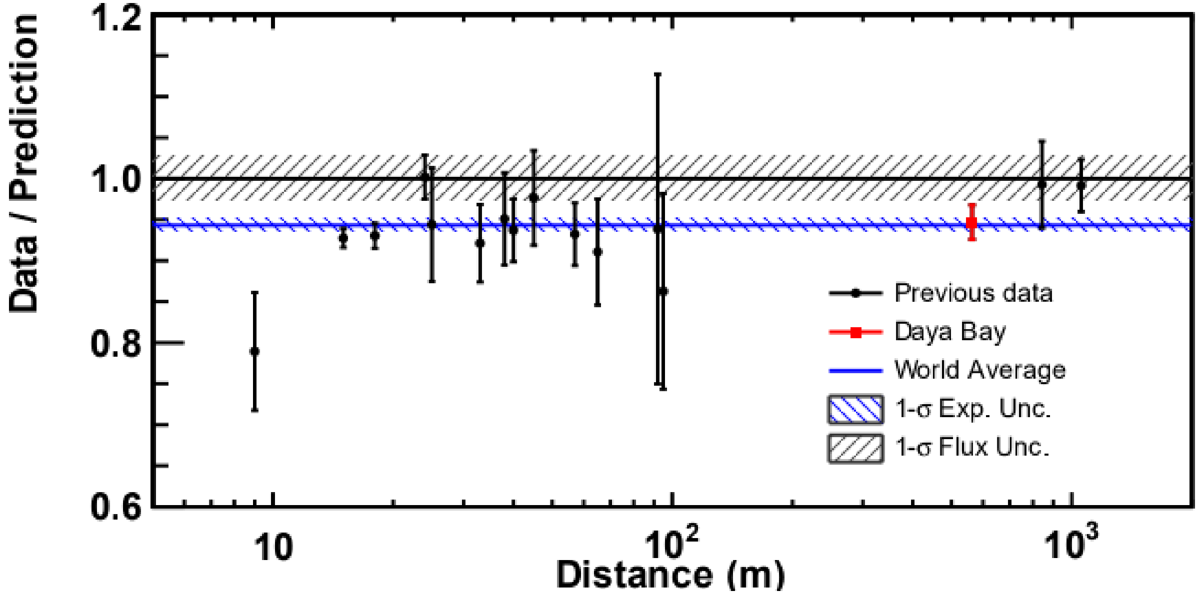
Absolute flux

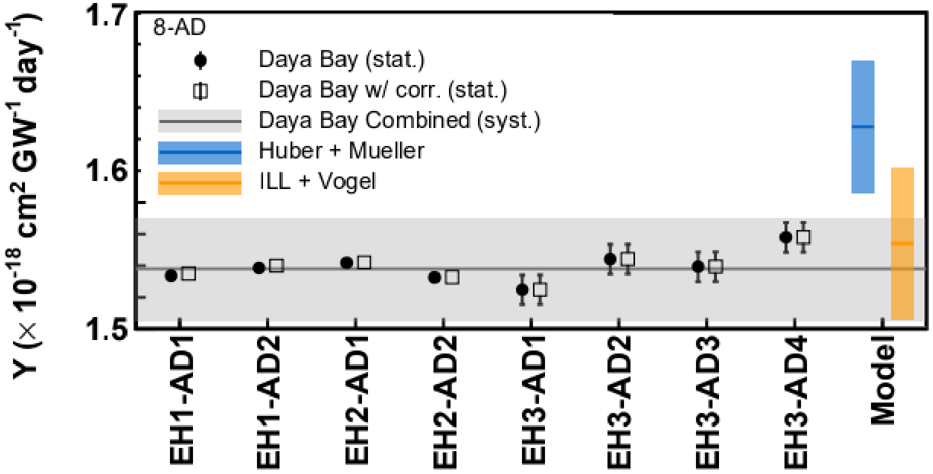
Consistent with other short-baseline reactor experiments

Observe 2.5σ (exp.) deficit versus Huber-Mueller prediction

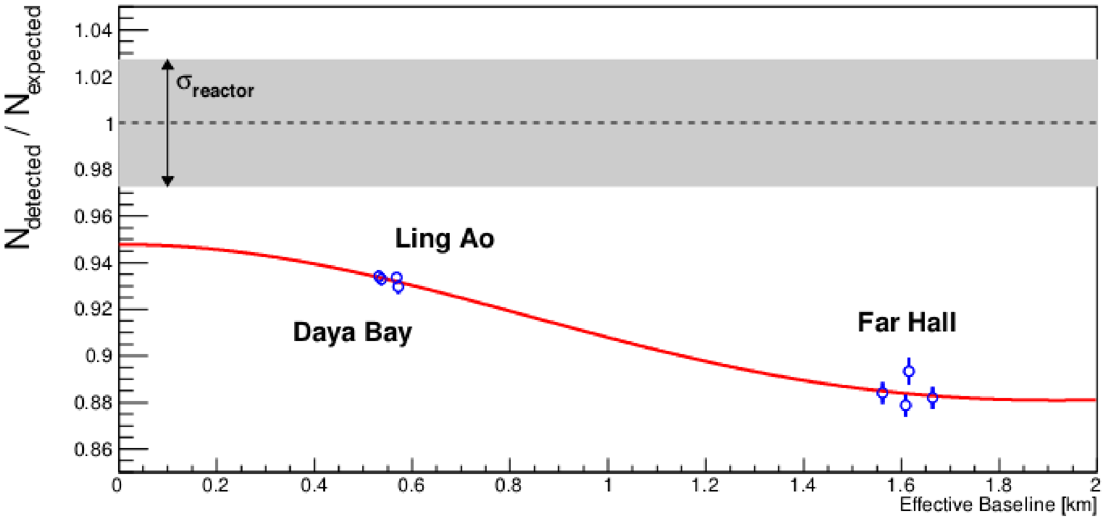
Possible causes:

