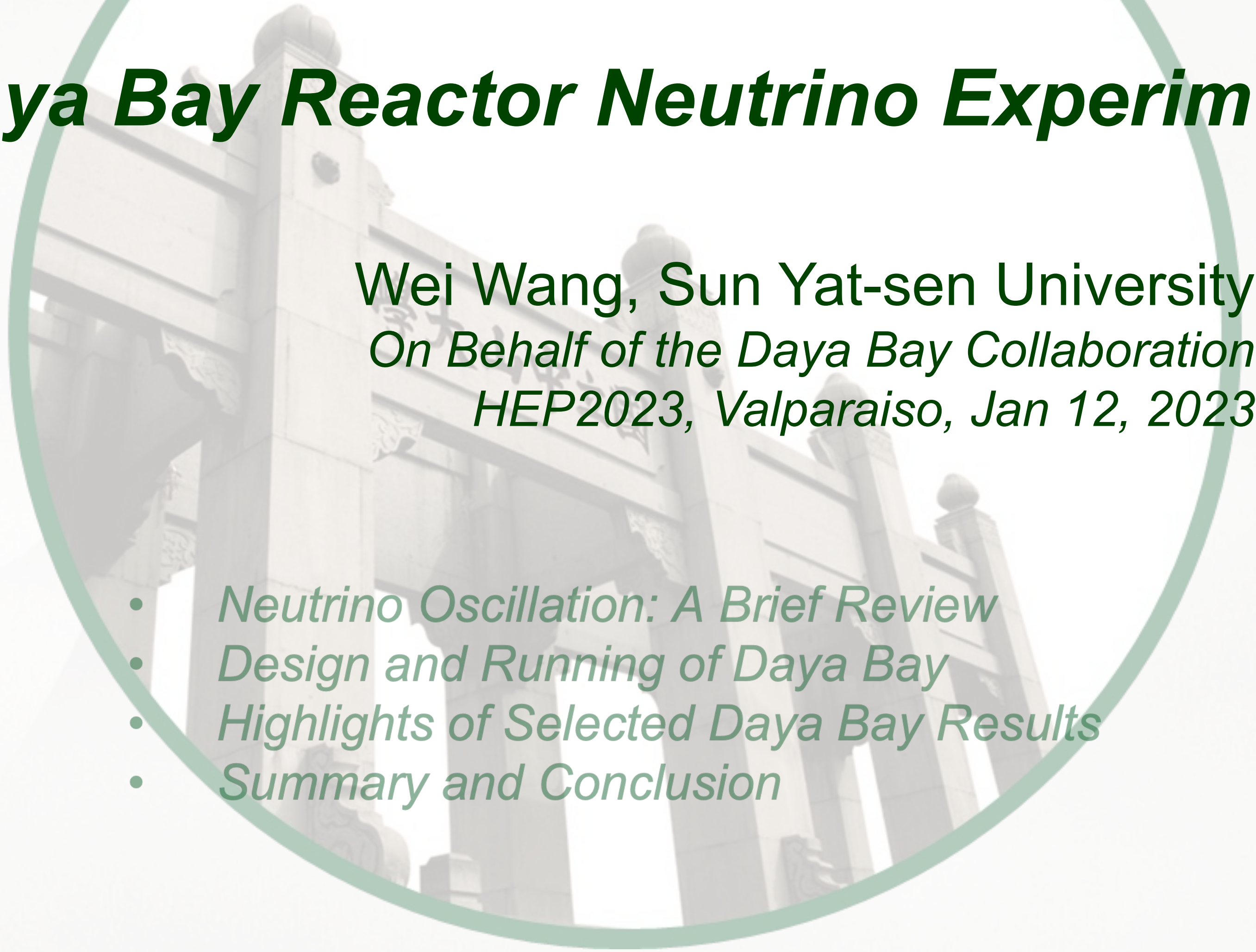
The Daya Bay Reactor Neutrino Experiment

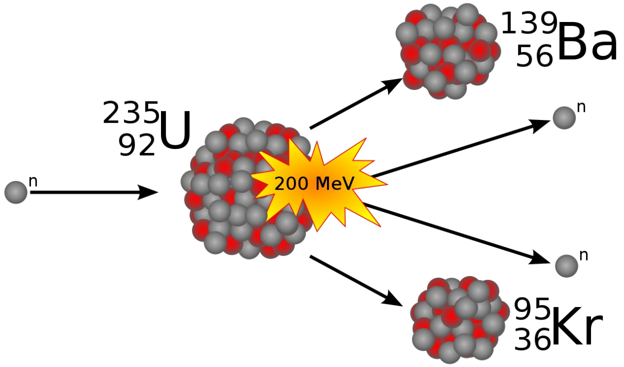


Wei Wang, Sun Yat-sen University
On Behalf of the Daya Bay Collaboration
HEP2023, Valparaiso, Jan 12, 2023

- *Neutrino Oscillation: A Brief Review*
- *Design and Running of Daya Bay*
- *Highlights of Selected Daya Bay Results*
- *Summary and Conclusion*

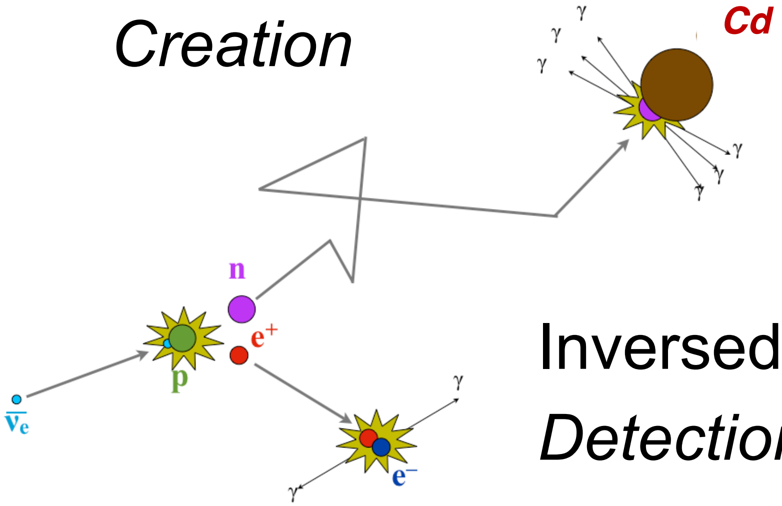
Reines&Cowan Detected Reactor Neutrinos in 1956

- Cowan and Reines at the Savannah River Power Plant (1956-1959)



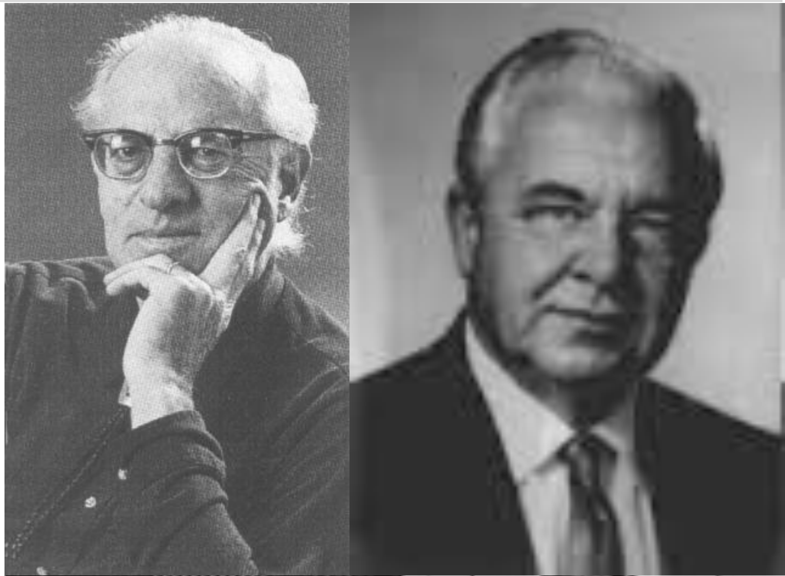
β decay :N ⟶ N′ + e + ν

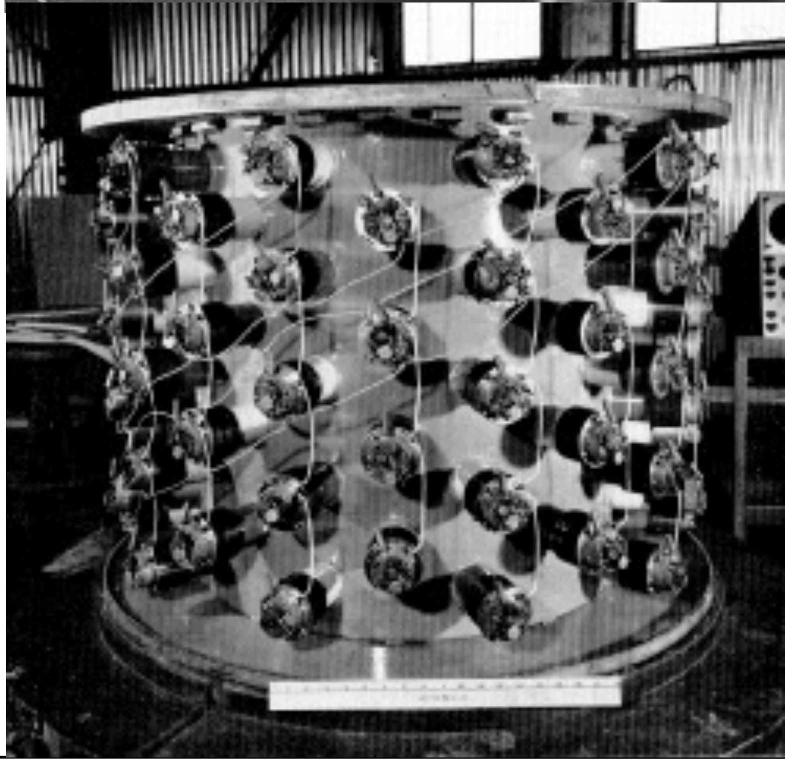
Creation



Inversed β decay

Detection: p+ ν ⟶ e^+ + n





Neutrino Mixing & Oscillation Proposed

Бруно Понтекорво

- Bruno Pontecorvo in 1957:

  Interaction Eigenstates ≠ Mass Eigenstates
  → Neutrino Mixing and Oscillation

- ➢ Extended to 3 flavor mixing by Maki, Nakagawa and Sakata, after muon neutrino was discovered at BNL in 1962

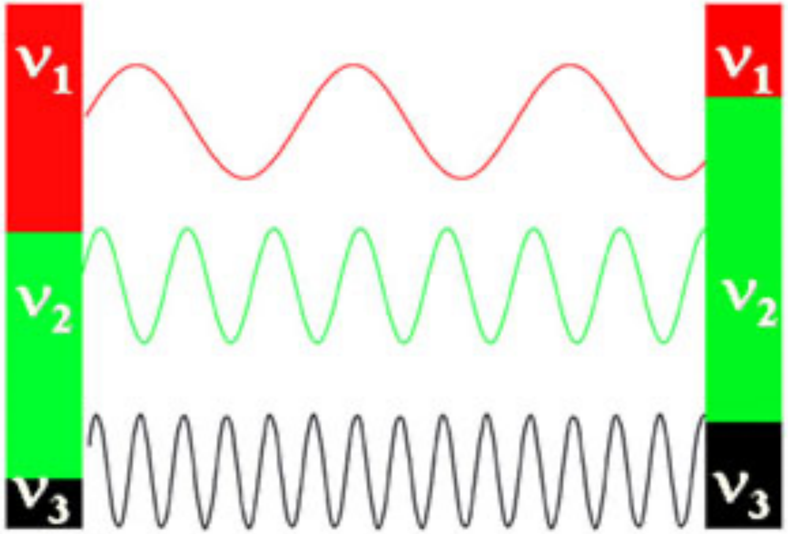
Courtesy of Sakata Memorial Archival Library

S. Sakata	Z. Maki	M. Nakagawa
1911-1970	1929-2005	1932-2001

Neutrino Mixing & Oscillation

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix,

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



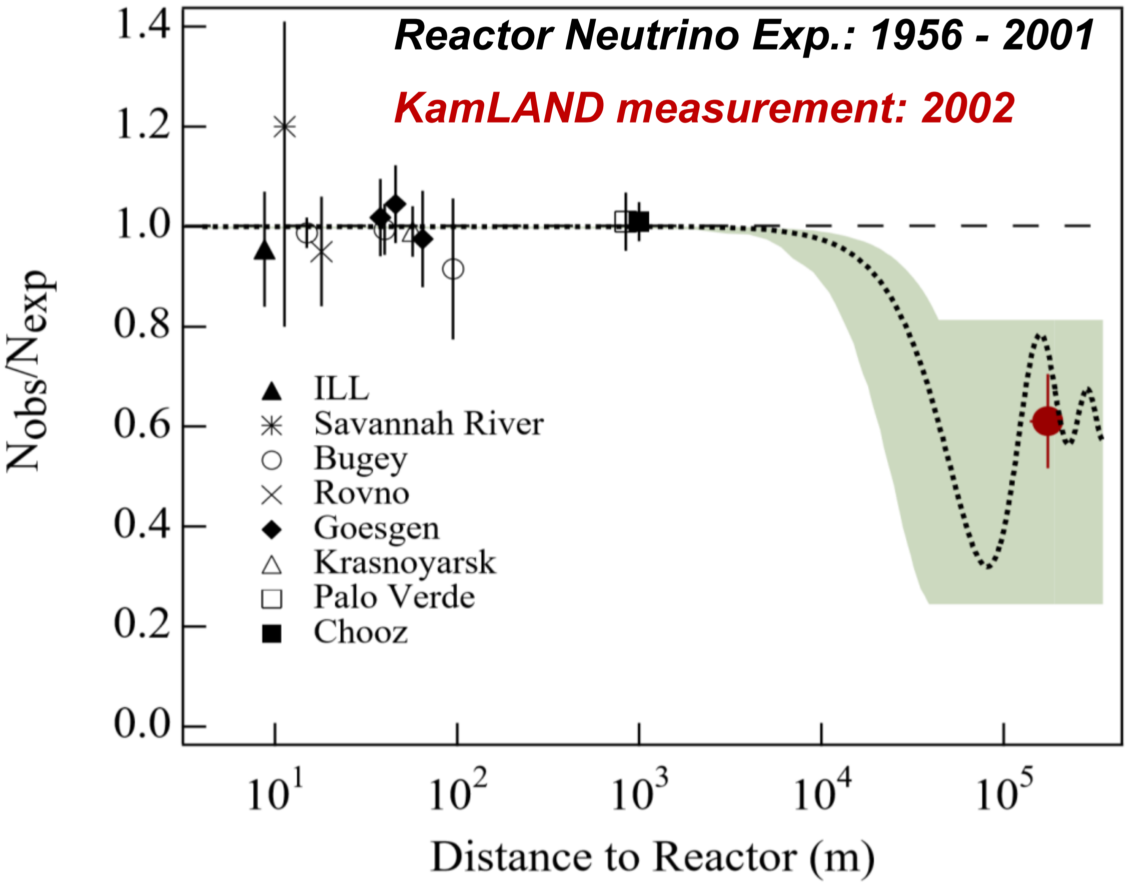
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

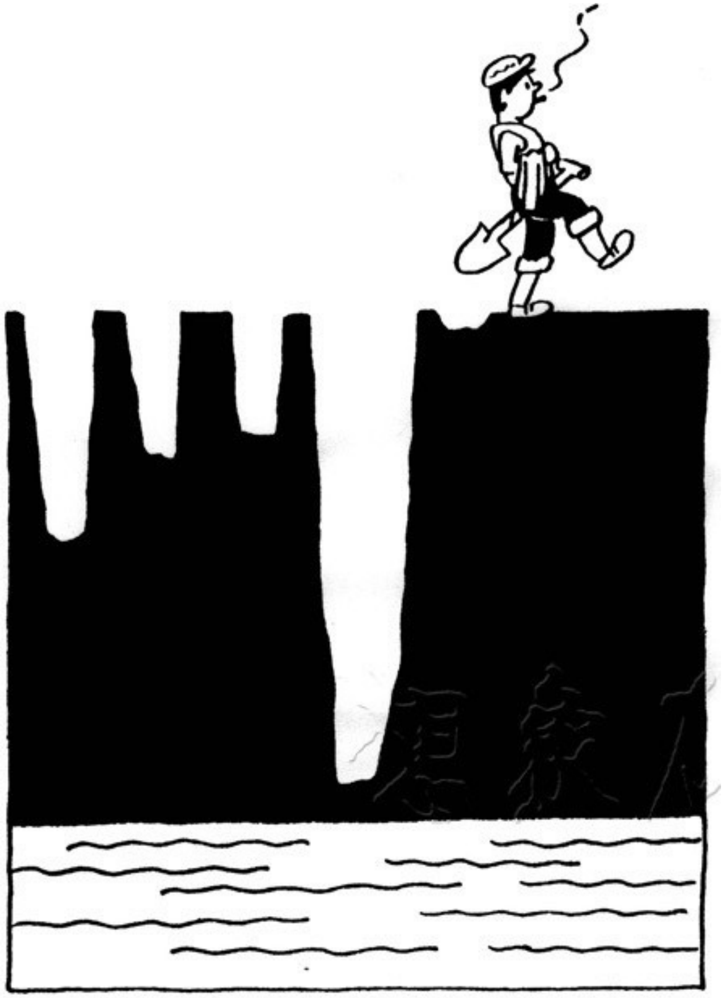
⇒ Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

Amplitude ∝ $\sin^2 2\theta$ **Frequency ∝ $\Delta m^2 L/E$**

The Search for Neutrino Oscillation 1957-1997





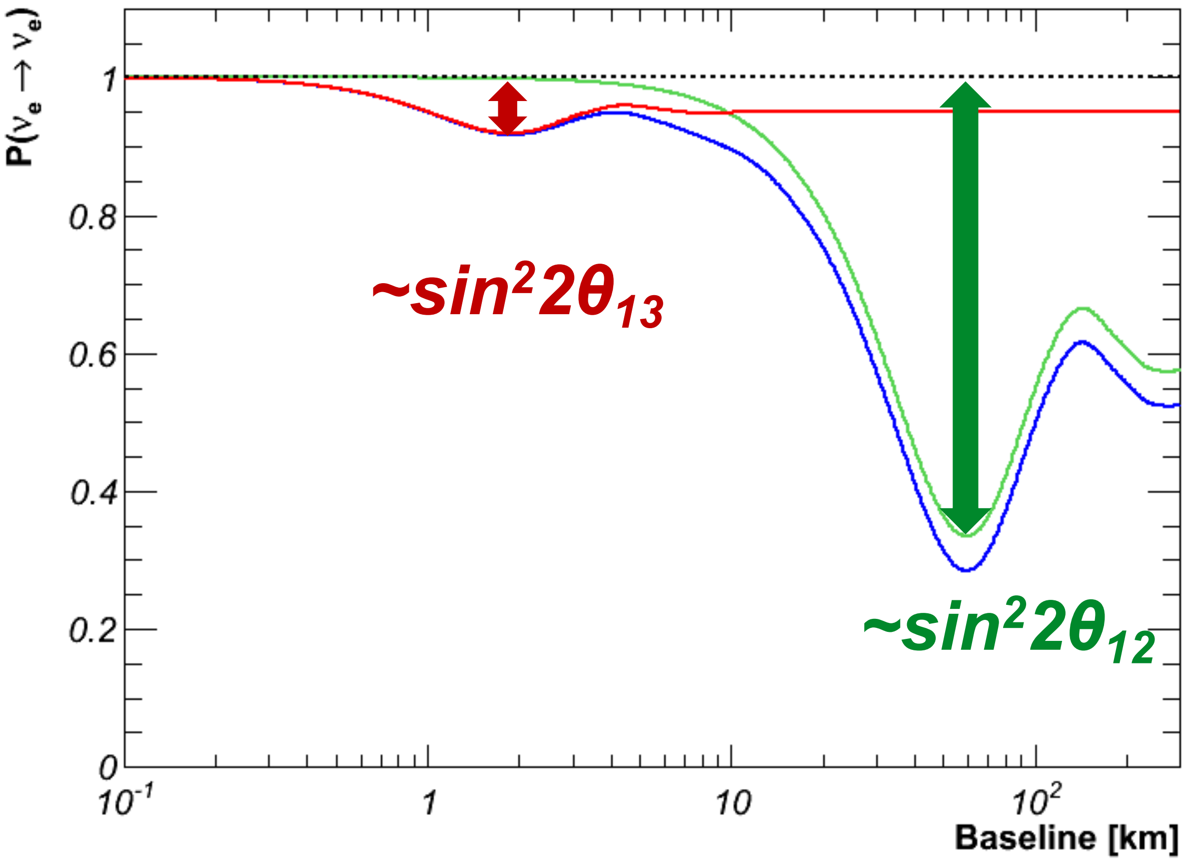
—这下面没有水，再换个地方挖　　　　张新华画

What Reactor Neutrinos Can Measure

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

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

- At different distances, the survival rate is dominated by different mixing angles
- To measure θ_{13}, a baseline of ~2 km is optimal



