Sterile Neutrino Search at Daya Bay

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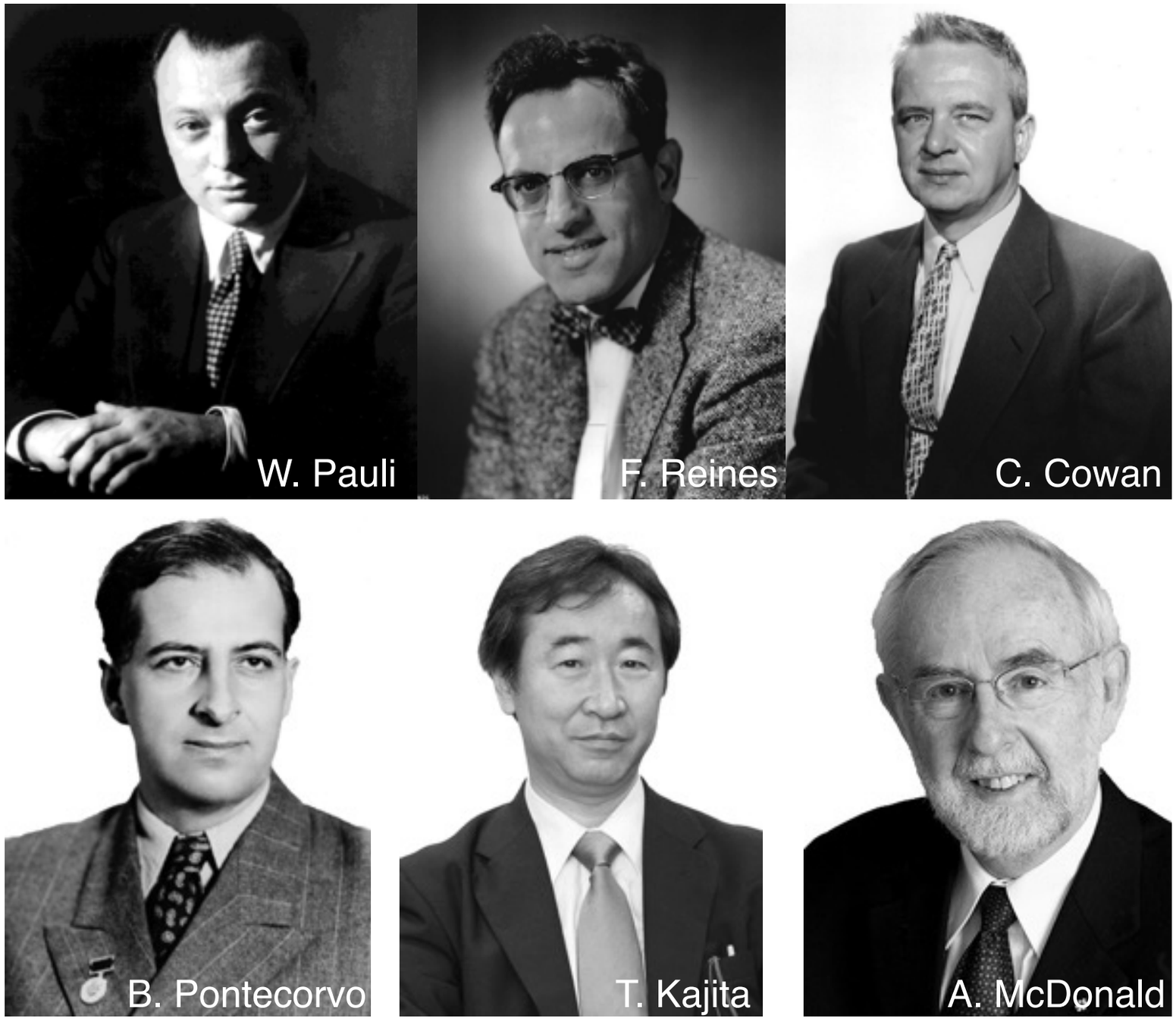
On behalf of the Daya Bay Collaboration

Particle Physics Seminar, September 30, 2016

Contents

- Introduction to (sterile) neutrinos
- Daya Bay experiment
- Sterile neutrino search at Daya Bay
- Combination of Daya Bay, Bugey-3 and MINOS sterile neutrino results
- Conclusion

Neutrino and Oscillation



1930

Neutrino was proposed

1956

First neutrino detection

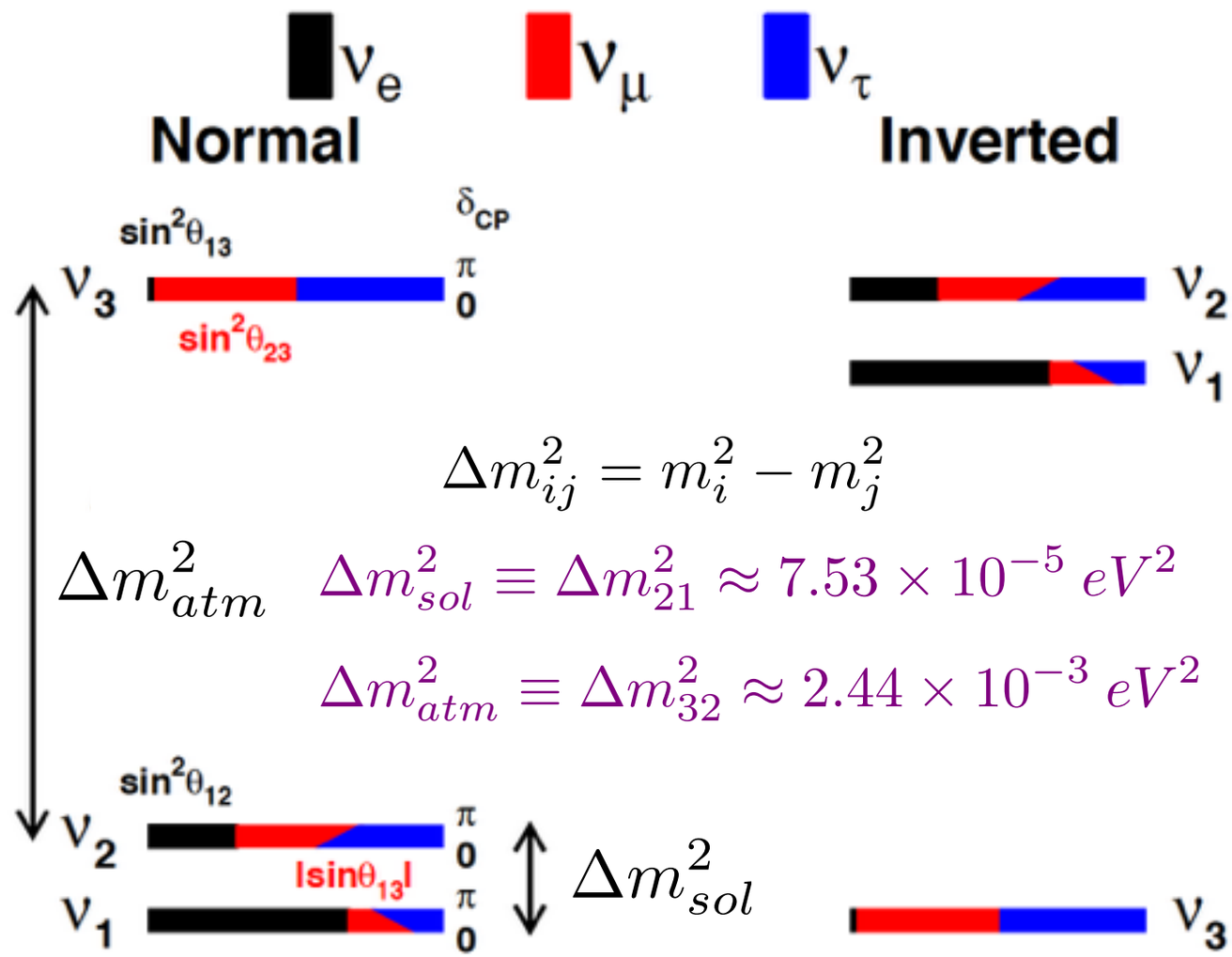
1957 – 1967

Neutrino oscillation theory was developed.

1998 – 2001

Discovery of neutrino oscillations

Neutrino Oscillation



$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{atm} \quad \Delta m^2_{sol} \equiv \Delta m^2_{21} \approx 7.53 \times 10^{-5}\, eV^2$$

$$\Delta m^2_{atm} \equiv \Delta m^2_{32} \approx 2.44 \times 10^{-3}\, eV^2$$

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

PMNS Matrix

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

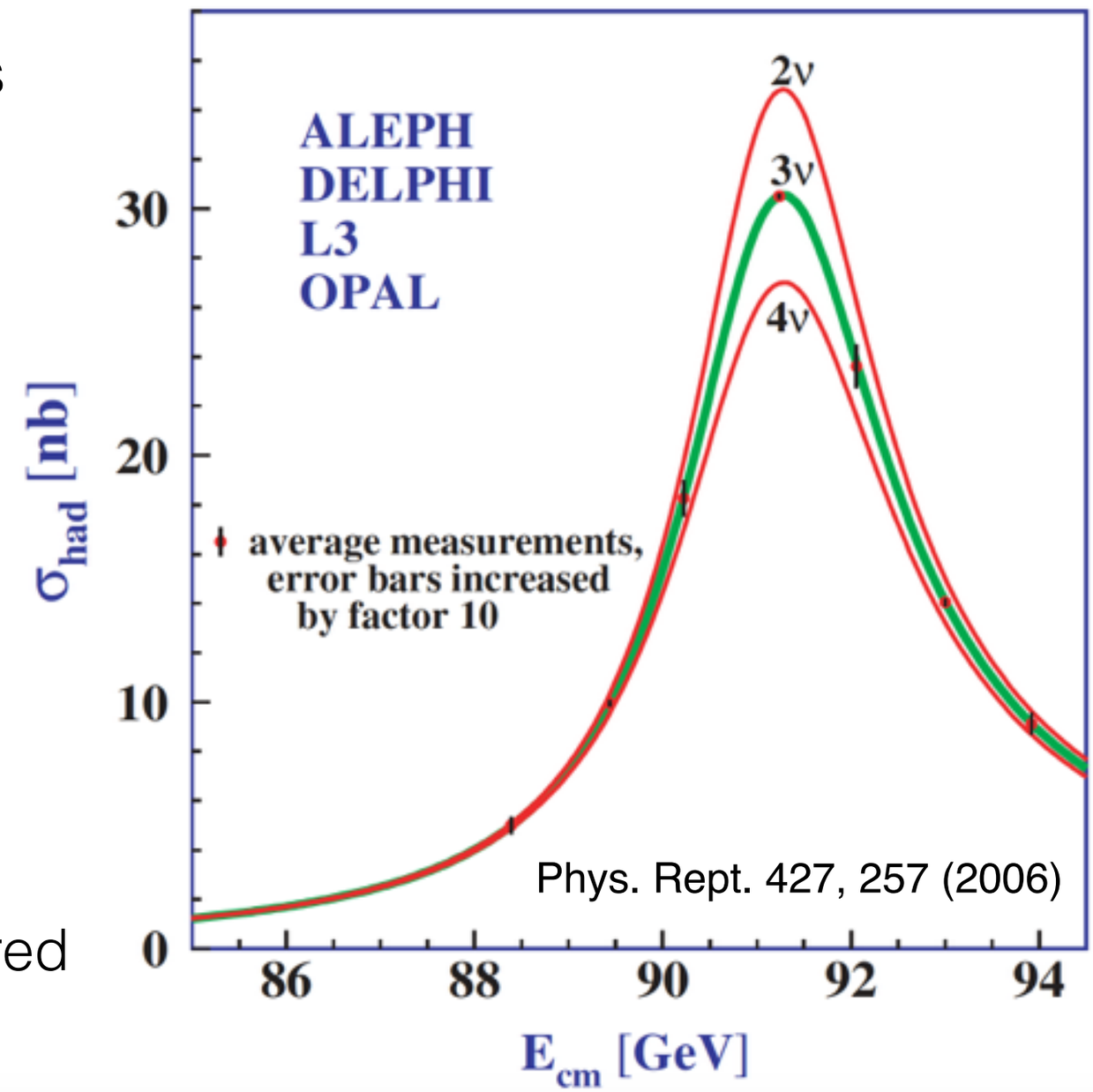
$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 8^\circ$ $\theta_{12} \approx 34^\circ$

Three Active Light Neutrinos

- Fit of Z-boson resonance cross section shows three different types of neutrinos (with mass < 1/2 M_Z)
  - They are called active neutrinos

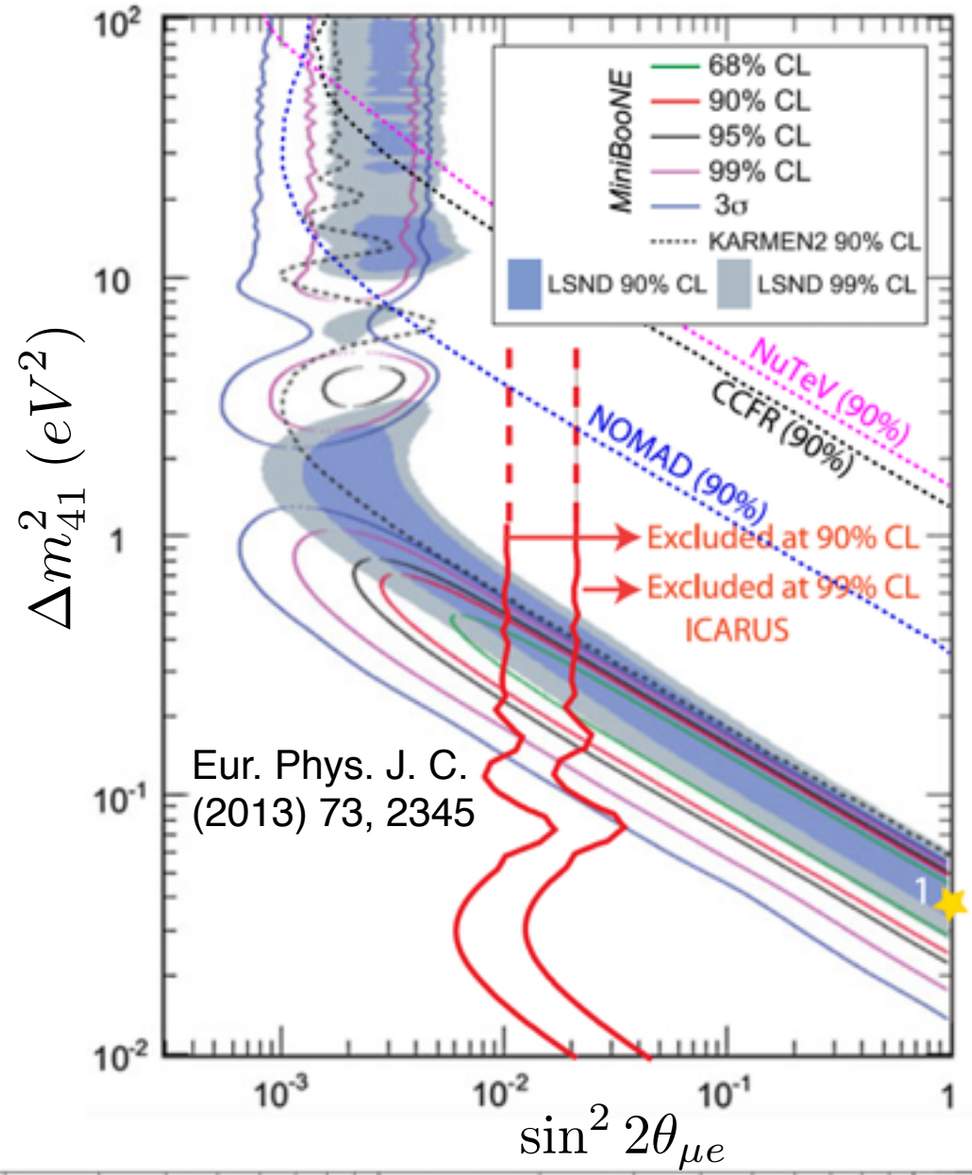
$$N_\nu = 2.984 \pm 0.008$$

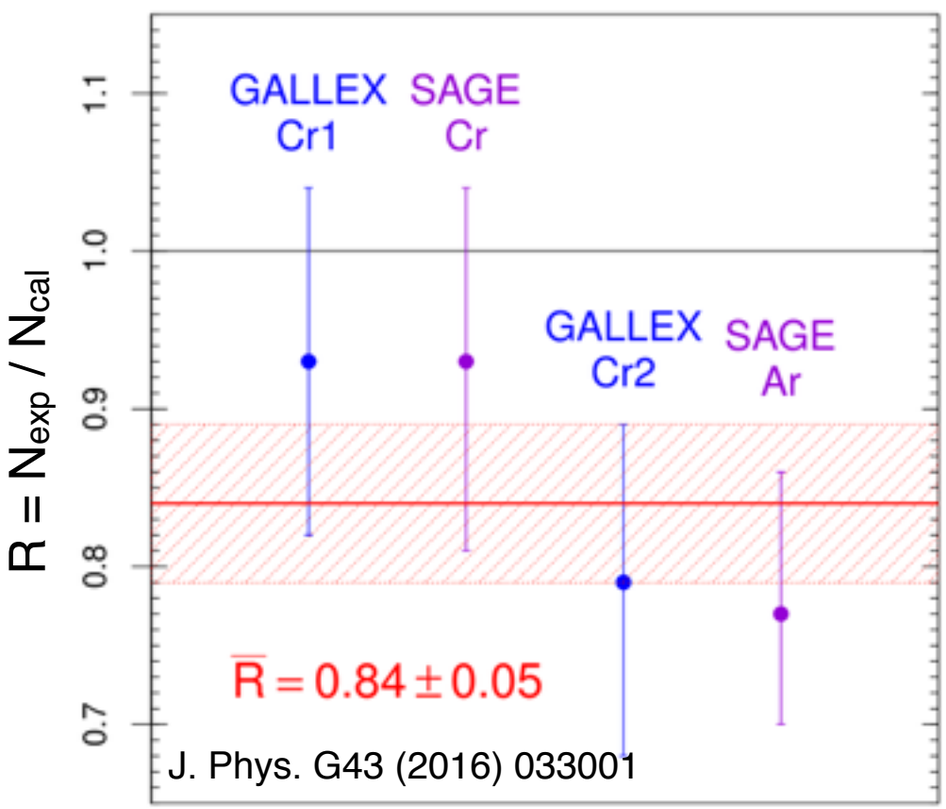
- Other types of neutrinos, if they do exist, are called sterile neutrinos
  - Not interact through weak force.
  - May mix with light active neutrinos, and could thus be indirectly measured through neutrino oscillation.

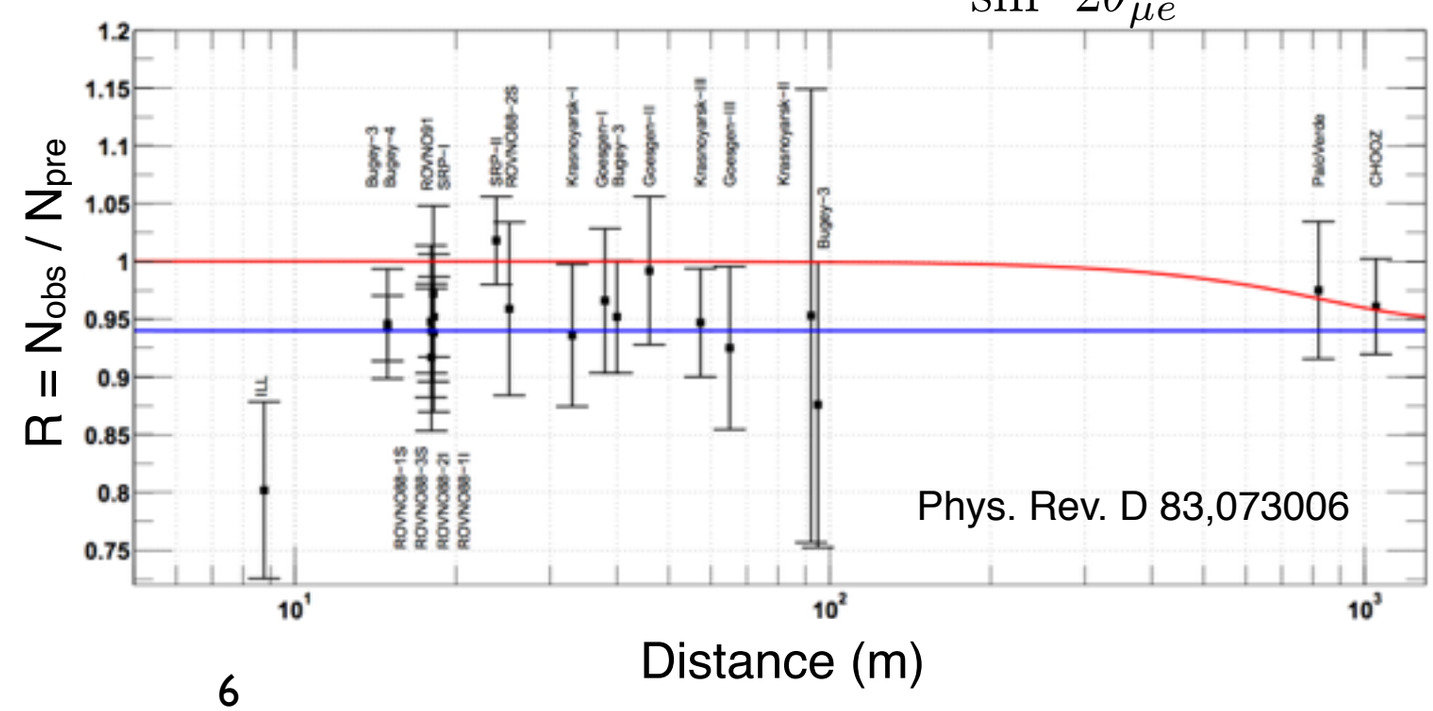


Experimental Anomalies (1)

- Accelerator Anomaly
  - LSND, MiniBooNE ($\bar{\nu}_\mu \to \bar{\nu}_e$)
- Reactor Anomaly
  - Reactor experiments ($\bar{\nu}_e \to \bar{\nu}_e$)
- Gallium Anomaly
  - GALLEX, SAGE ($\nu_e \to \nu_e$)







Experimental Anomalies (2)

- These experimental anomalies can not be explained by the standard 3ν oscillations.
- Oscillations due to sterile neutrino(s) could be an explanation.
  - An additional oscillation with mass-square splitting ~ 1 eV^2 could explain the data.
  - The evidences of the existence of sterile neutrino(s) are not strong (2 - 3.8 σ).
  - The reactor anomaly is related to reactor neutrino flux models which are in question.

3 (Active) + 1 (Sterile) Formalism

- If sterile neutrinos exist
  - There could be many flavors
- Introduce one flavor of sterile neutrino into the three active neutrino framework (the simplest extension)

Introduce a 4th neutrino

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{3+1} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

flavor states **mass states**

$$U_{3+1} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

U_{PMNS}

Measure these in experiments

Experiment sensitivities

- Daya Bay and Bugey-3 experiments $|U_{e4}|^2 = \sin^2\theta_{14}$
  - $\bar{\nu}_e \to \bar{\nu}_e$ disappearance
- MINOS experiment $|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$
  - $\nu_\mu \to \nu_\mu$ disappearance
- LSND/MiniBooNE experiments $4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24}$
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance $= \sin^2 2\theta_{\mu e}$

If a neutrino appearance exists, then there must be two corresponding neutrino disappearance exist.

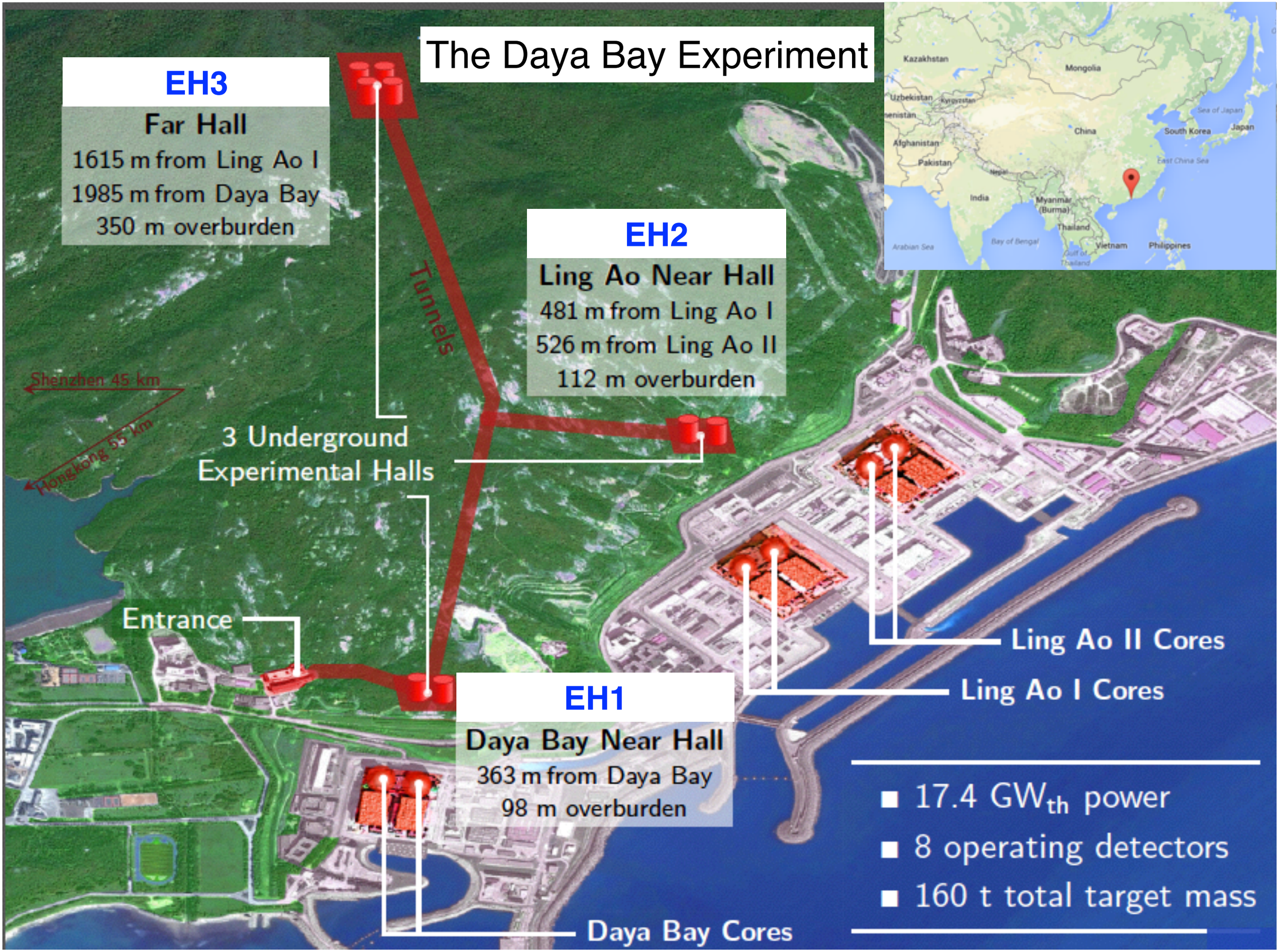
$$\sin^2 2\theta^{(k)}_{\alpha\alpha} \approx 4|U_{\alpha k}|^2$$

$$\sin^2 2\theta^{(k)}_{\alpha\beta} = 4|U_{\alpha k}|^2|U_{\beta k}|^2$$

- $\sin^2 2\theta^{(k)}_{\alpha\beta} \approx \frac{1}{4}\sin^2 2\theta^{(k)}_{\alpha\alpha}\sin^2 2\theta^{(k)}_{\beta\beta}$ *
- This is general situation and not limited to 3+1 framework

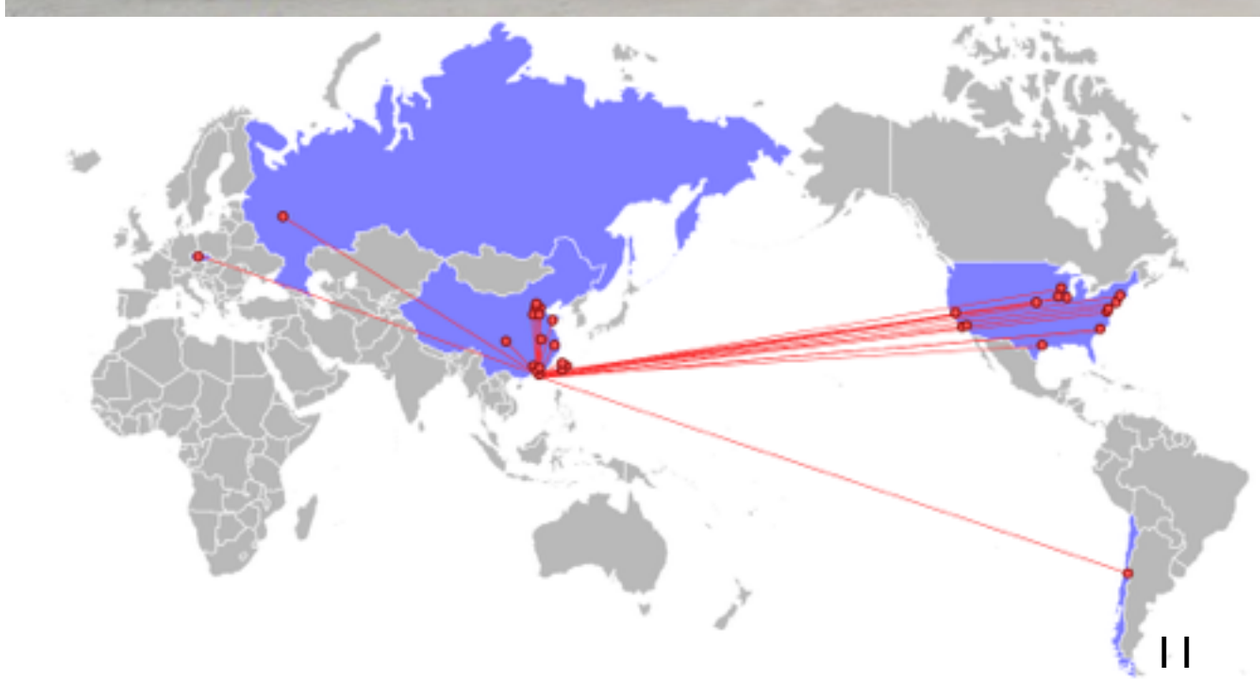
*C. Giunti and E. M. Zavanin, Mod. Phys. Lett. A 31, 1650003