- Sterile neutrino
- Overprediction by H-M model



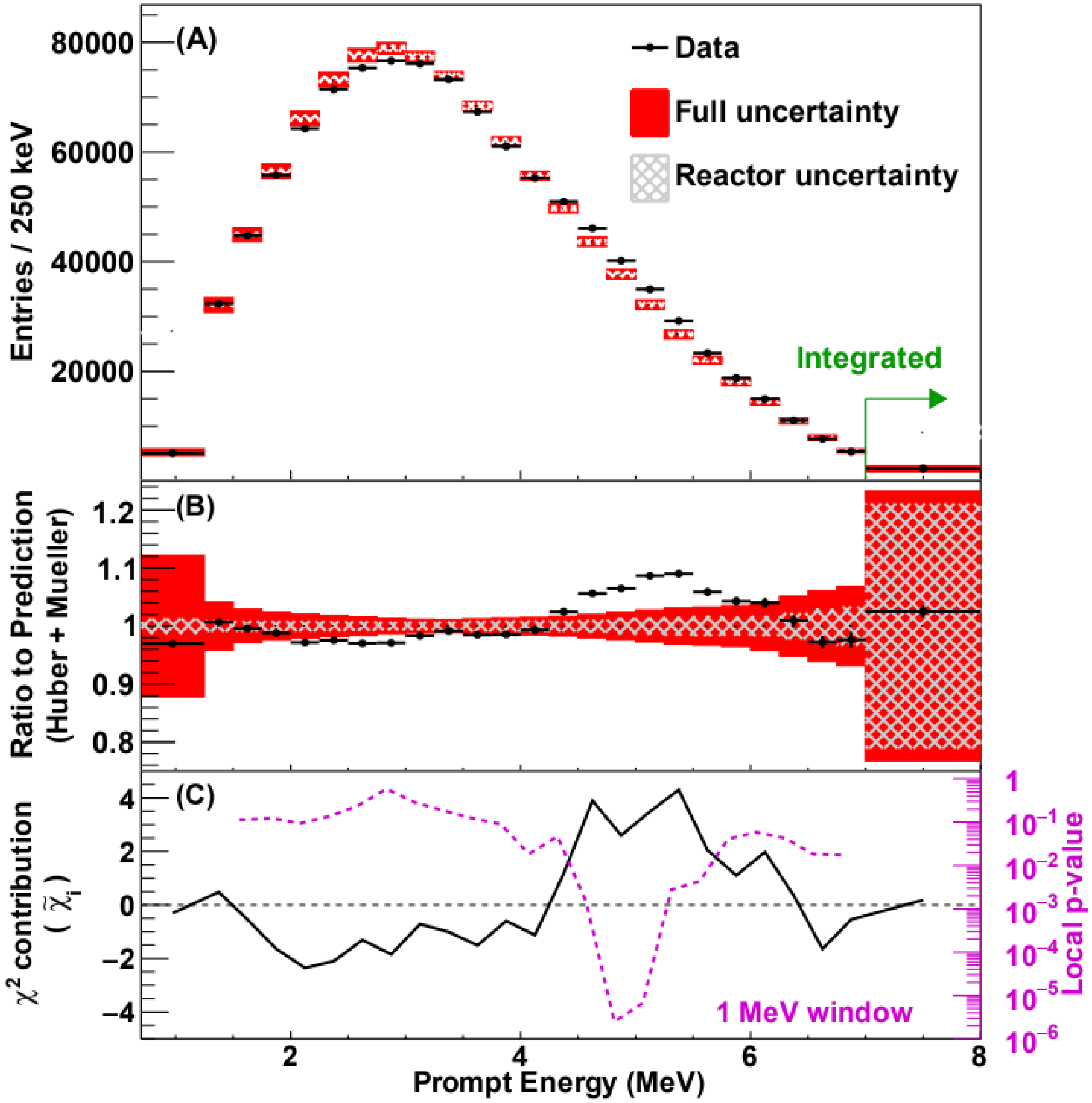


Chin. Phys. C 41, 13002 (2017)



Reactor spectrum

Chin. Phys. C 41, 13002 (2017)

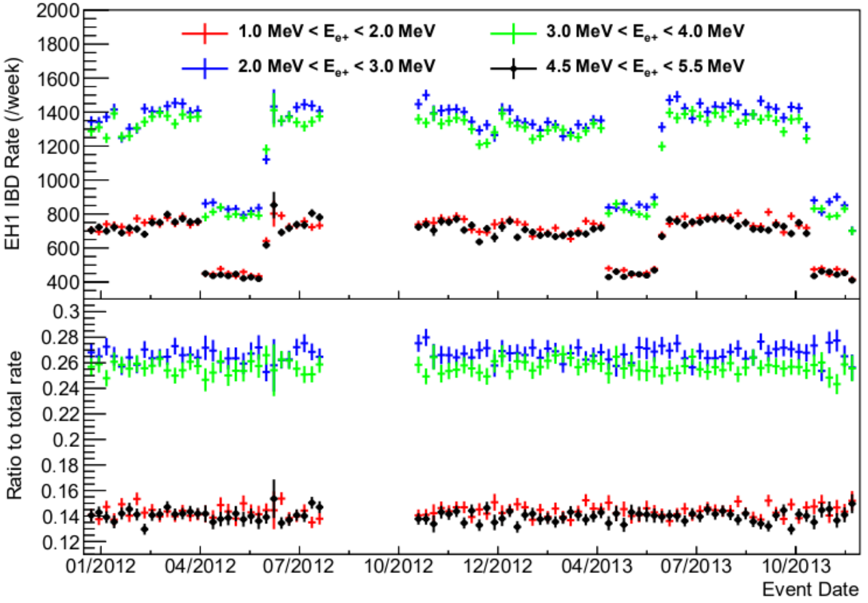


Observe 2.9σ discrepancy versus H-M prediction (4.4σ, 4-6 MeV)

Excess events completely consistent with IBDs, correlated with reactor power (not a background)