Between the Breakthroughs (2002-2012)

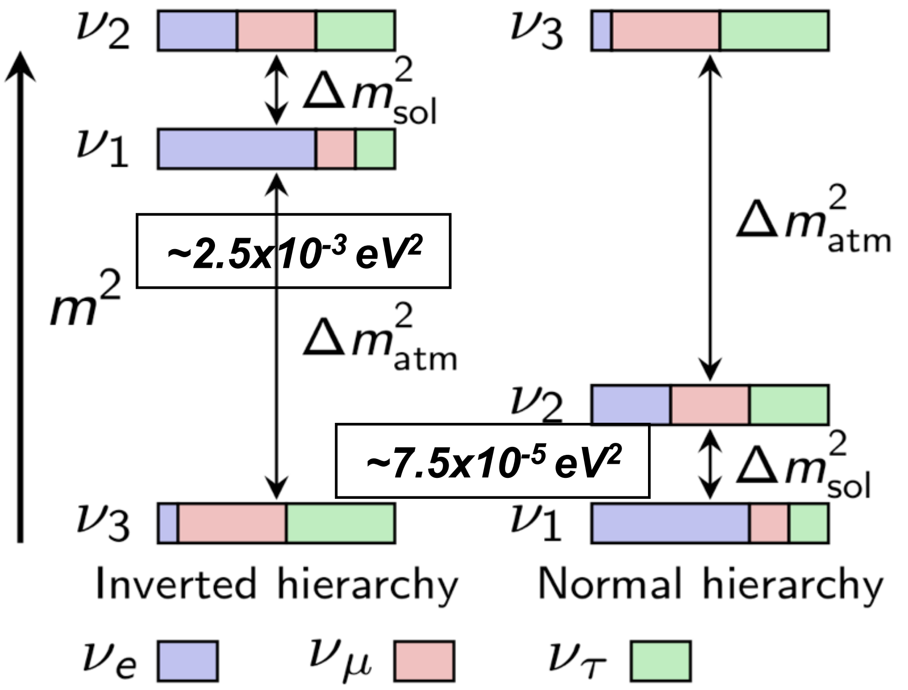
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

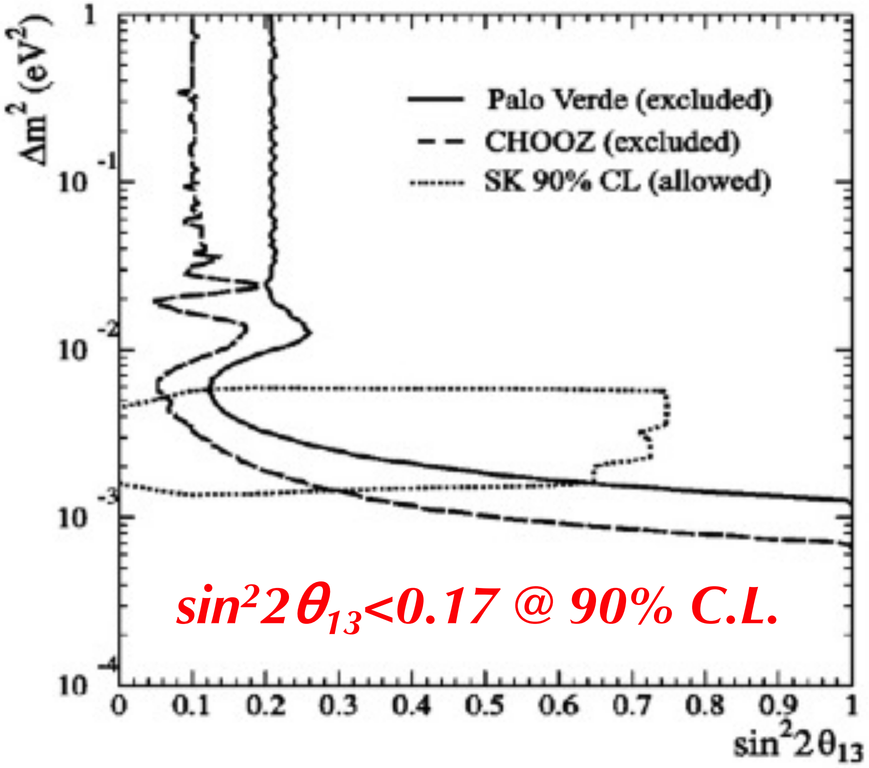
?

Atmospheric Sector:
SK, K2K, T2K, MINOS, etc

Reactor Sector:
CHOOZ, Palo Verde

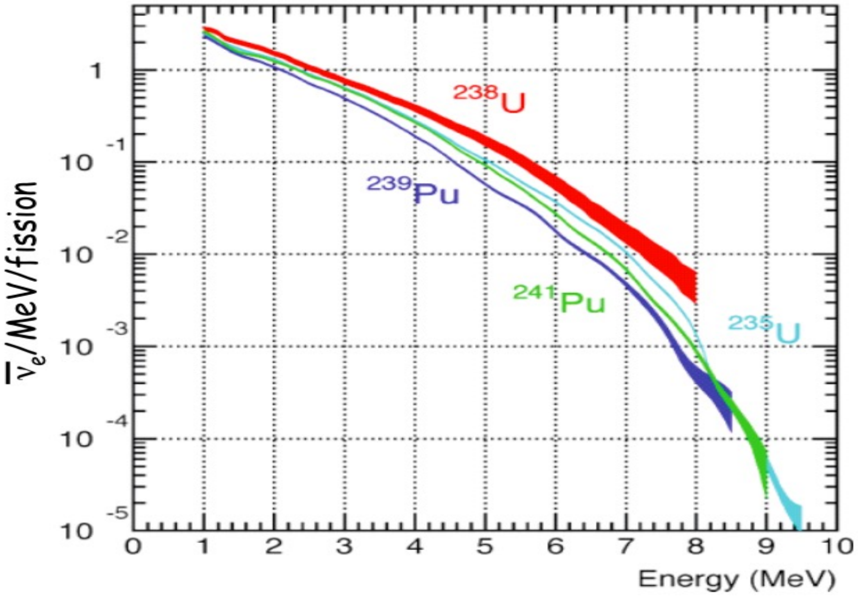
Solar Sector:
SNO, SK, KamLAND etc

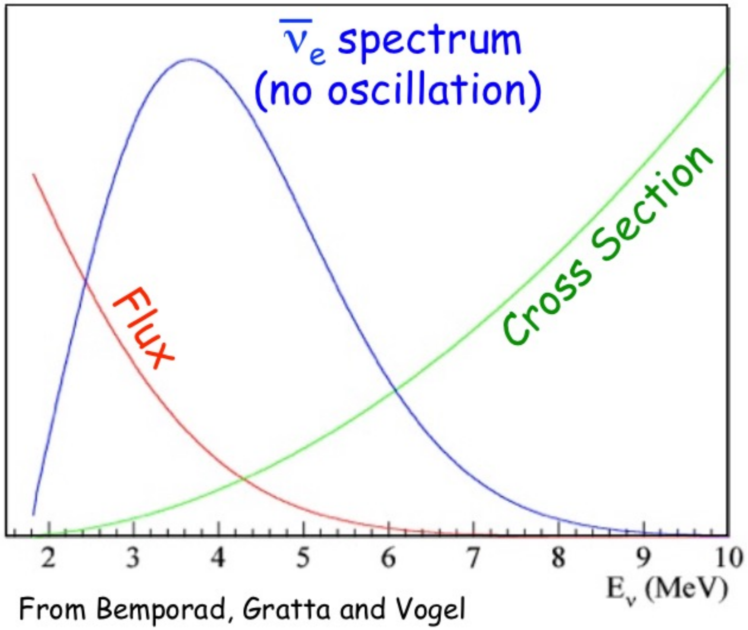




$\sin^2 2\theta_{13} < 0.17$ @ 90% C.L.

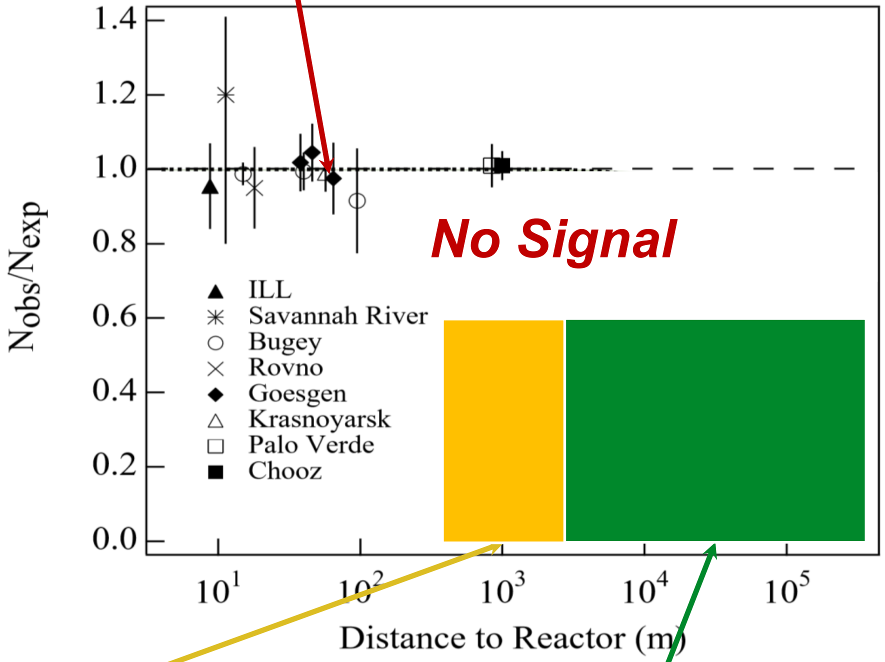
Reactor Neutrinos for Theta13: Challenges





From Bemporad, Gratta and Vogel

Six antineutrinos/fission: ~2-8MeV, ~5% accuracy



No Signal

θ_{13} Dominated

θ_{12} Dominated

Daya Bay: A Powerful Neutrino Source at an Ideal Location

Mountains shield detectors from cosmic ray background

Daya Bay NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Ling Ao I NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Ling Ao II NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Entrance to Daya Bay experiment tunnels

Among the top 5 most powerful reactor complexes in the world, 6 cores produce $17.4\,\mathrm{GW_{th}}$ power, 35×10^{20} neutrinos per second

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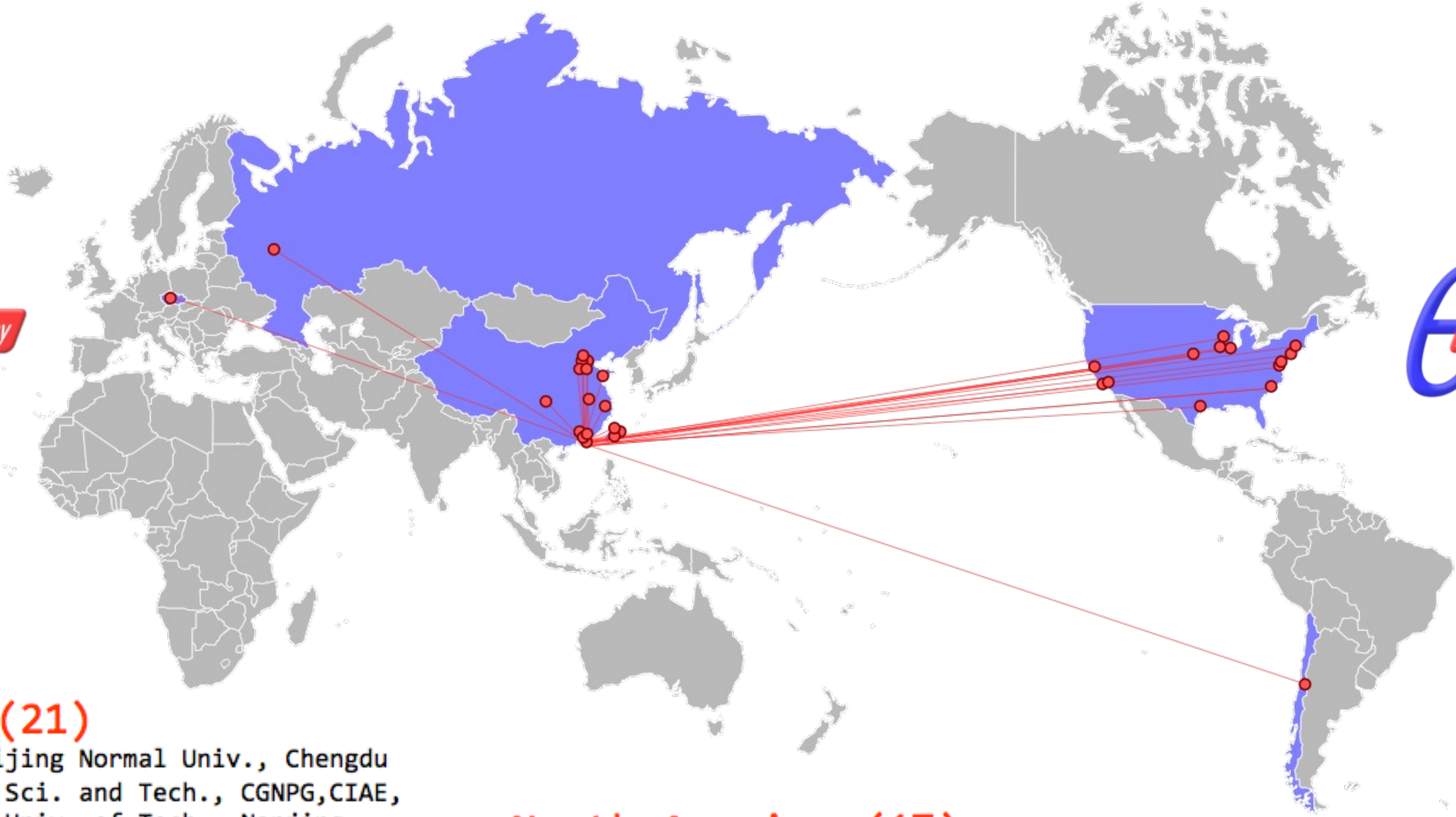
The Daya Bay International Collaboration



Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., **Sun Yat-sen Univ,** Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

BNL, LBNL, Iowa State Univ., RPI, Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ, Yale

Europe (2)

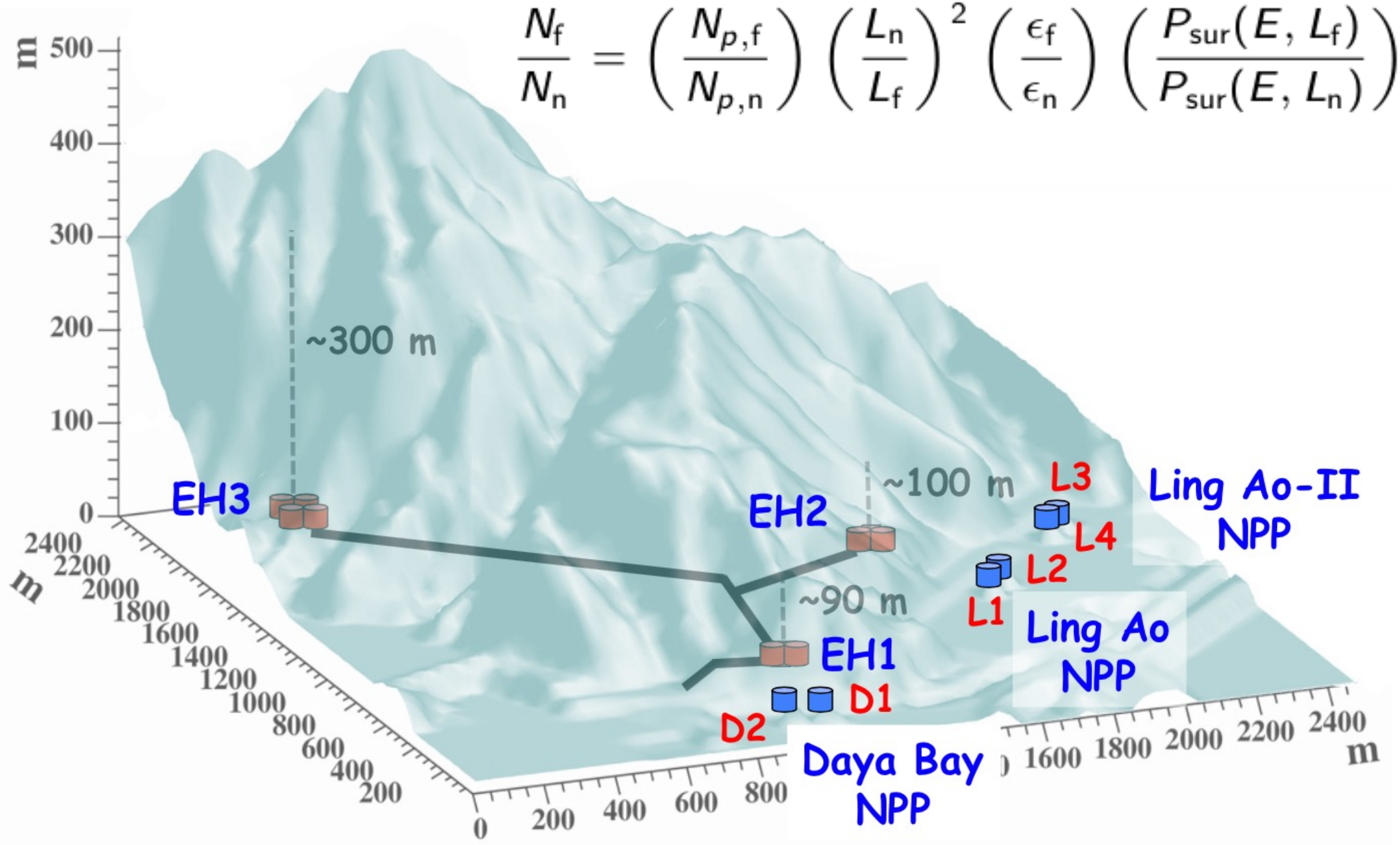
JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

Catholic Univ. of Chile (2014-2019)

Multi-Baseline and Multi-Detector Design of Daya Bay

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



The Daya Bay Antineutrino Detector (AD)