The Daya Bay Experiment



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

The Daya Bay Collaboration



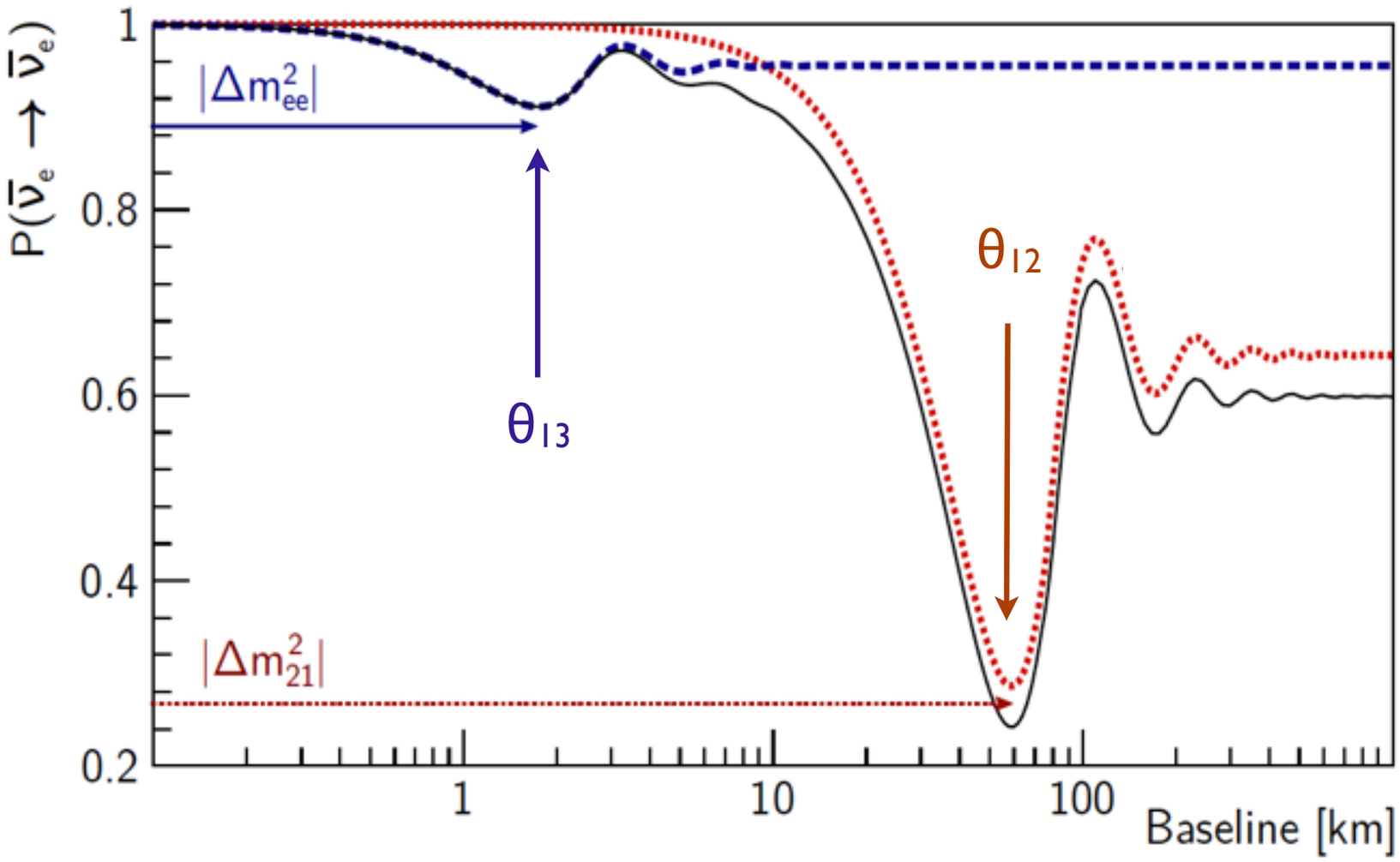
Asia:	23	institutions
North America:	16	institutions
Europe:	2	institutions
South America:	1	institution

42 institutions
203 collaborators

Daya Bay's Main Goal: Measure θ_{13}

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

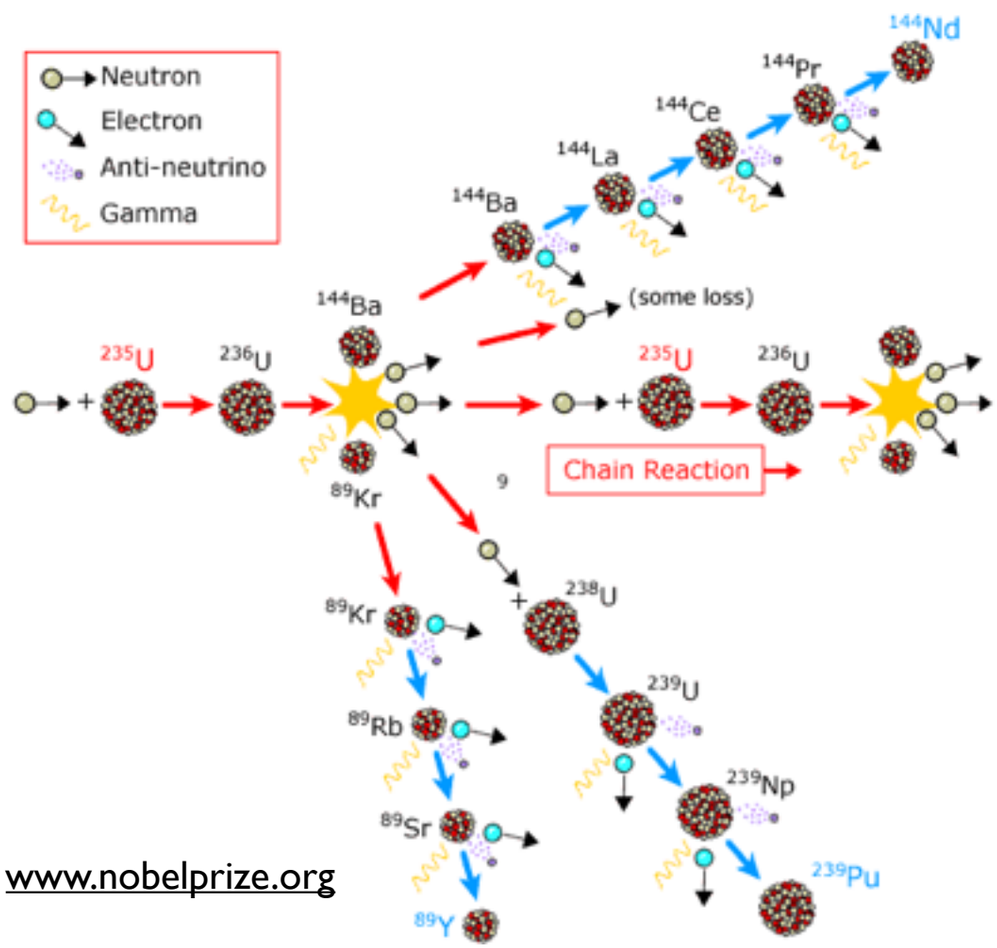
$$\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) \approx \cos^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



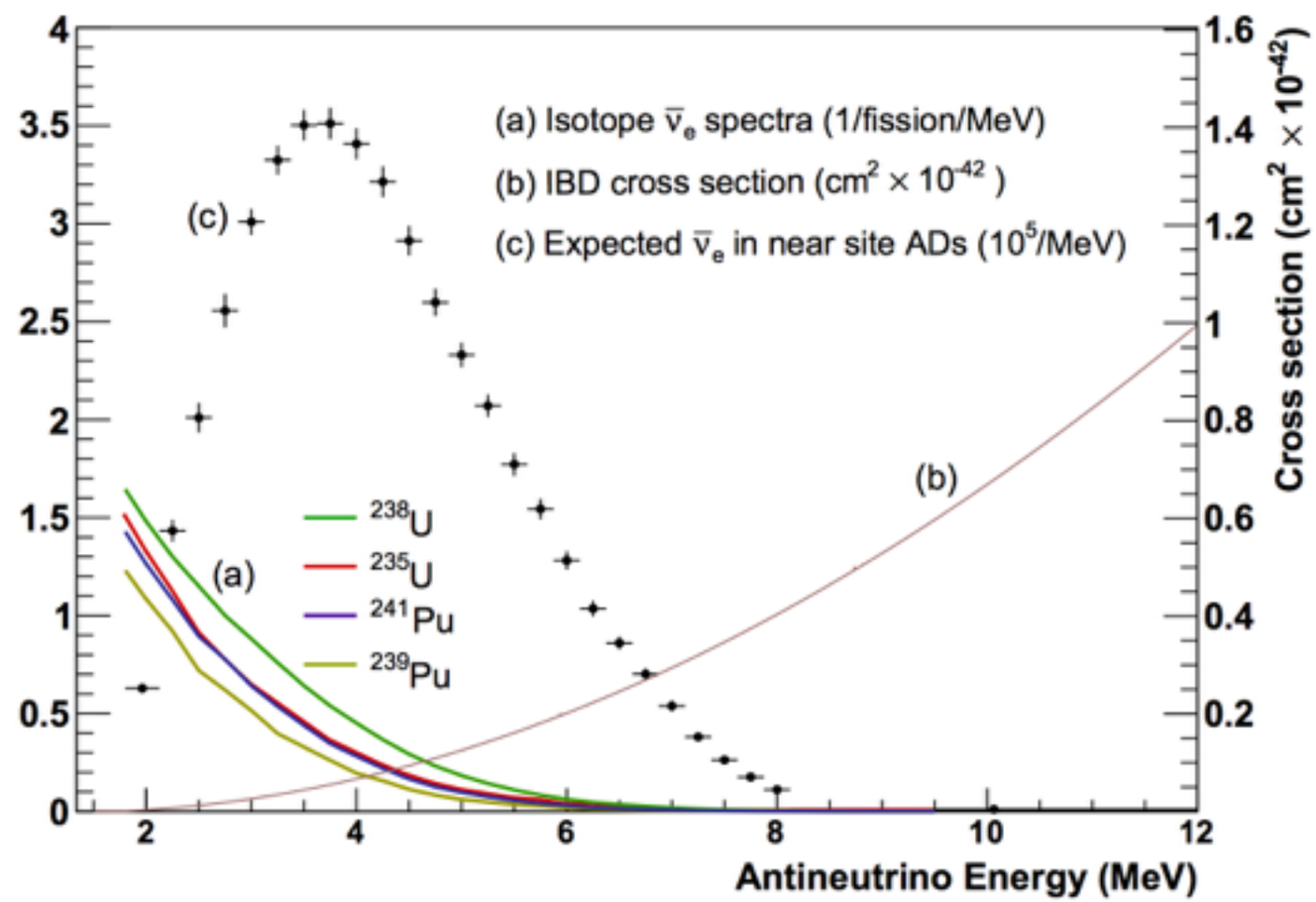
Reactor Anti-Neutrinos

Reactor produces electron anti-neutrinos ($\bar{\nu}_e$).

- 99.9% are produced by fissions of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu.
- 1 GW reactor produces ~ 2x10^{20} $\bar{\nu}_e$ per second
- 99.5% of them with energy below 8 MeV.



www.nobelprize.org



Reactor Neutrino Flux Models

Two Approaches to predict reactor neutrino flux

- ‘ab initio’ summation
  - Extract reactor neutrino flux by summing all β branches of all fission products of a specific isotope based on the nuclear databases.
  - Incomplete databases → 10-20% uncertainties.
  - ^{238}U: P. Vogel (1980), T. Mueller(2011)
- Convert from ILL β-spectra
  - Converted from the measured β spectra of each fission isotope at Institut Laue-Langevin (ILL)
  - A few percent uncertainties.
  - ^{235}U, ^{239}Pu, ^{241}Pu: ILL (1985-1989), P. Huber (2011)

^{235}U, ^{239}Pu, ^{241}Pu		^{238}U		
ILL (1985-1989)	+	P. Vogel (1980)	→	**ILL + Vogel Models**
P. Huber (2011)	+	T. Mueller (2011)	→	**Huber + Mueller Models**

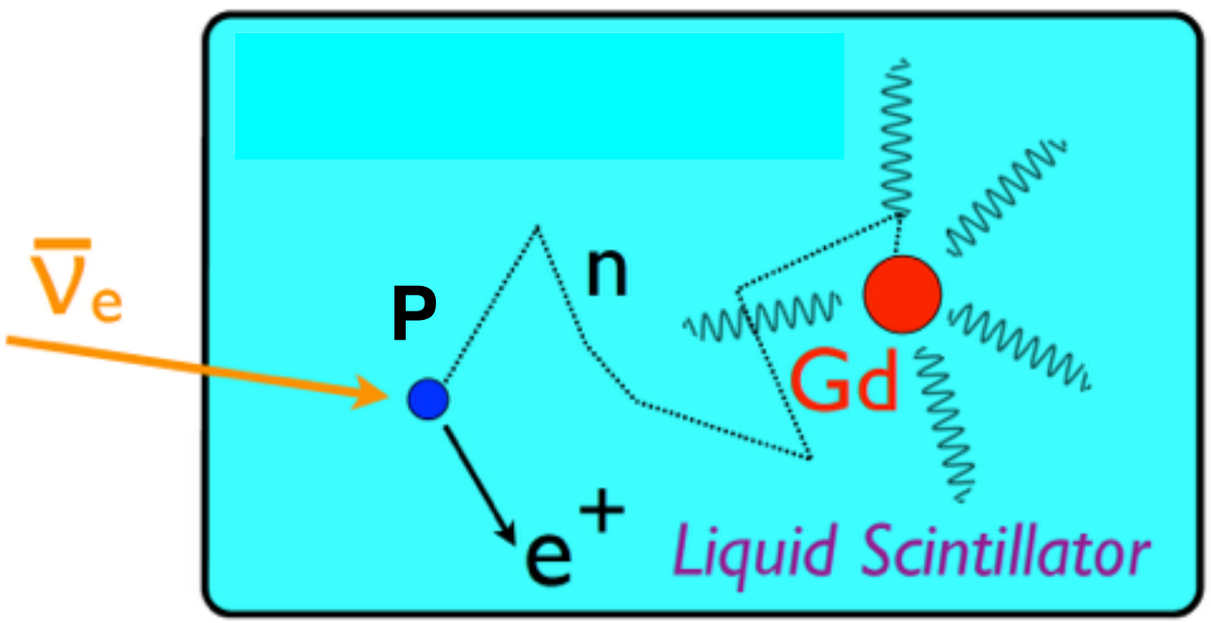
Reactor Anti-Neutrino Detection

Inverse Beta Decay (IBD)

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

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s$$

(~8.0 MeV 30μs)



Signature of IBD signal

- IBD threshold is ~ 1.8 MeV
- Positron prompt signal
  - Positron ionization and annihilation

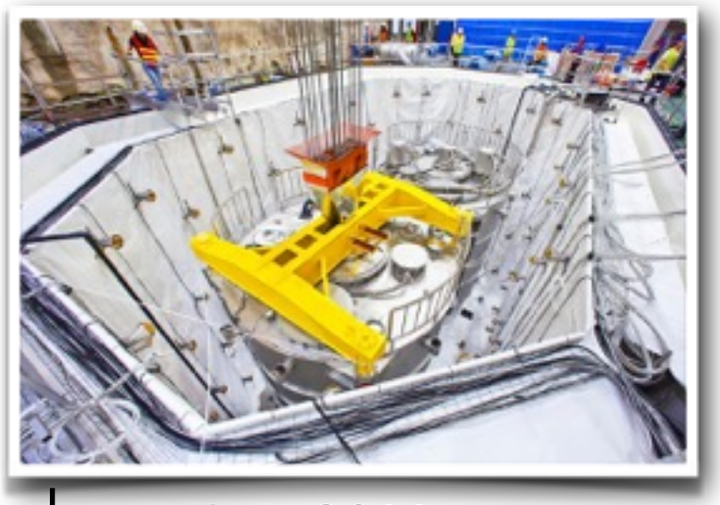
$$E_p \approx E_{\bar{\nu}_e} - 0.8 \text{ MeV}$$

- Delayed neutron capture signal
  - Energy released from n capture by Gadolinium (~ 8 MeV)

Coincidence of the prompt and delayed signals provides distinctive signature for IBD