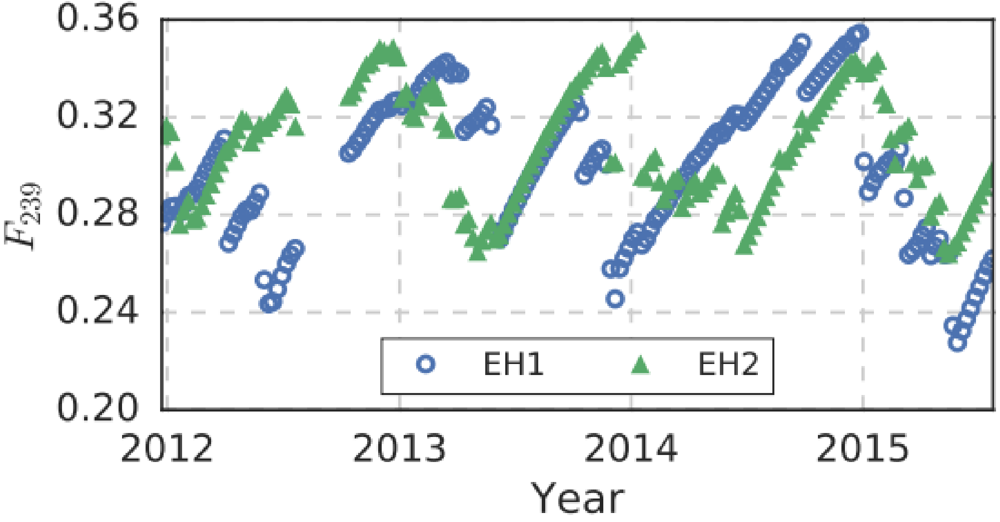
Distortion absent from ^{12}B spectrum (not a detector effect)

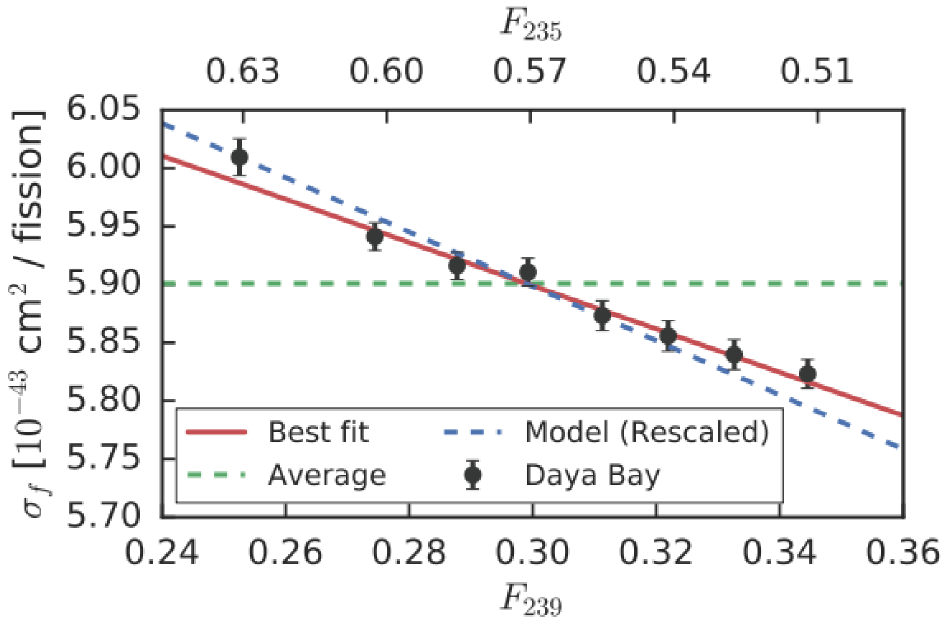
Bump structure inconsistent with sterile neutrino explanation of rate deficit

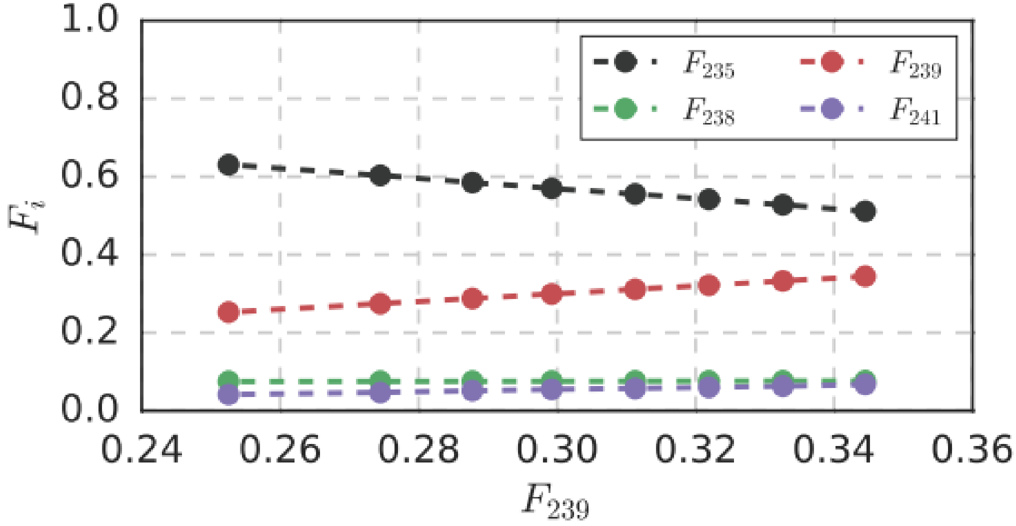


Flux evolution

PRL 118, 251801 (2017)