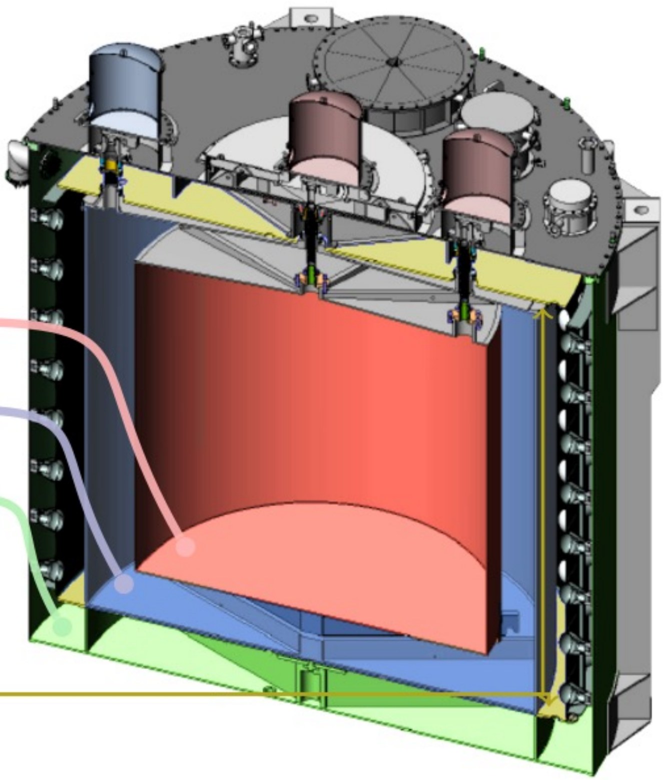
8 functionally identical detectors reduce systematic uncertainties

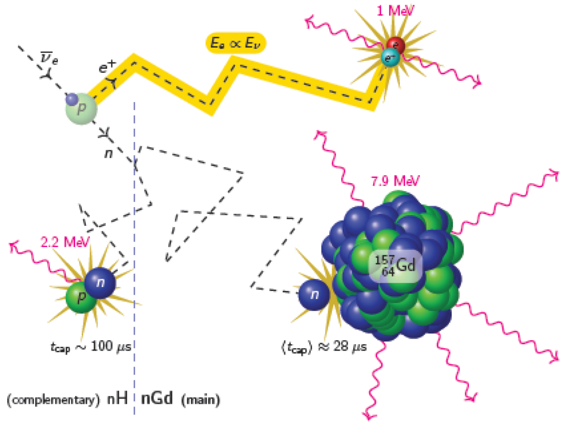
3 zone cylindrical vessels

	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

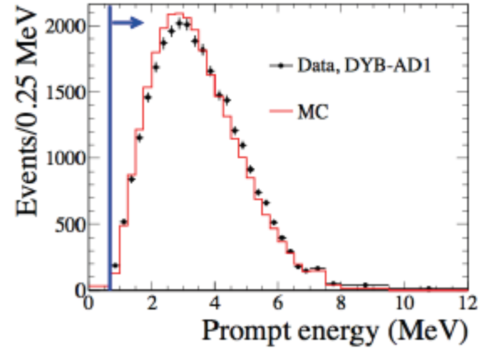
192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield and flatten detector response

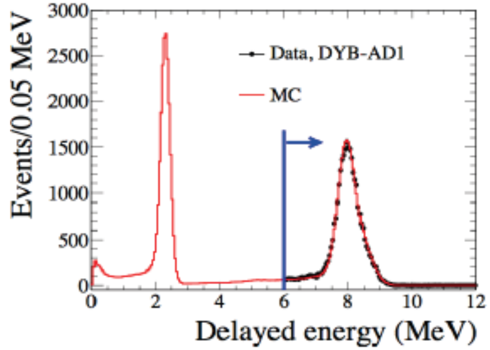




Prompt Energy Signal



Delayed Energy Signal



$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

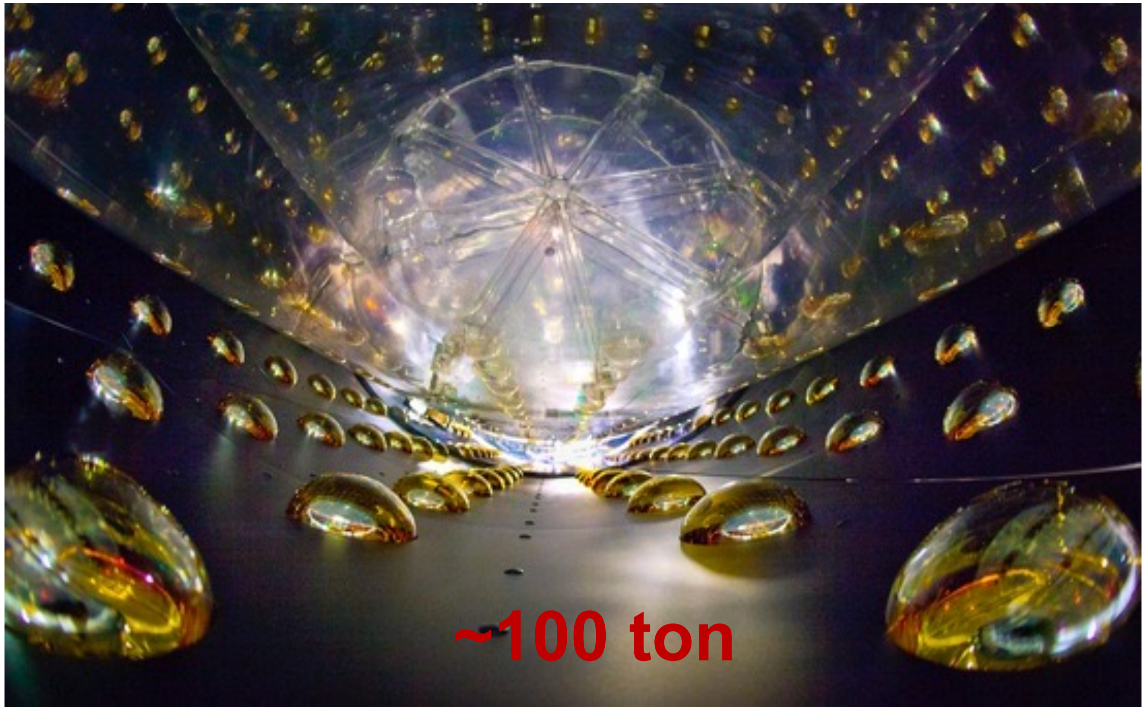
~180μs → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed signal)

→ $+ \text{Gd} \rightarrow \text{Gd}^*$

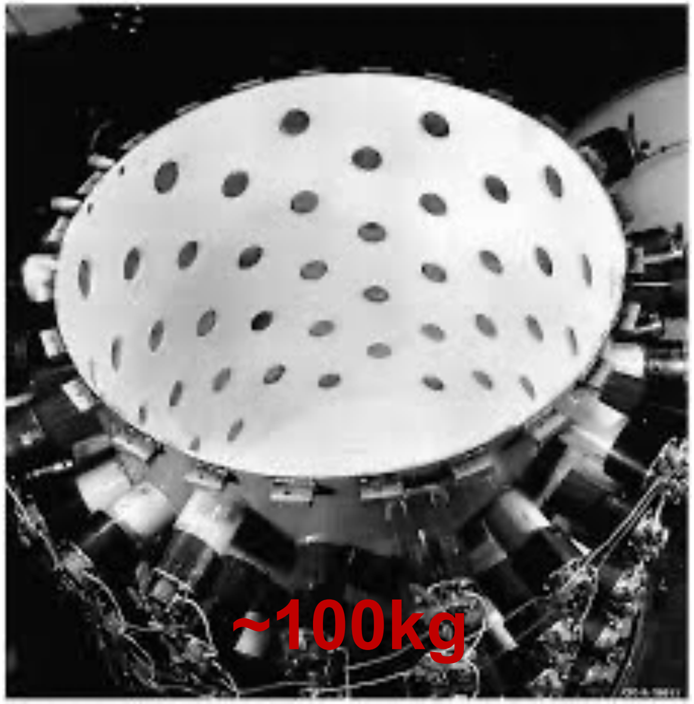
~30μs for 0.1% Gd

→ $\text{Gd} + \gamma\text{'s}$ (8 MeV) (delayed signal)

The Daya Bay Detector and the Reines&Cowan Design



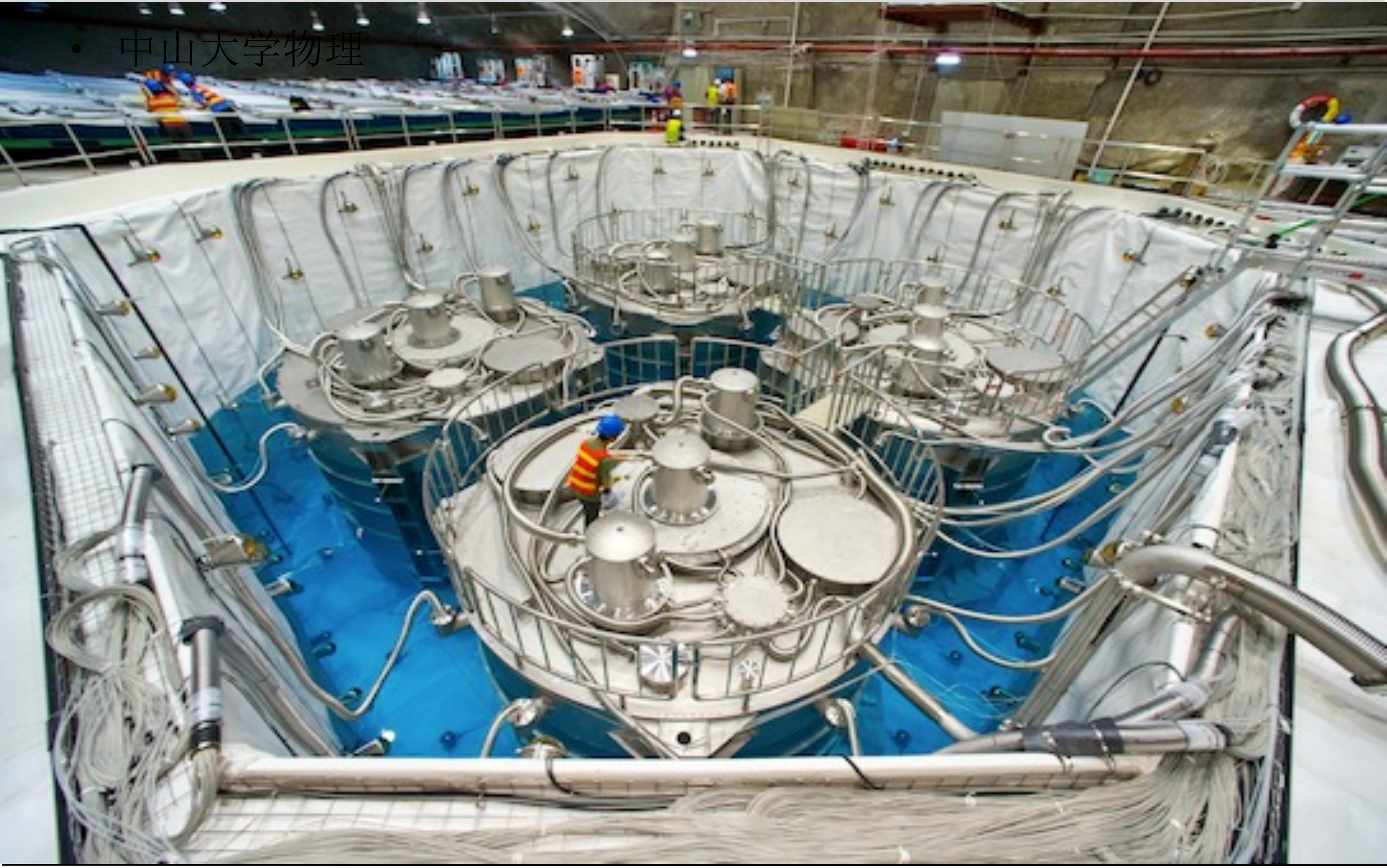
“Standing on the shoulder of giants”



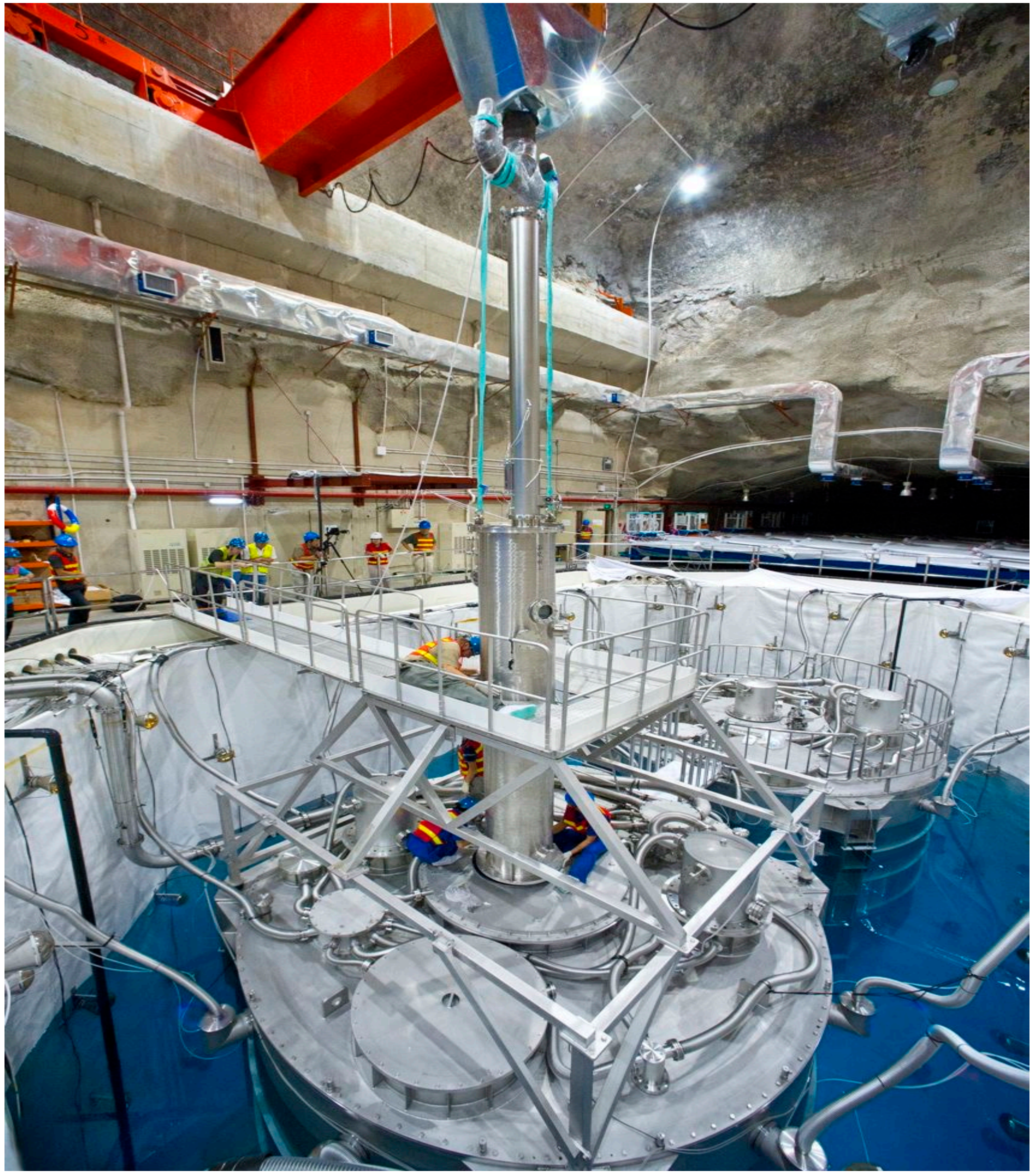
A Small Big Science Project

A Small Big Science Project

- 中山大学物理



Daya Bay Calibration Systems



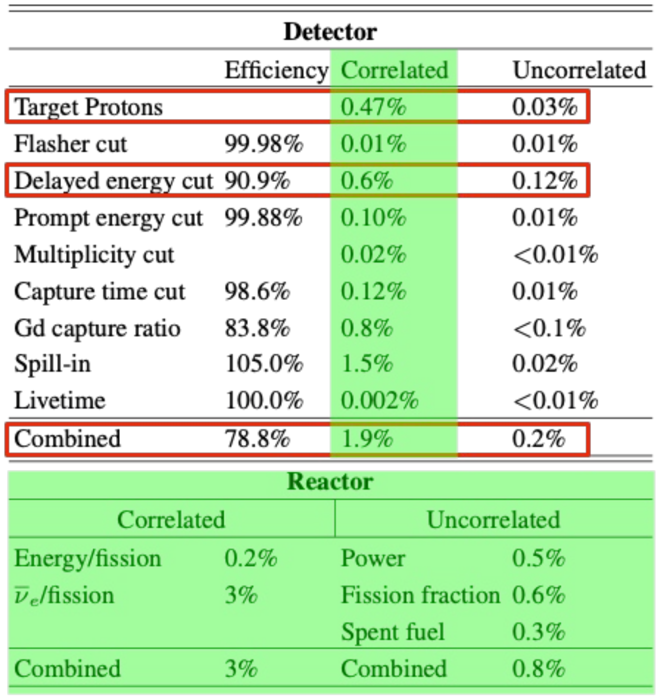
- Automatic Calibration Units (ACUs)
- Manual calibration by CIAE

The Daya Bay Running & Data Taking

Date	Operation	Duration
Dec 24, 2011	**Data taking with 6 ADs** EH1: 2 ADs EH2: 1 AD EH3: 3 ADs	217 Days
Jul 28 – Oct 19, 2012	Special calibration runs; Installation of the last 2 ADs	
Oct 19, 2012	**Data taking with 8 ADs**	1,524 Days
Dec 20, 2016 – Jan 26, 2017	Special calibration runs **EH1 AD1 used for JUNO LS studies**	
Jan 26, 2017	**Data taking with 7 ADs** EH1: 1 ADs EH2: 2 AD EH3: 4 ADs	1,417 Days
Dec 12, 2020	**Shutdown; Decommissioning started**	/

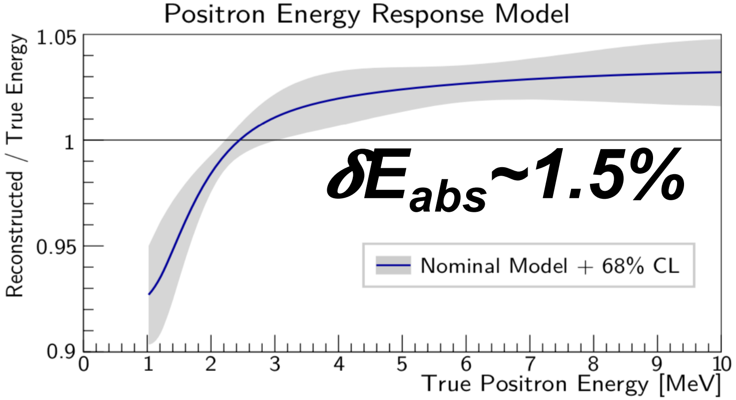
Understanding the Detector *to Extreme*

2012



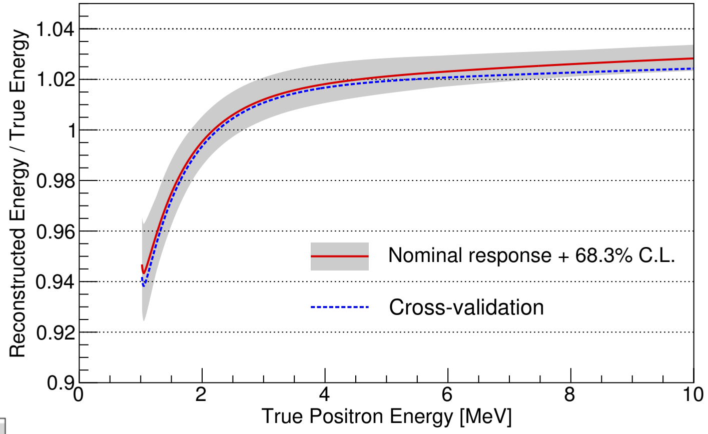
Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\bar{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%