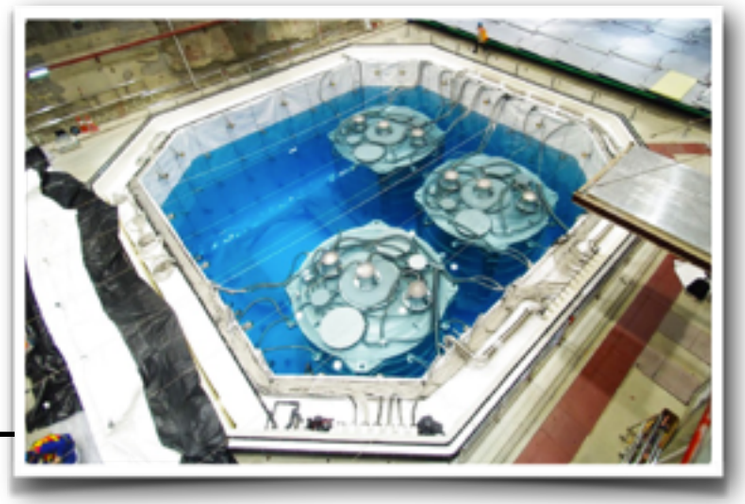
The Timeline of Daya Bay Experiment

EH1



Aug. 2011

EH3



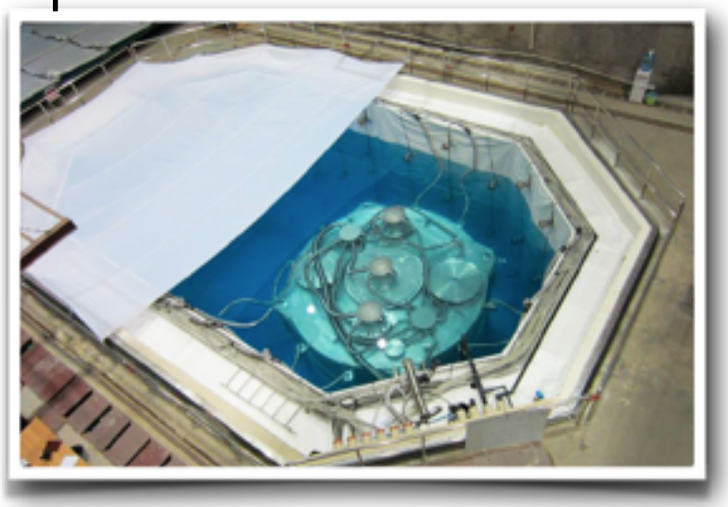
Dec. 2011

Aug. 2012

6-AD Running

8-AD Running

2011/12 - 2012/07



Nov. 2011

EH2

2012/10 -

Aug. 2012

621 days data

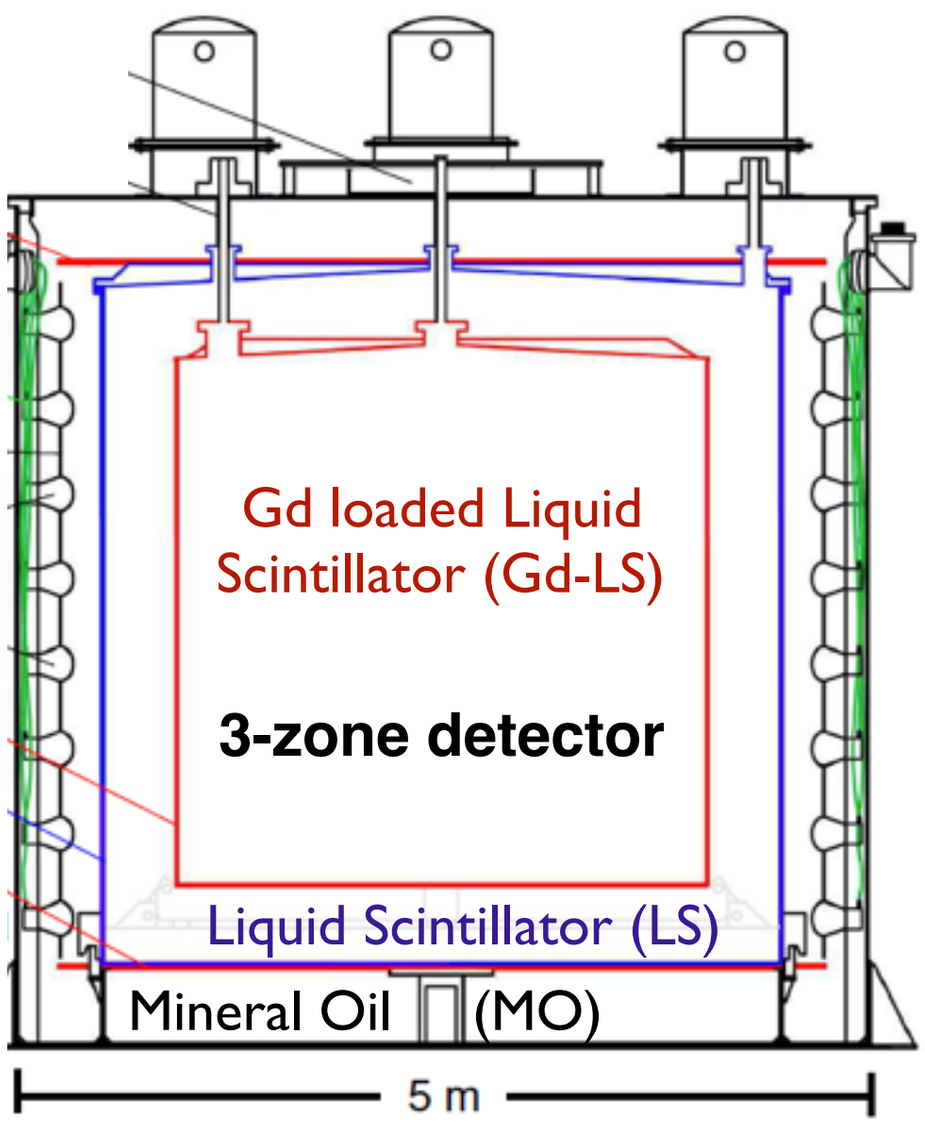
December, 2013

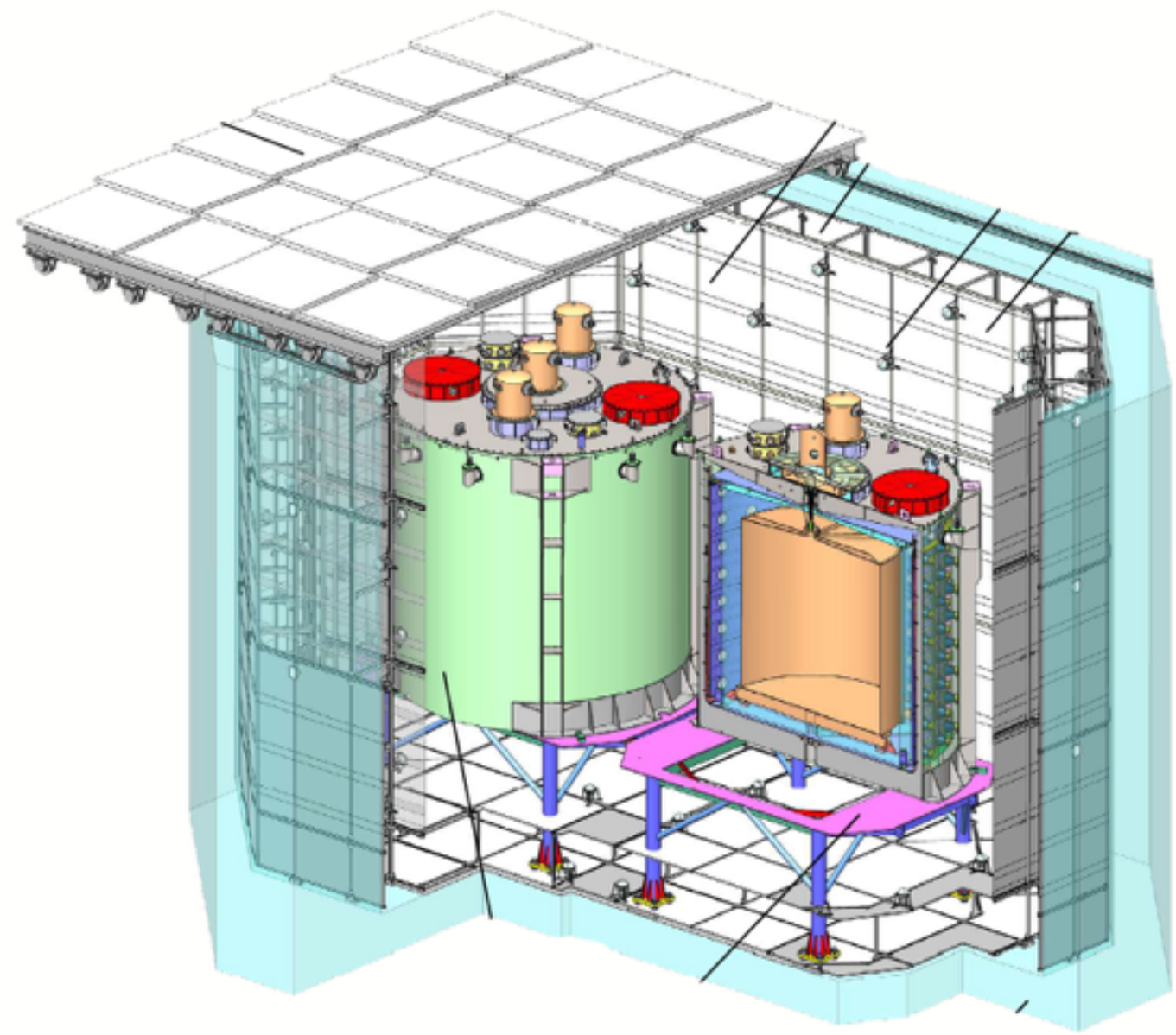
1230 days data

August, 2015

Daya Bay Detector System

3-zone detectors immersed in highly purified water pools

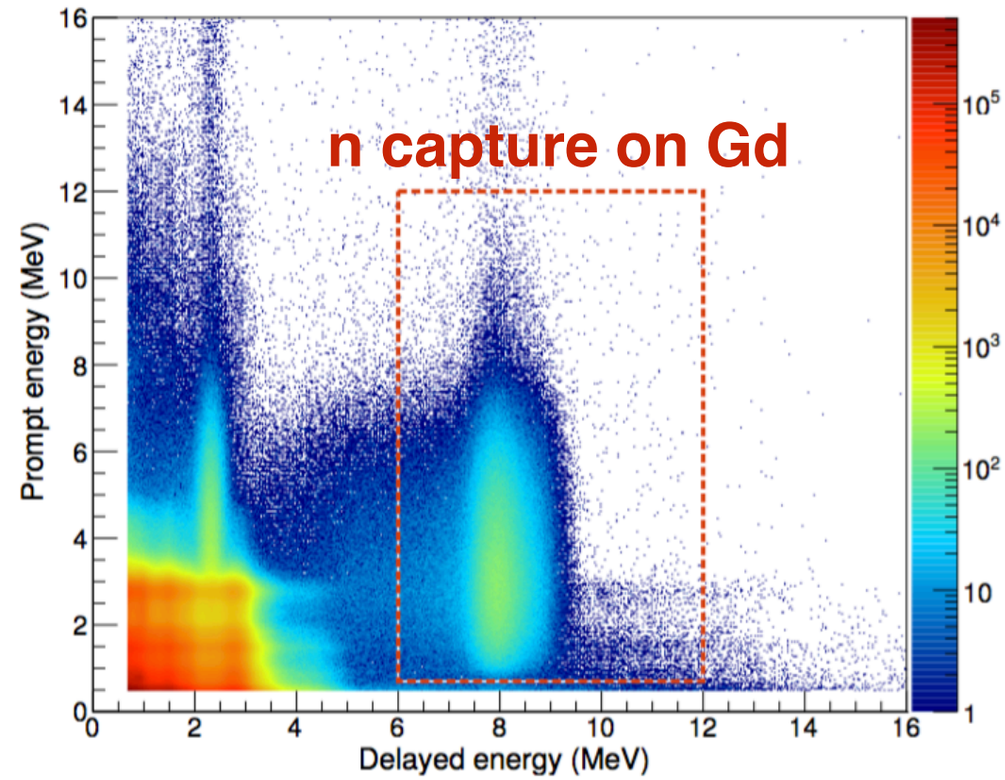




Anti-Neutrino Candidate Selection

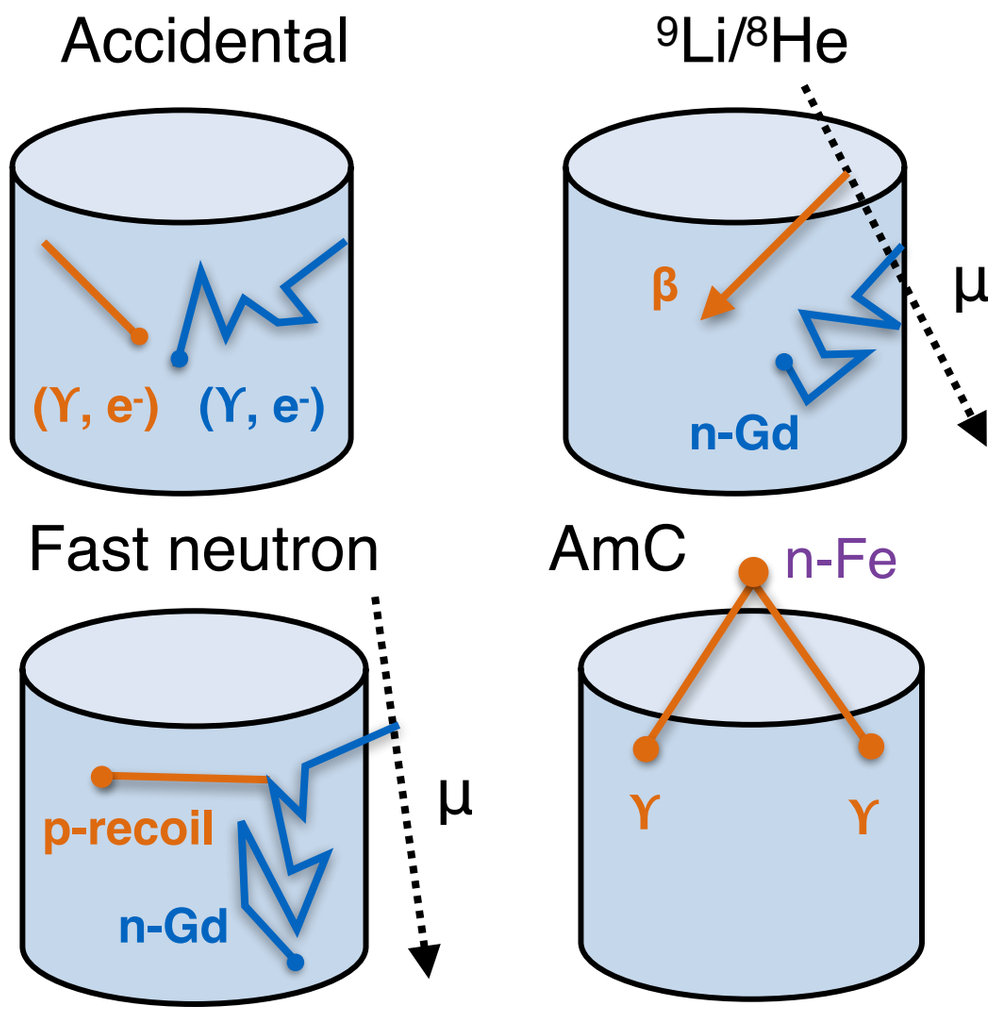
IBD selections

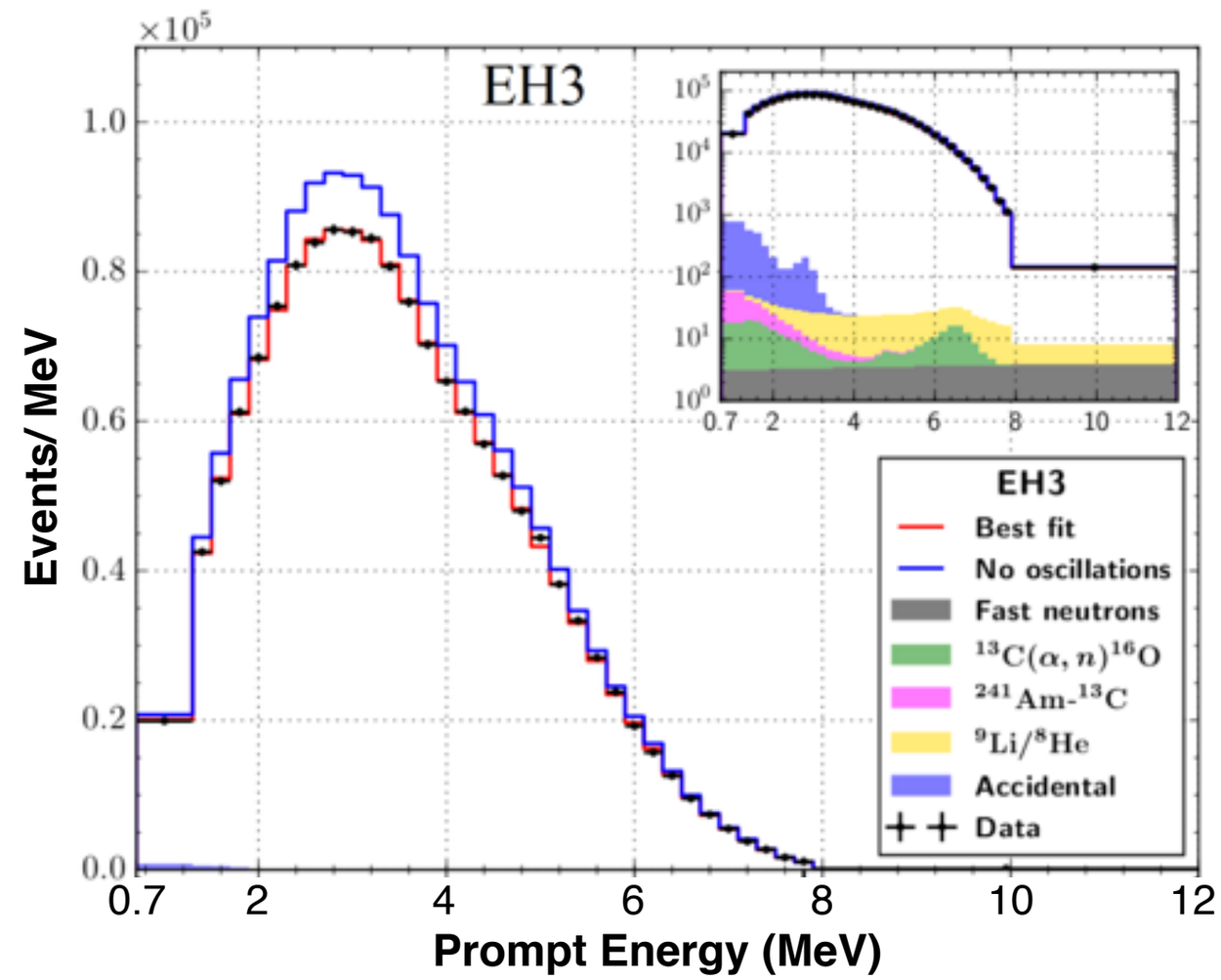
- Reject PMT flashers
- Muon veto cut
  - Water pool Muon: reject 0.6us
  - AD Muon (> 20 MeV): reject 1 ms
  - AD Shower Muon (> 1.8 GeV): reject 0.4 s
- Prompt positron Energy
  - 0.7 MeV < Ep < 12 MeV
- Delayed neutron Energy
  - 6 MeV < Ed < 12 MeV
- Neutron Capture time
  - 1 us < Δt < 200 us
- Multiplicity cut
  - only select isolated candidate 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%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

IBD Candidates and Background



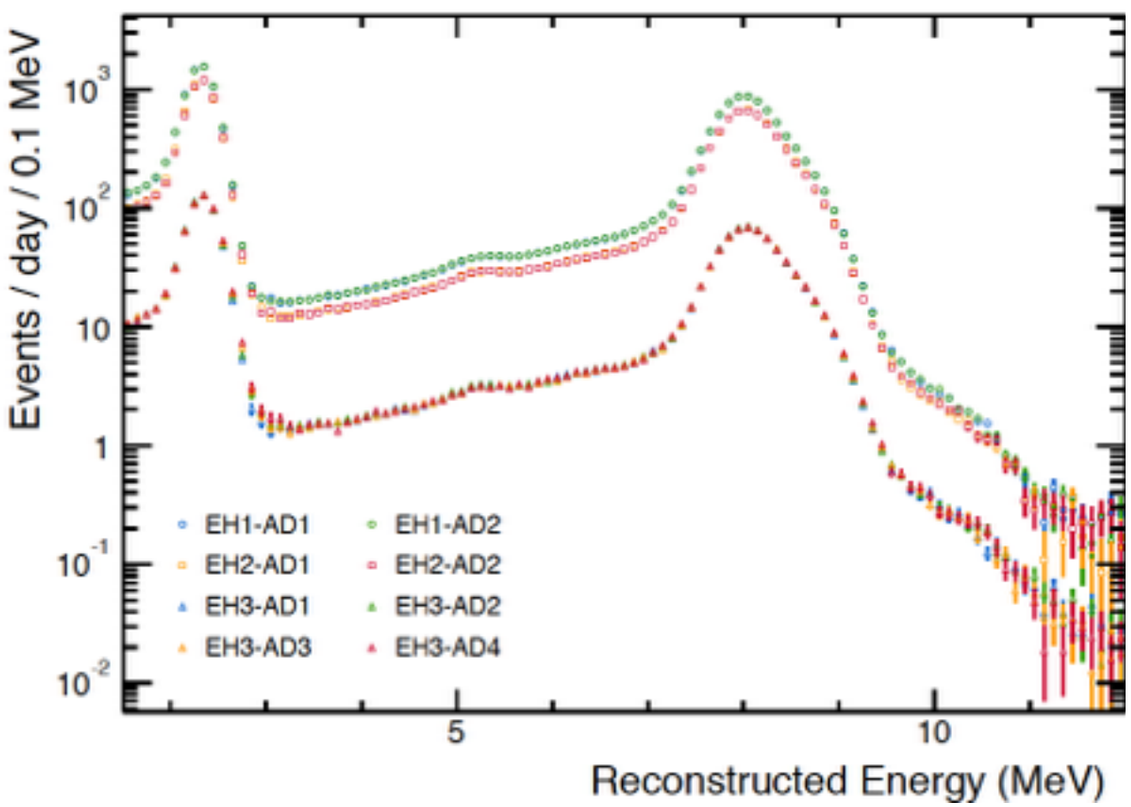


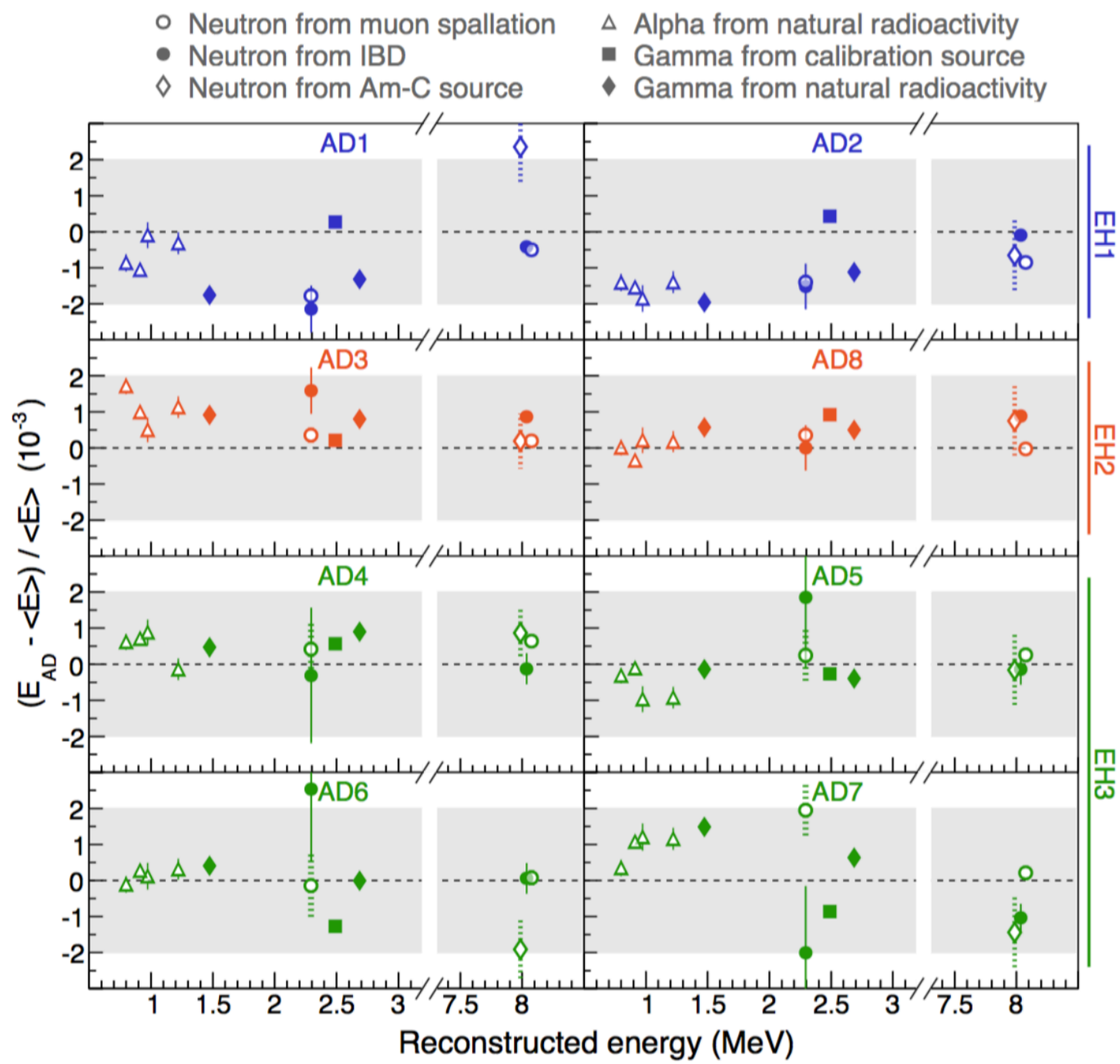
1230 days data			
	EH1	EH2	EH3
IBD candiates	1,203,969	1,033,209	**308,150**
B/S ratio	1.8 ± 0.2%	1.5 ± 0.2%	2.0 ± 0.2%

Relative Energy Scale

- ACU: ^{60}Co, ^{68}Ge, $^{241}Am^{13}C$
- Spallation: nGd, nH
- Gamma: ^{40}K, ^{208}Ti
- Alpha: ^{212}Po, ^{214}Po, ^{215}Po

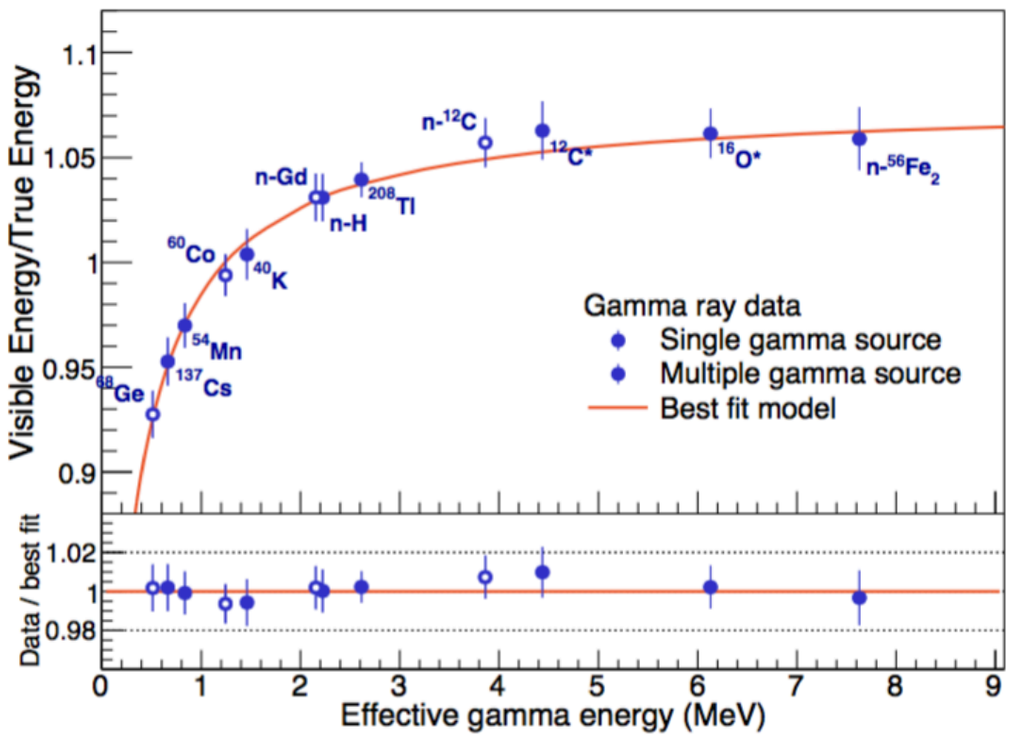
Spallation neutron capture spectrum

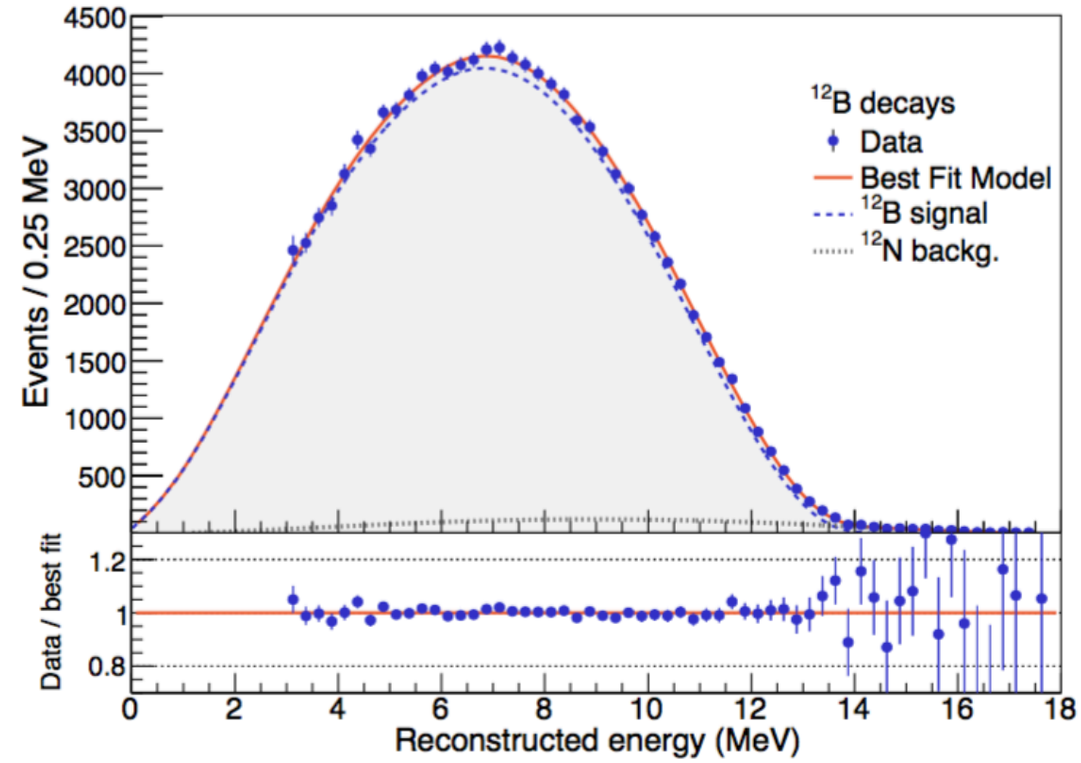




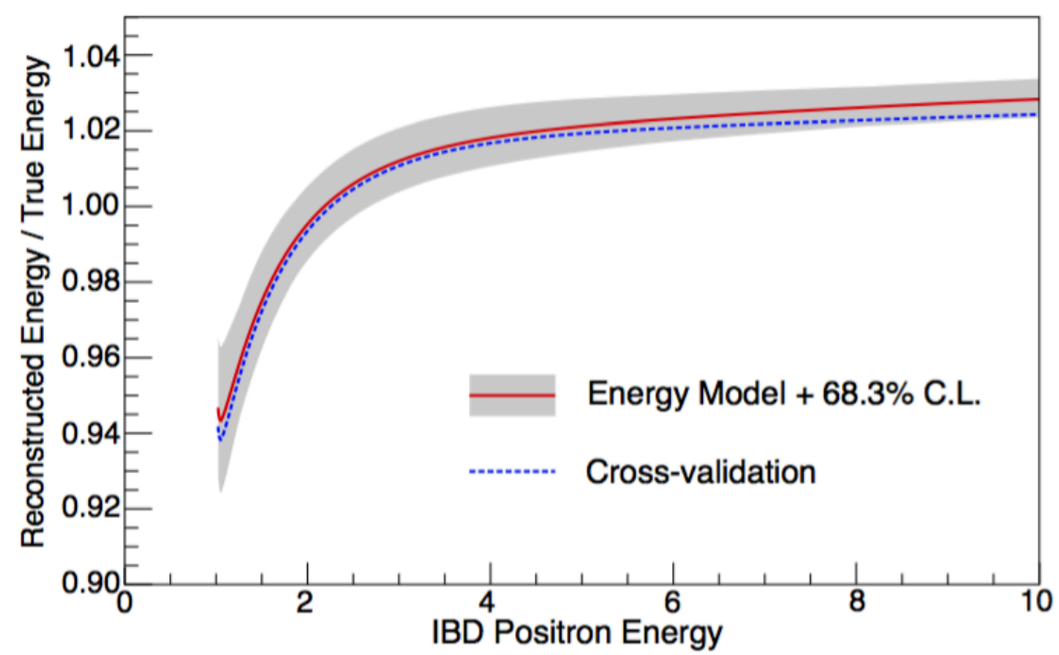
Less than 0.2% variation in reconstructed energy among ADs

Energy Nonlinearity Calibration



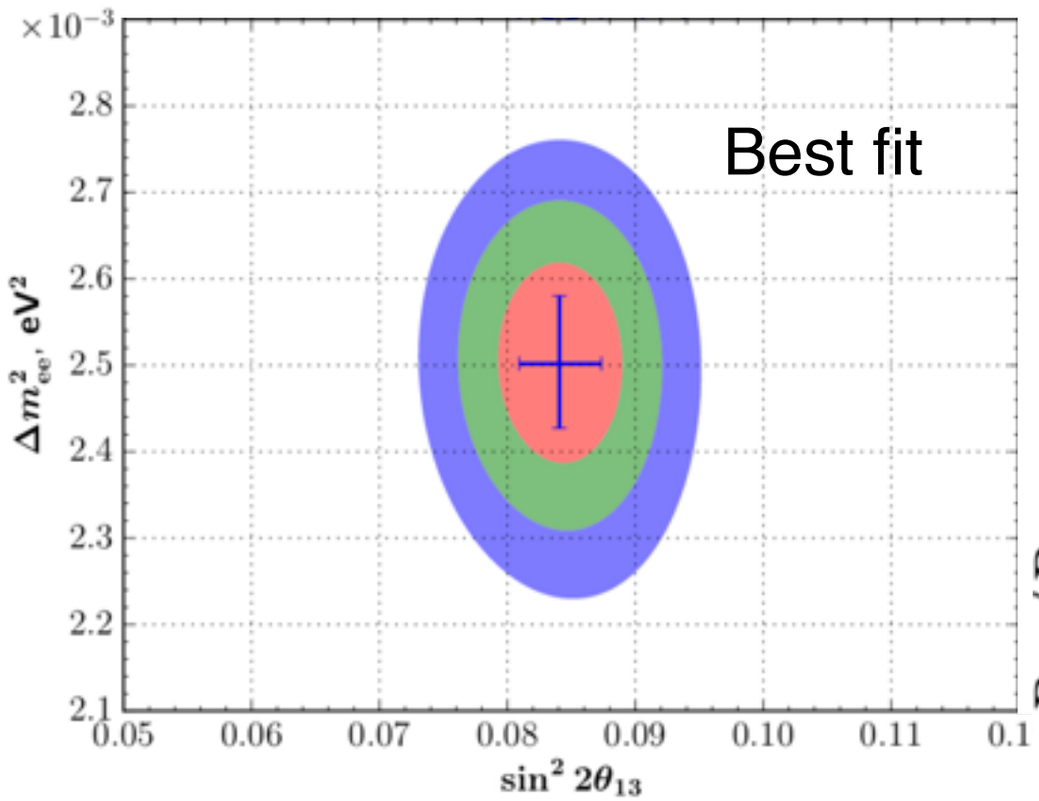


- Sources of energy nonlinearity
  - Scintillator response
  - Readout electronics
- Energy model is constrained with gamma and electron sources.



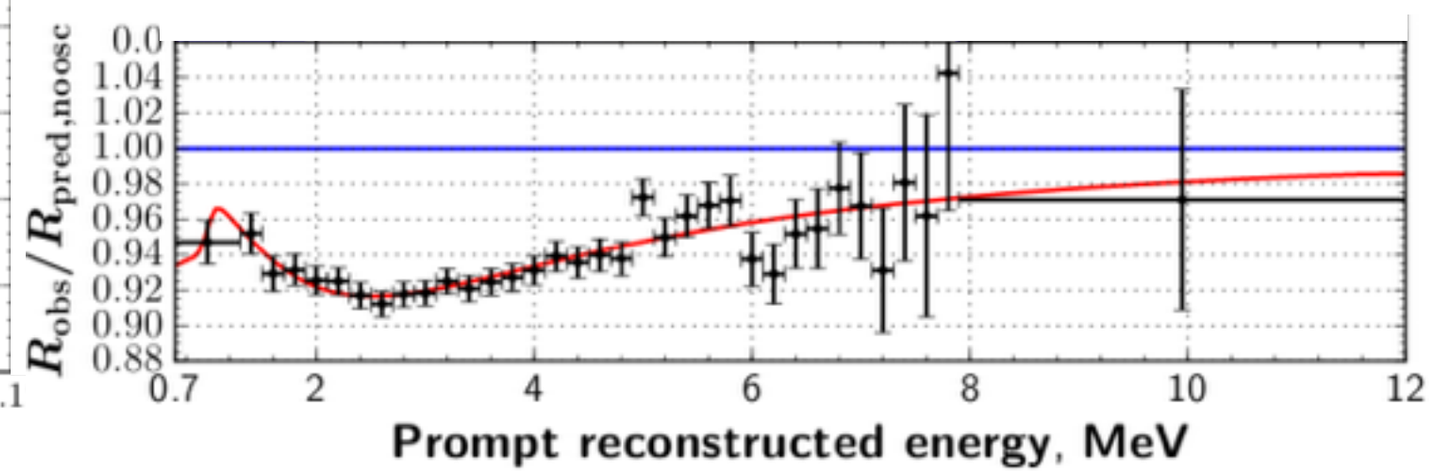
~1% uncertainty (correlated among detectors)

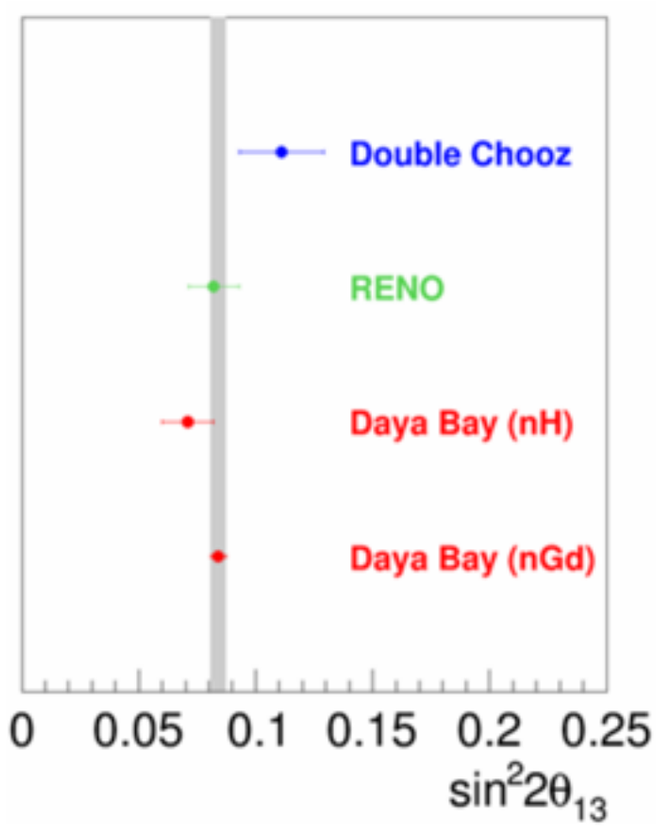
Main Oscillation Results (1230 Days data)