Observe variation in reactor flux versus F239 (i.e. fuel burnup) at >10σ

Slope is inconsistent with H-M prediction at 3σ*

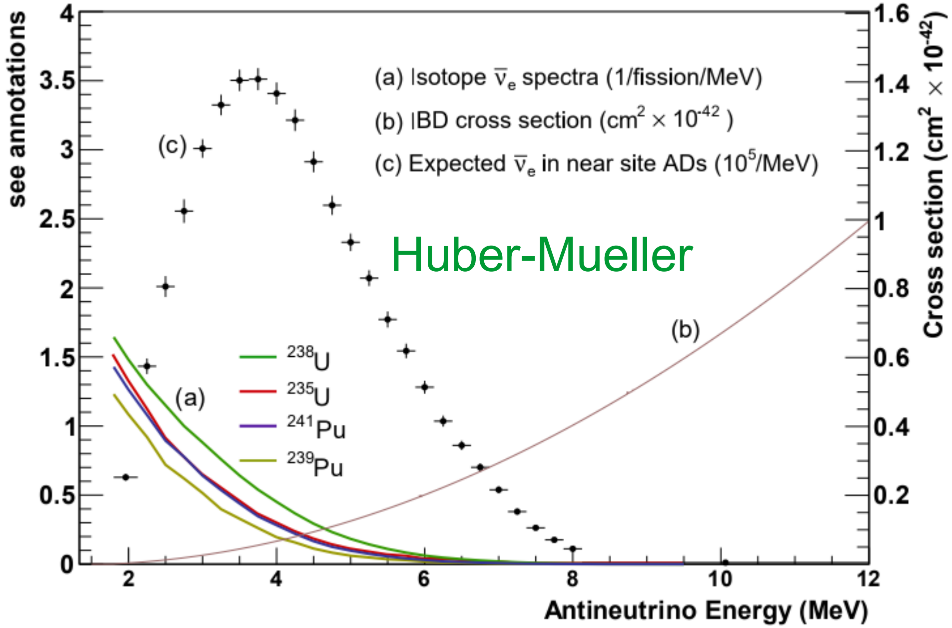
Results suggest that H-M overprediction is not equally distributed among the four isotopes

* *Caveat: Potentially reduced significance when additional time-dependent corrections are included in H-M model*

Isotope decomposition

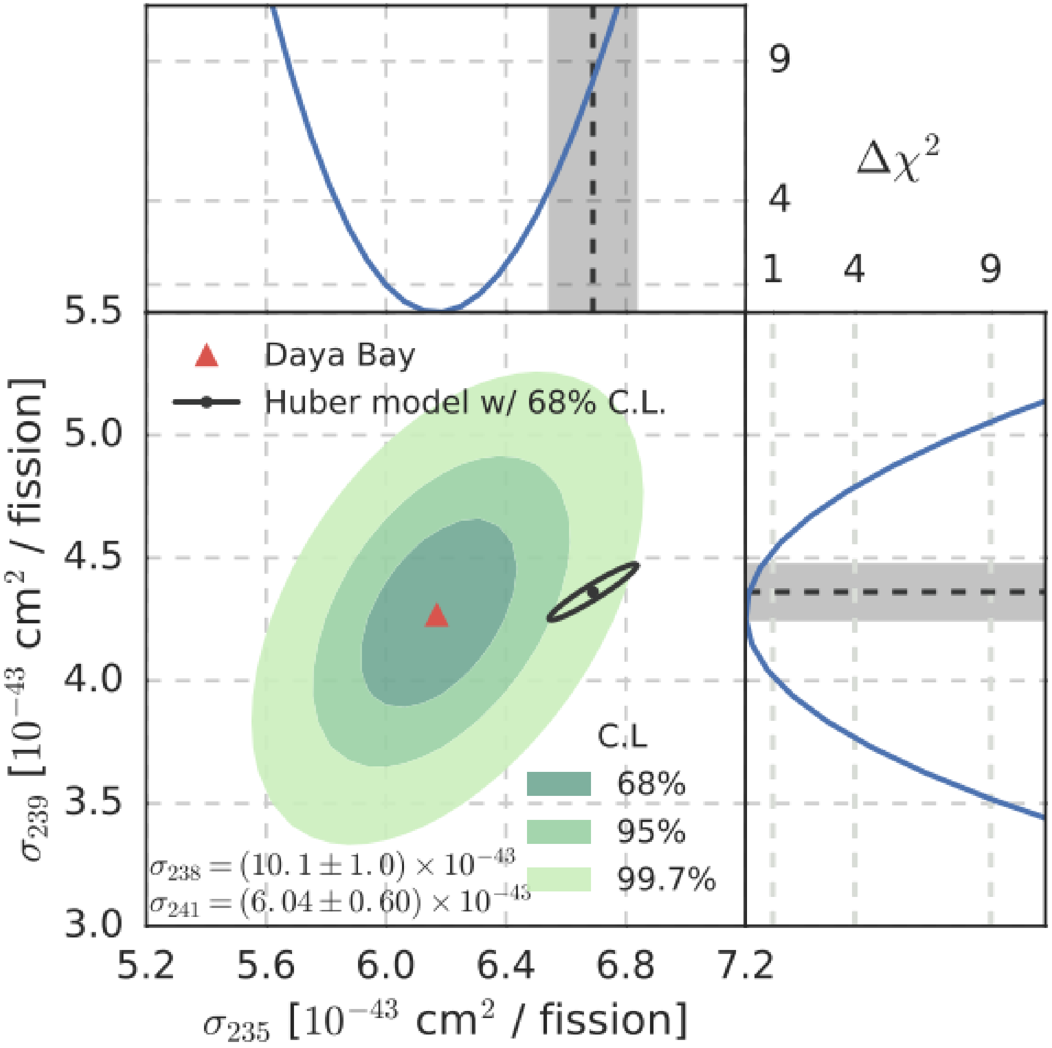
Using conservative (~10%) constraints on minor fission isotopes ^{238}U and ^{241}Pu, extract individual neutrino yields for ^{235}U and ^{239}Pu:

- Clear evidence that bulk of rate deficit comes from ^{235}U
- Equal deficit of all isotopes disfavored at 2.8σ*, furthering argument against sterile neutrino interpretation