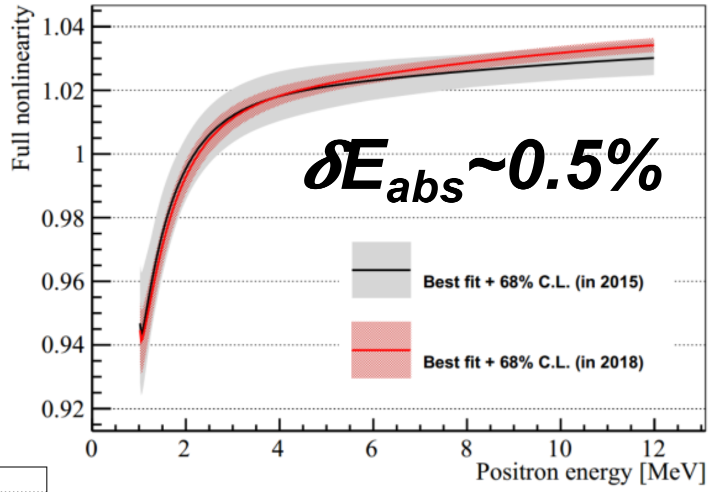
$\delta E_{abs}\sim 1.5\%$

2015

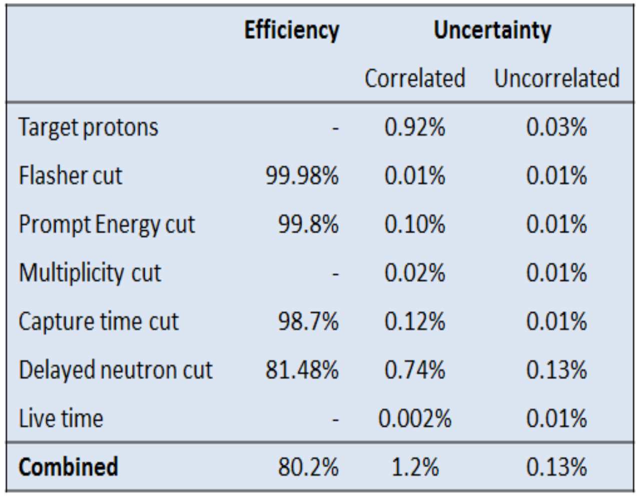


$\delta E_{abs}\sim 1\%$

2018



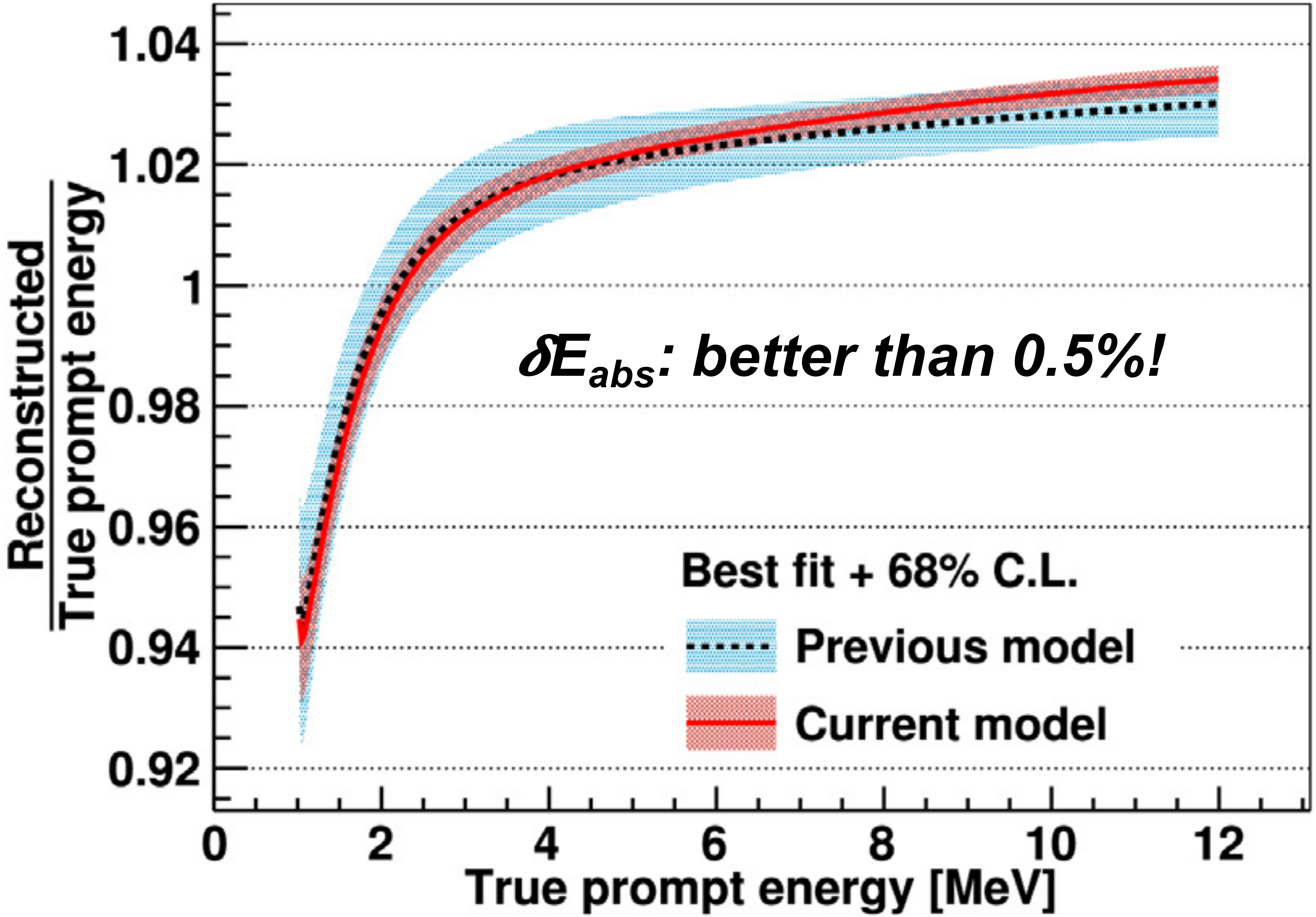
$\delta E_{abs}\sim 0.5\%$



	Efficiency	**Uncertainty**	
		Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Prompt Energy cut	99.8%	0.10%	0.01%
Multiplicity cut	-	0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Delayed neutron cut	81.48%	0.74%	0.13%
Live time	-	0.002%	0.01%
Combined	80.2%	1.2%	0.13%

The Best Understood LS Reactor Neutrino Detector

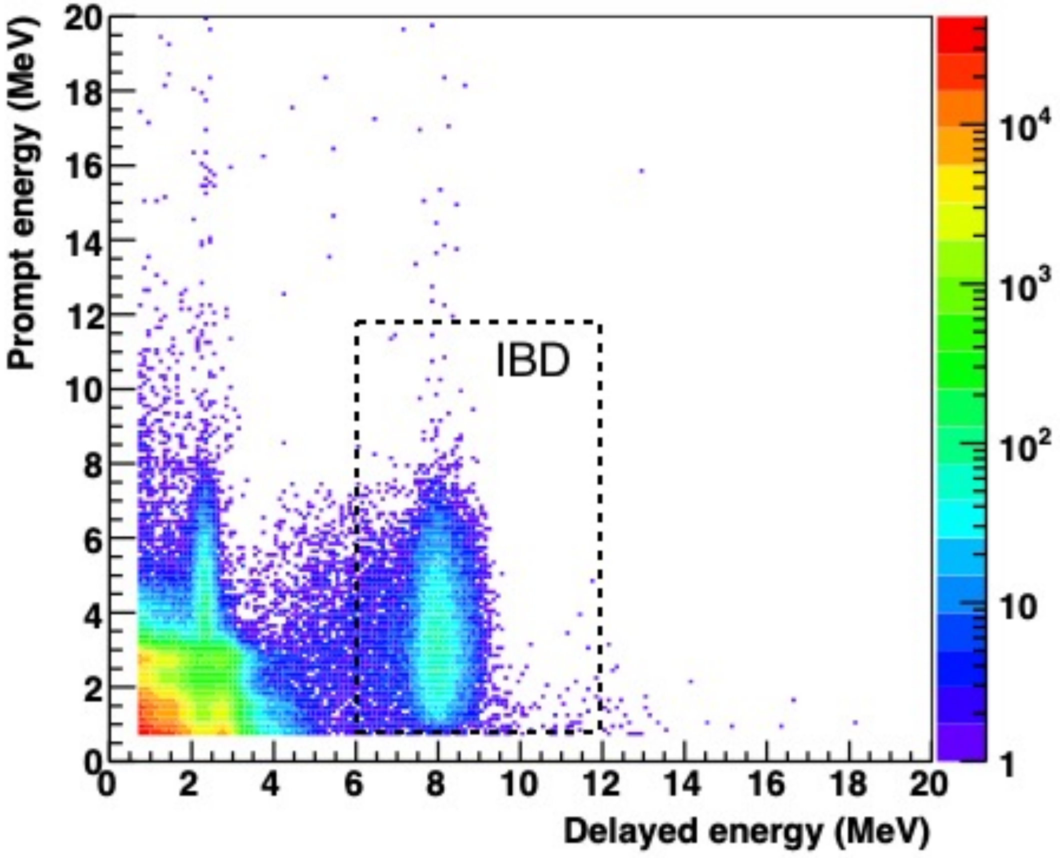
2019



δE_{abs}: better than 0.5%!

For Details: Nuclear Inst. and Methods in Physics Research, A 940 (2019) 230–242

How to Select Antineutrino Events



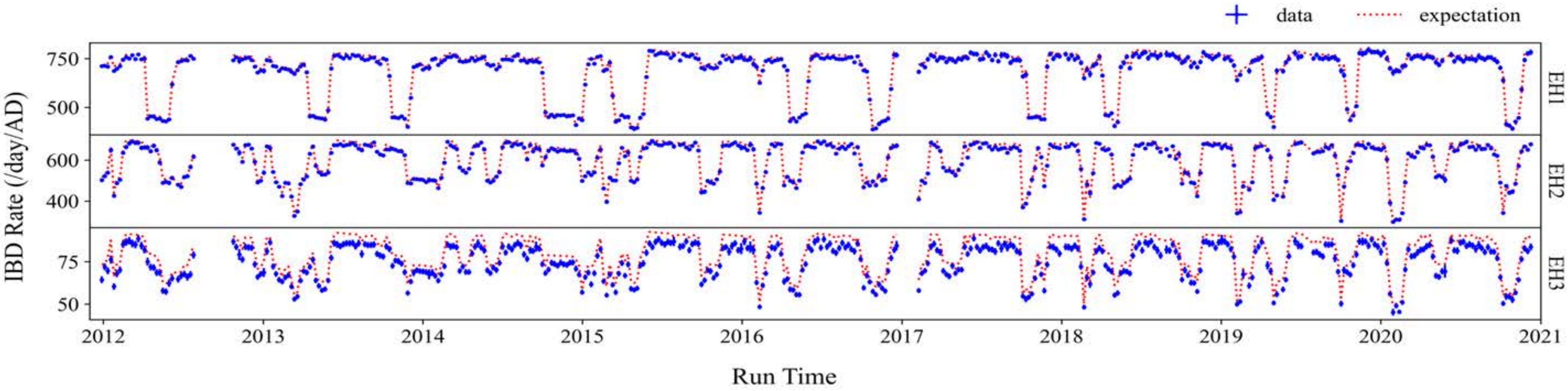
Daya Bay Collaboration, PRD95 (2017) 072006

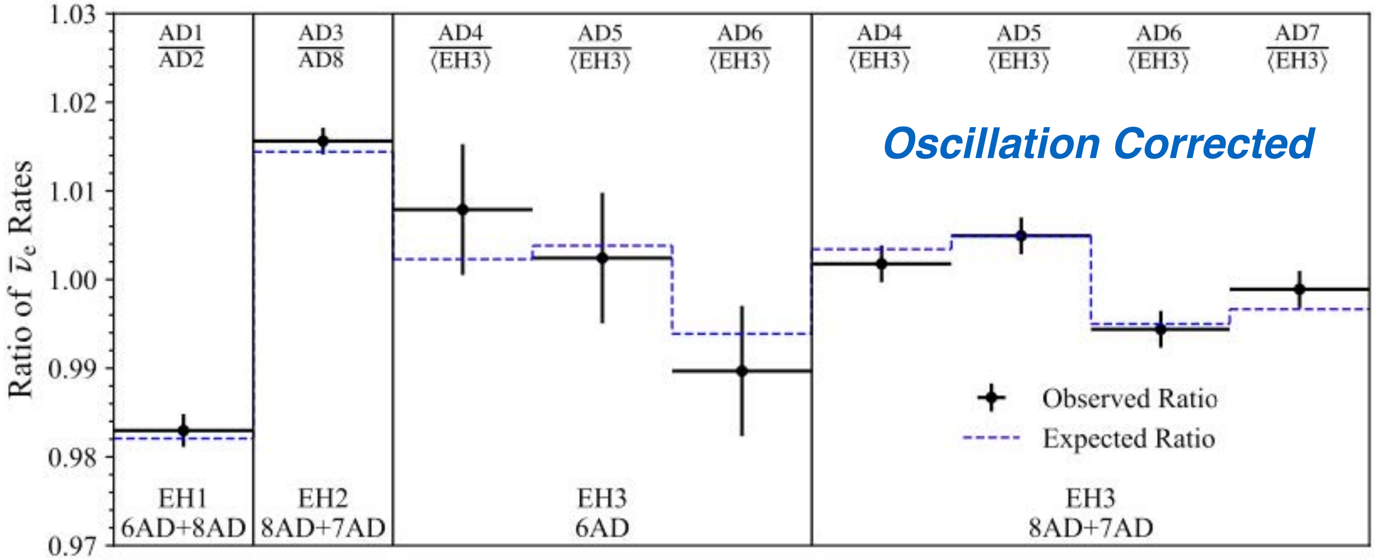
- First apply flasher cuts to clean up the data
- Muon veto to get rid of cosmogenic products
- IBD cuts
  - Prompt energy cut: (0.7, 12) MeV
  - **Delayed energy cut: (6, 12) MeV**
  - **Time correlation (Multiplicity)** cut to pick up IBD pairs

Inversed Beta Decay Like Background Events

- Uncorrelated background: accidental pairs
- Correlated backgrounds:
  - Fast neutron: cosmogenic outside → AD
  - ^{9}Li/^{8}He: cosmogenic from spallation products of cosmic-ray muons
  - ^{241}Am-^{13}C: ACU neutron calibration sources
  - $^{13}C(\alpha,n)^{16}O$: α decay of natural radioactive isotopes
  - New backgrounds: Residual PMT flasher & Muon-x

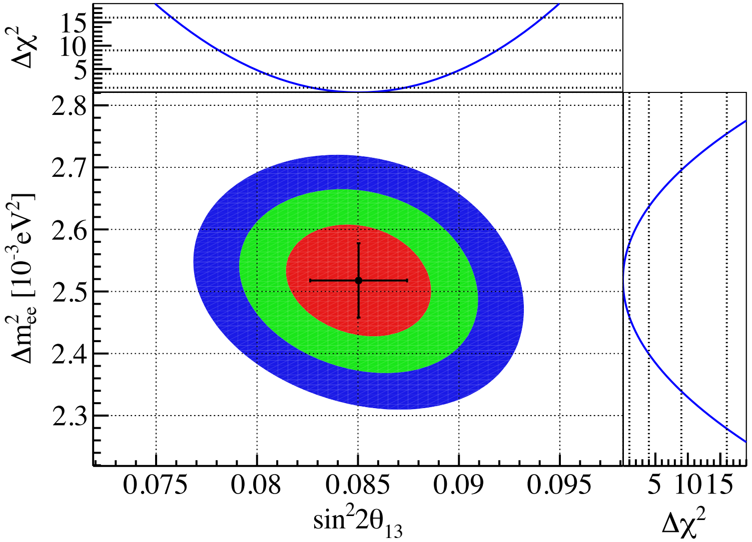
Event Rates at Daya Bay Detectors





- Daya Bay uses a combined Huber-Muller model to predict reactor neutrino fluxes --- the HM model

The Latest Daya Bay Oscillation Results

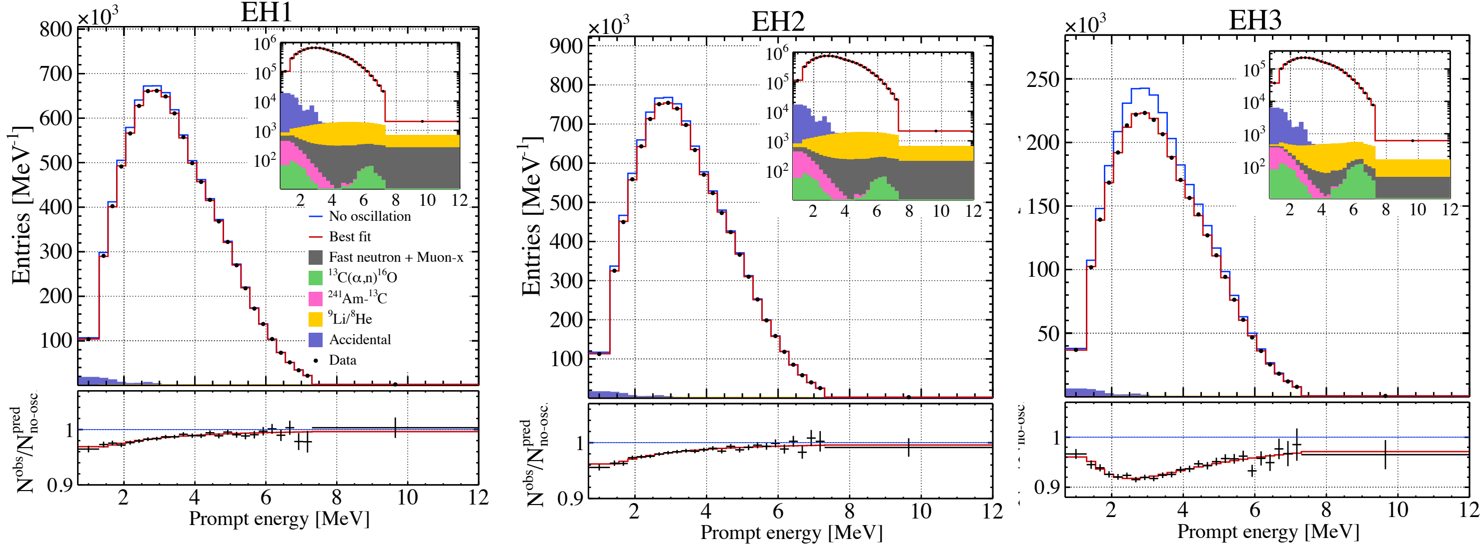


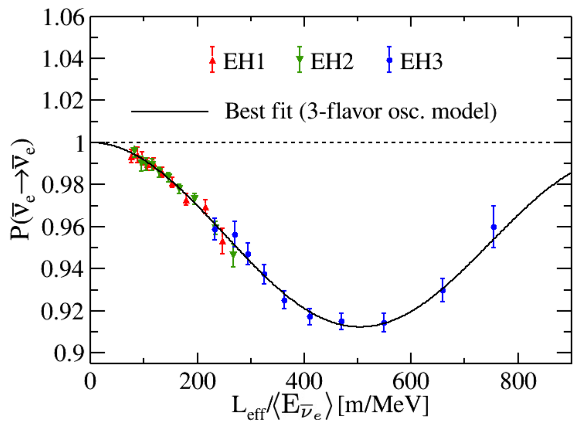
$$\sin^2 2\theta_{13} = 0.0852 \pm 0.0024$$
$$|\Delta m^2_{ee}| = (2.519 \pm 0.060)\times 10^{-3}\ eV^2$$

$$\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$$
$$\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$$