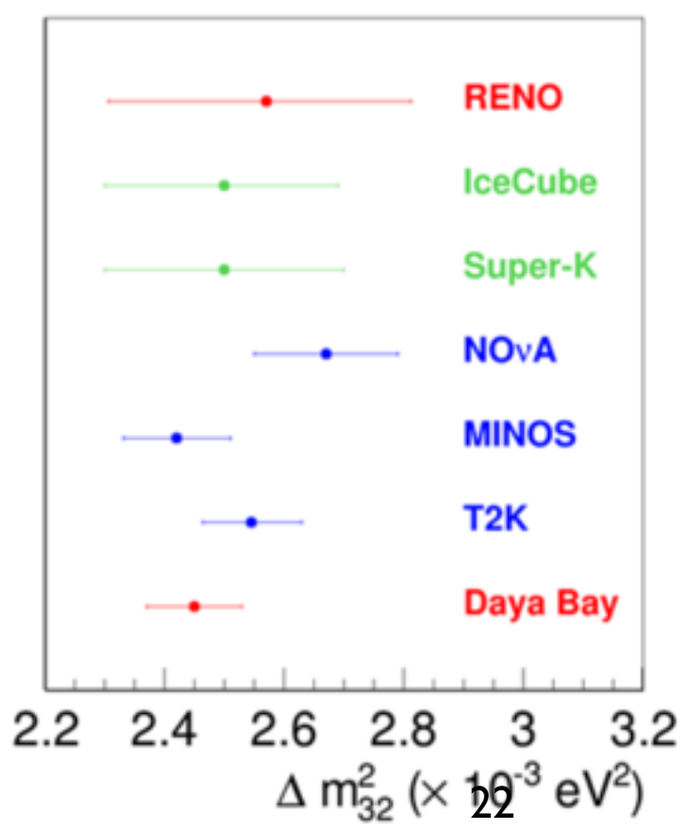


$$\sin^2 2\theta_{13} = (8.41 \pm 0.27 \pm 0.19) \times 10^{-2}$$

$$|\Delta m^2_{ee}| = (2.50 \pm 0.06 \pm 0.06) \times 10^{-3} (eV^2)$$







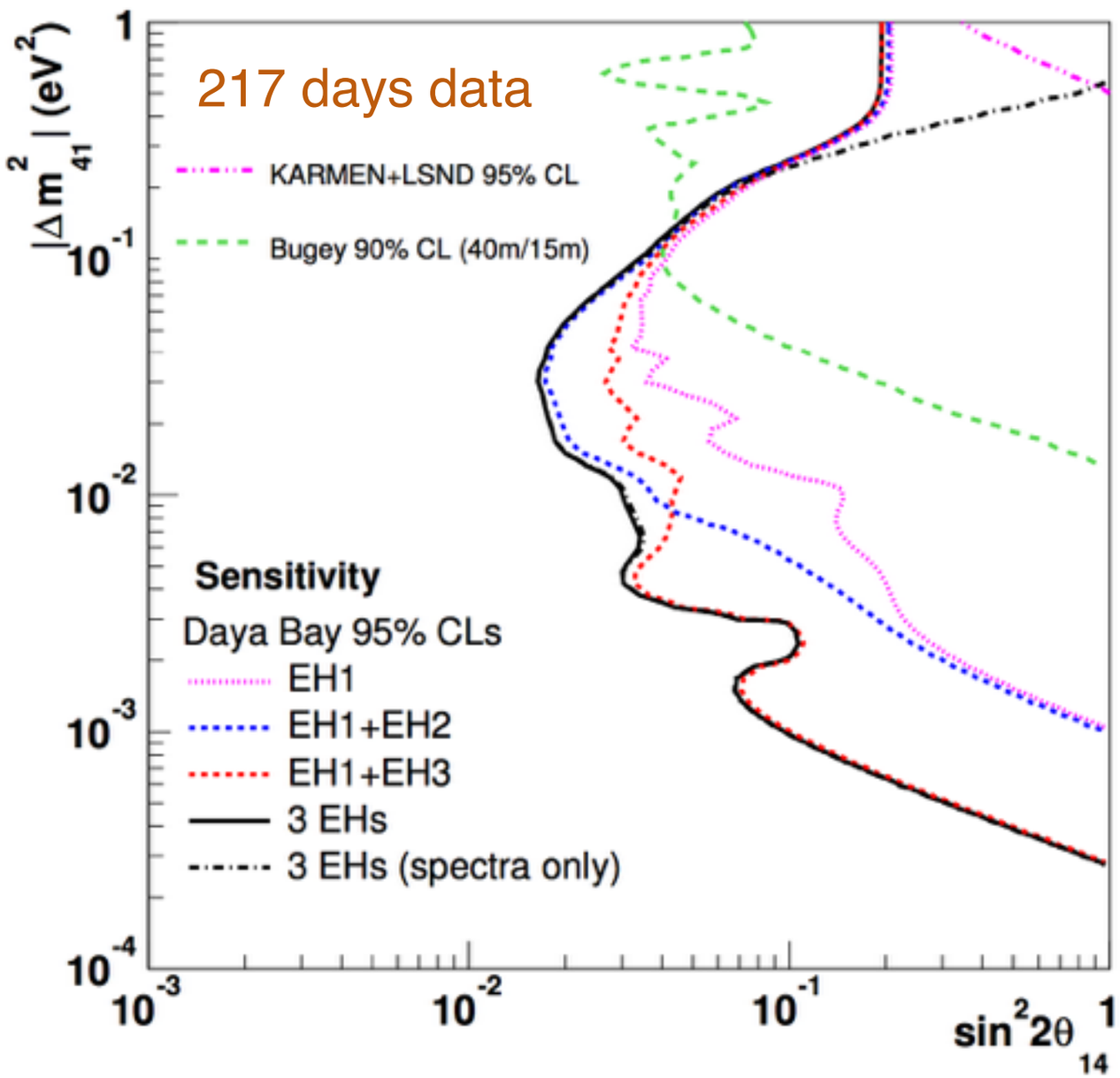
- $\sin^2 2\theta_{13}$ reaches a precision of 4%.
- Δm^2_{32} precision reaches 3.4%, which surpass that of T2K and MINOS experiments.

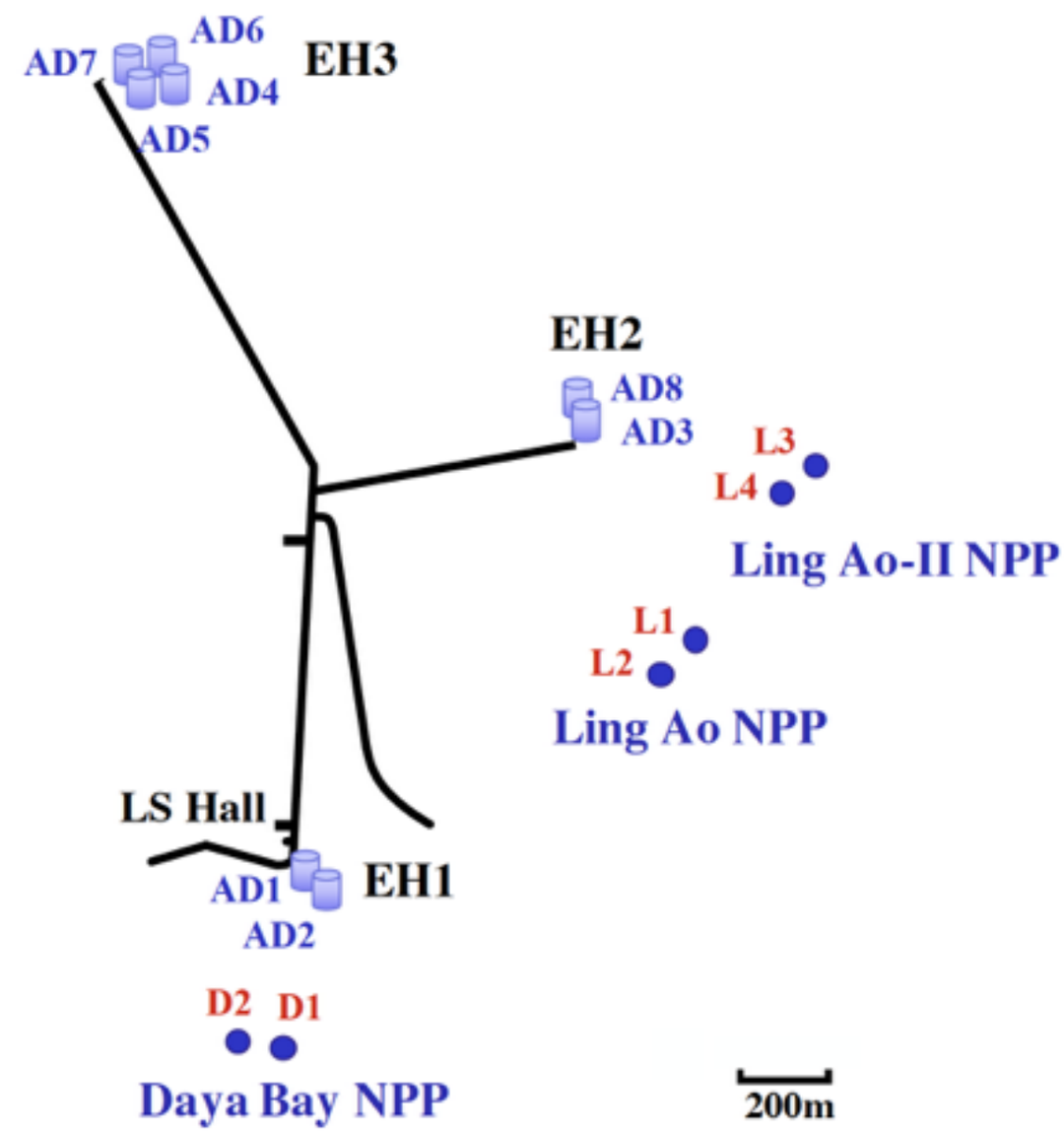
Daya Bay Recent Results in 2016

- 1230 days data
  - Main nGd oscillation analysis (paper is in preparation)
- 621 days data
  - nH oscillation analysis (PRD 93, 072011)
  - Light sterile neutrino search (arXiv:1607.01174)
  - Daya Bay, Bugey-3 and MINOS sterile neutrino results combination (arXiv:1607.01177)
  - Reactor neutrino flux and spectrum measurement (arXiv:1607.05378)
  - Wave packet neutrino oscillation (arXiv:1608.01661)
- 217 days data
  - Reactor neutrino flux and spectrum measurement (PRL 116, 061801)
- Others
  - Daya Bay detector system (NIM A 811, 133-161)

Daya Bay's Sensitivity to Sterile Neutrino

- Unique configuration of multiple baselines detectors is an asset for sterile neutrino search.



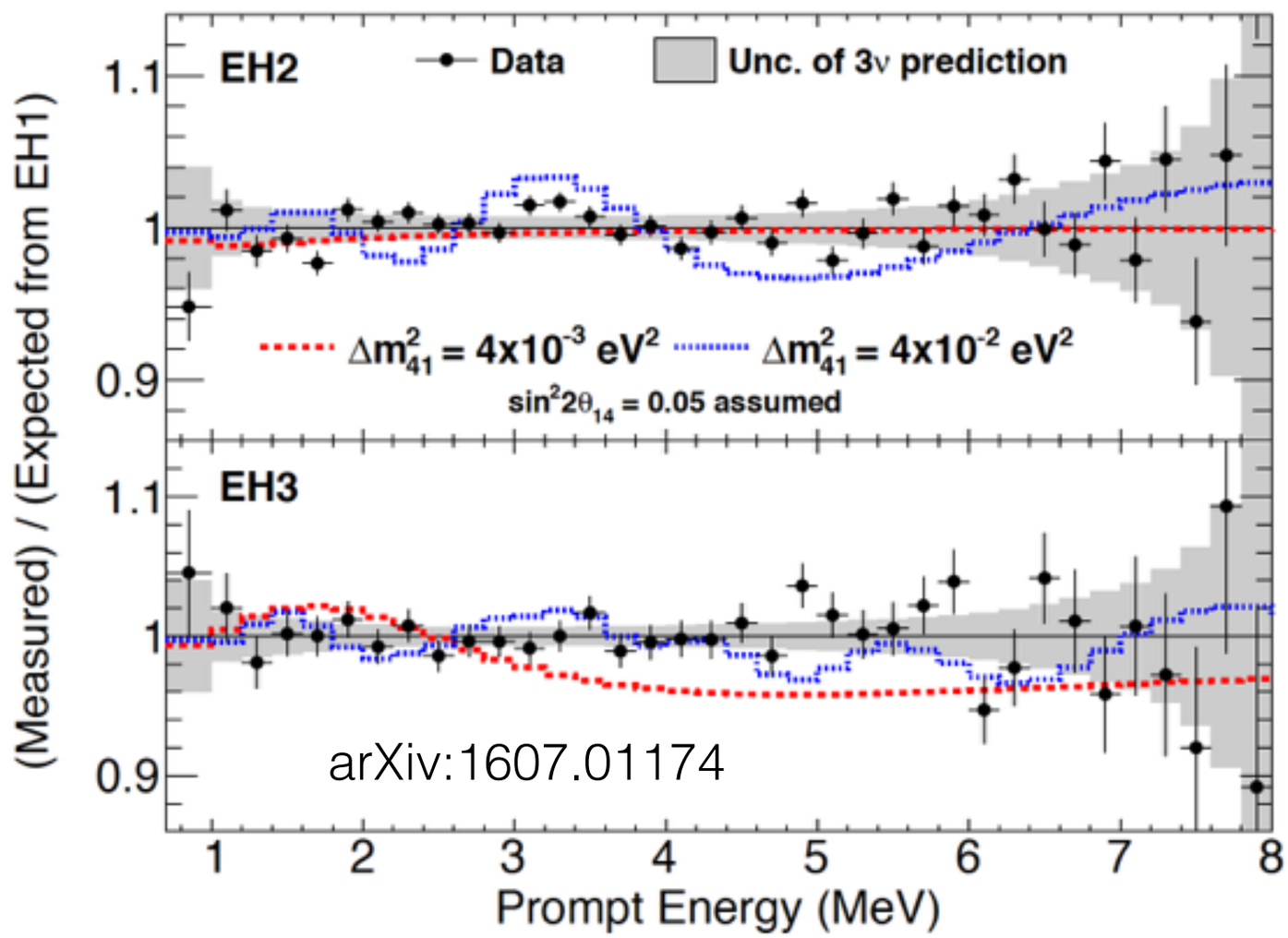


Phys.Rev. Lett.113,141802 (2014)

Light Sterile Neutrino Search

- 3.6 times more statistics compare to previous publication[1].
  - More than 1 M IBD candidates collected.

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2(\frac{\Delta m^2_{41} L}{4E}) - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{ee} L}{4E})$$



[1] Phys. Rev. Lett. 113, 141802 (2014)

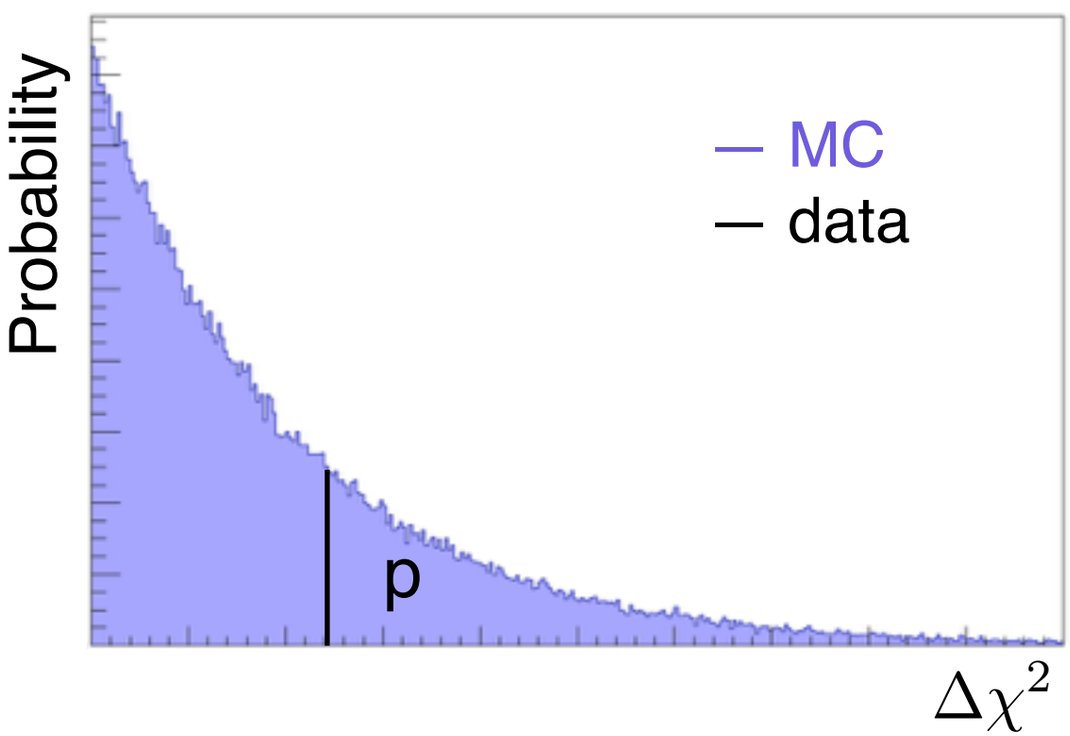
Fieldman-Cousins (FC) Method

For each (θ_{14} , Δm^2_{41}) calculate χ^2 and find the global minimum value

Then define

$$\boxed{\Delta\chi^2 = \chi^2(\theta_{14}, \Delta m^2_{41}) - \chi^2_{min}(\theta_{14}(min), \Delta m^2_{41}(min))}$$

For each (θ_{14} ,Δm^2_{41}) calculate $\Delta\chi^2$ distribution using MC, from which a p-value can be extracted for that point.



Confidence interval of α is set at

$$p = 1 - \alpha$$

FC method is very computation demanding and time consuming

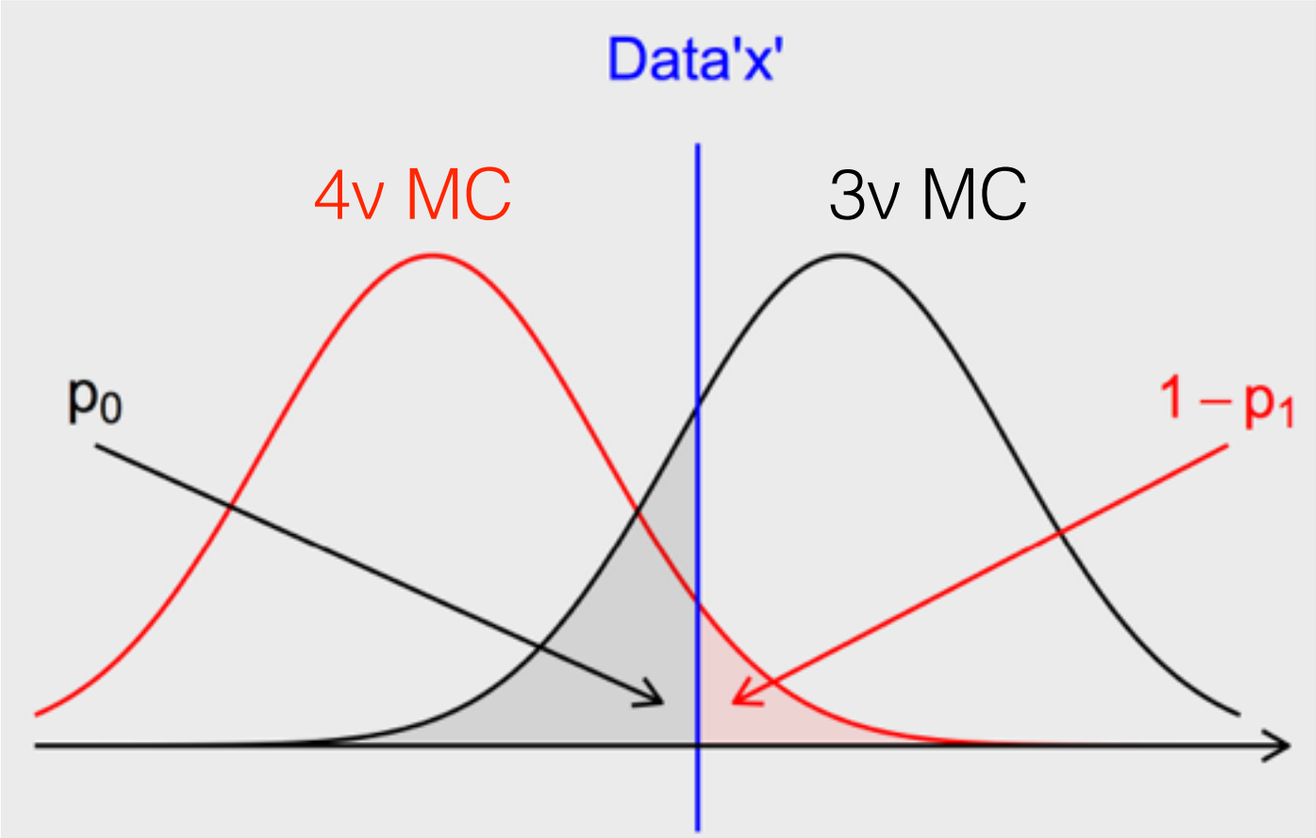
Gary J. Fieldman and Robert D. Cousins, PRD 57, 3873 (1998)

CL_s Method*

For each (θ_{14} , Δm^2_{41}) compare two hypotheses: 3v and 4v.

Define $$\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$$

then $$CL_s = \frac{1 - p_1}{1 - p_0}$$



For Gaussian CLs†, calculate

$\Delta\chi^2_{data}$ — data

$\Delta\chi^2_{3\nu}$ — 3v Asimov data

$\Delta\chi^2_{4\nu}$ — 4v Asimov data

$$CL_s = \frac{1 + Erf\left(\frac{\Delta\chi^2_{4\nu} - \Delta\chi^2_{data}}{\sqrt{8|\Delta\chi^2_{4\nu}|}}\right)}{1 + Erf\left(\frac{\Delta\chi^2_{3\nu} - \Delta\chi^2_{data}}{\sqrt{8|\Delta\chi^2_{3\nu}|}}\right)}$$

* A.L. Read J. Phys. G28, 2693
* T. Junk NIMA 434, 435
† X. Qian et al. NIMA 827, 63 (2016)

Combination using CL_s method

Why CL_s method?

- FC method is too complicated to combine results from different experiments.
  - Finding the global χ^2 minimum for the combined experiments is a big challenge.
- CL_s is easy for combining results from different experiments.
  - Compare two hypothesis directly and no need to find the global minimum χ^2.

Combining steps

- Combine Daya Bay and Bugey-3 results.
- Combine Daya Bay/Bugey-3 and MINOS results.

Combination using CL_s method

Daya Bay and Bugey-3 combination

$$\Delta\chi^2_{data} = \Delta\chi^2_{data}|_{DayaBay} + \Delta\chi^2_{data}|_{Bugey}$$

$$\Delta\chi^2_{3\nu} = \Delta\chi^2_{3\nu}|_{DayaBay} + \Delta\chi^2_{3\nu}|_{Bugey}$$

$$\Delta\chi^2_{4\nu} = \Delta\chi^2_{4\nu}|_{DayaBay} + \Delta\chi^2_{4\nu}|_{Bugey}$$

→ CL_s values

Daya Bay/Bugey-3 and MINOS combination

- Daya Bay/Bugey-3 and MINOS

$$\Delta\chi^2_{com} = \Delta\chi^2_{DB} + \Delta\chi^2_{M}$$

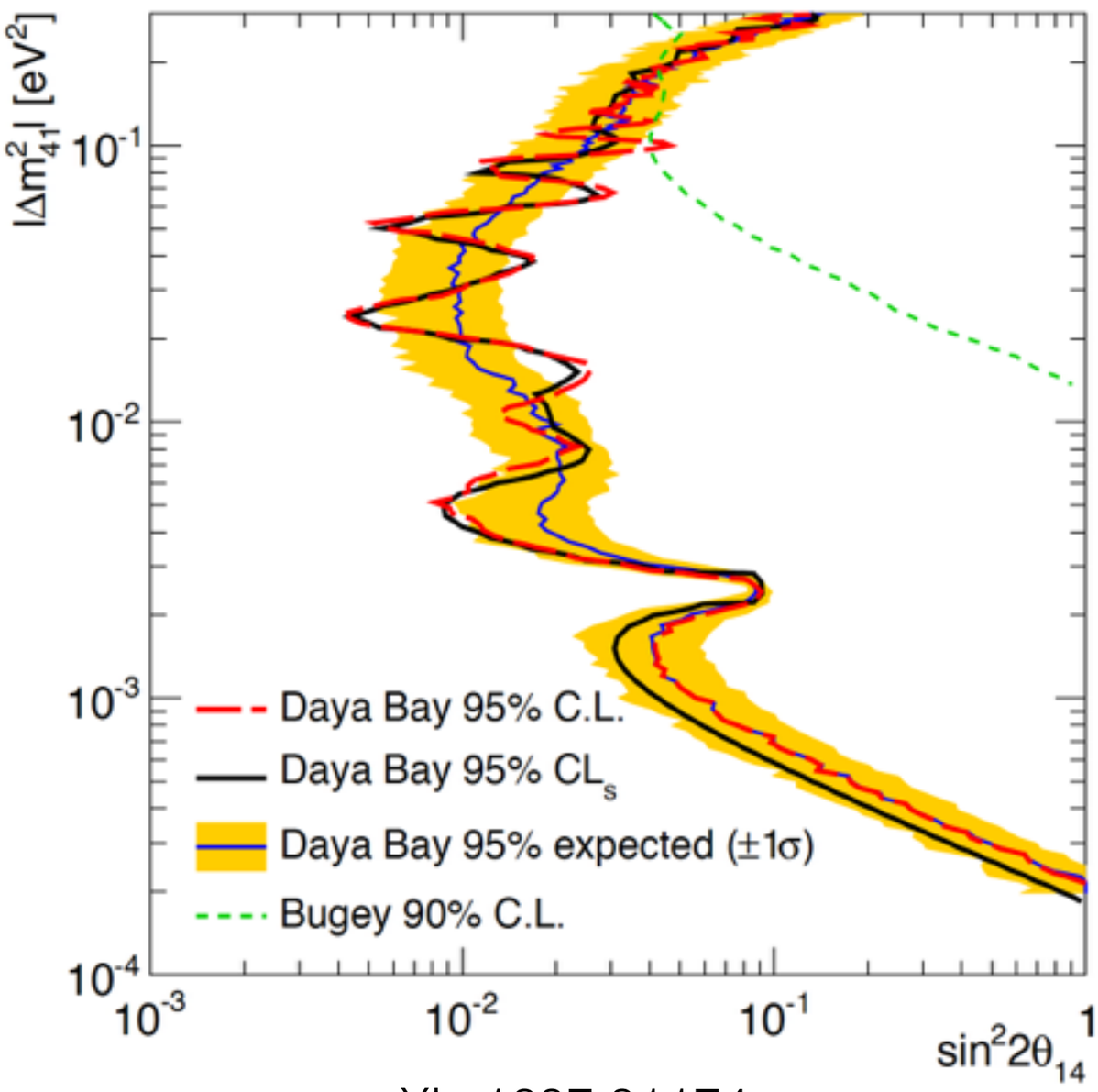
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

- Then calculate the CL_s value for each (Δm^2_{41}, $\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$)

- The largest CL_s value is picked for the $\sin^2 2\theta_{\mu e}$ to be conservative.