** Caveat: Reduced significance in combination with global flux data (1708.01133, 1707.07728)*

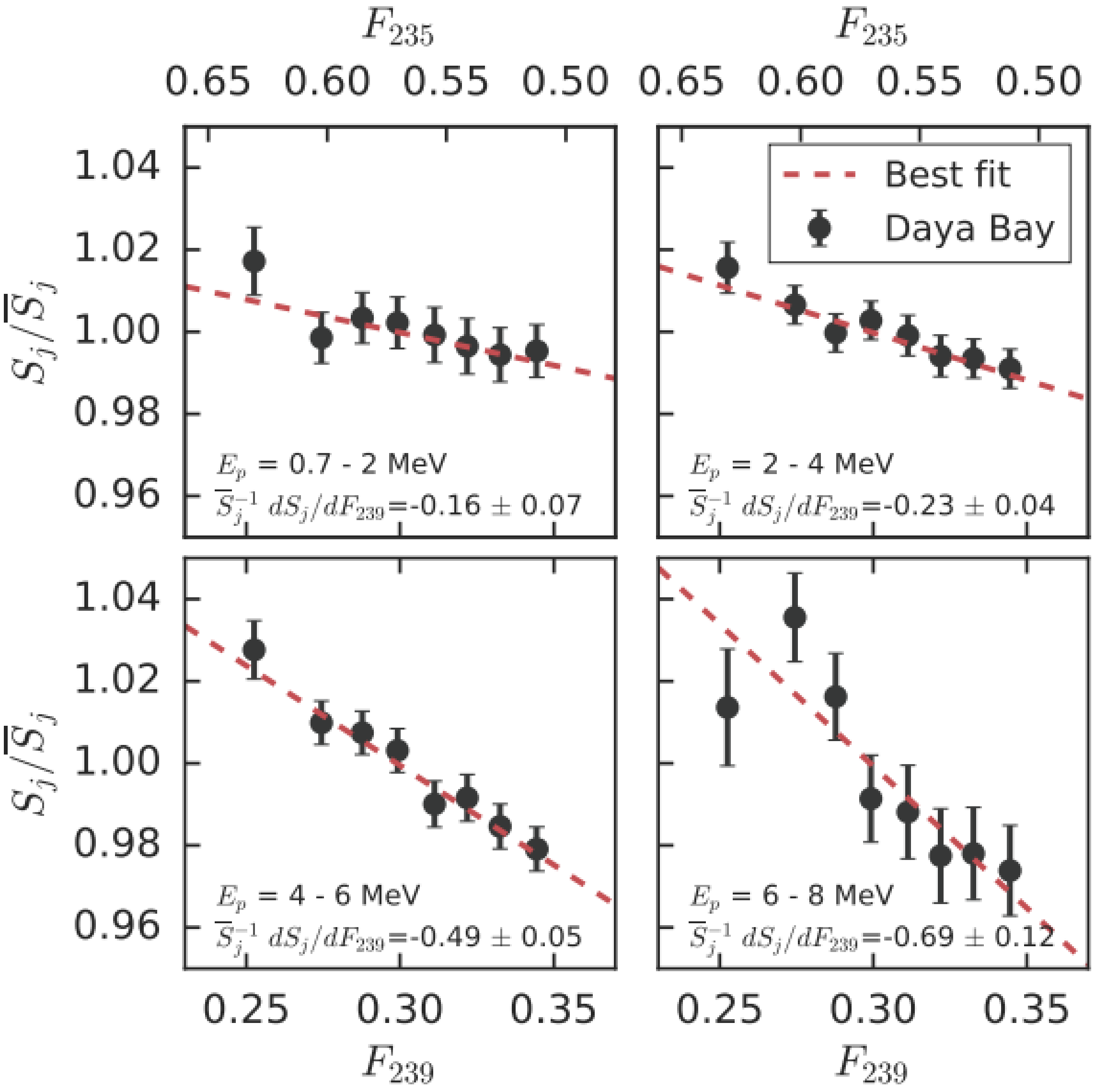
PRL 118, 251801 (2017)



Shape evolution

Energy-binned analysis of flux evolution

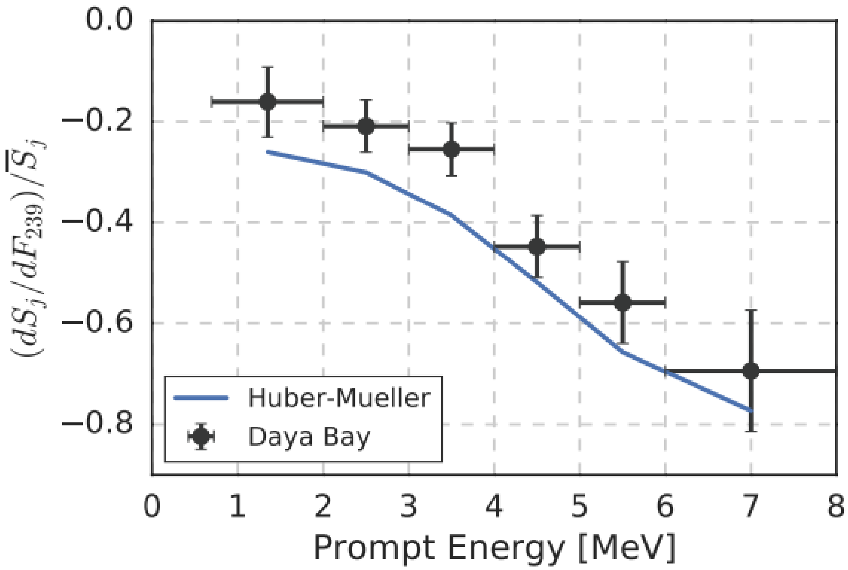
PRL 118, 251801 (2017)



Observe different slopes in different energy bins, implying change of spectral shape with burnup

Evolution is generally consistent with Huber-Mueller

Precision limited by Daya Bay uncertainties. Good argument for future short-baseline experiments with highly-enriched uranium