- ❖ **θ_{13} measured to a precision of 2.8%, currently the best known mixing angle**
- ❖ **Also the most precise Δm^2_{atm}**

➢ ***Kam-Biu will offer more details during his parallel talk this afternoon***

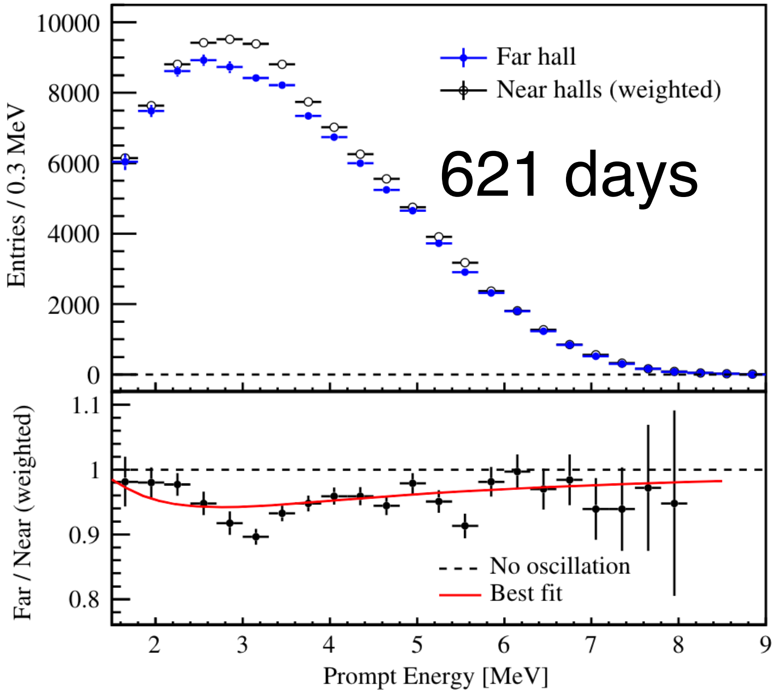


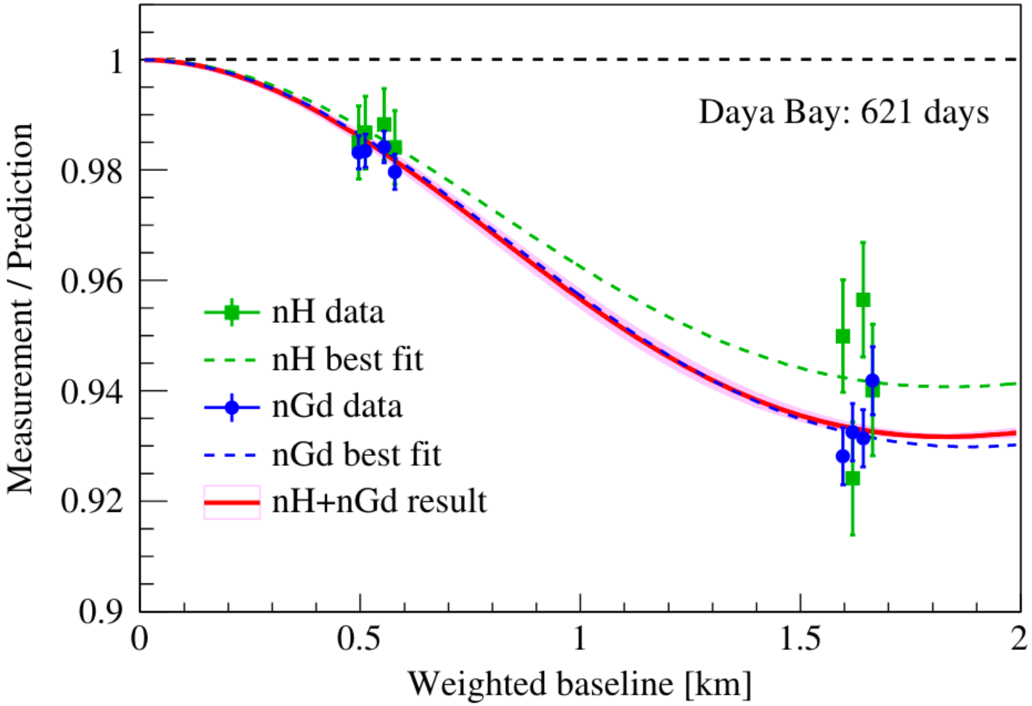


$\sin^2 2\theta_{13}$ from nH-IBD analysis

PRD 93 072011 (2016)

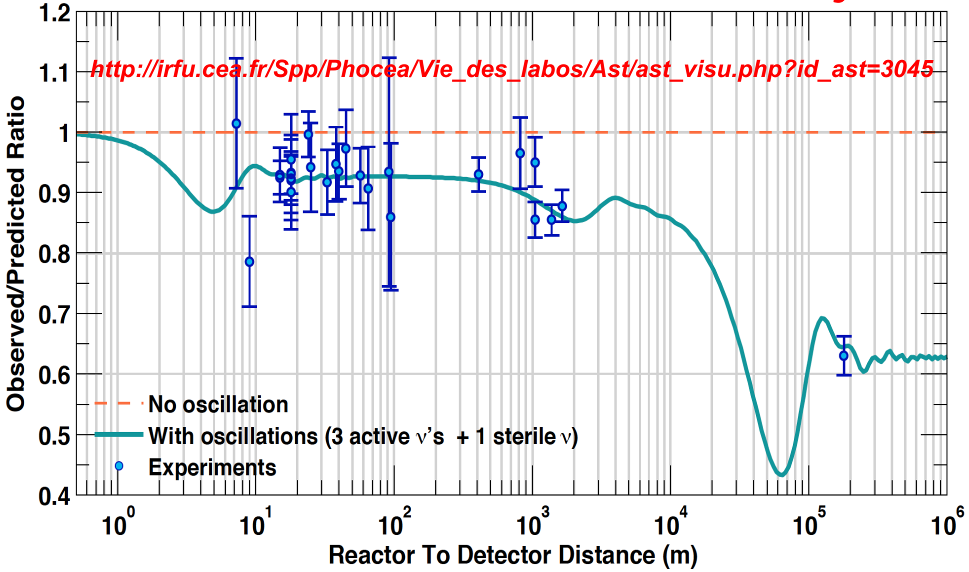
- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging: much more low-energy backgrounds
  - Signal to background ratio is about 1:1 at the far hall
- Rate-only analysis result: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$
- Improved measurement is coming soon

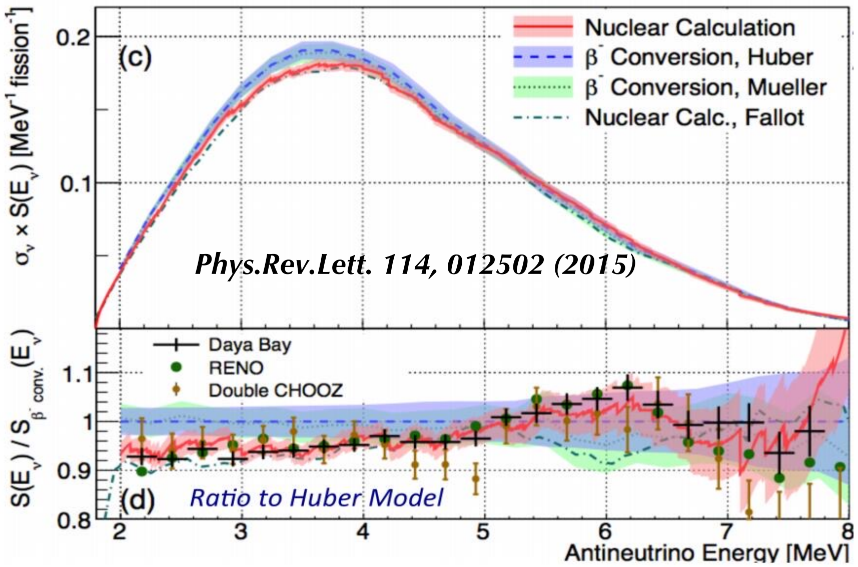




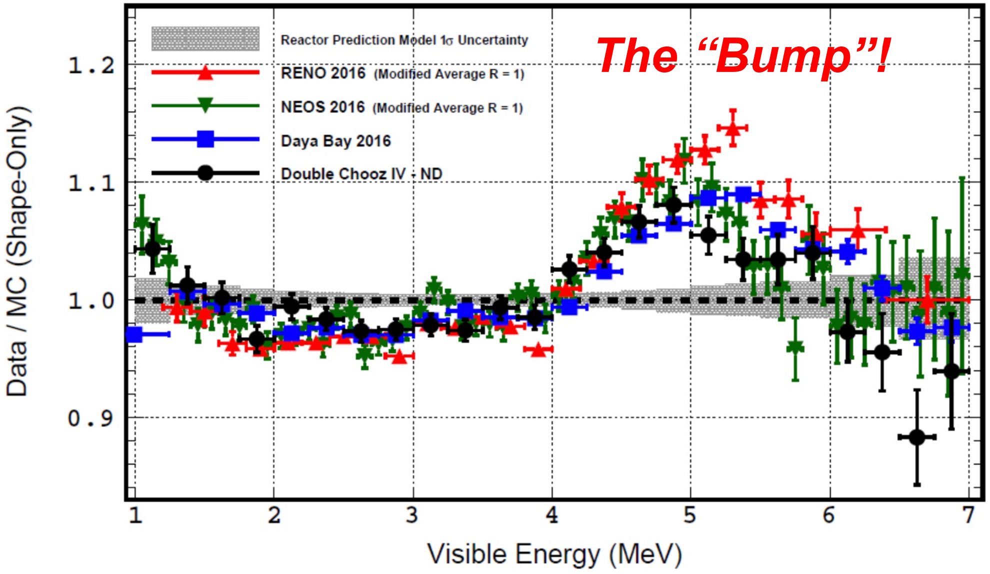
Reactor Neutrinos *NOT* Perfect: RAA and a “Bump”

The Reactor Antineutrino Anomaly



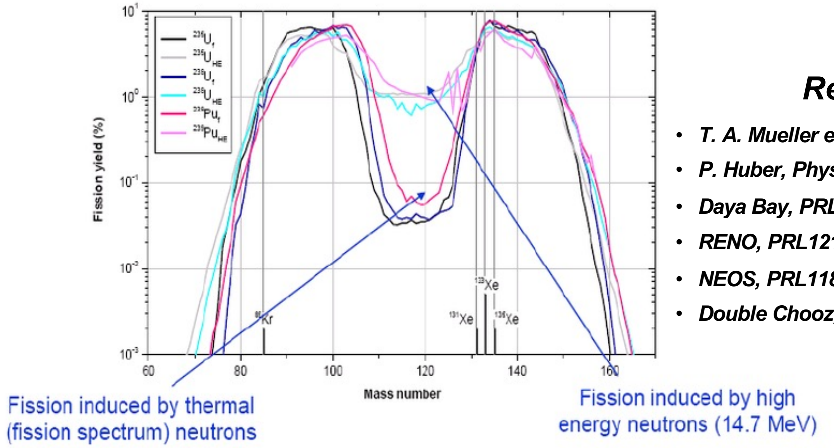


Phys.Rev.Lett. 114, 012502 (2015)



The “Bump”!

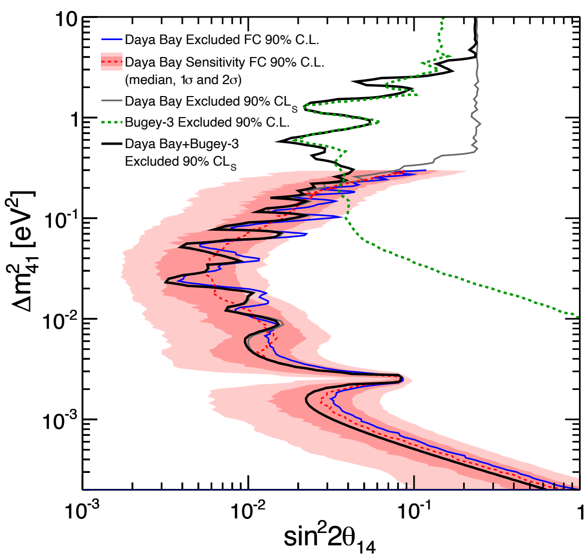
(Fission yield is a function of the fissioning nuclide and the incident neutron energy)

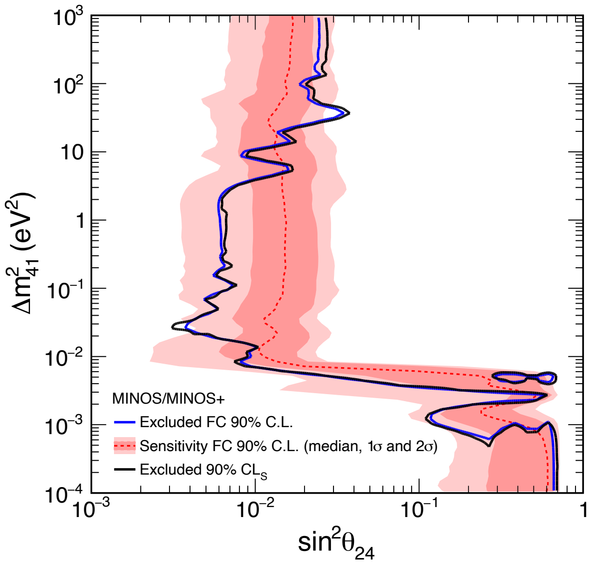


References

- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*

Sterile Neutrino Searches at Daya Bay (and Combined with MINOS/MINOS+ & Bugey-3)





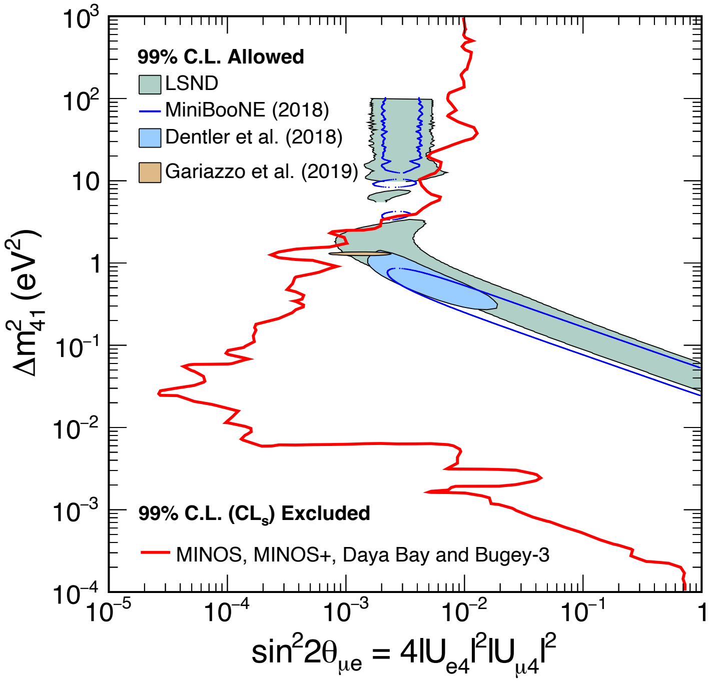
- Daya Bay has multiple baselines
- Daya Bay and MINOS are sensitive to ~0.1 eV^2 but different flavors
- Together, better sensitivity to the LSND result

Appearance probability:

$$4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Where:

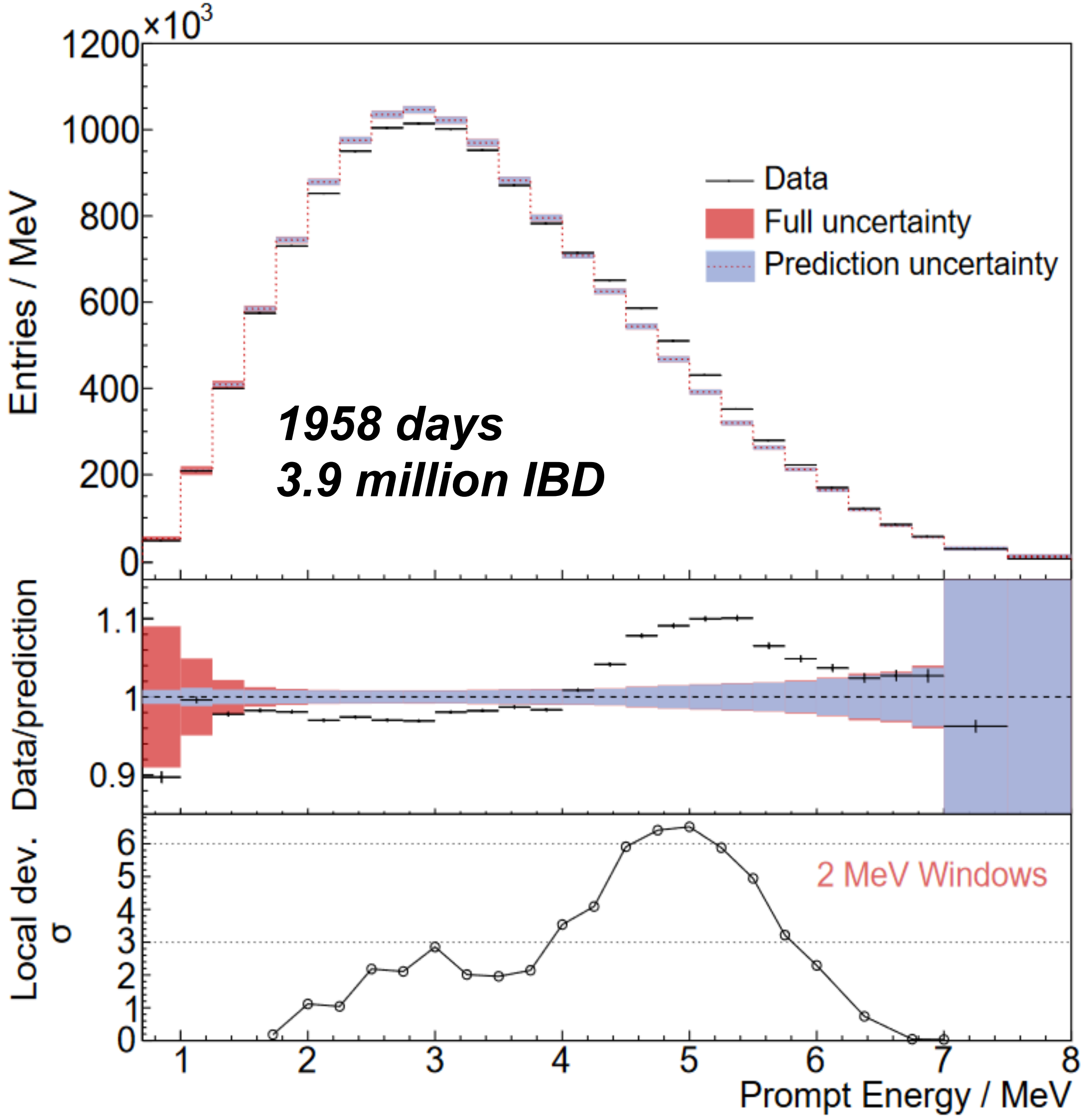
$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14} \sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$