Light Sterile Neutrino Search Results

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2(\frac{\Delta m^2_{41} L}{4E}) - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{ee} L}{4E})$$



arXiv:1607.01174

- FC and CLs results are consistent
- No evidence of sterile neutrino in

$$2 \times 10^{-4}\, eV^2 \lesssim |\Delta m^2_{41}| \lesssim 0.3\, eV^2$$

- Most stringent constraints to date in $|\Delta m^2_{41}| \lesssim 0.2\, eV^2$

Light Sterile Neutrino Search Results

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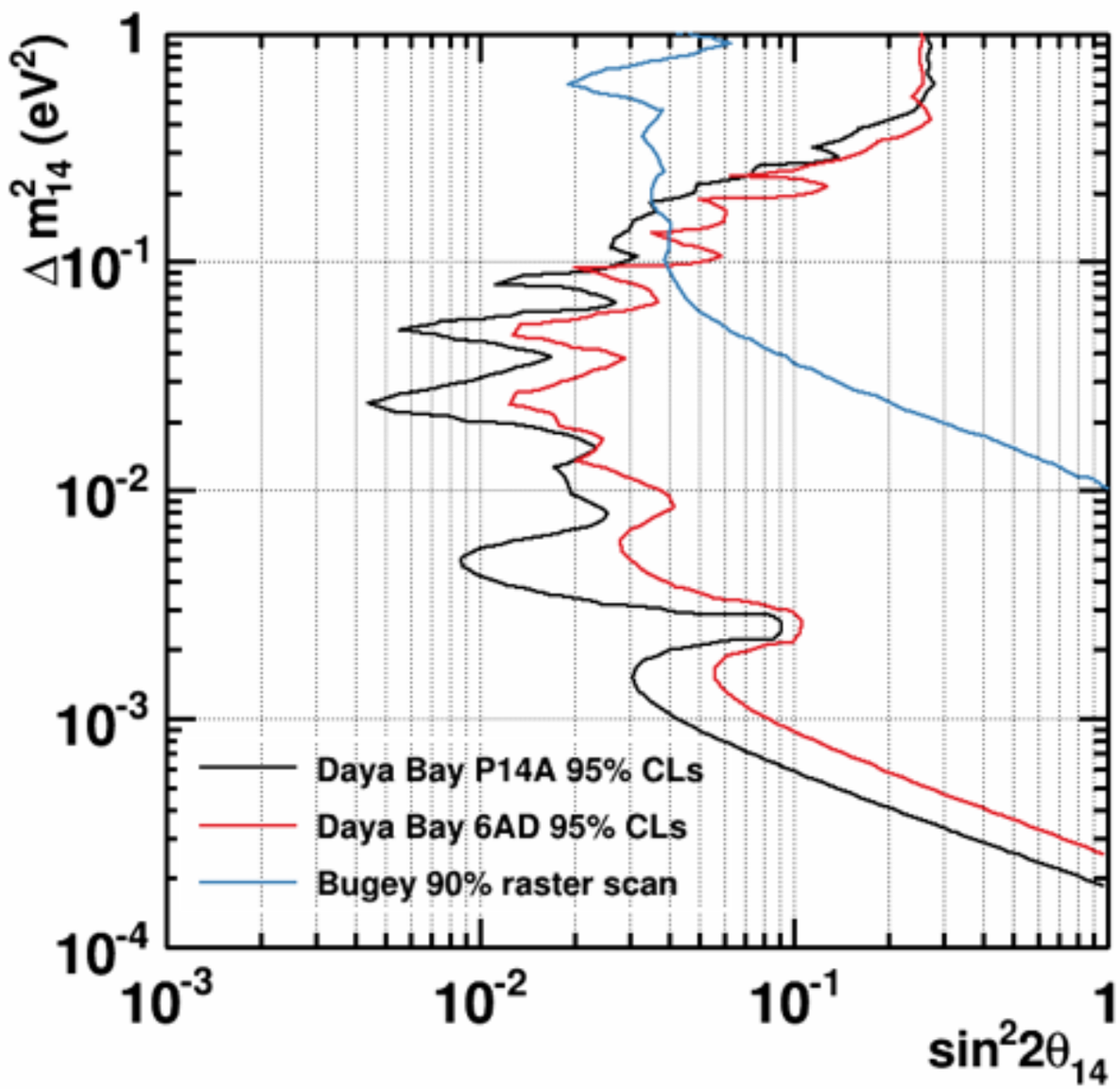

- FC and CLs results are consistent
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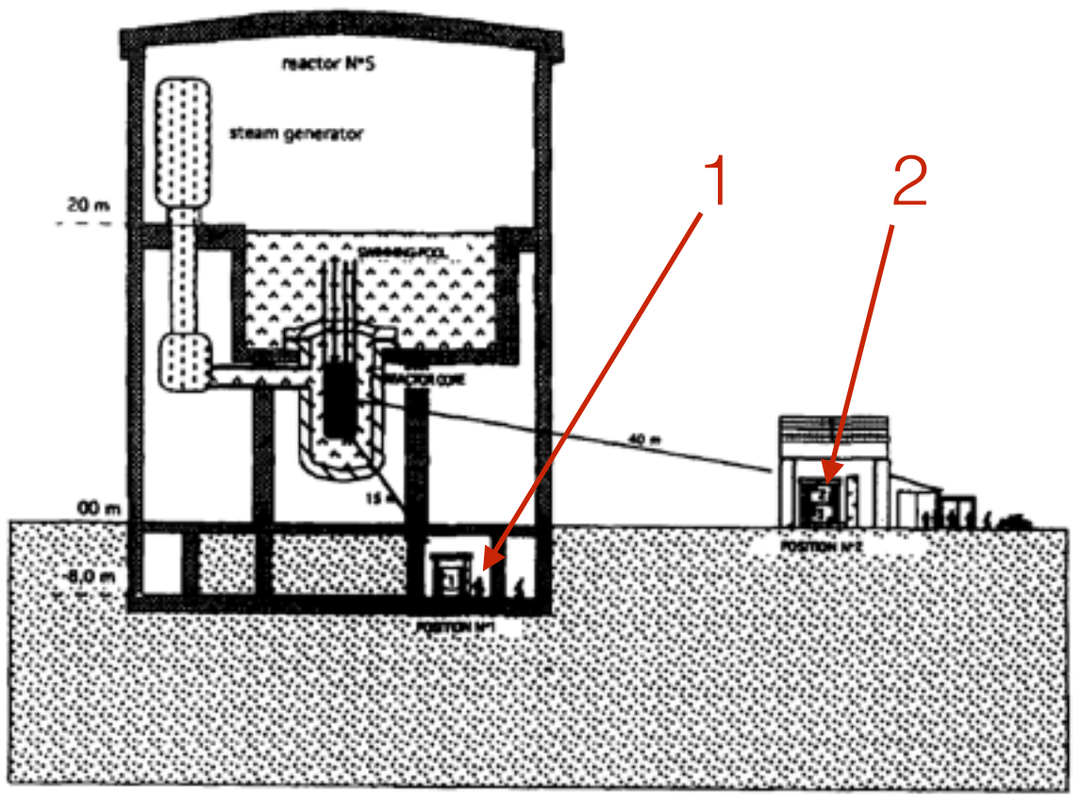
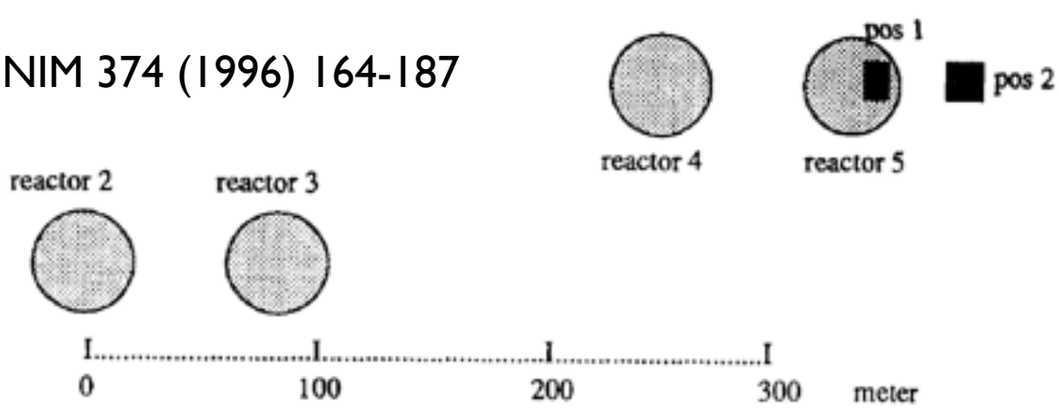
$$2 \times 10^{-4}\, eV^2 \lesssim |\Delta m^2_{41}| \lesssim 0.3\, eV^2$$

- Most stringent constraints to date in $|\Delta m^2_{41}| \lesssim 0.2\, eV^2$
- The result limits on $\sin^2 2\theta_{14}$ are improved by a factor of ~2 over previous results.

Bugey-3 experiment overview



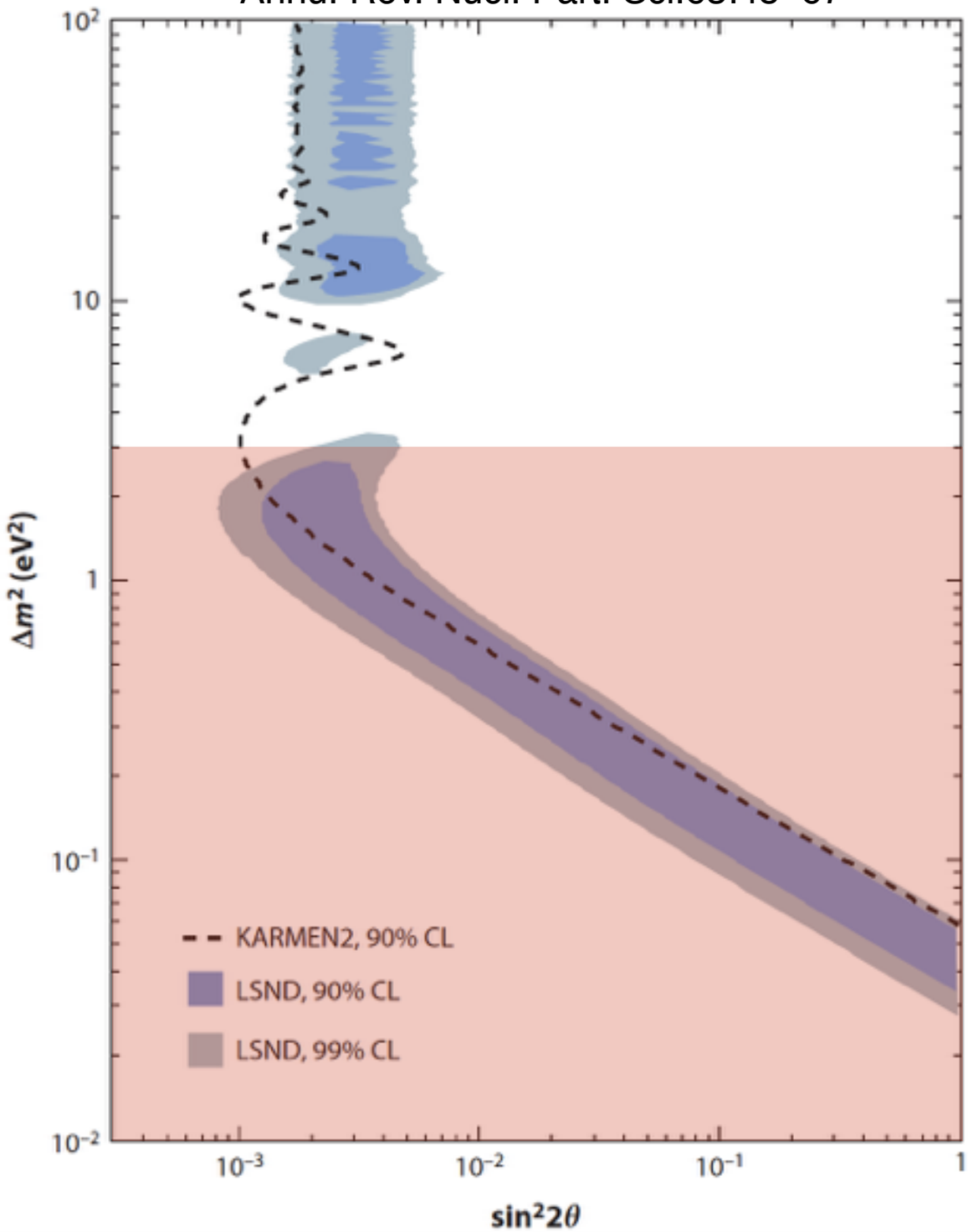
NIM 374 (1996) 164-187



- Bugey-3 experiment was carried out in 1990s to search for neutrino oscillation.
  - No neutrino oscillation was observed.
- Detecting reactor neutrinos use three functional identical detector modules placed at two positions.
  - 15, 40 and 95m
  - Probe different sensitivity region of Δm^2_{41}.

Why Bugey-3?

Annu. Rev. Nucl. Part. Sci.63:45–67



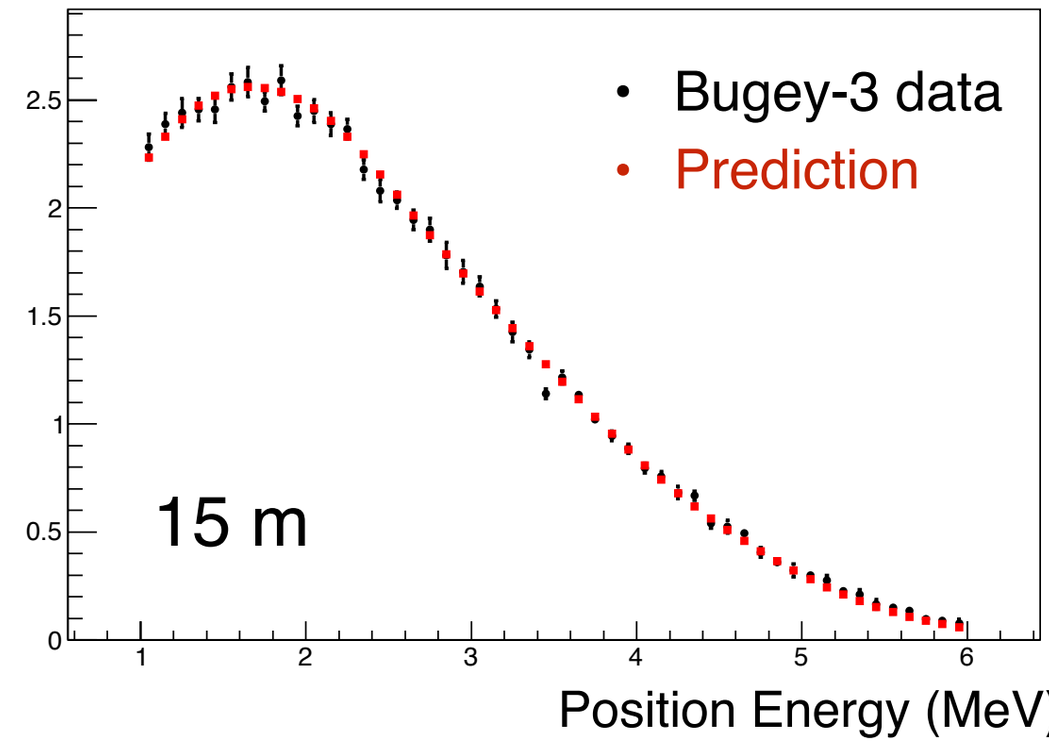
Daya Bay and Bugey-3 combine can probe LSND/MiniBooNE allowed region for:

$$\Delta m^2_{41} \lesssim 3\, eV^2$$

Why reproduce Bugey-3 result?

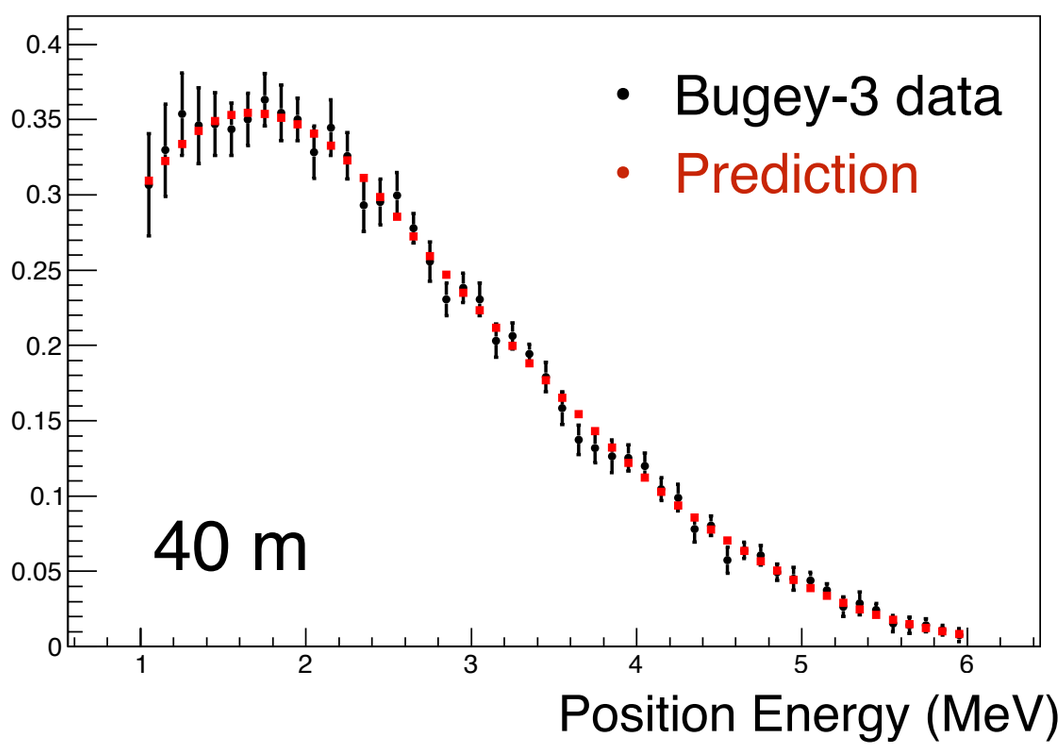
- Combination at fitter level allows us to take into account the correlations from reactors.
- Bugey-3's original fitter is not available anymore.

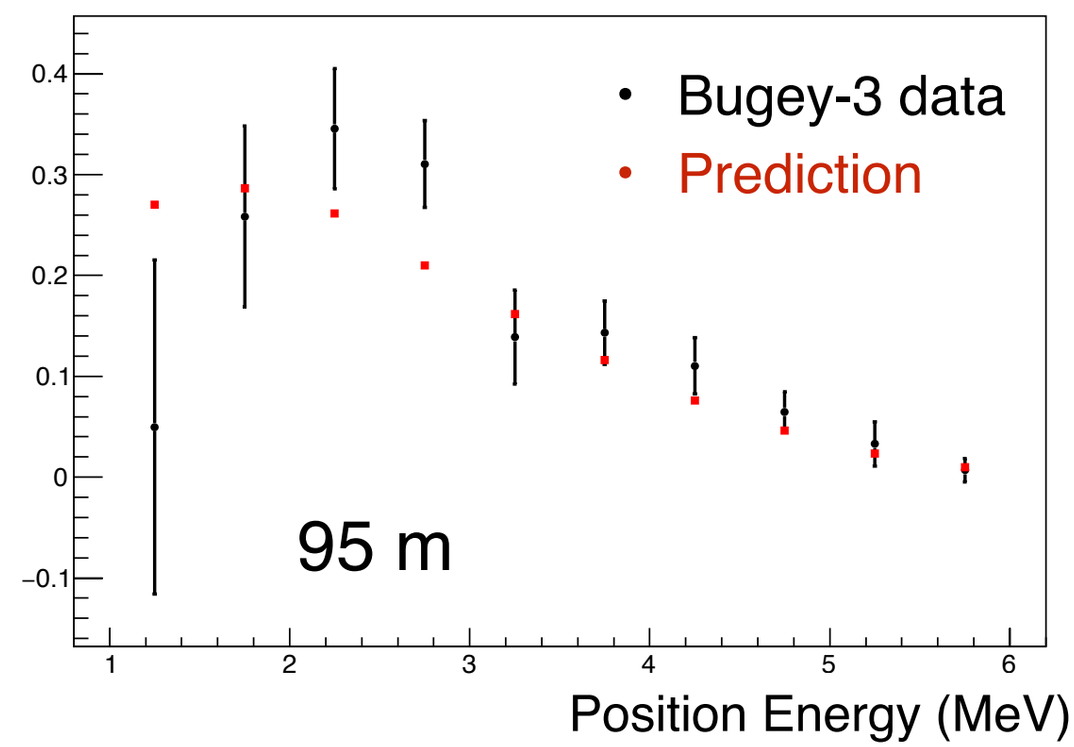
Reproduced Bugey-3 Positron Spectrum



Bugey-3's positron spectra at 15, 40 and 95 m baselines are successfully reproduced.

Predicted spectra are normalized to the Bugey-3 measured spectra.





Bugey-3 data used and chi-2 format

Nucl. Phys. B 434 (1995) 503-532

$$\chi_1^2 = \sum_{i=1}^{25} \frac{\{[(1-a_0)\cdot(1+a_2)+a_1\cdot(E_i-1.0)]\cdot R_i^{pre} - R_i^{obs}\}^2}{\sigma_i^2}$$

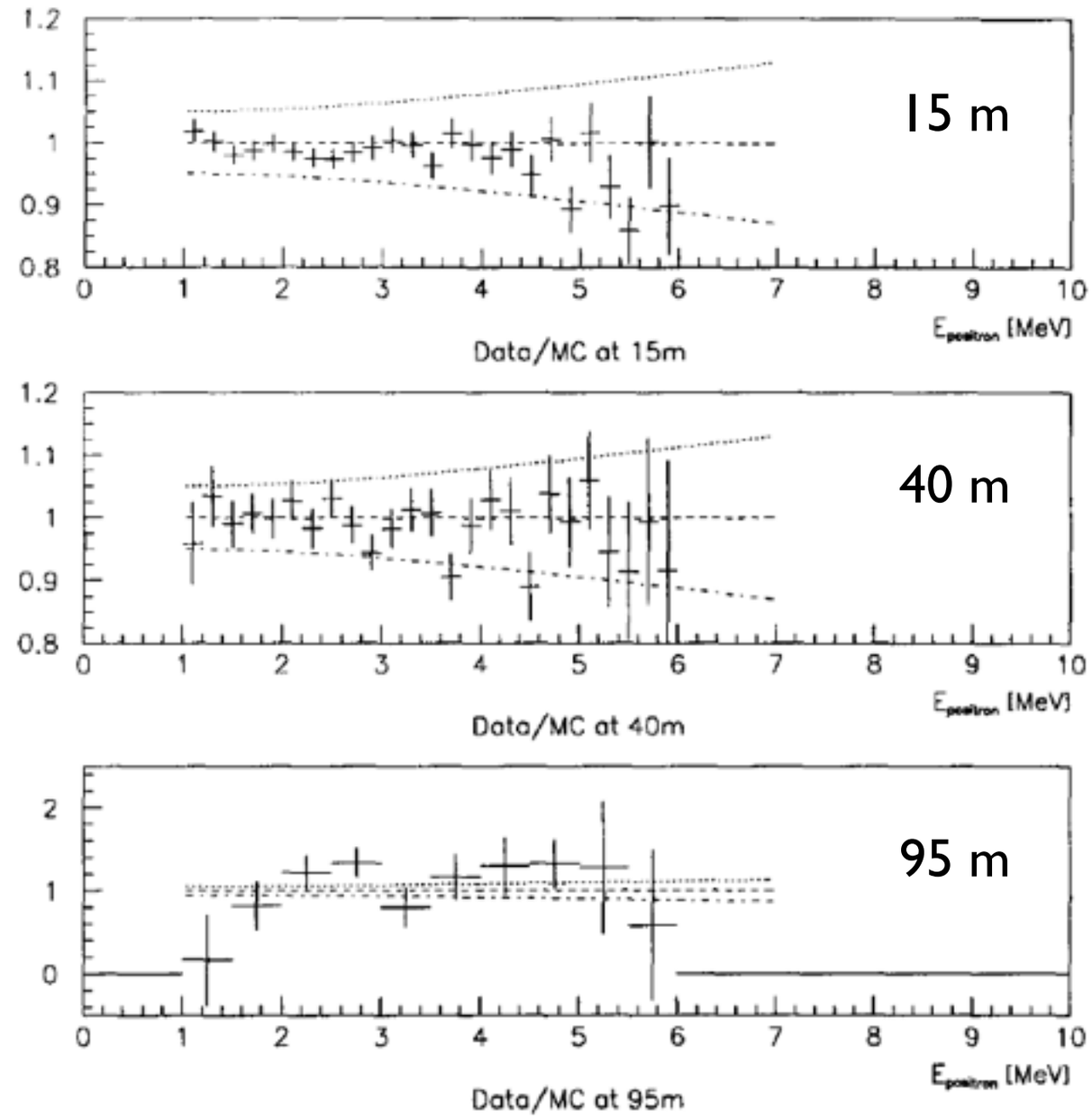
$$\chi_2^2 = \sum_{i=1}^{25} \frac{\{[(1-a_0)\cdot(1+a_3)+a_1\cdot(E_i-1.0)]\cdot R_i^{pre} - R_i^{obs}\}^2}{\sigma_i^2}$$

$$\chi_3^2 = \sum_{i=1}^{10} \frac{\{[(1-a_0)\cdot(1+a_4)+a_1\cdot(E_i-1.0)]\cdot R_i^{pre} - R_i^{obs}\}^2}{\sigma_i^2}$$

$$\boxed{\chi_{total}^2 = \chi_1^2 + \chi_2^2 + \chi_3^2 + \sum_{i=0}^{4} \frac{a_i^2}{\sigma_{a_i}^2}}$$

$$R^{pre} = \frac{N_{pre}^{osc}}{N_{pre}^{no-osc}}$$

$$\sigma_{a_0} = 5\%$$
$$\sigma_{a_1} = 2\%$$
$$\sigma_{a_2} \rightarrow \sigma_{a_4} = 1.4\%$$



ILL+Vogel flux is used here for the reproduction!

Bugey-3 Contour Reproduction

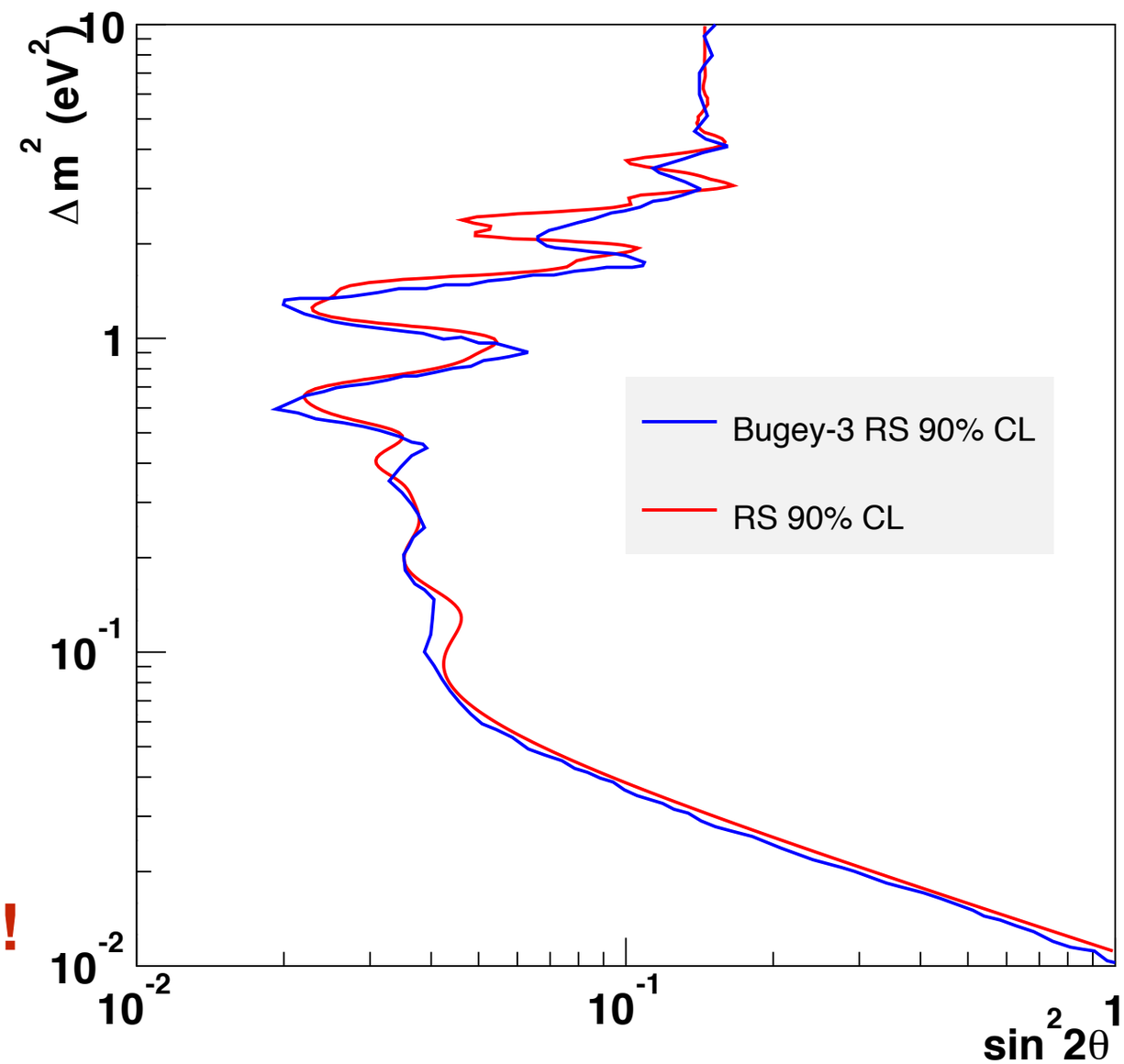
Raster Scan (RS) method

For a fixed Δm^2_{41} , scan the whole θ_{14} space, and find the χ^2 minimum.

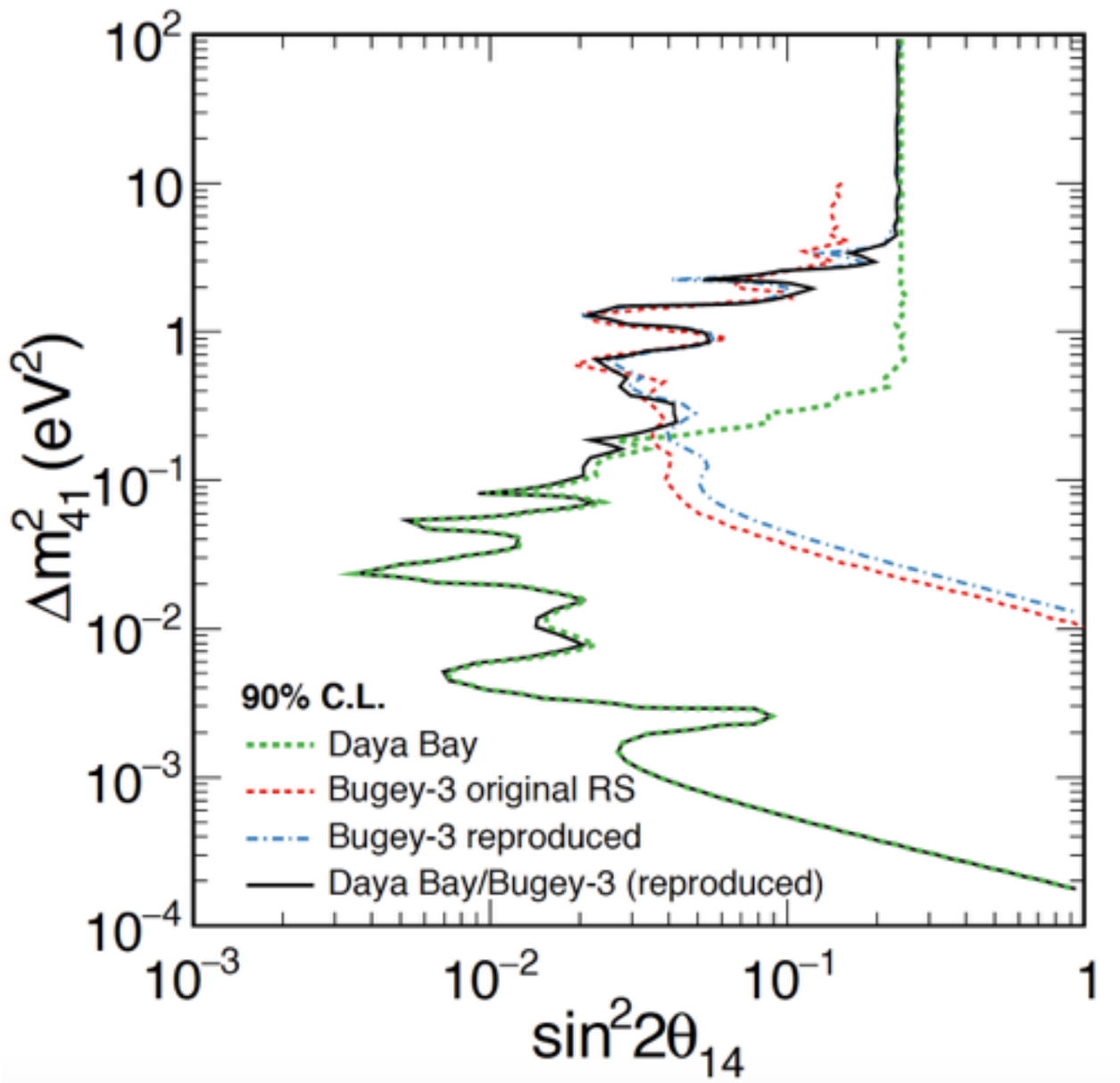
$$\Delta\chi^2 = \chi^2(\theta_{14}, \Delta m^2_{41}) - \chi^2_{min}(\theta_{14}(min), \Delta m^2_{41})$$

Similar processes like FC afterwards.