Neutrino decoherence

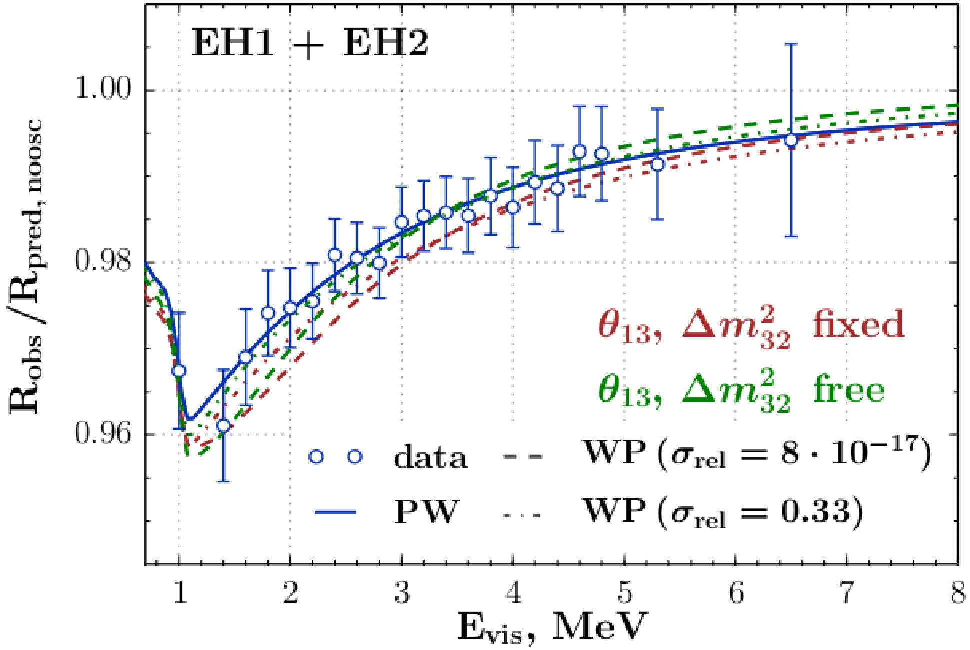
Plane wave approximation is successful but not rigorous

Full wave packet treatment adds one new parameter, instrinsic momentum dispersion:

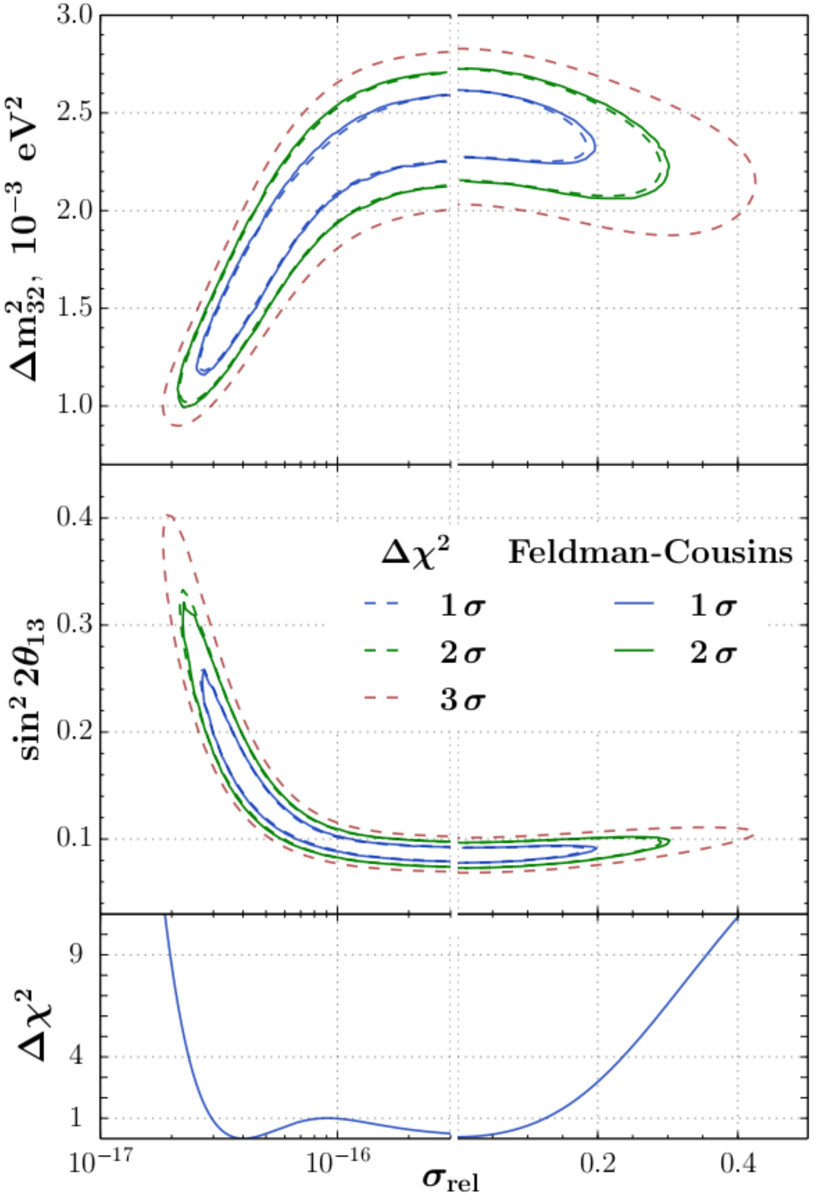
$\sigma_{rel} \equiv \sigma_p/p$

First measurement by any experiment:

$10^{-14} < \sigma_{rel} < 0.23$



Eur. Phys. C 77:606 (2017)