For details, see Daya Bay, PRL125 (2020) 7, 071801

PRL113 (2014) 141802, PRL117 (2016), PRL117 (2016) 15, 151801

Measuring the Reactor Antineutrinos Spectrum



- With 1958 days of data, Daya Bay has confirmed the discrepancy between 4-6 MeV (visible energy) with a ~6σ significance
- This discrepancy, the "Bump", is not correlated with burn-up, i.e. the operation of reactors, or the operations of the Daya Bay detectors

- *For details, see PRL 123 (2019) 111801, PRL 116 (2016) 061801*

Fuel Evolution and Responsible Fuel Components

- *See PRL 118 (2017) no.25, 251801 and CPC, 2017, 41(1) for details*

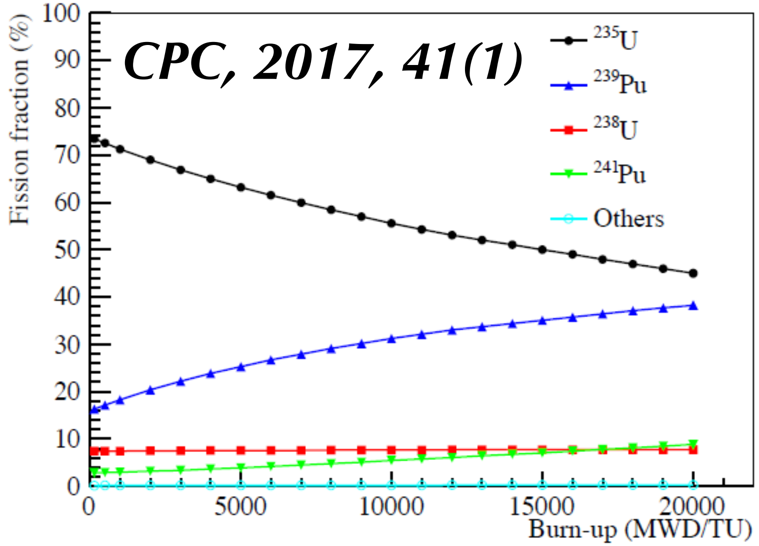
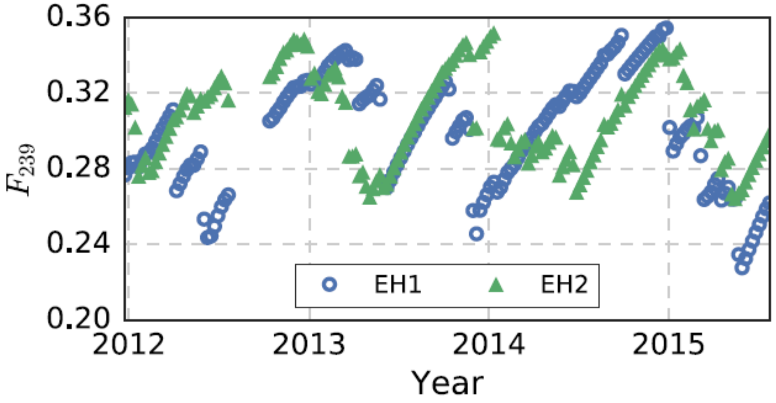
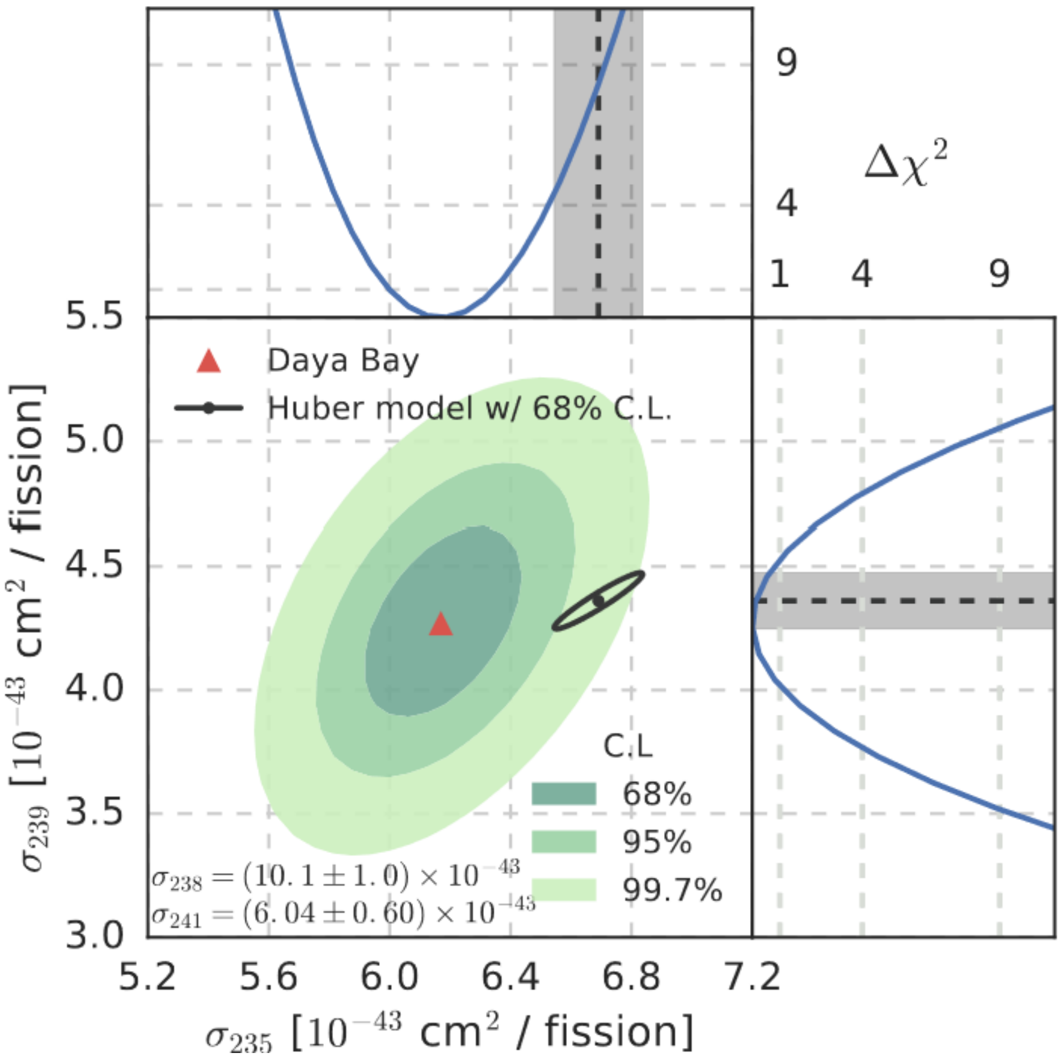


Fig. 4. Fission fractions of isotopes in reactor core D1 as a function of cycle burn-up from a simulation of a complete refueling cycle. Other isotopes contribute less than 0.3%.

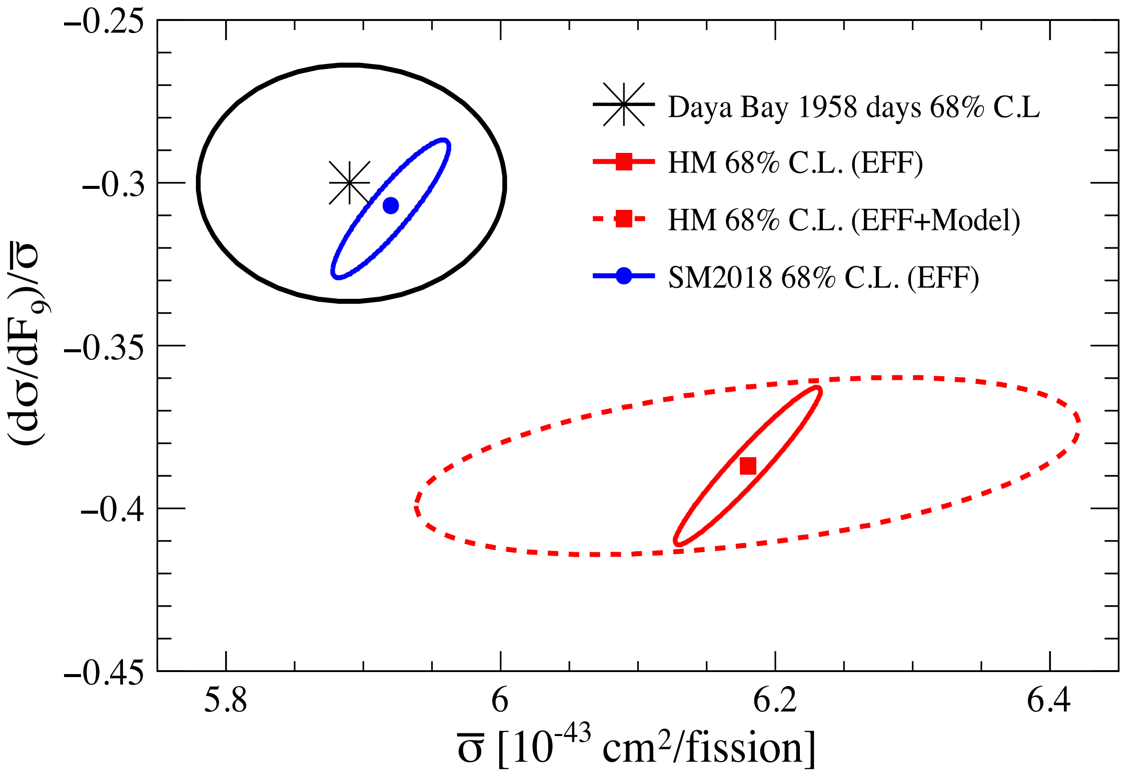


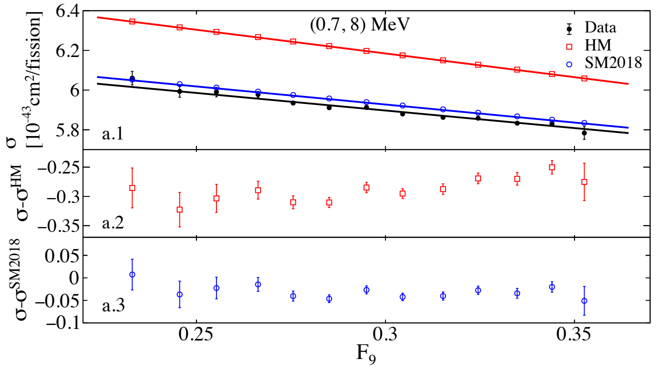


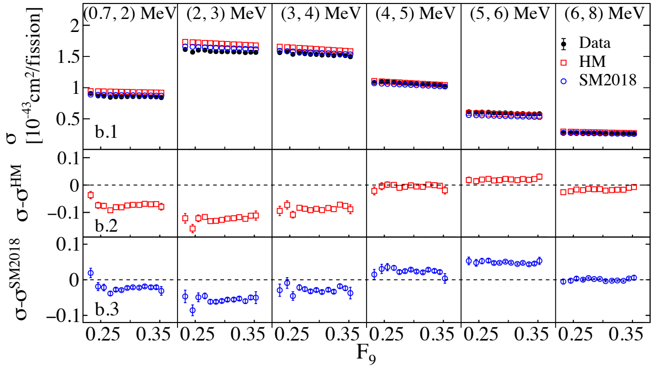
PRL 118 (2017) no.25, 251801

The Lates Fuel Evolution Analysis

- *An improved analysis on fuel evolution by the Daya Bay Collaboration just released, see arXiv:2210.01068*



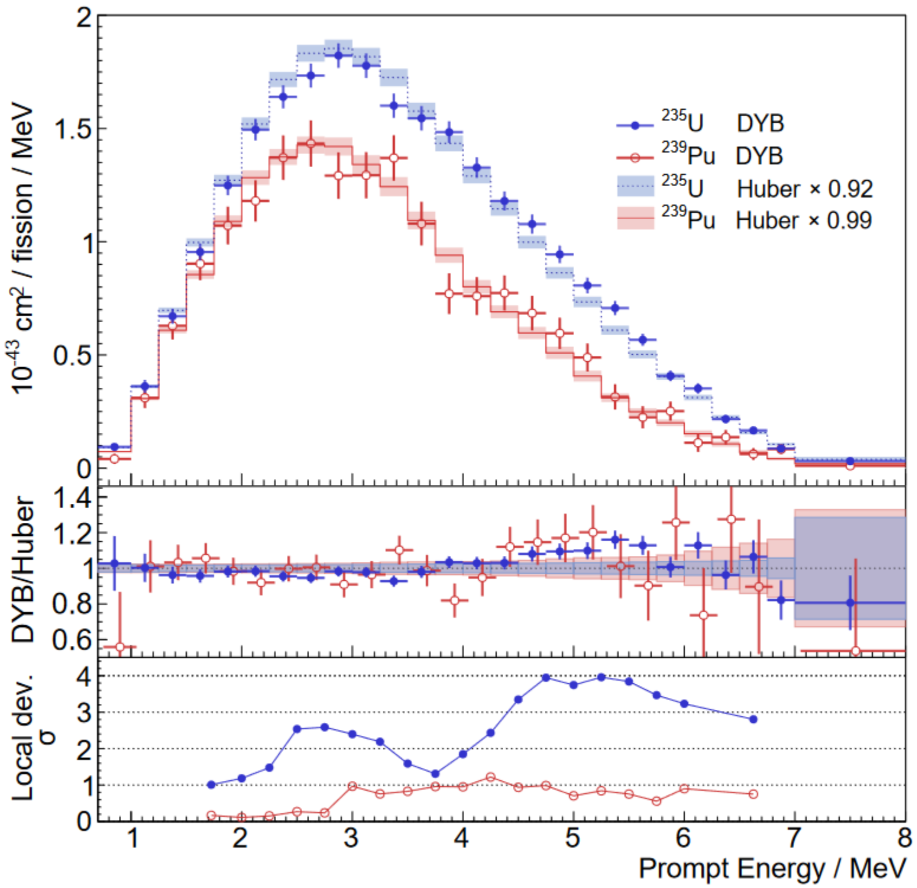




Analysis Improvements besides more statistics (1230 days → 1958 days)

- SM2018: a new summation method by M. Estienne *et al.*, PRL123, 022502 (2019)
- Better correlated and uncorrelated detector uncertainties
- Improved reactor related uncertainties
- Checking two characteristic variables: average neutrino yields and their evolution slope wrt. F_9, the ^{239}Pu fraction bred within the reactor

Decomposing Reactor Antineutrino Components



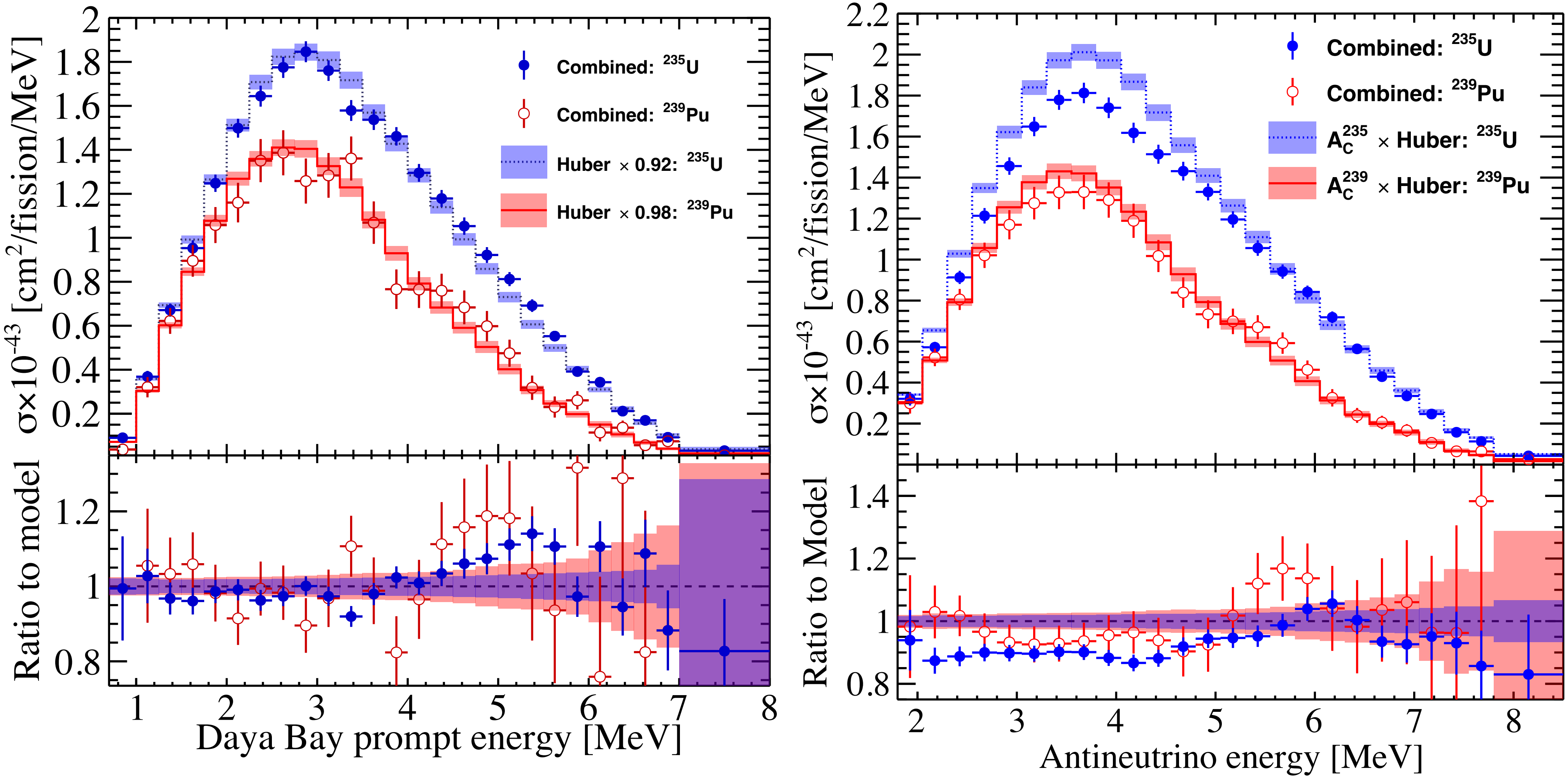
- The very first measurement of the ^{235}U and ^{239}Pu spectra at commercial reactors
- An excess, data over prediction, around 4-6 MeV for ^{235}U is more pronounced but the ^{239}Pu one is consistent with null bump

^{235}U: a 4σ effect; ^{239}Pu: a 1.2σ effect

- *For details of the isotope decomposition analysis, see PRL 123 (2019) no.11, 111801*