Bugey-3's 90% C.L. exclusion contour is successfully reproduced!



Daya Bay and Bugey-3 combined



Modifications to Bugey-3 results

- Update the reactor flux models

ILL + Vogel ⟶ **Huber + Mueller**

$$R'^{obs}_{Bugey} = R^{obs}_{Bugey} \cdot \frac{MC(ILL + Vogel)}{MC(Huber + Mueller)}$$

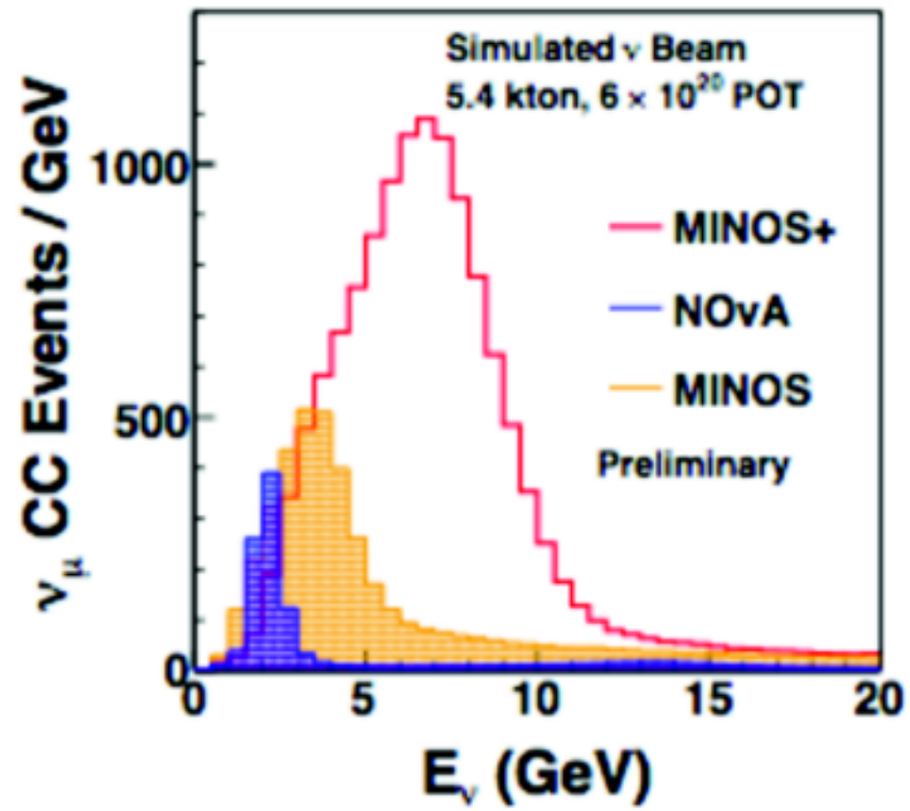
- Update IBD cross sections

- Cross sections inversely proportional to the neutron lifetime.
- The measured neutron lifetime changes since Bugey-3 experiment and affect the IBD cross sections.

CLs method is used for the combination.

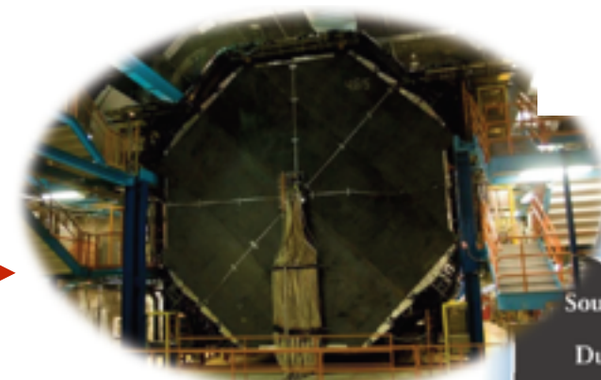
MINOS Overview

- ν_μ dominant beams generated from 120 GeV protons.
- Two functional identical detectors
- Detect ν_μ in both CC and NC modes



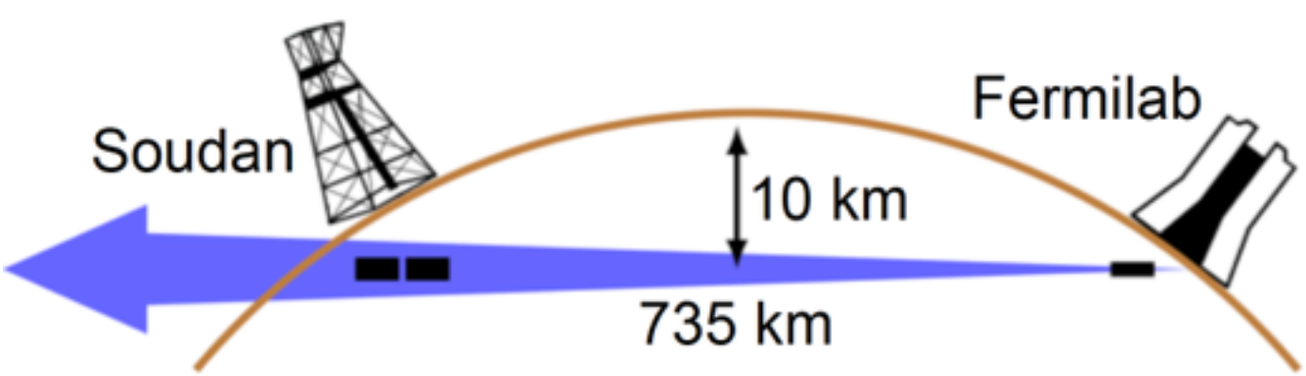
Far detector:

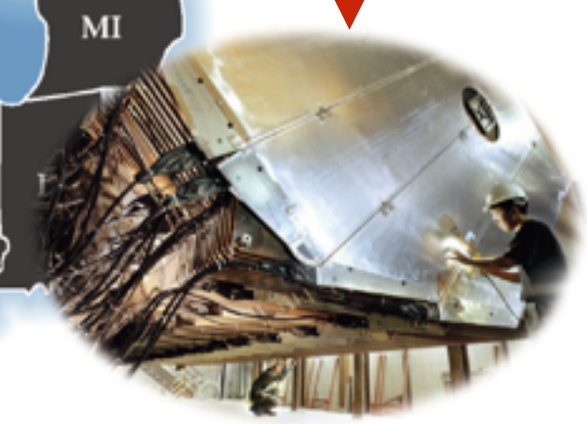
- 735 km baseline
- 5.4k tons mass



Near Detector:

- 1 km baseline
- 1k ton mass

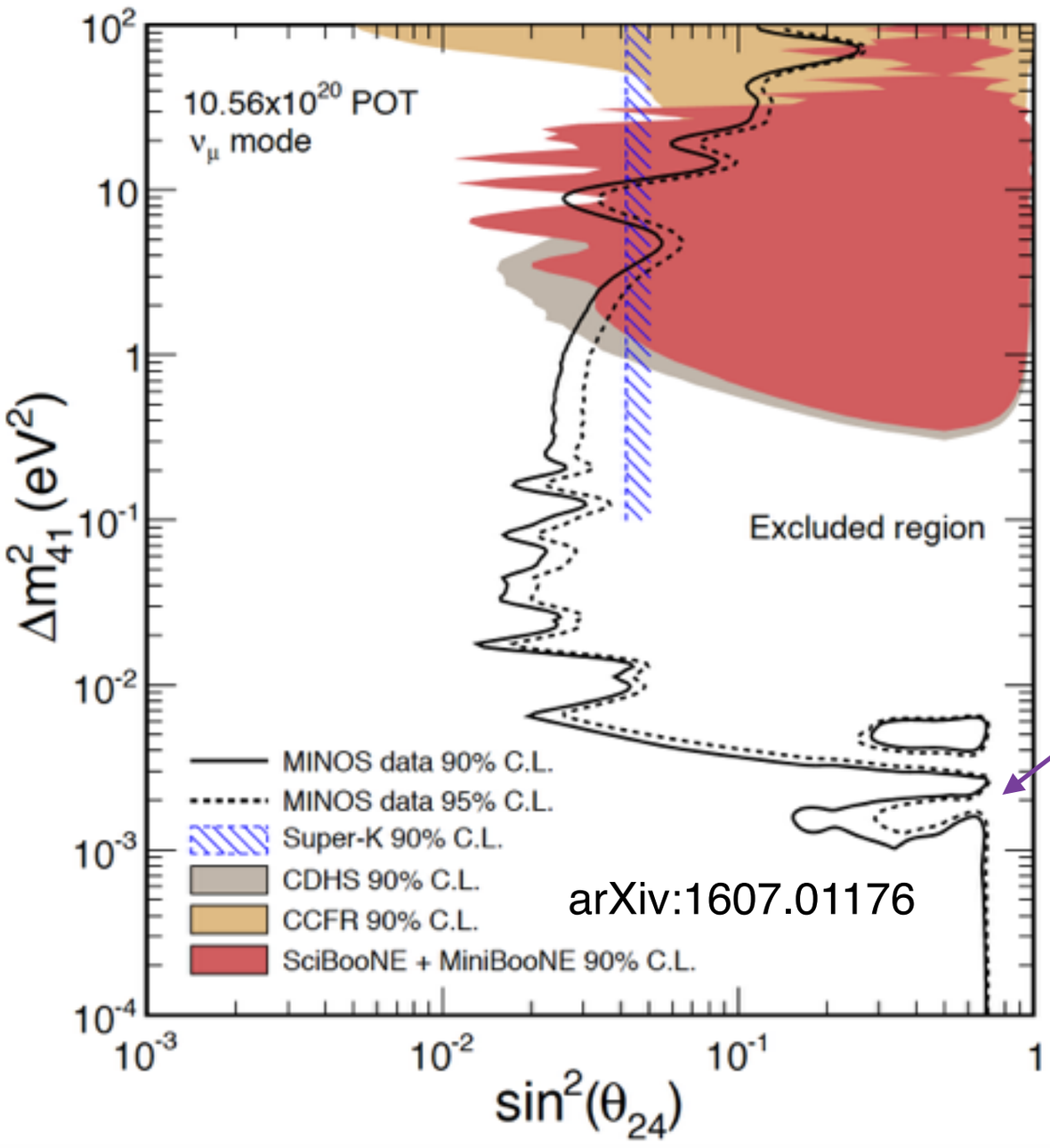




Justin Evans (MINOS), Neutrino 2016

MINOS Sterile Neutrino Result

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2(\frac{\Delta m^2_{31} L}{4E}) - \sin^2 2\theta_{24} \sin^2(\frac{\Delta m^2_{41} L}{4E})$$



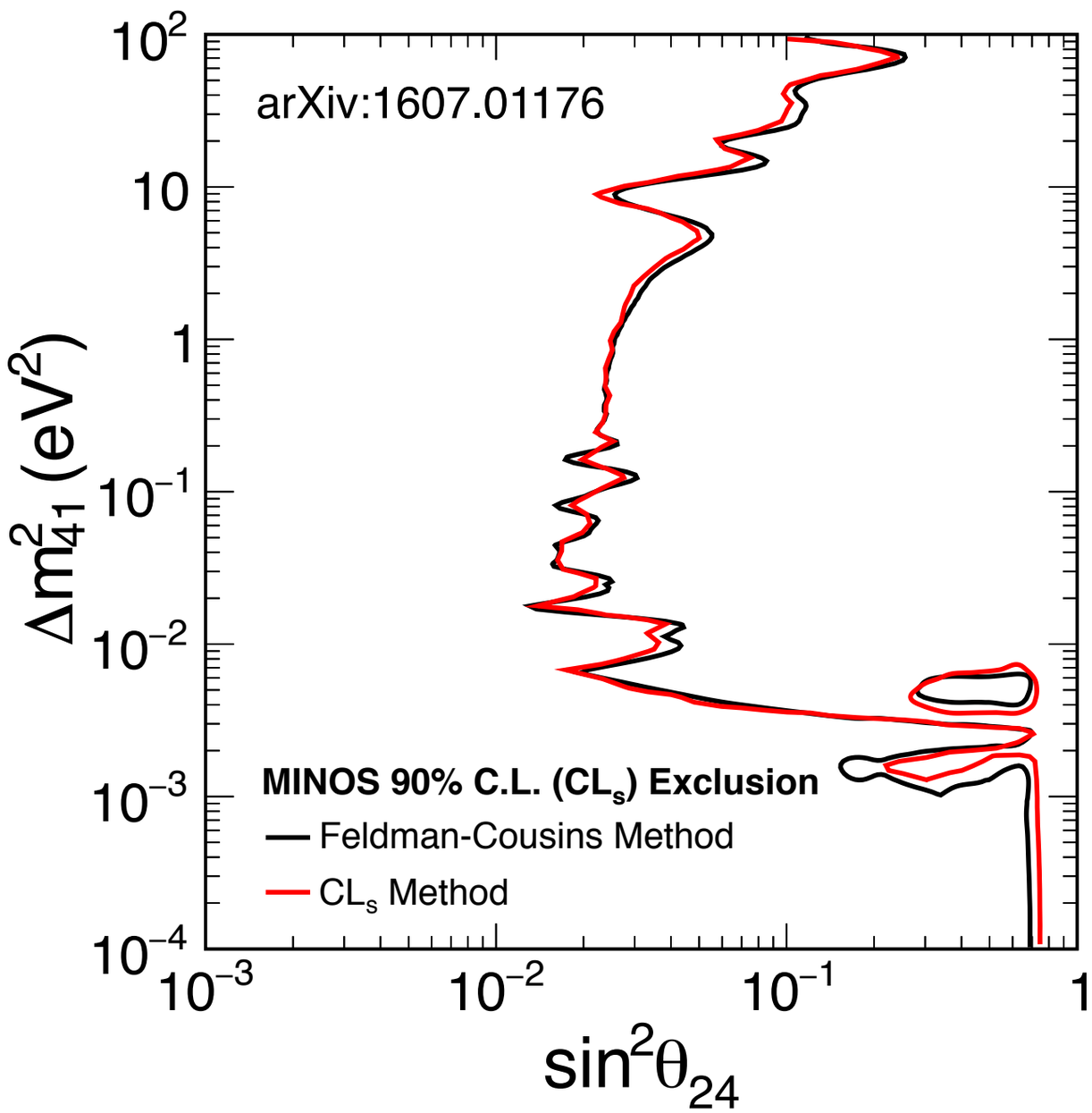
- No sterile neutrino evidence is found for $\nu_\mu \to \nu_s$ oscillation.
- Set most stringent limit on θ_{24} in $|\Delta m^2_{41}| \lesssim 1\, eV^2$

Internal allowed region due to degenerate solutions.

- θ_{24} take on the role of θ_{23}.
- 4v oscillations degenerate with 3v oscillations.

MINOS CLs exclusion contour

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2(\frac{\Delta m^2_{31} L}{4E}) - \sin^2 2\theta_{24} \sin^2(\frac{\Delta m^2_{41} L}{4E})$$



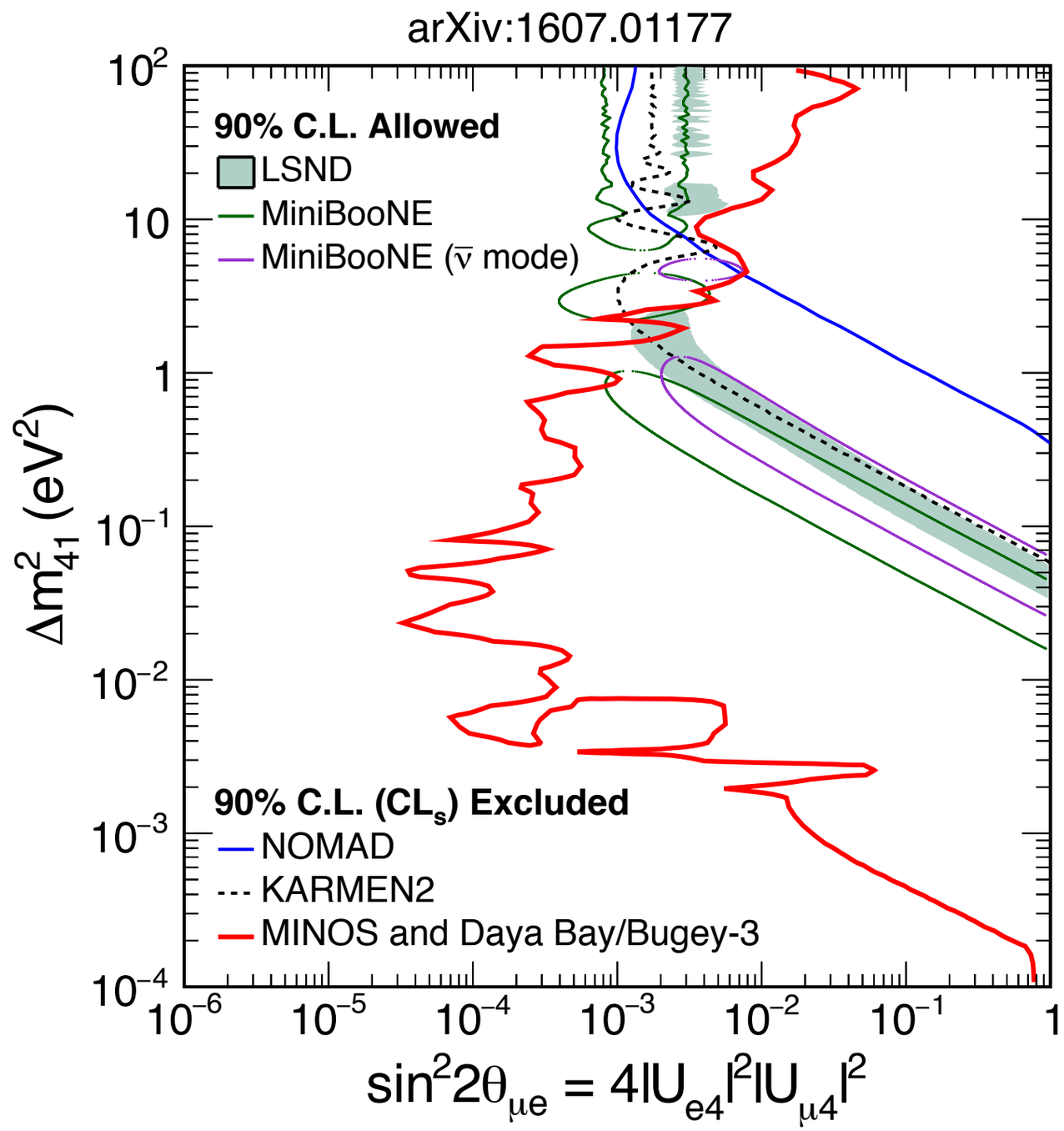
- Standard CLs method is used
  - Gaussian CLs not hold for MINOS
- MC generated for 3v and 4v models.
  - PDG values used for 3v model.
  - θ_{23}, θ_{34}, Δm^2_{32} set to the best fit to data at each (θ_{24}, Δm^2_{41}) point for 4v model

Contours extracted from FC and CLs are consistent!

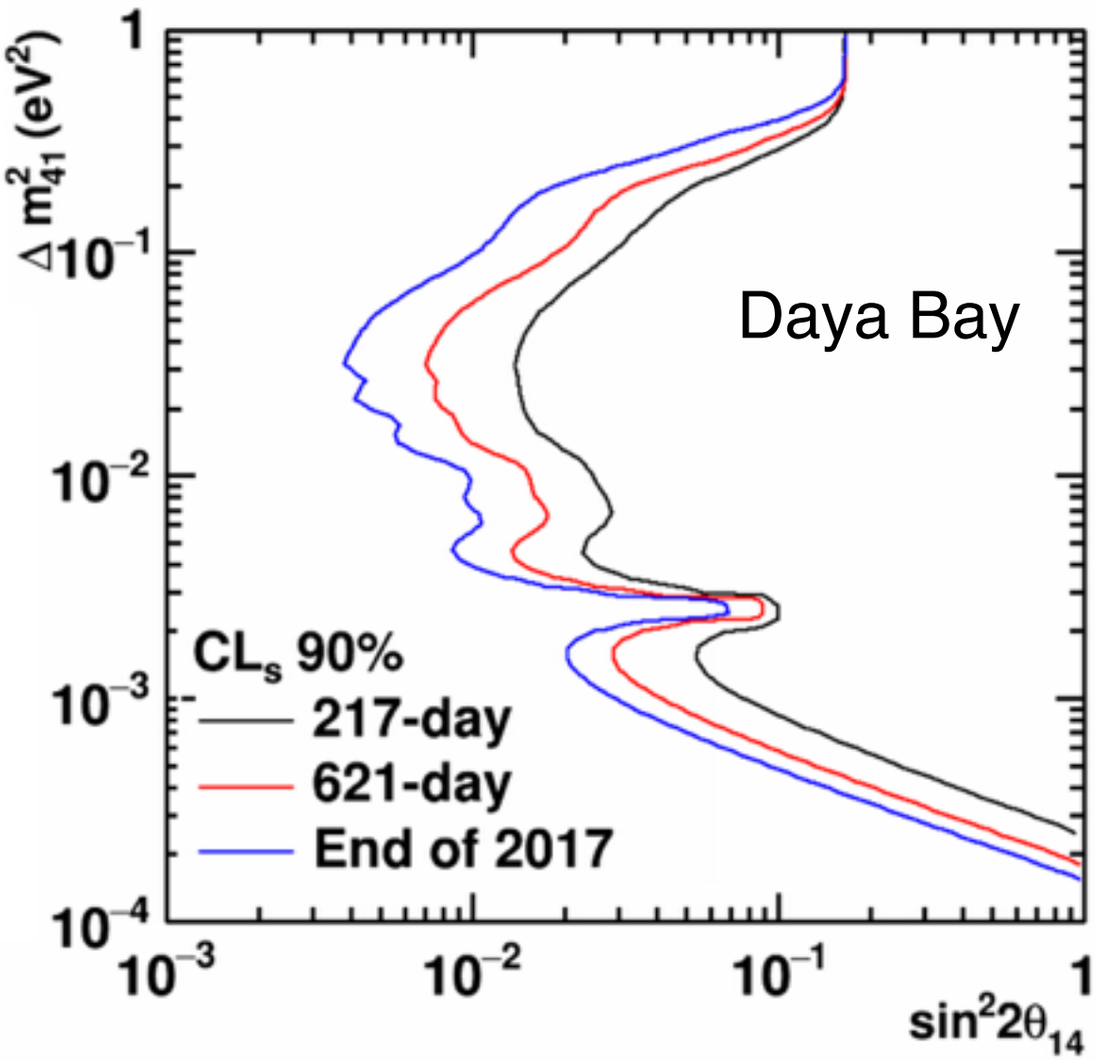
Combination Result

- Stringent limits set on $\sin^2 2\theta_{\mu e}$ over 6 orders of Δm^2_{41}
- The combined 90% C.L. limits excludes regions allowed by LSND and MiniBooNE appearance measurements for

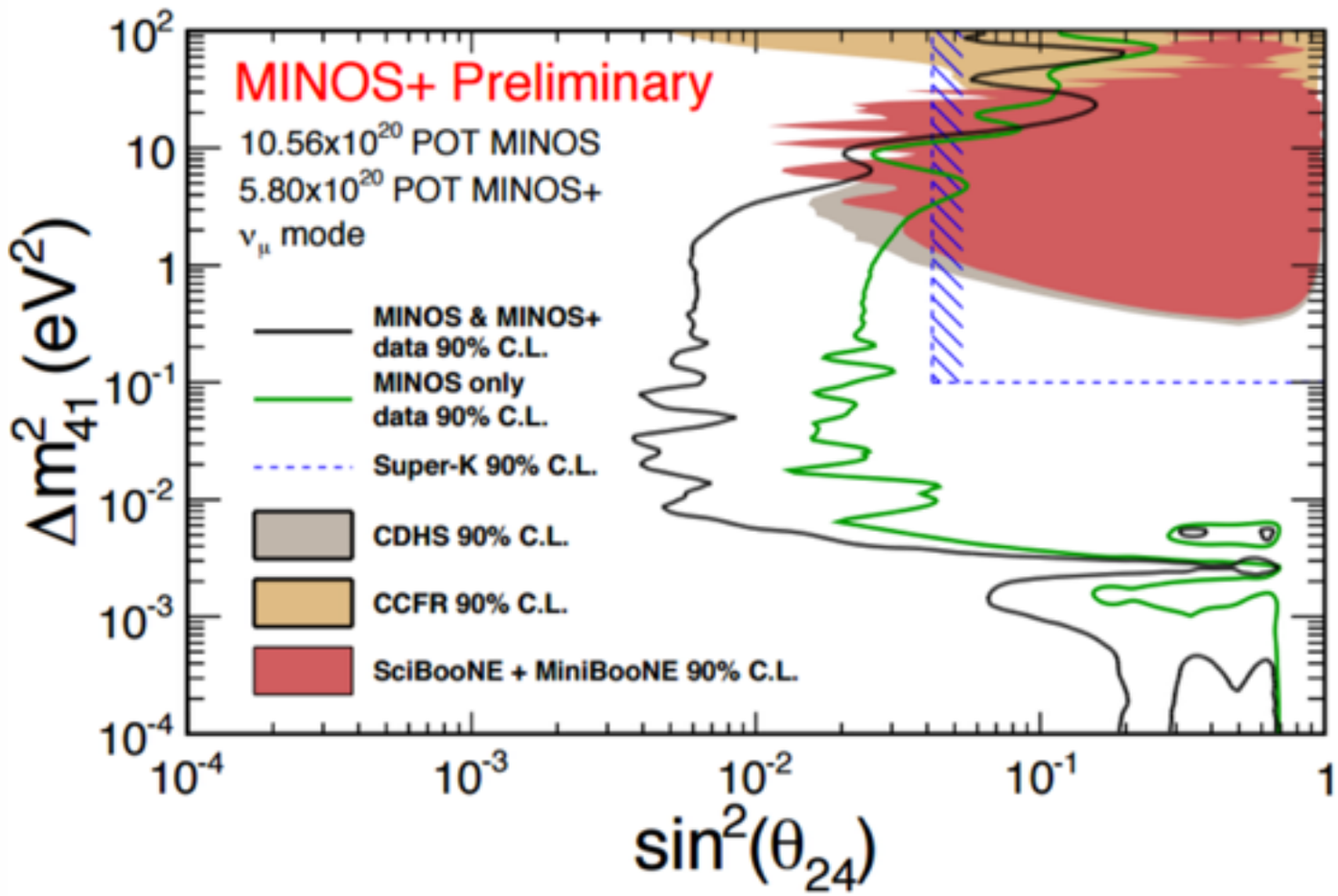
$$\Delta m^2_{41} < 0.8\, eV^2$$



Future Expectation from Daya Bay and MINOS



Expected sensitivity from Daya Bay by the end of 2017.