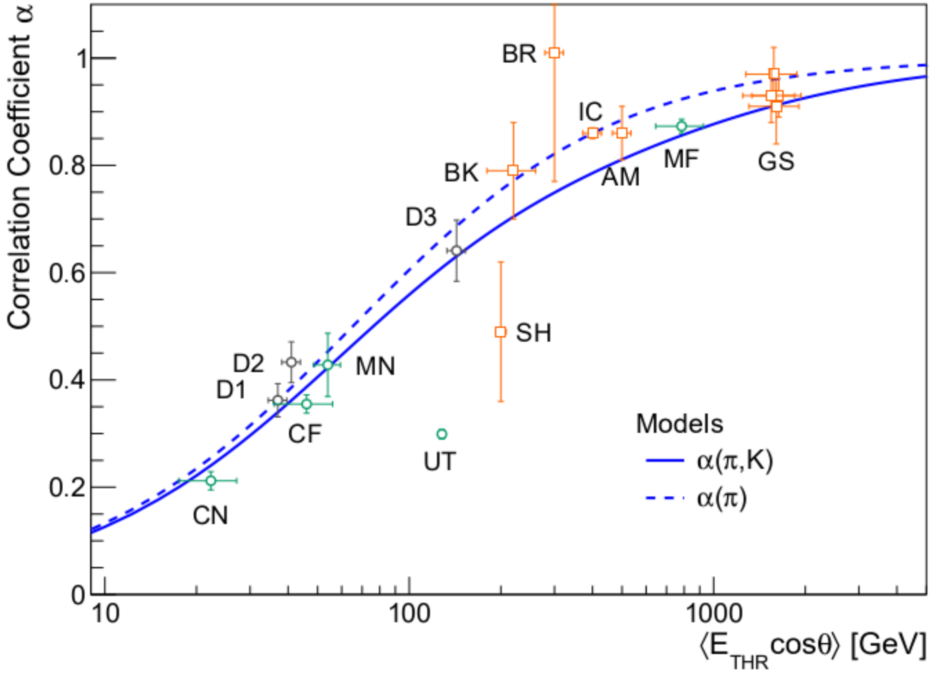
Muon modulation

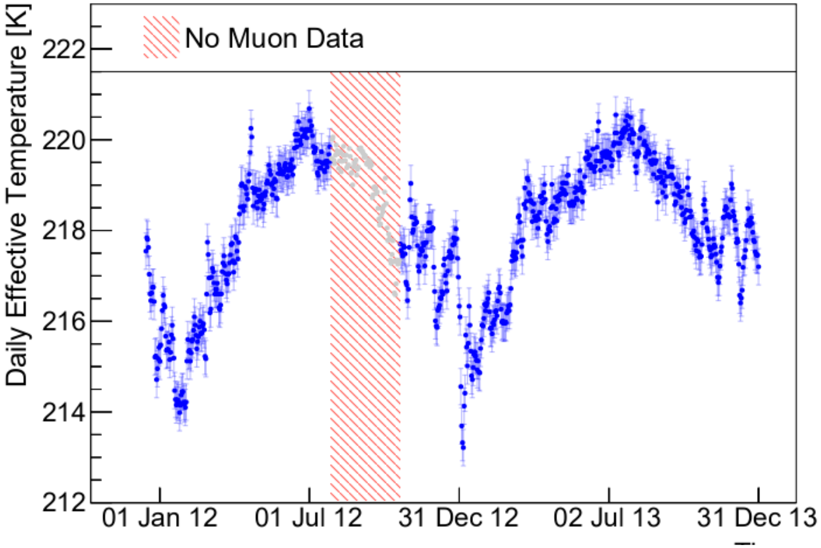
Precisely measured muon flux at three overburdens (i.e. average muon energies)

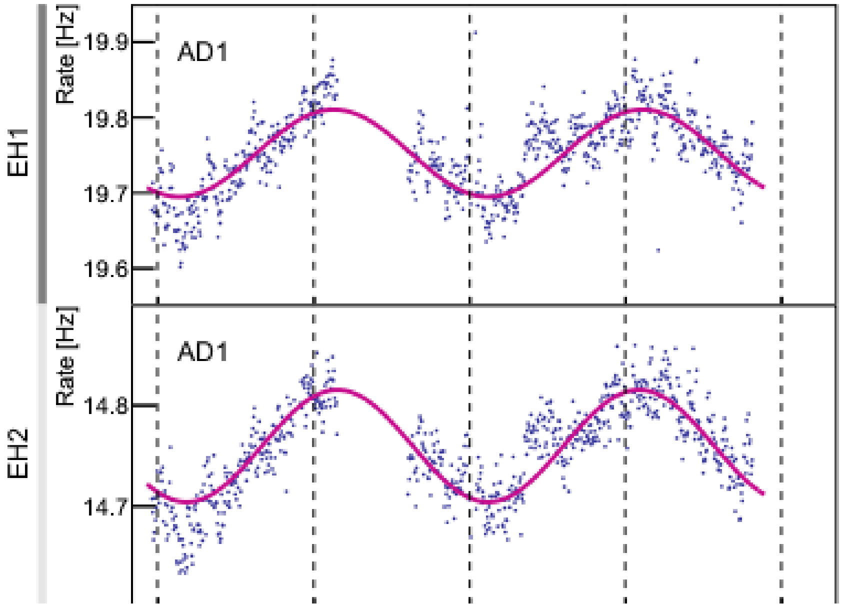
Observed clear correlation with effective atmospheric temperature (i.e. density), as expected