Combined Flux Analysis of Daya Bay and PROSPECT

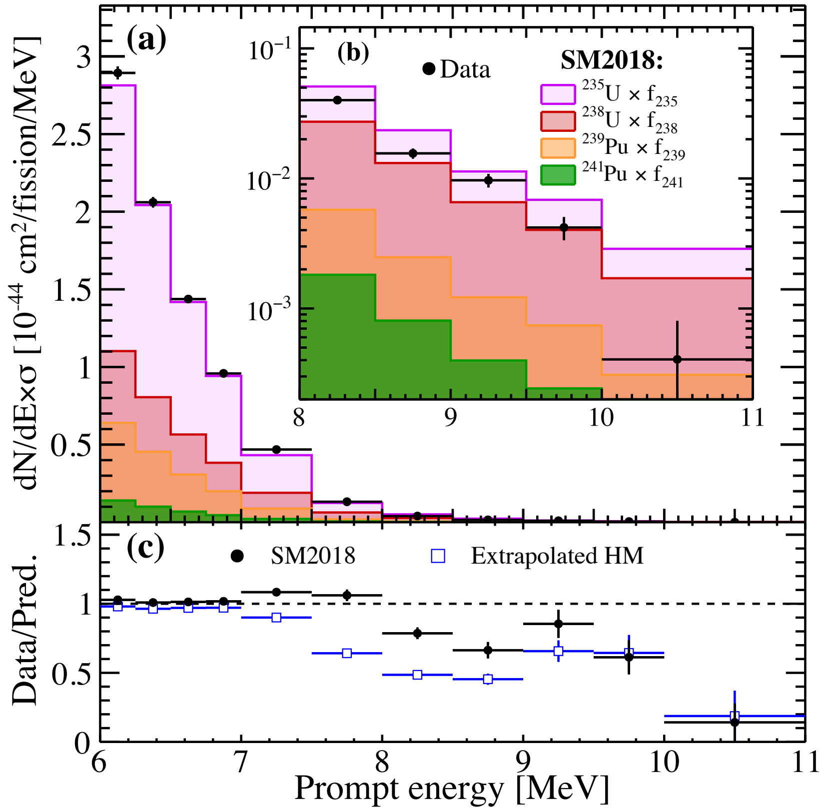
- *Daya Bay + PROSPECT Collaborations, see PRL 128 (2022) 8, 081801*

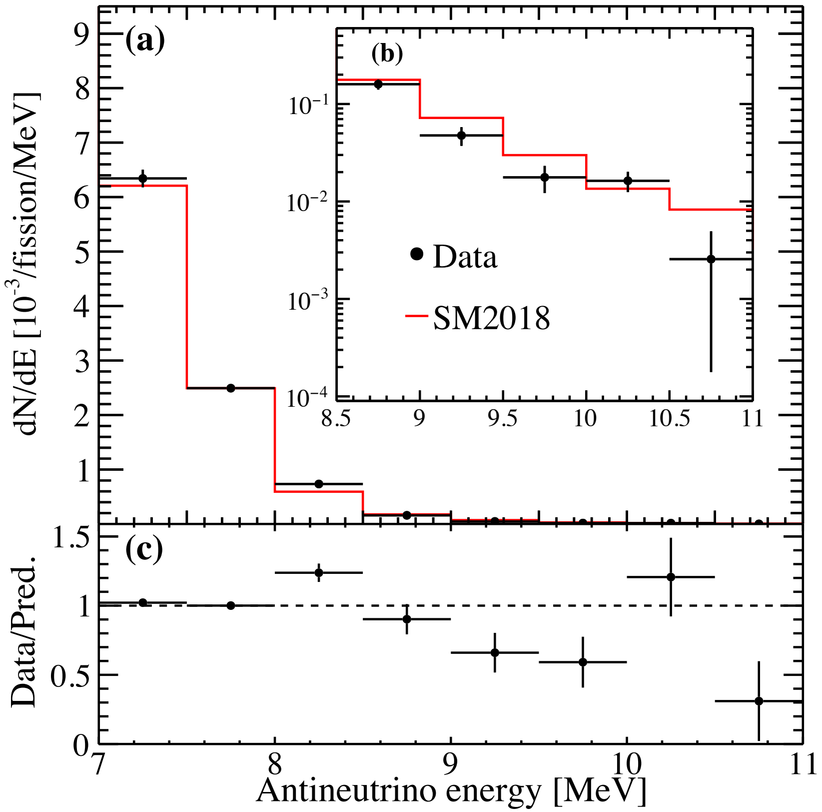


- First ever results: A HEU reactor + LEU reactors (commercial PWR reactors)
- ^{235}U flux improved to 3%; Degeneracy between U and Pu contributions reduced

First Evidence of High-Energy Reactor Neutrinos

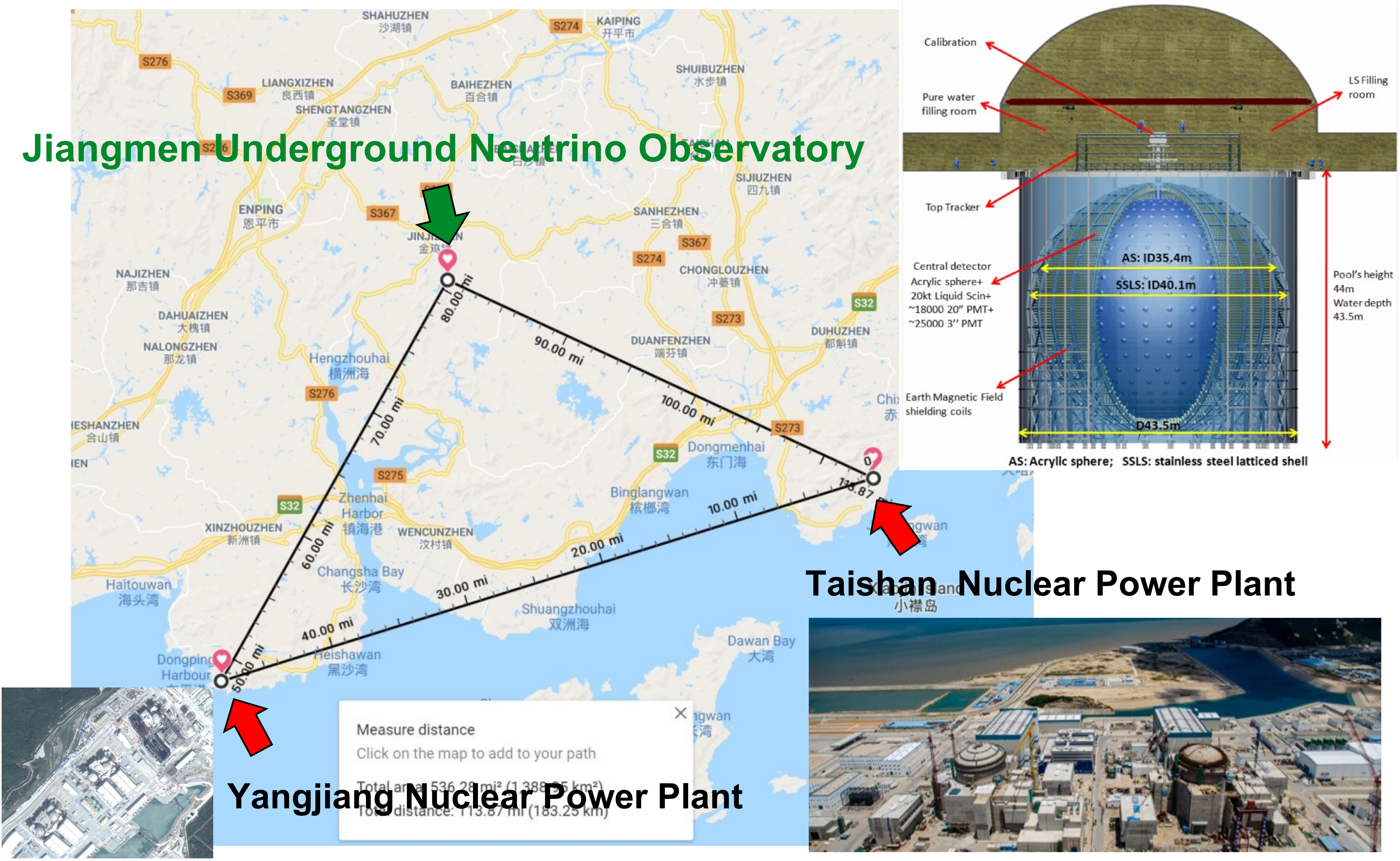
- Daya Bay discovers reactor neutrinos above 10MeV with a 6.2σ significance for the first time
- A deficit of 29% in the high-E region (8-11MeV) is observed compared with the SM2018 ab-initio prediction
- The first direct observation of antineutrinos from several high-Q_β isotopes in commercial reactors





- ***For details, see PRL 129 (2022) 4, 041801***

Future Reactor Neutrino: JUNO for Neutrino Mass Ordering



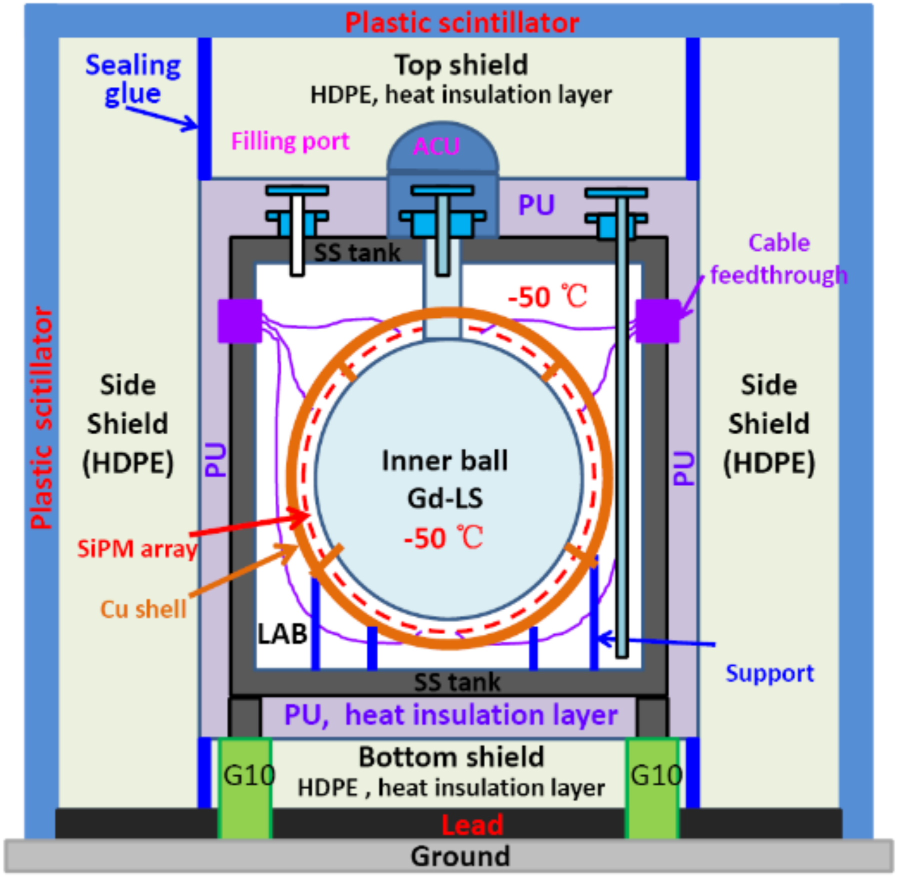
Jiangmen Underground Neutrino Observatory

Taishan Nuclear Power Plant

Yangjiang Nuclear Power Plant

JUNO-TAO: A Satellite Experiment of JUNO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector, at 30-35 m from a 4.6 GW_{th} core, a satellite exp. of JUNO
- 2.6 ton Gd_LS | acrylic vessel | SiPM and Cu shell| Cryogenic vessel| water or HDPE



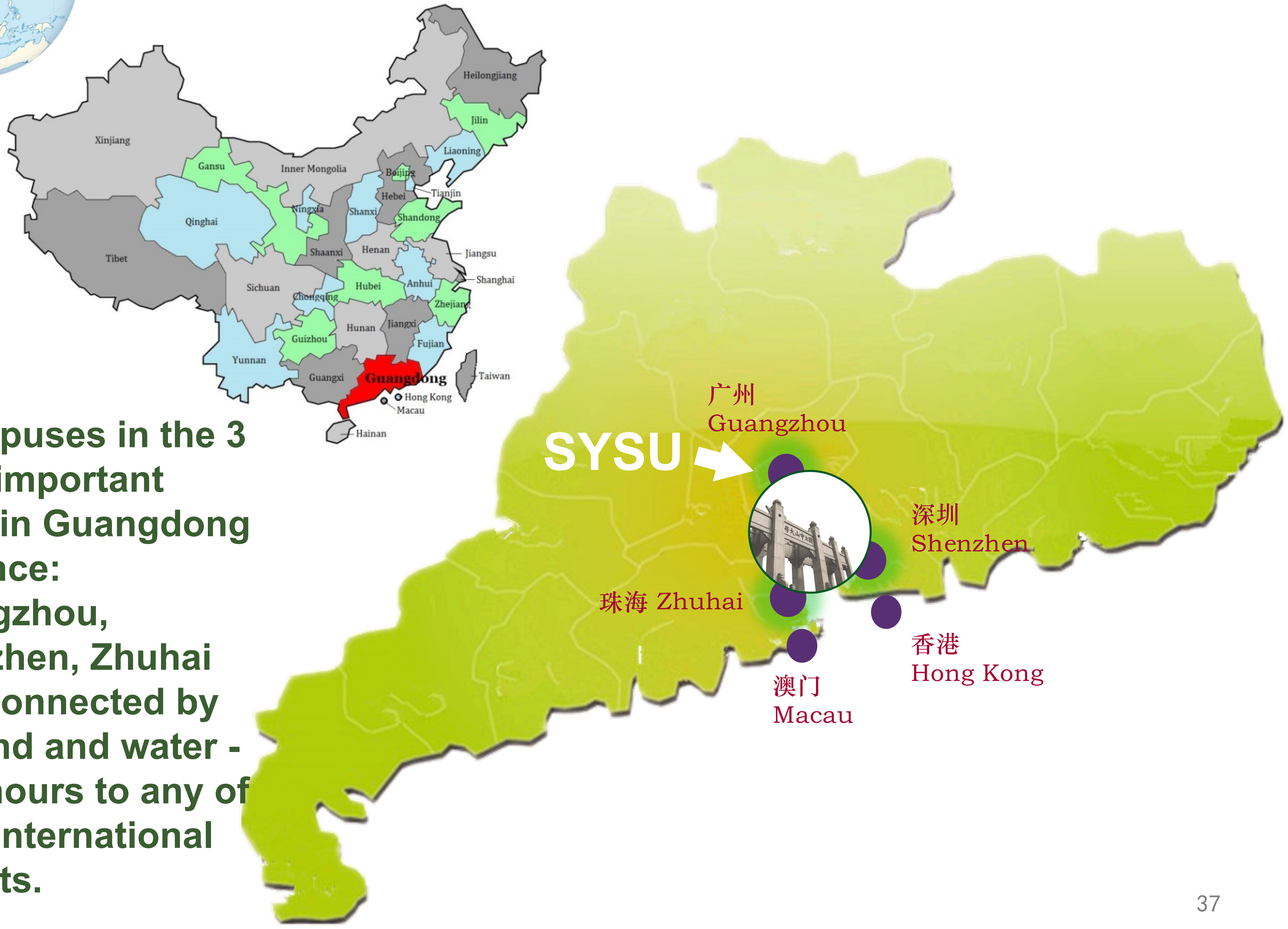
- ◆ TAO will be used to measure reactor neutrino spectrum
- ◆ Full coverage of SiPM with PDE > 50%
  Operate at -50 ℃ (lower SiPM dark noise)
  - ➢ 4500 p.e./MeV → $1.5\%\sqrt{E(MeV)}$
- ◆ Taishan Nuclear Power Plant
  2000 IBD/day (4000)

Summary and Conclusion

- **Reactor neutrino has played irreplaceable roles in neutrino studies**
- **Daya Bay has made the most precise measurement of $\sin^2 2\theta_{13}$, which makes**
  - **mass ordering resolution possible using reactor antineutrinos; CP phase measurement possible**
- **Daya Bay has made precise measurements of reactor antineutrino flux, its spectrum and contributions of the 2 major fission isotopes**
  - **Confirms Reactor Antineutrino Anomaly and the spectrum discrepancy**
  - **Both direct search (combined) and fuel evolution analysis disfavor sterile neutrino assumptions**
  - **Provide the best flux measurements of commercial reactors for future reactor neutrino experiments such as JUNO**
  - **“Repaying” the nuclear energy community: a different perspective for nuclear data studies relevant to reactor physics**
- **Daya Bay data will be open to the scientific community: proposals welcome!**

Thanks for your Attention!

- SYSU was founded in 1924 by Dr. Sun Yat-sen
- One of the top 10 comprehensive universities



- 5 campuses in the 3 most important cities in Guangdong province: Guangzhou, Shenzhen, Zhuhai
- Well connected by air, land and water --- <2 hours to any of the 5 international airports.

Welcome to Sun Yat-sen University (Zhuhai Campus) for Weak Interactions and Neutrinos 2023: July 3-8

Guangzhou South Campus

Guangzhou East Campus

Guangzhou North Campus

Shenzhen Campus

Zhuhai Campus

Wushunde Academic Center and Multiple Auditoriums (Venue of ~300 plenary and multiple parallel sessions)

The Latest Daya Bay Reactor Neutrino Data Set

- Summary of the Daya Bay data sample:

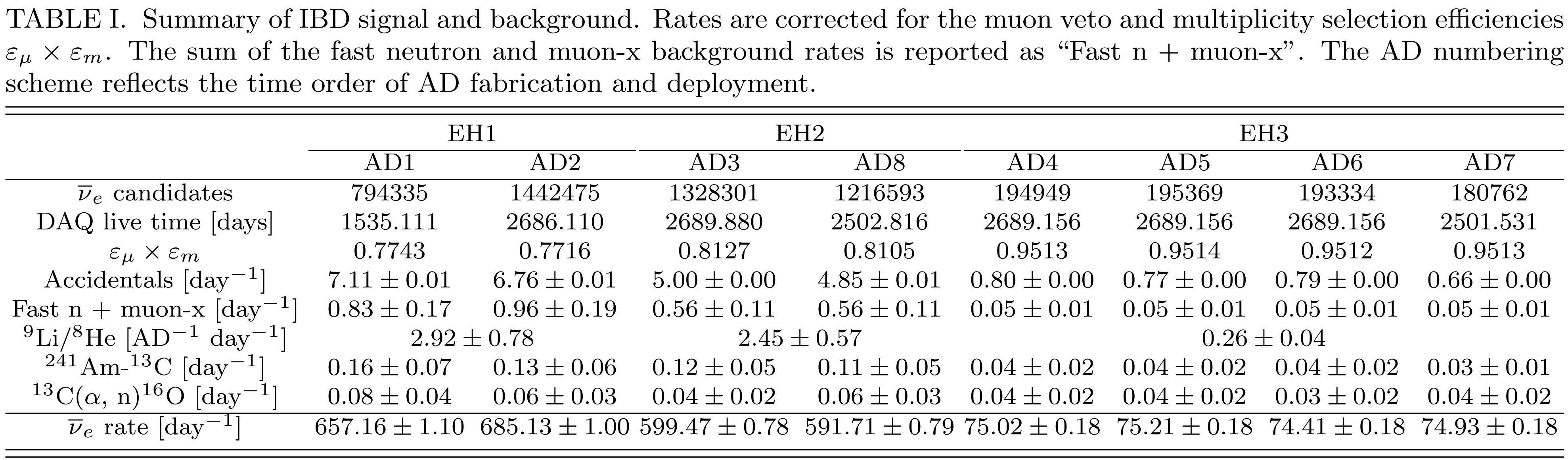
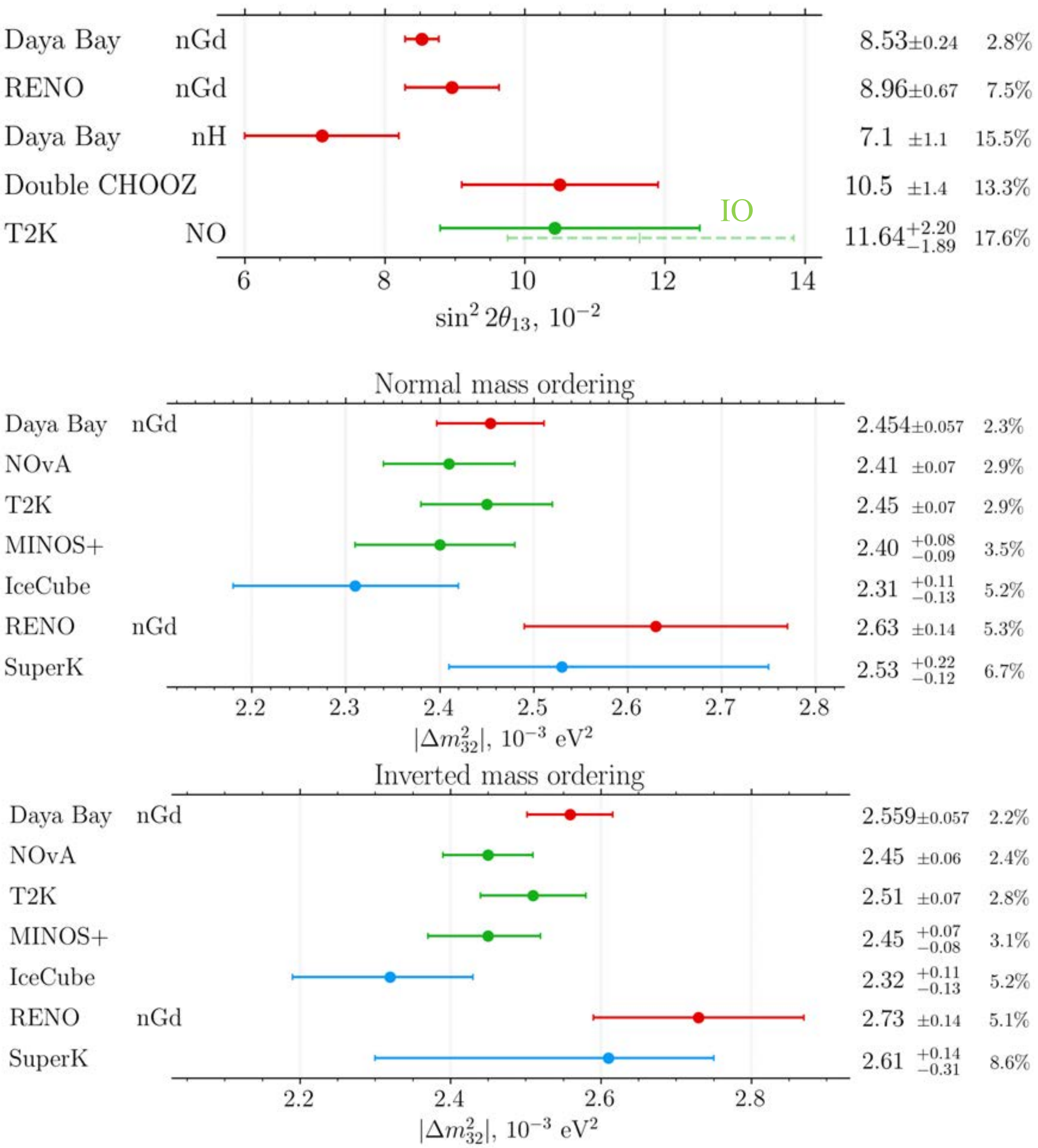


TABLE I. Summary of IBD signal and background. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \times \varepsilon_m$. The sum of the fast neutron and muon-x background rates is reported as "Fast n + muon-x". The AD numbering scheme reflects the time order of AD fabrication and deployment.

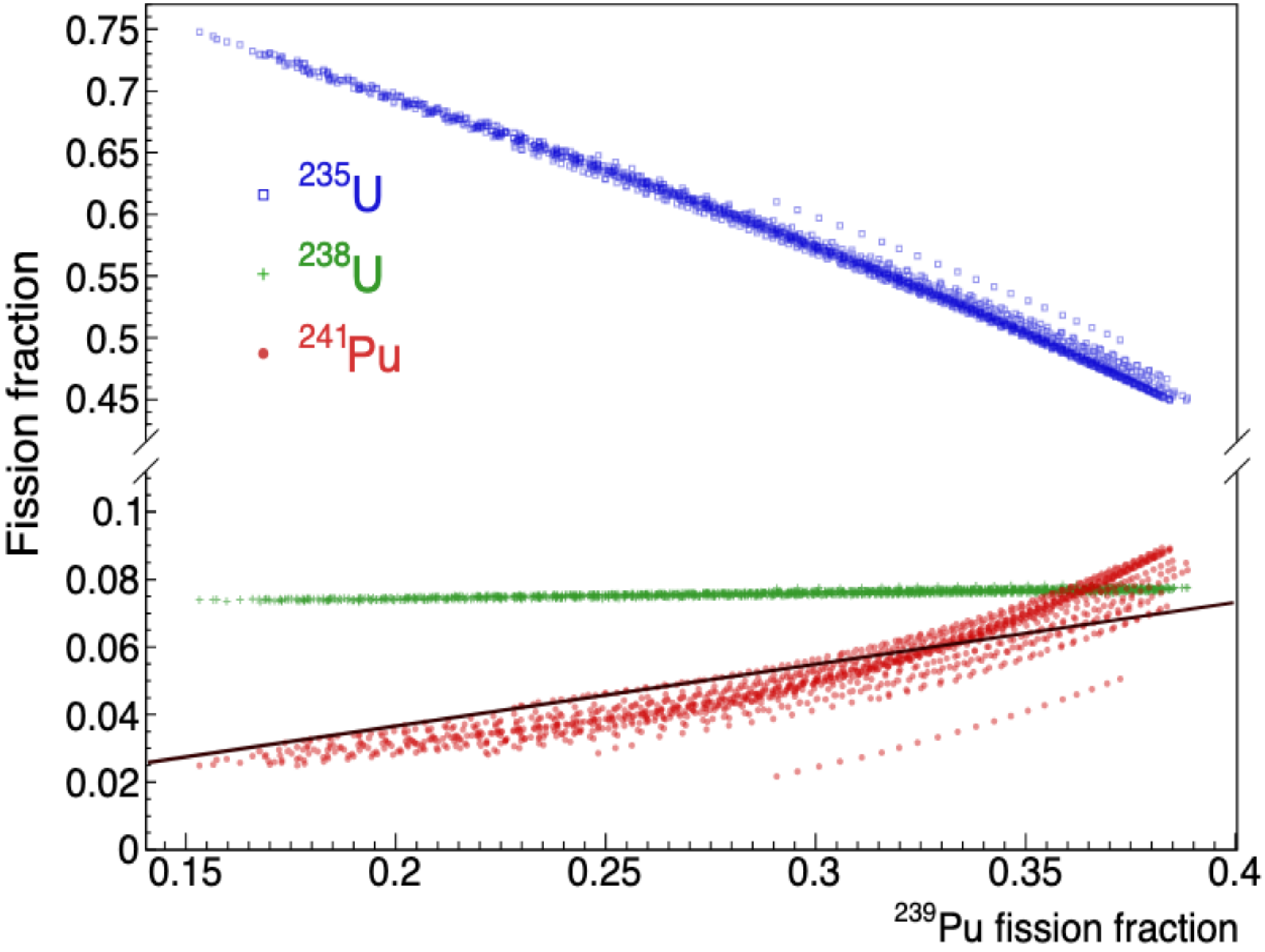
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	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}]	657.16 ± 1.10	685.13 ± 1.00	599.47 ± 0.78	591.71 ± 0.79	75.02 ± 0.18	75.21 ± 0.18	74.41 ± 0.18	74.93 ± 0.18

- Largest Reactor Neutrino Data Ever:
  - More than **5.5 million IBDs (~0.7 million at far site)**

Daya Bay Oscillation Results and Global Comparison



Fission Fraction Evolution



Sterile Neutrino Search Advantages of Daya Bay

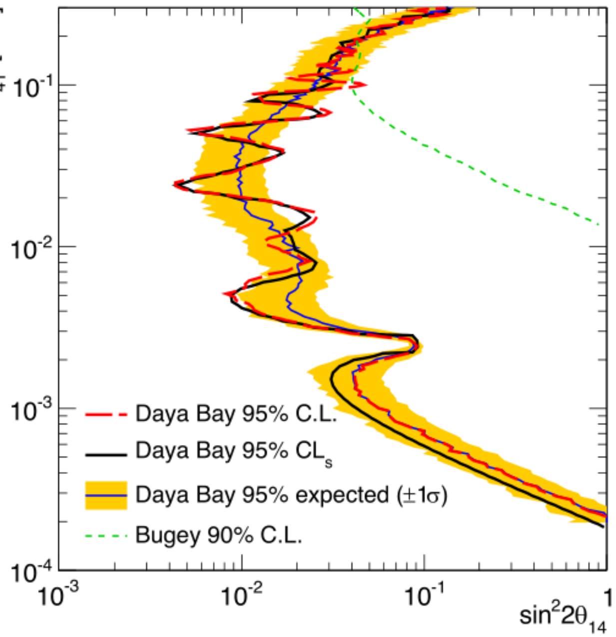
- Unique multi-baseline opportunity

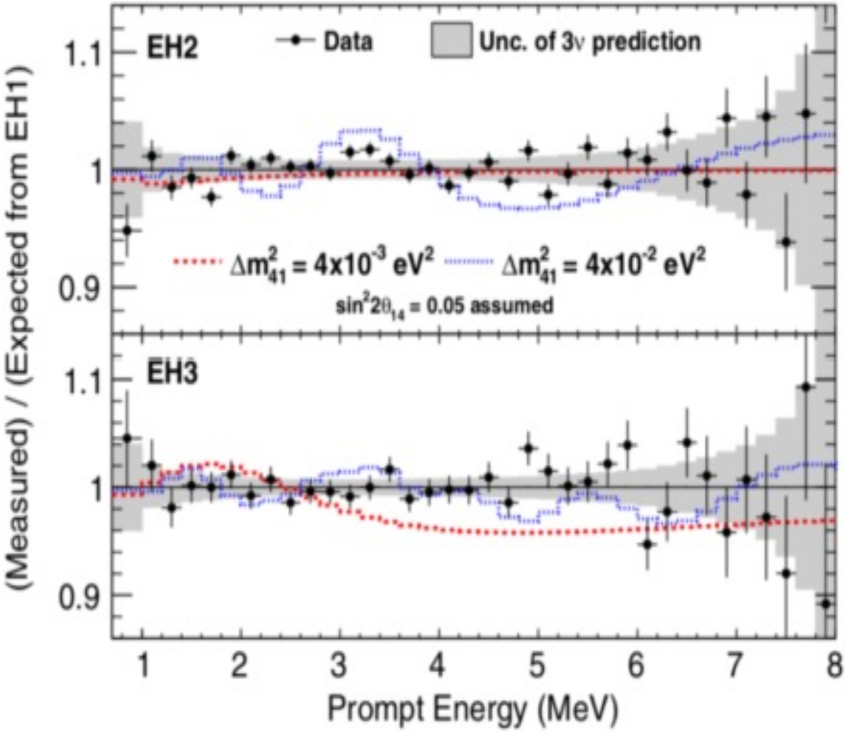
Exclusion Contours

- Two-hypothesis test for 3ν and 3+1-ν
- Gaussian CLs[4] approach to set exclusion contour

$$\mathrm{CL}_s = \frac{1-p_1}{1-p_0},$$

p_0: 3ν p_1: 3+1-ν



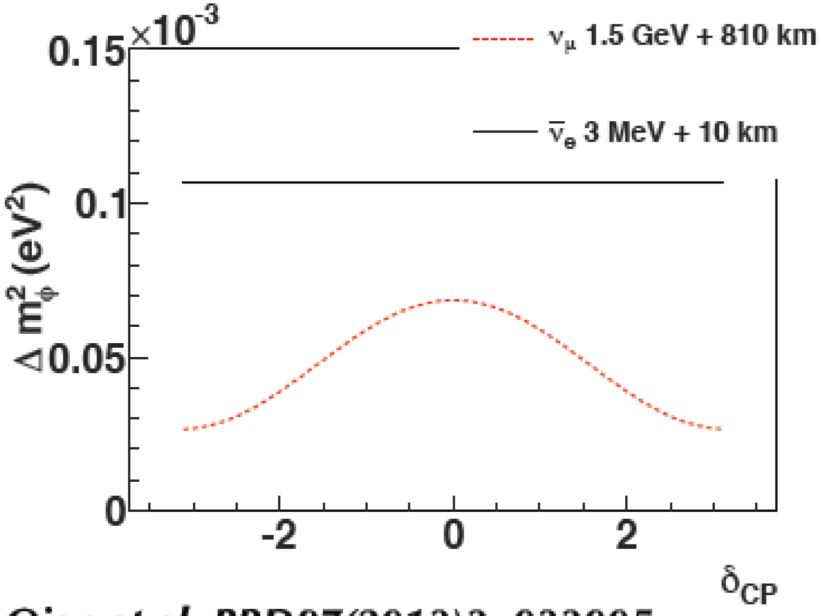


e- / μ-Flavor "Senses" Mass Ordering Differently

A fair question to ask: Why care $|\Delta m^2_{ee}|$ from reactor experiments?

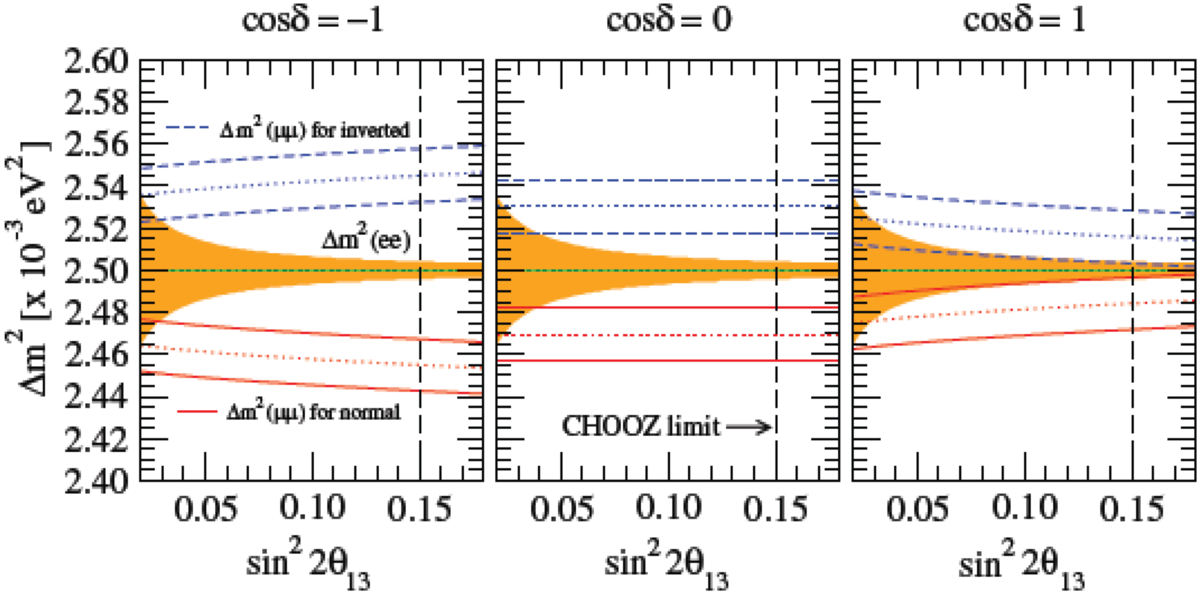
$$P_{\nu_\mu \to \nu_\mu} = 1 - P^{\mu}_{21} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m^2_{32} \pm \phi)L}{4E}$$

Impractical: Need 1% accuracy!



Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



Minakata et al PRD74(2006), 053008

Also See: Zhang&Ma, arXiv:1310.4443/ Mod. Phys. Lett. A29 (2014) 1450096

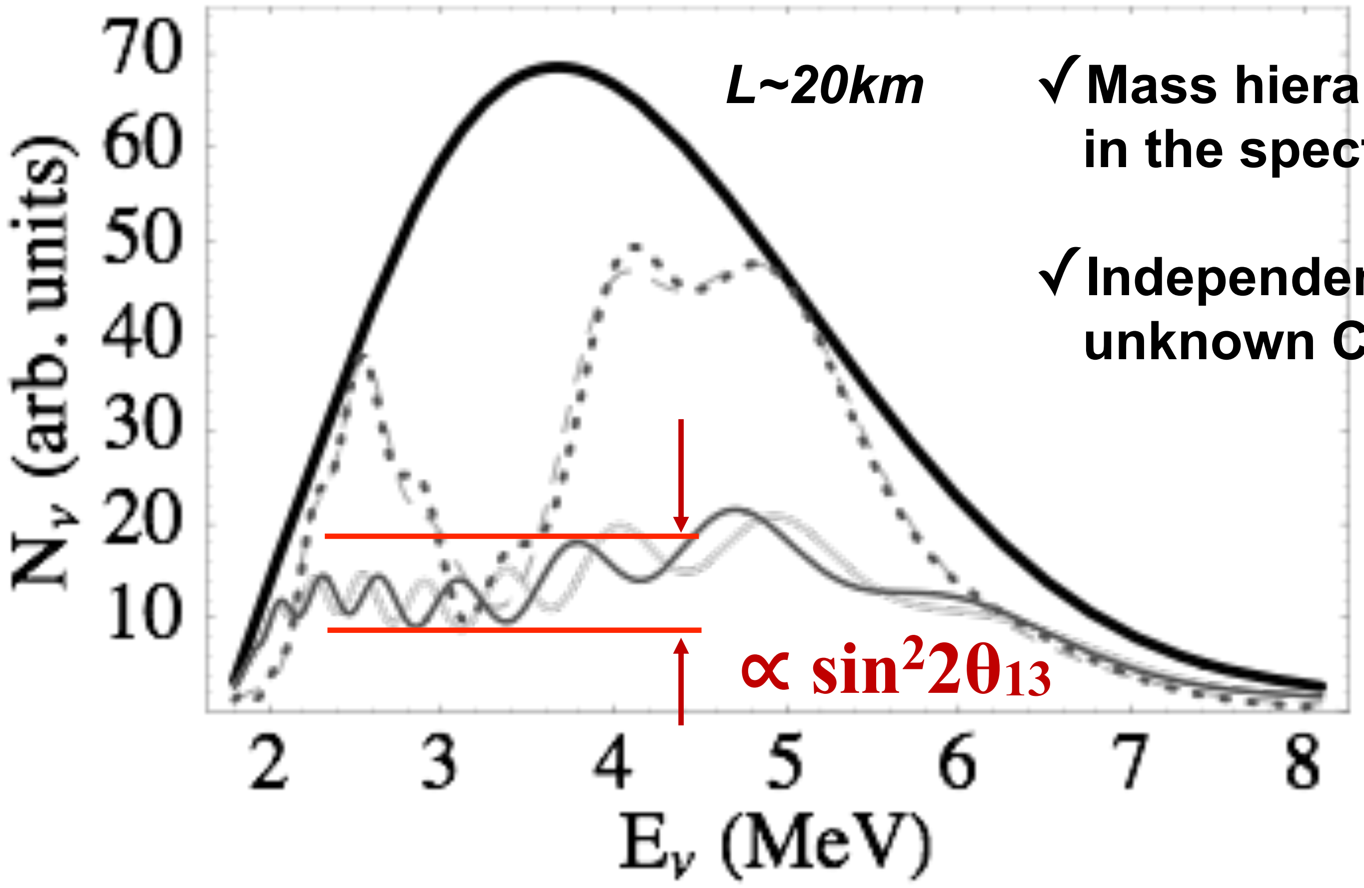
Global Efforts Resolving ν Mass Hierarchy

Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO+Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0νββ

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

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

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



- ✓ **Mass hierarchy reflected in the spectrum**
- ✓ **Independent of the unknown CP phase**