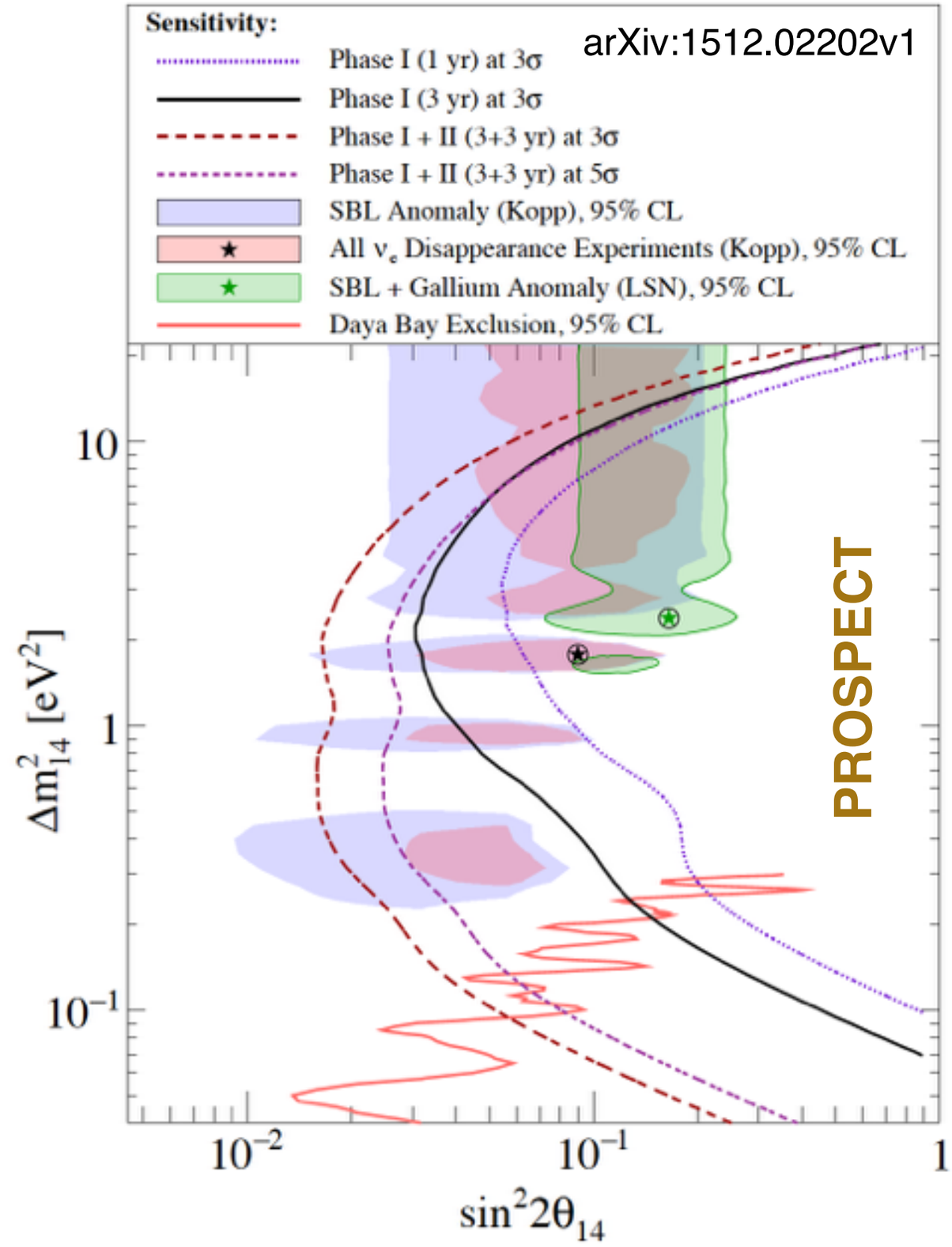
Preliminary results combining with 1/2 MINOS+ data

Future Experiment to Probe Reactor Anomaly

Main Goals of the PROSPECT reactor experiment:

- Search for $\Delta m^2 \sim 1\ eV^2$ sterile neutrinos.
- Precise measurement of ^{235}U spectrum.

PROSPECT can replace Bugey-3 in the near future for the better exclusion power



Reactor Flux Measurement at Daya Bay

621 days data

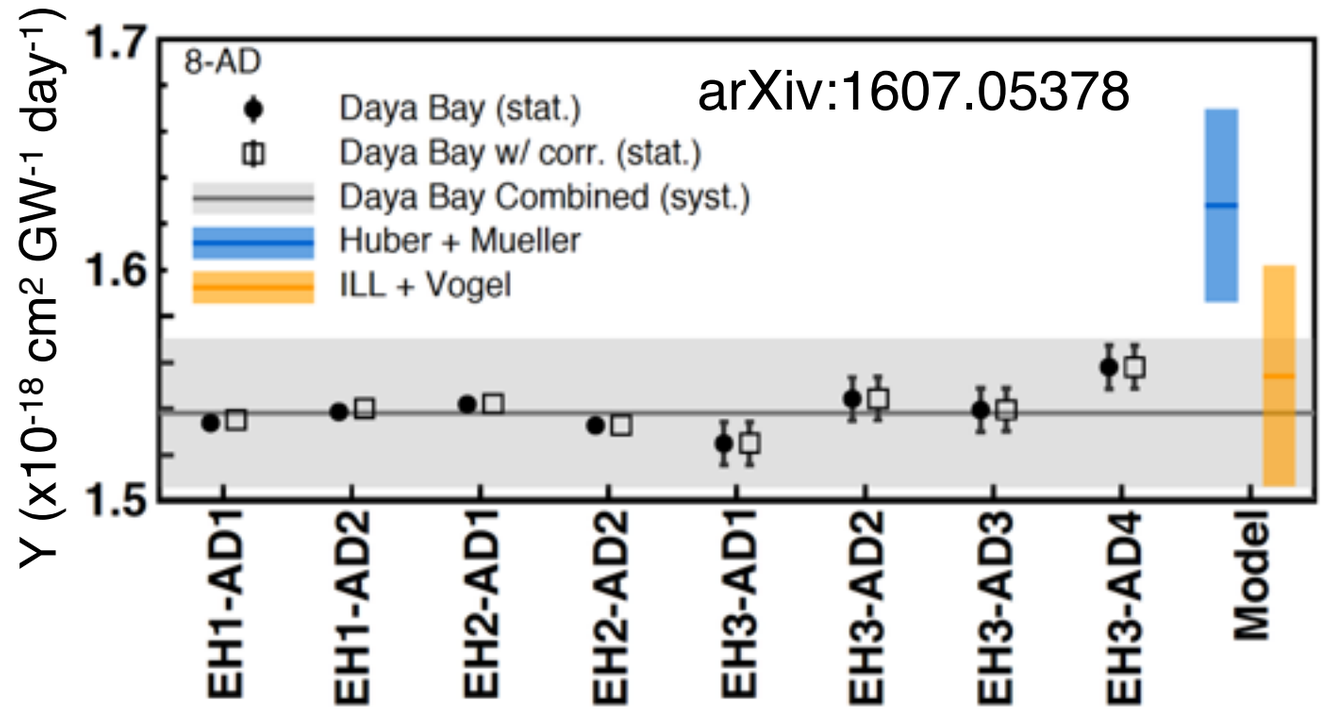
- Daya Bay result:

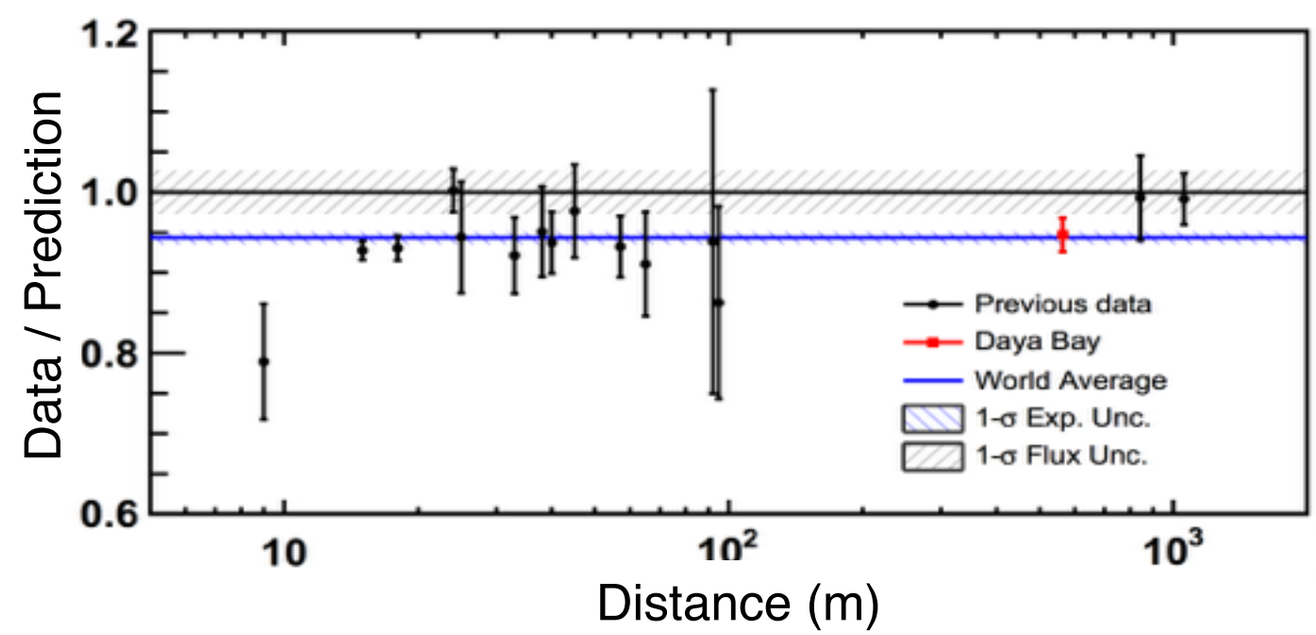
  $R_{dyb} = 0.946 \pm 0.02$ (exp.)

- The World Average:

  $R_{globe} = 0.942 \pm 0.009$ (exp.)

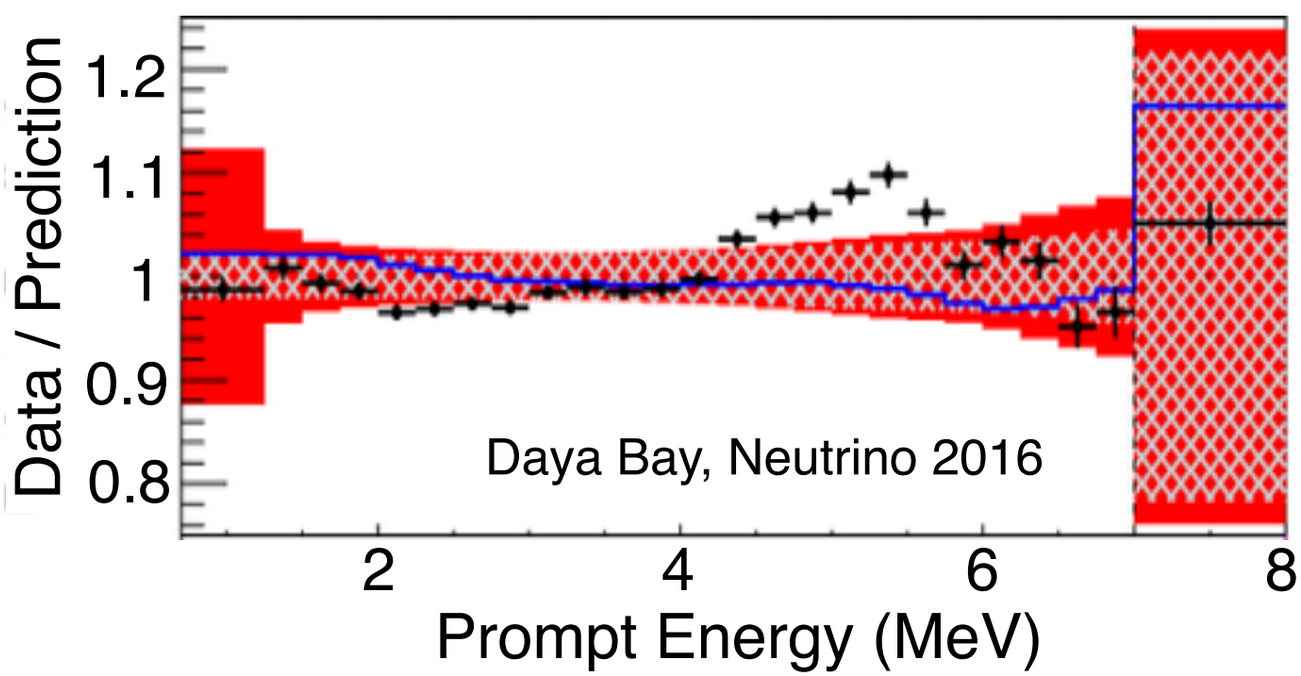
To resolve reactor anomaly, more precise prediction of reactor flux is necessary, since Huber+Mueller model's uncertainties may be as large as 5% according to a recent reevaluation.*



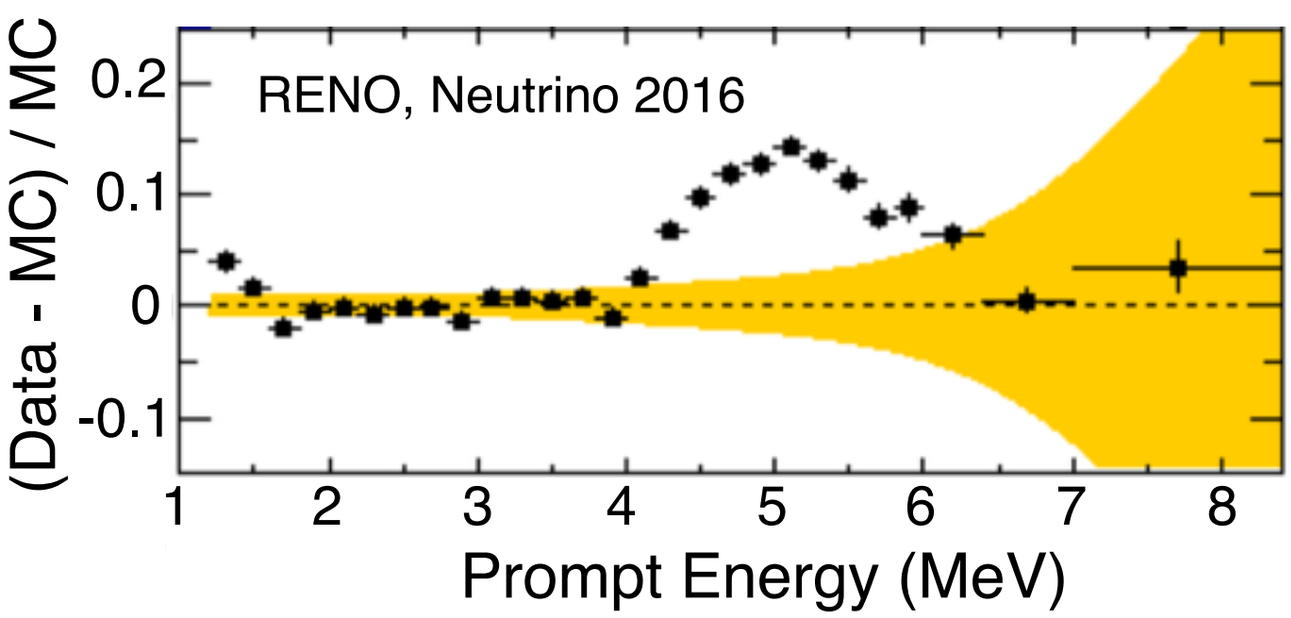


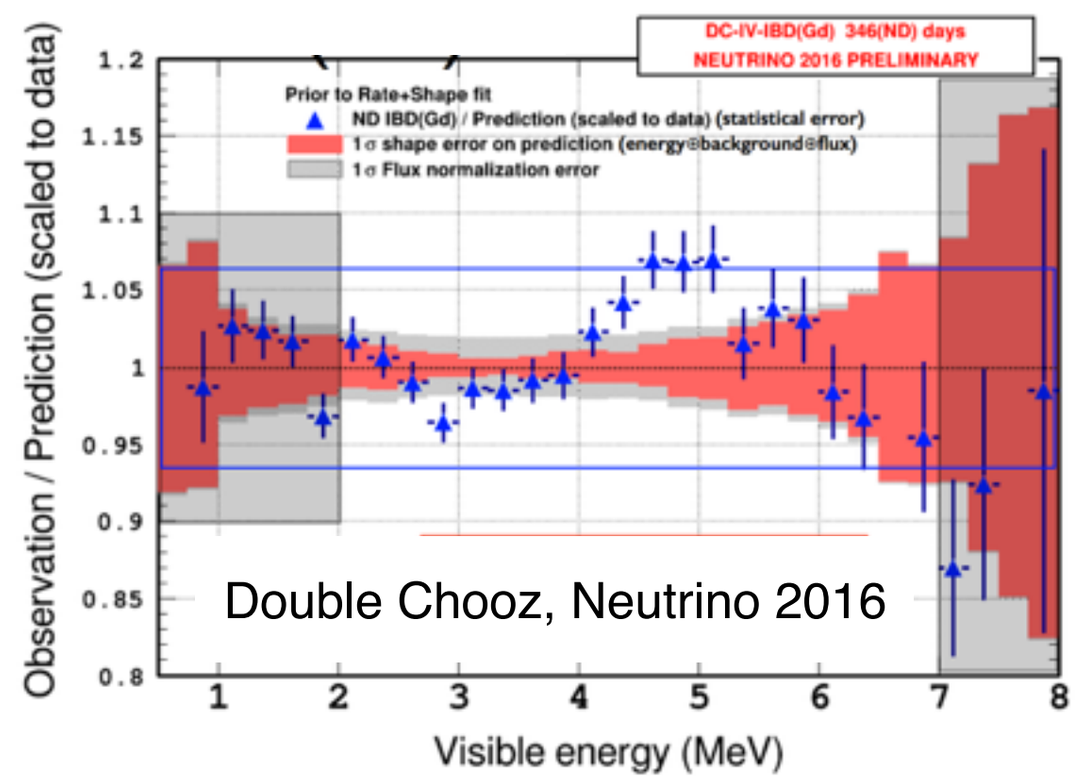
*A. Hayes and P. Vogel, arXiv:1605.02047

Reactor Spectrum "Bump" in 4-6 MeV



- Daya Bay, Double Chooz and RENO all see the "bump" around 5 MeV
- The "bump" is not due to the sterile neutrino oscillations
  - Both near and far sites see similar structure.
- Shaking the foundation of reactor anomaly.





Conclusions

- Daya Bay's is able to search for sterile neutrinos

- Daya Bay's constraints of $\sin^2 2\theta_{14}$ have improved a factor of ~2 over previous results.
  - Most stringent today in $|\Delta m^2_{41}| \lesssim 0.2\, eV^2$

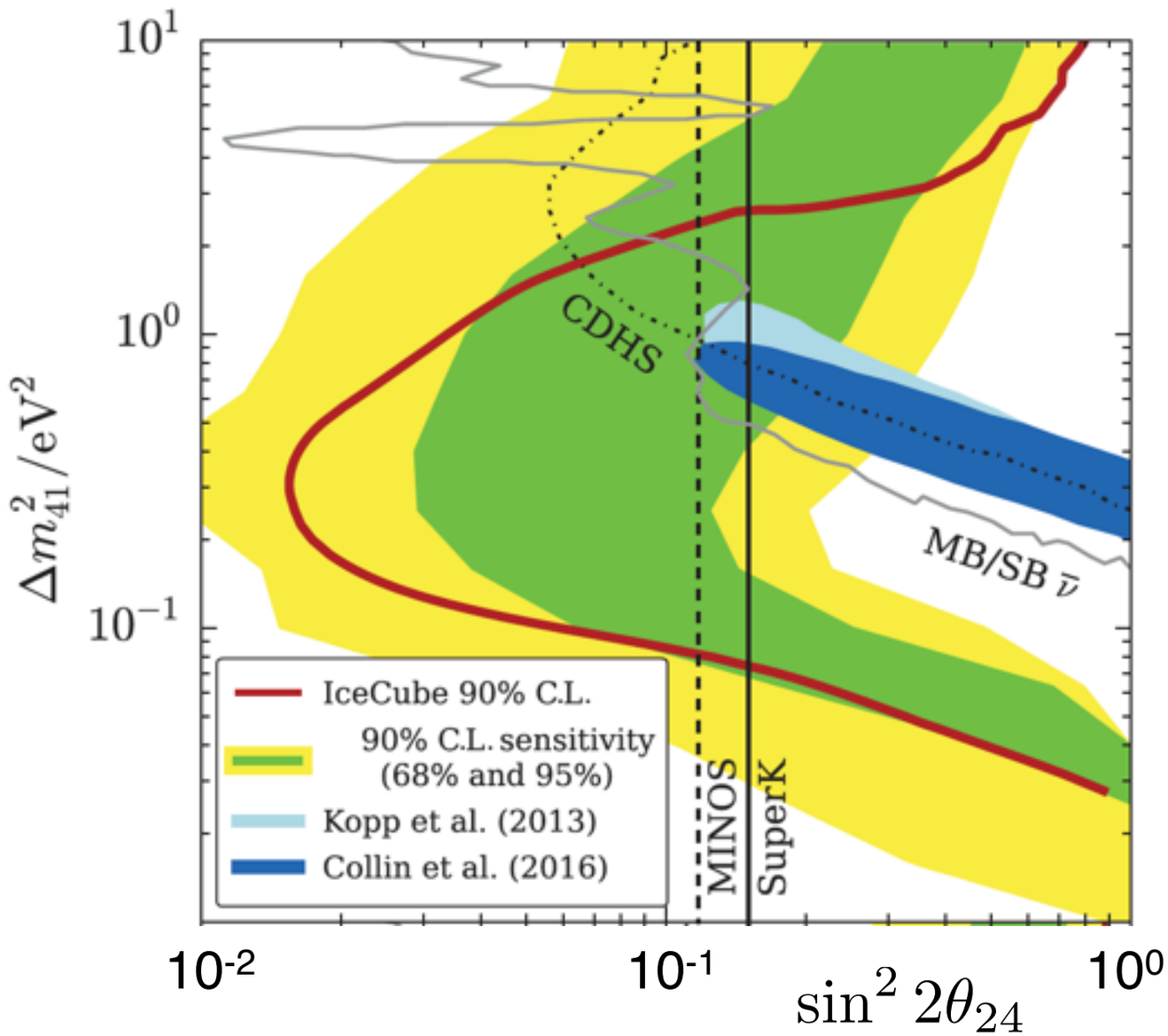
- Daya Bay, Bugey-3 and MINOS combined results exclude the sterile neutrino allowed by LSND and MiniBooNE experiments for $|\Delta m^2_{41}| < 0.8\, eV^2$ at 90% C.L.


Thank You

Back Up

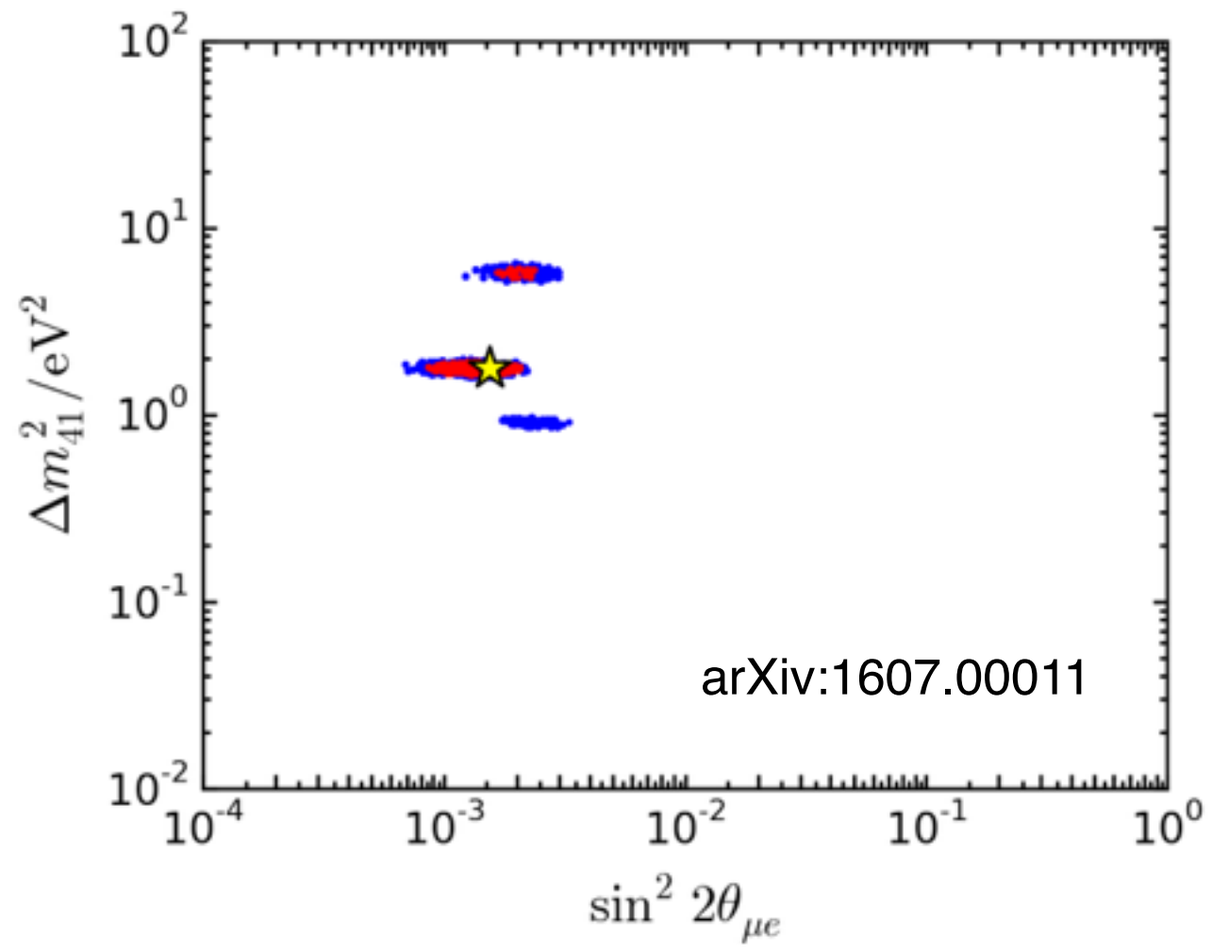
What about other experiments?