Correlation of flux to temperature is consistent with model prediction

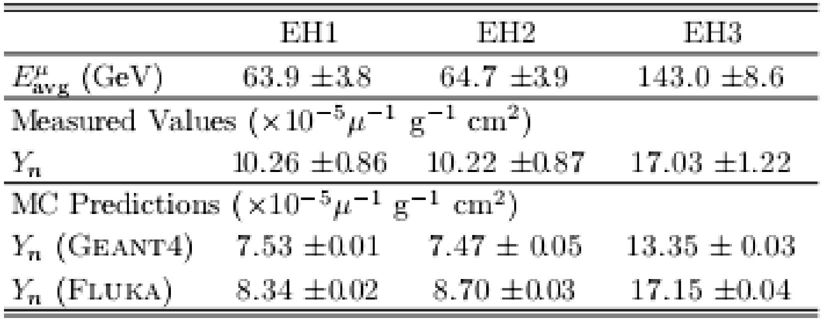
JCAP01(2018)001







Neutron yield



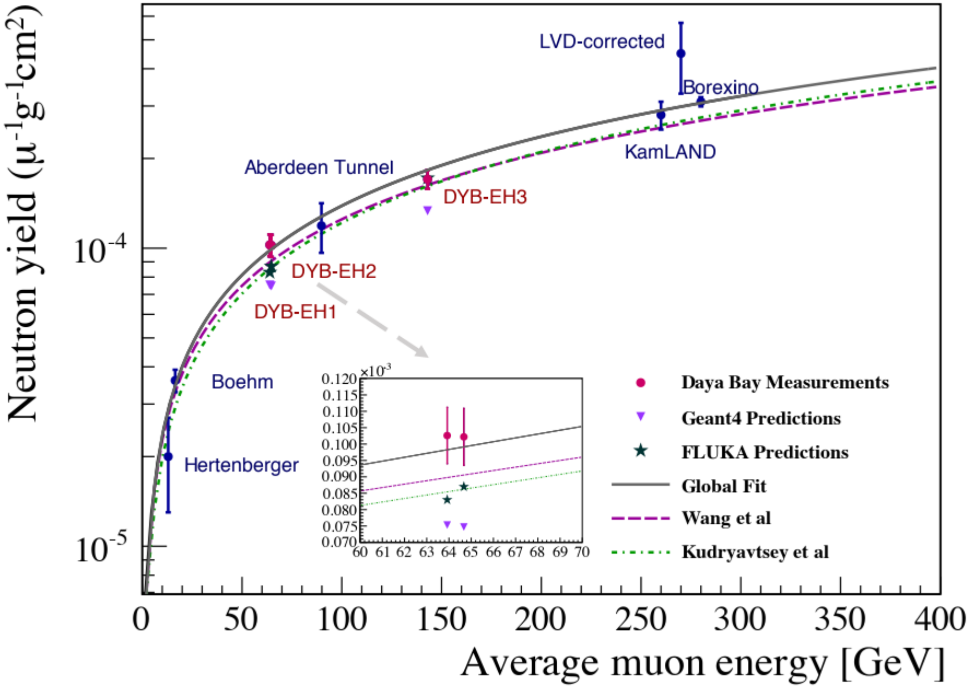
	EH1	EH2	EH3
E^{μ}_{avg} (GeV)	63.9 ±3.8	64.7 ±3.9	143.0 ±8.6
Measured Values ($\times 10^{-5}\mu^{-1}$ g^{-1} cm^{2})			
Y_n	10.26 ±0.86	10.22 ±0.87	17.03 ±1.22
MC Predictions ($\times 10^{-5}\mu^{-1}$ g^{-1} cm^{2})			
Y_n (GEANT4)	7.53 ±0.01	7.47 ± 0.05	13.35 ± 0.03
Y_n (FLUKA)	8.34 ±0.02	8.70 ±0.03	17.15 ±0.04

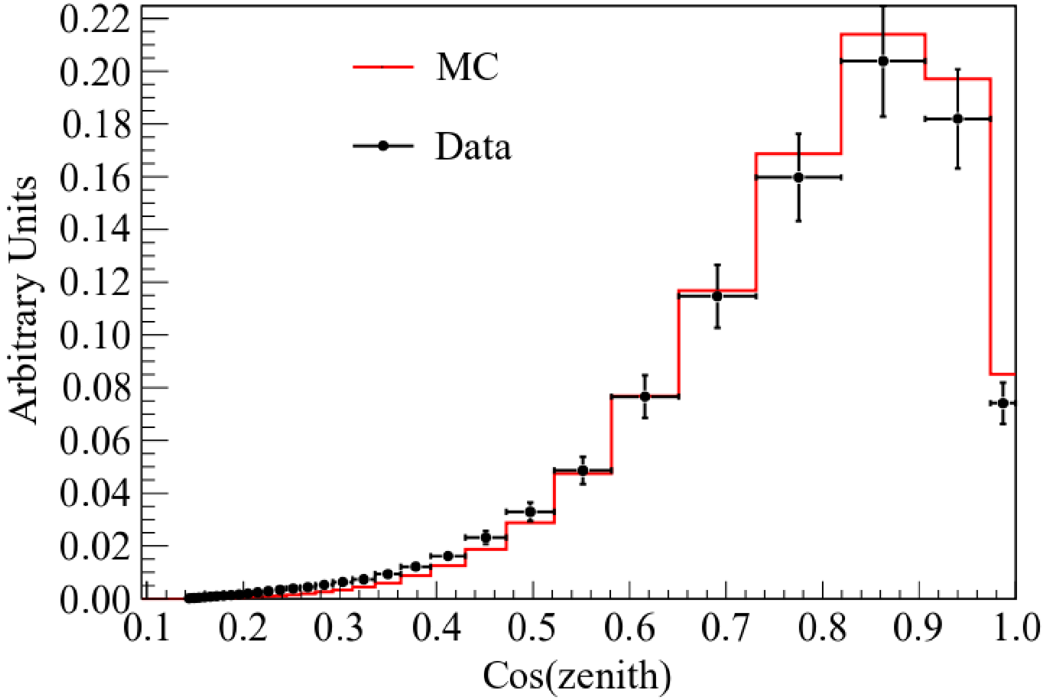
PRD 97, 052009 (2018)

Muon-induced fast neutrons are an important background for underground experiments

Measured neutron yield at three overburdens (i.e. average muon energies)

Disagreements found with MC, providing input for tuning of Geant4/FLUKA models





Conclusion

- Daya Bay has published significant (often world-leading!) results in:
    - Measurement of θ_{13} and Δm^2_{ee}
    - Limits on light sterile neutrino mixing
    - Reactor flux/spectrum and their evolution
    - Neutrino wave packet decoherence
    - Cosmic muon flux and neutron production
- Various new/updated scientific and technical publications in the pipeline, featuring improved systematics and statistics
- The Daya Bay experiment is a rich source of data for studying reactor neutrinos, cosmic rays, and beyond!

Thanks!