IceCube

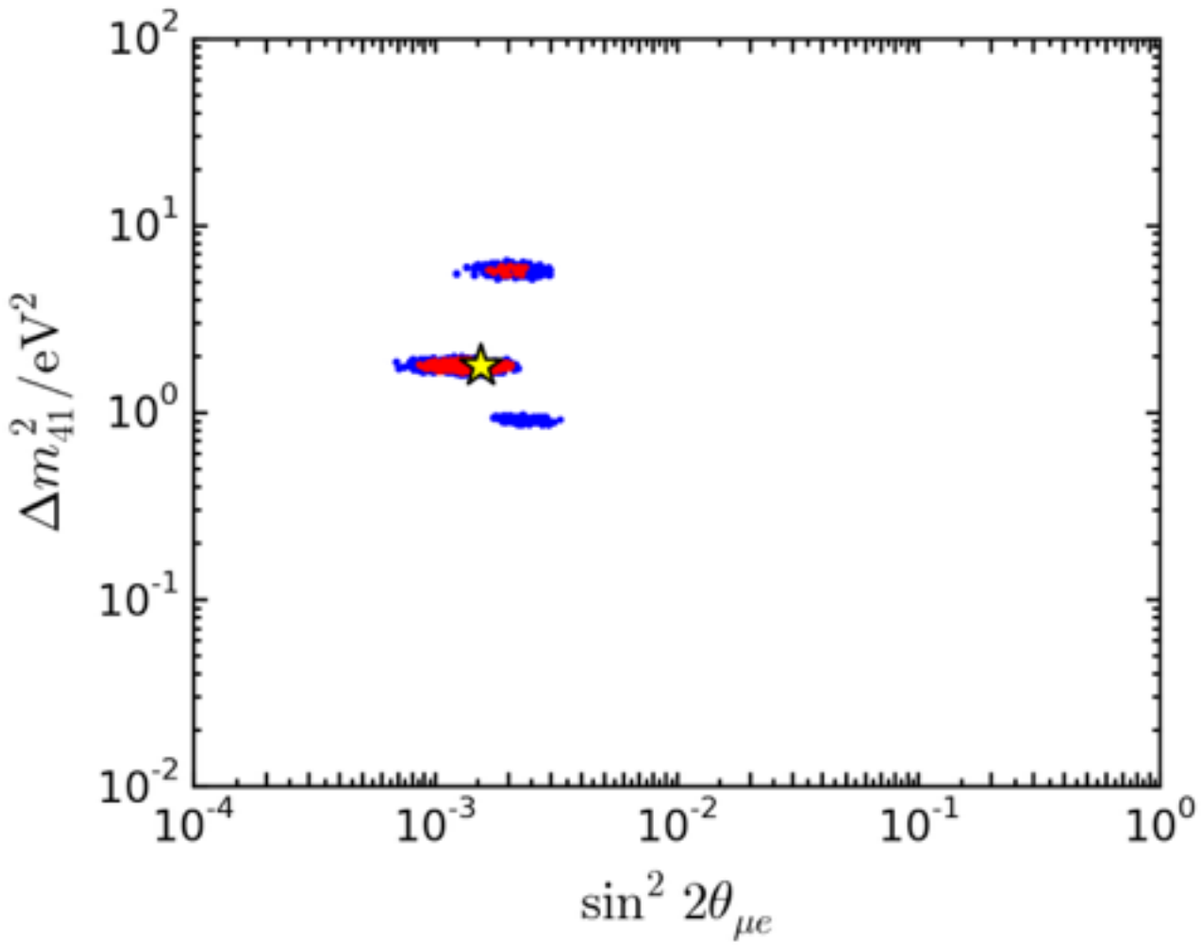


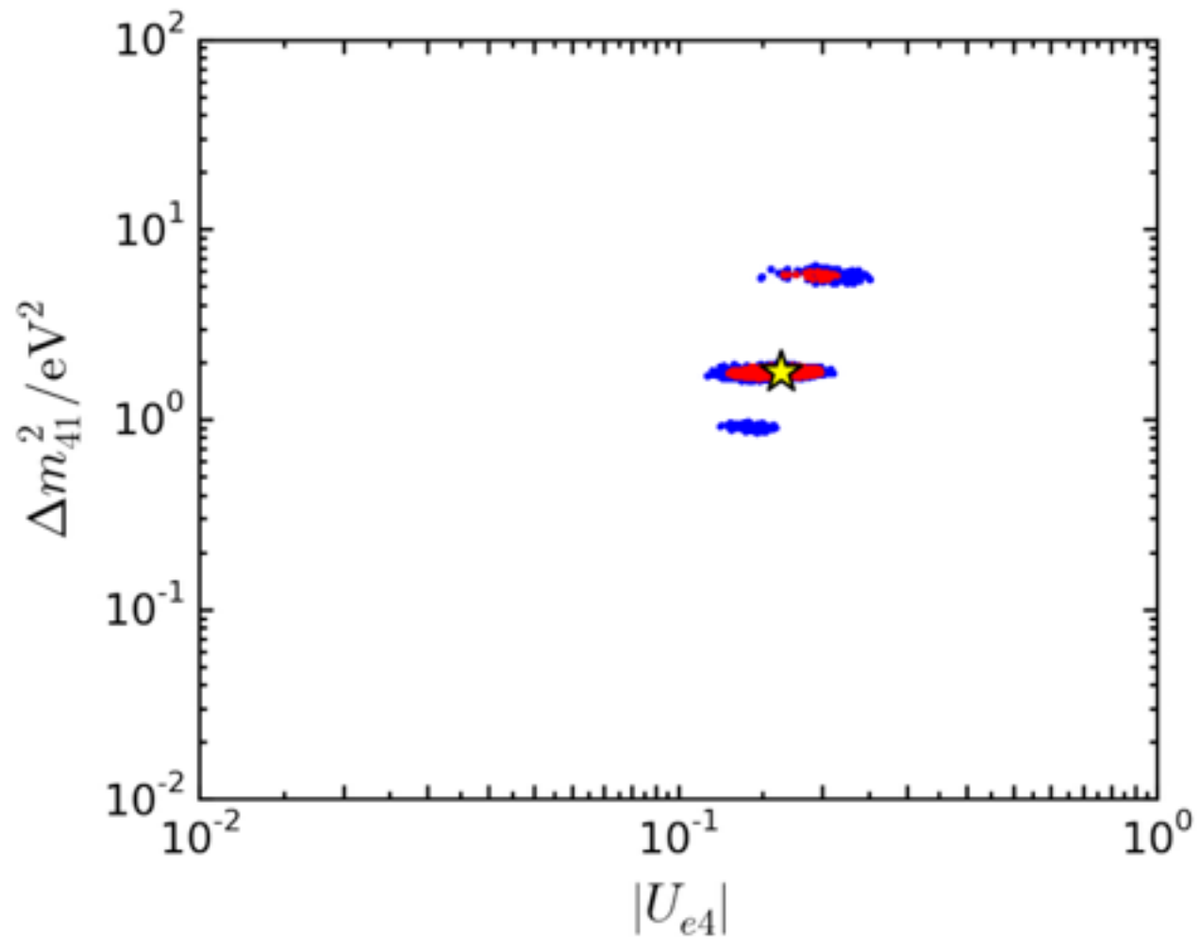
Phys. Rev. Lett. 117, 071801

SBL + IceCube global fit



SBL + IceCube fit

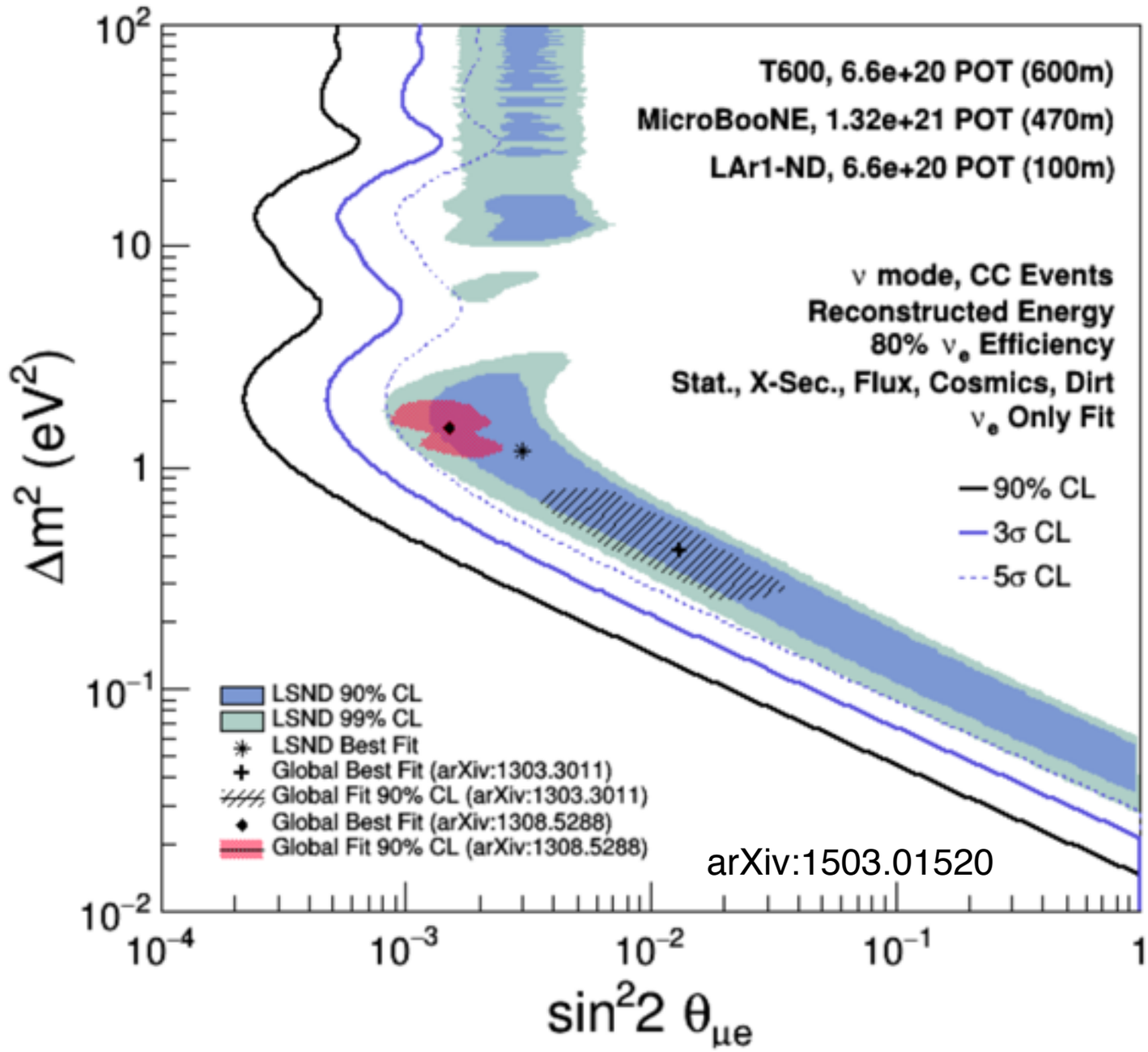




arXiv:1607.00011

SBN experiment

SBN sensitivity



Adjust Ratio

- For each ratio

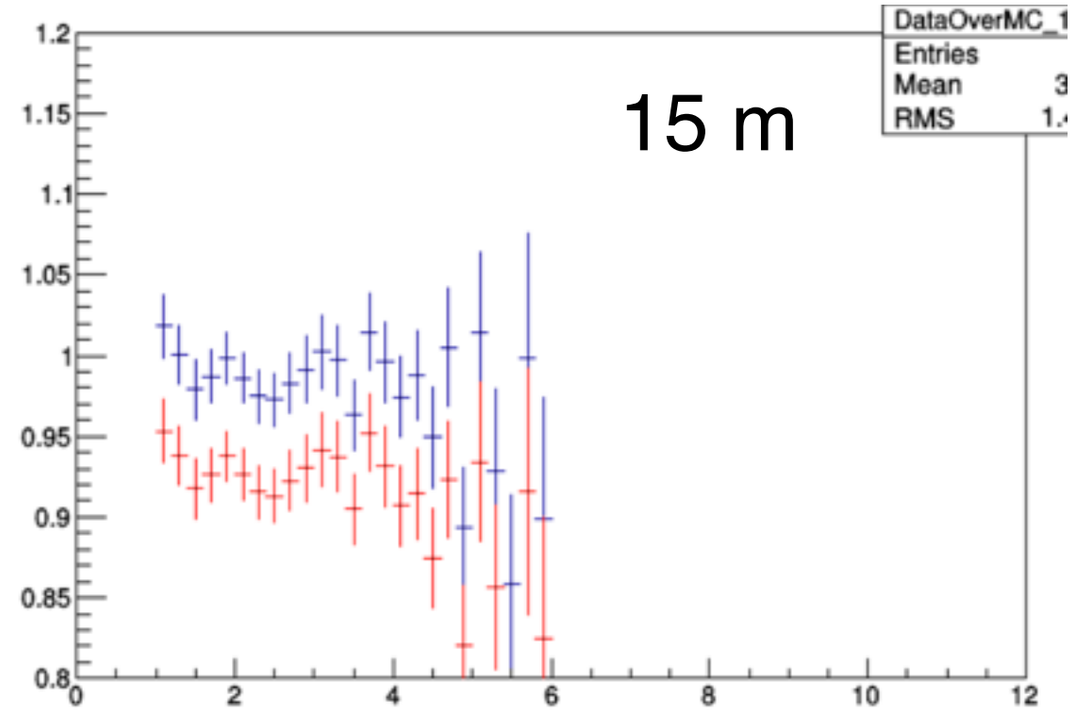
$$\frac{Observed}{New\ Pred} = \frac{Observed}{Bugey\ MC} \cdot \frac{Old\ Pred.}{New\ Pred.}$$

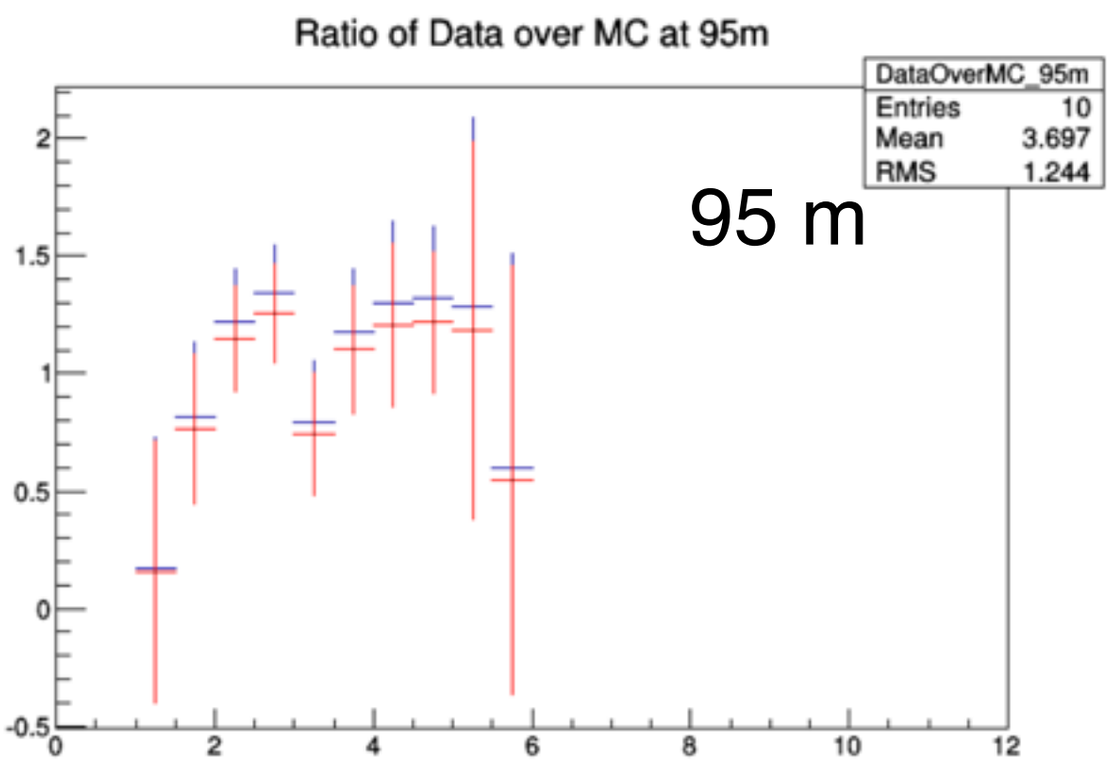
$$= \frac{Observed}{Bugey\ MC} \cdot \frac{Old\ Spec}{New\ Spec} \cdot \frac{Old\ CrossSection}{New\ CrossSection}$$

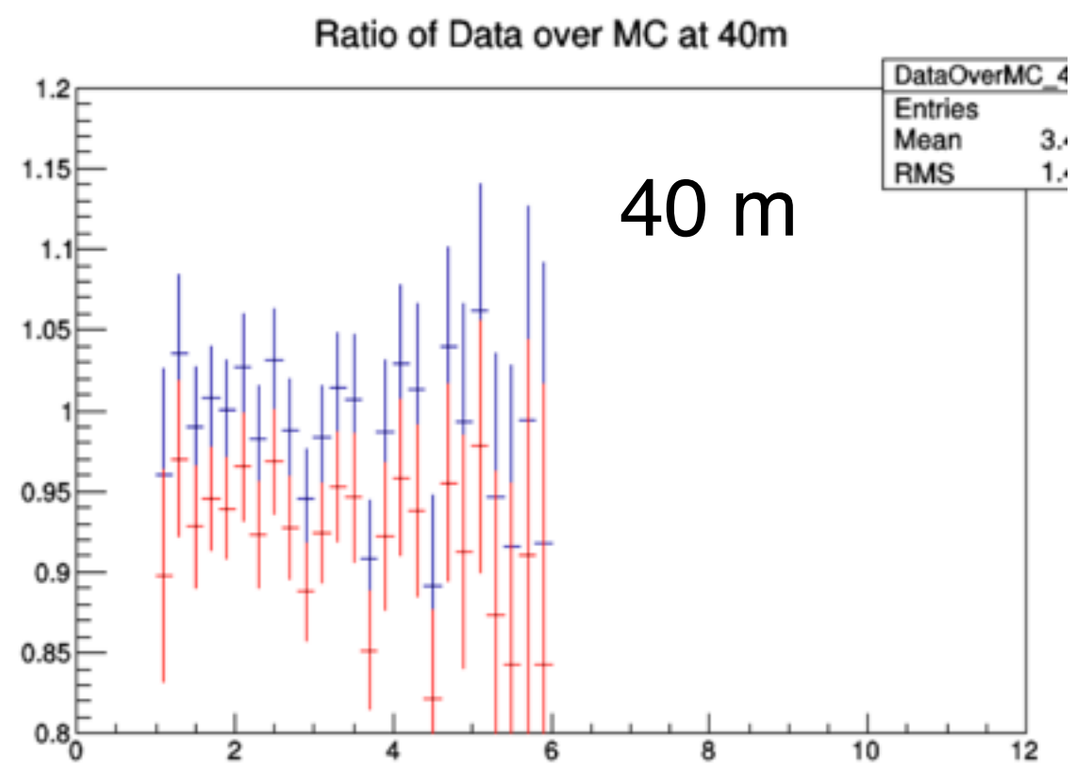
From Bugey

(ILL+Vogel)/Huber

99%

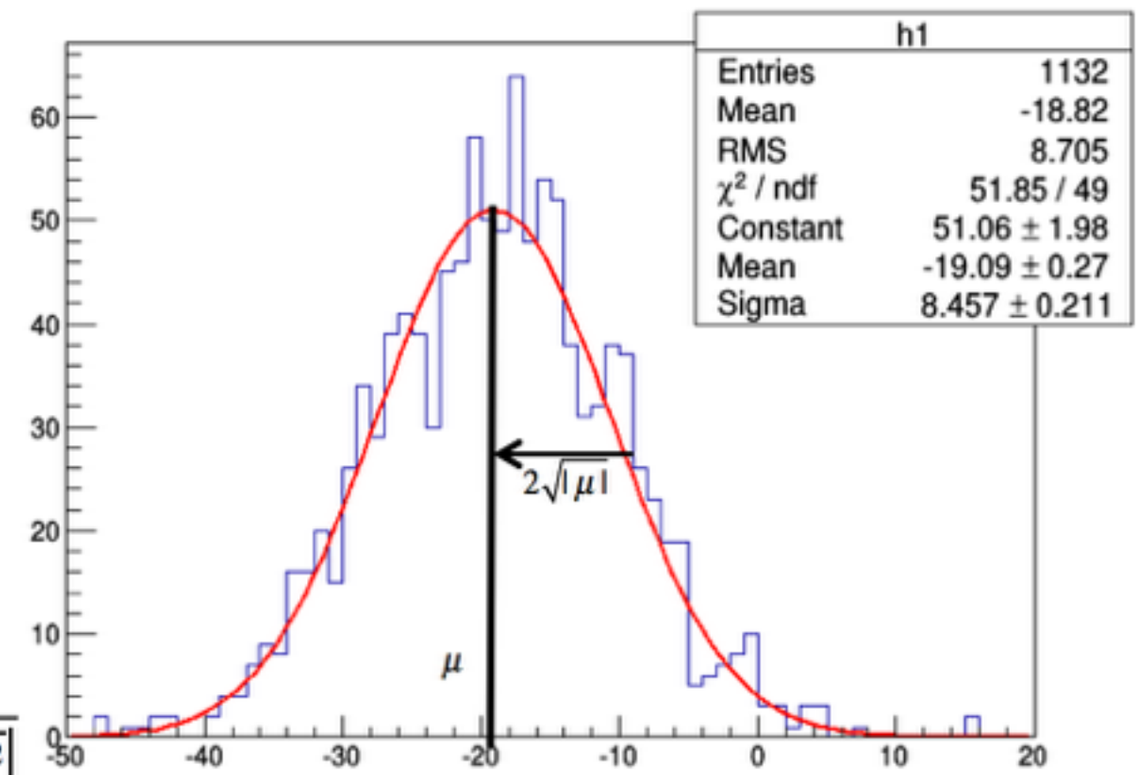






Gaussian Distribution of $\Delta\chi^2$

- When number of events is big enough
  - The distribution of $\Delta\chi^2$ is a Gaussian
  - The standard deviation of of $\Delta\chi^2$ is equal to $2\sqrt{|\Delta\chi^2|}$

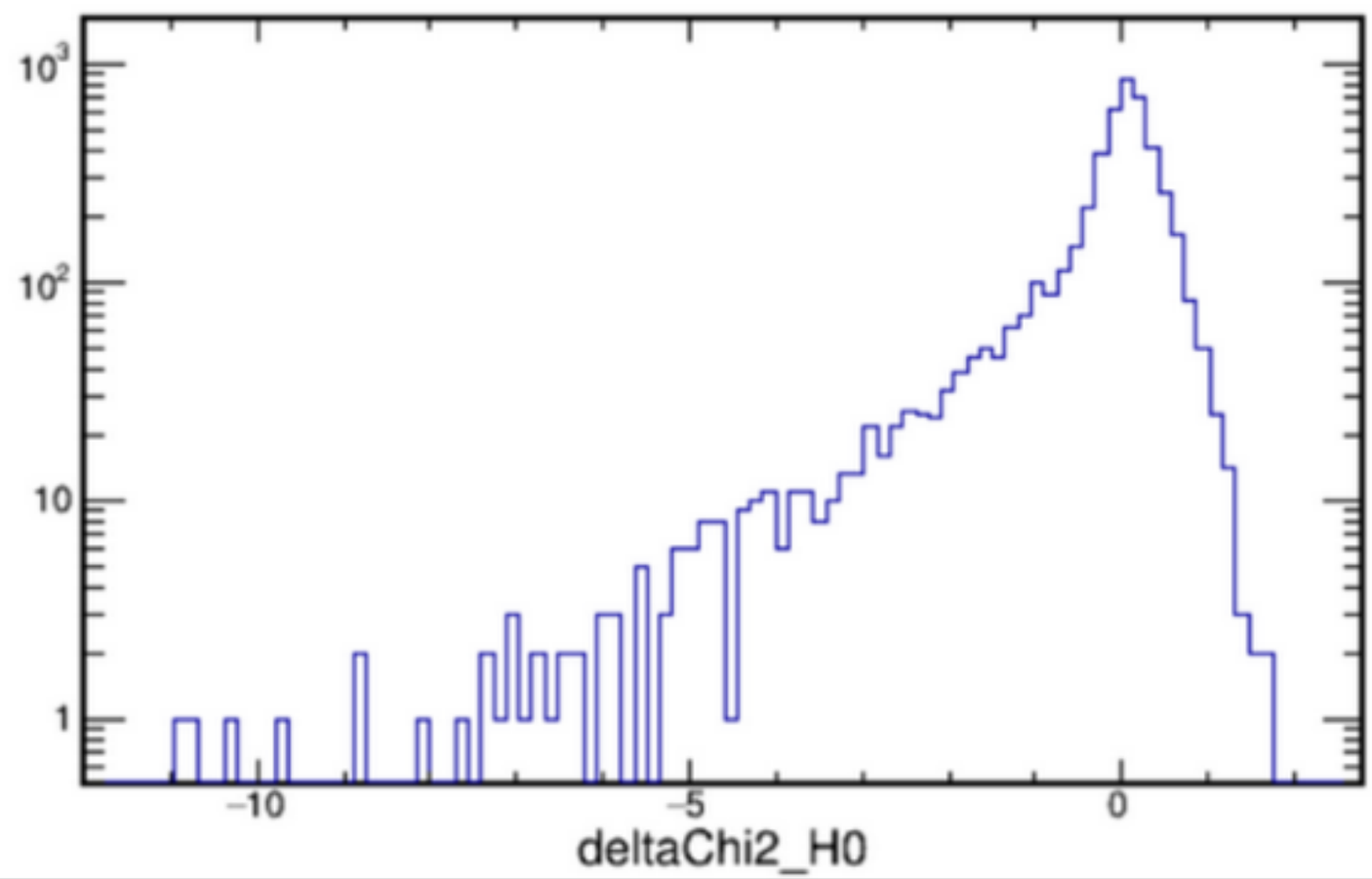


- The distribution can then be obtained by fitting the Asimov (no statistic) data set.
  - $\Delta\chi^2_{Asimov} = \overline{\Delta\chi^2}$

Daya Bay

MINOS' Problem

- For MINOS, since they didn't fix θ_{34}, they couldn't get the Gaussian distribution. They use MC to determine the $\Delta\chi^2$ distribution at each point to set the exclusion area.



Combination Steps

1) N numbers of $\Delta\chi^2_{3\nu,4\nu}|_{DB}$ are randomly generated follow a Gaussian distribution with Gaus($\Delta\chi^2_{3\nu,4\nu}(Asimov)$, $2\sqrt{|\Delta\chi^2_{3\nu,4\nu}(Asimov)|}$)

2) N numbers of $\Delta\chi^2_{3\nu,4\nu}|_M$ are randomly generated follow the distribution that obtained via MC test.

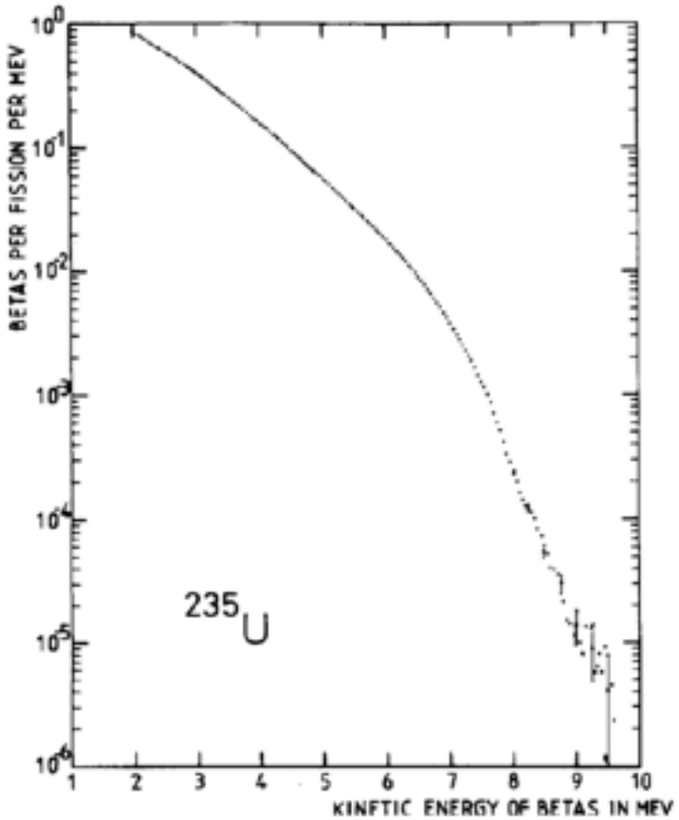
3) Each $\Delta\chi^2_{3\nu,4\nu}|_{DB}$ is randomly added with one value of $\Delta\chi^2_{3\nu,4\nu}|_M$ to form a new distribution of $\Delta\chi^2_{3\nu,4\nu}|_{DBM}$.

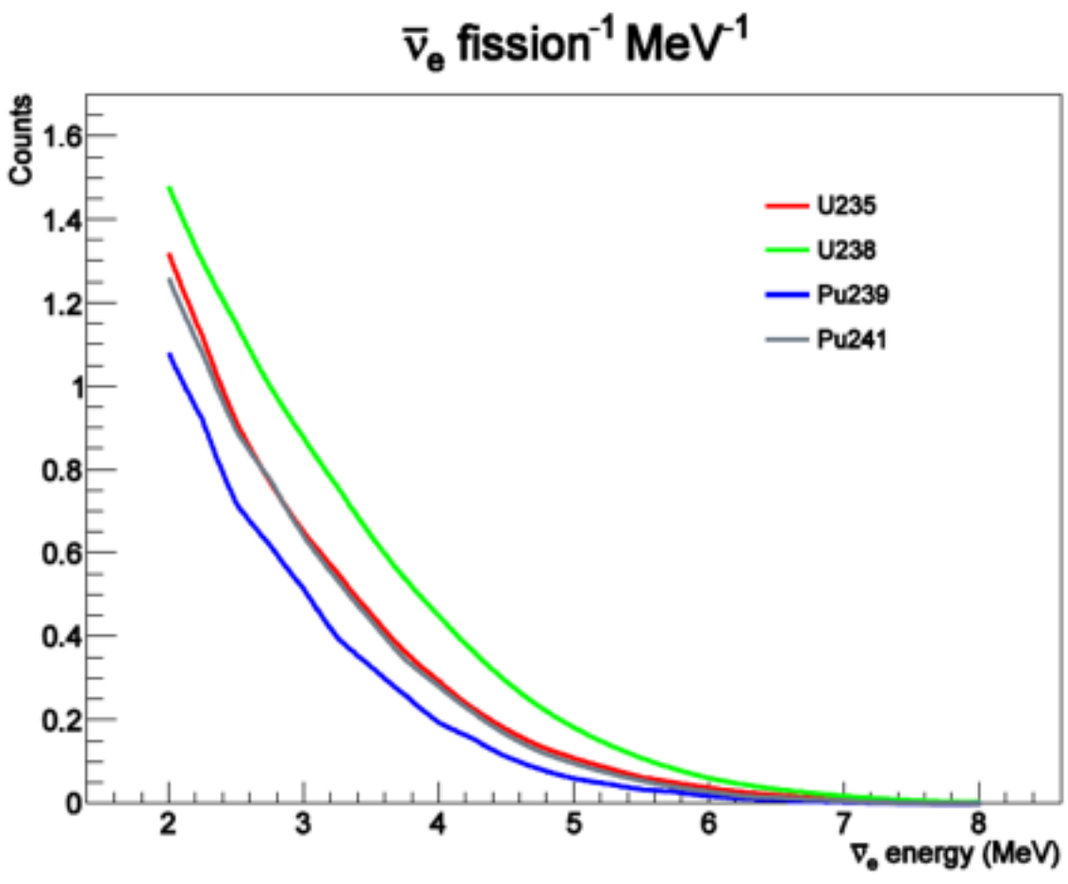
4) Then a CLs value can be calculate for a (Δm^2_{41}, $\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$).

5) For CLs value for a (Δm^2_{41}, $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$), since a single $\sin^2 2\theta_{\mu e}$ can corresponds to different ($\sin^2 2\theta_{14}$,$\sin^2\theta_{24}$) combinations, the largest CLs value is picked for the $\sin^2 2\theta_{\mu e}$ to be conservative.

En-Chuan Huang, Ph.D. Thesis UIUC, 2016

Reactor anti-ν spectra





- The cumulated β-spectra of ^{235}U, ^{239}Pu and ^{241}Pu from thermal neutron induced fission were measured in 1980s with the magnetic beta spectrometer BILL at the High Flux Reactor of the Institut Laue-Langevin (ILL) in Grenoble, France
- Anti-ν_e were converted from the β-spectra for the isotope of ^{235}U, ^{239}Pu and ^{241}Pu.
  - ILL anti-neutrino spectra
  - Th. Mueller
  - P. Huber

^{238}U fission is mainly induced by fast neutron, no experiment have been performed.

- Vogel
- Mueller

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MINOS Sterile Neutrino Analysis

- Compare far/near ratio data to the expectations with oscillations.
  - Near detector is sensitive to large Δm^2_{41} mass (a few eV^2)
  - Allows to probe larger range of Δm^2_{41} region.
- Fix the insensitive parameters during the fitting.
  - Set δ_{13}, δ_{14}, δ_{24} and θ_{14} to zero.
- Fit NC and CC spectra simultaneously to determine
  - θ_{23}, θ_{24}, θ_{34}, Δm^2_{32} and Δm^2_{41}.