Search for a light sterile neutrino at Daya Bay

plus

Combined search with MINOS and Bugey-3

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Physics 290E, Berkeley
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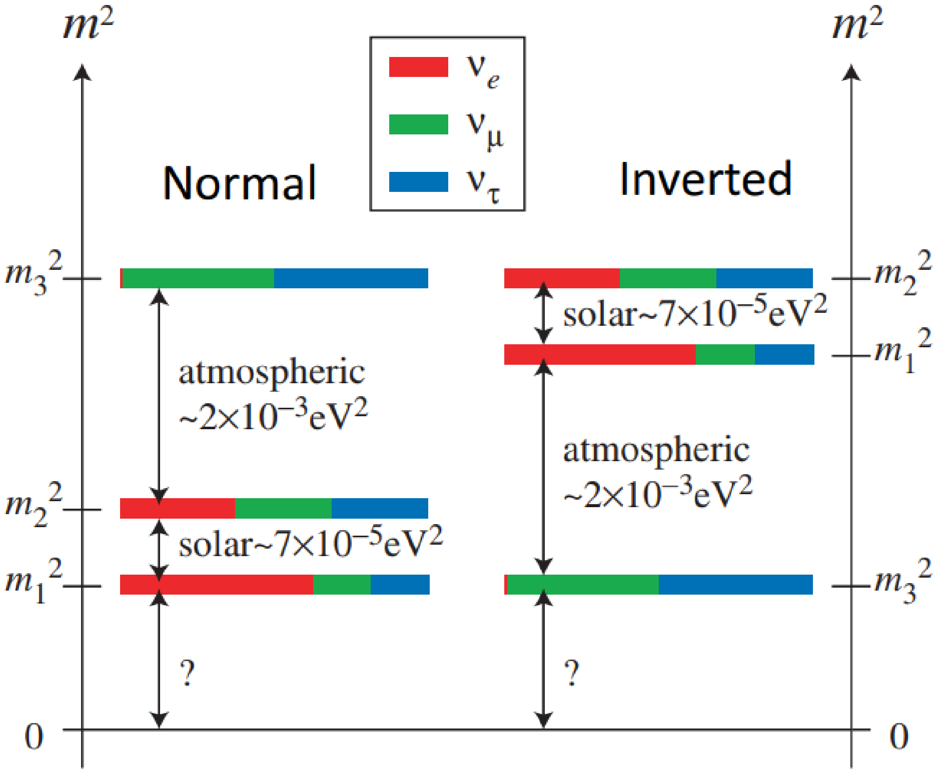
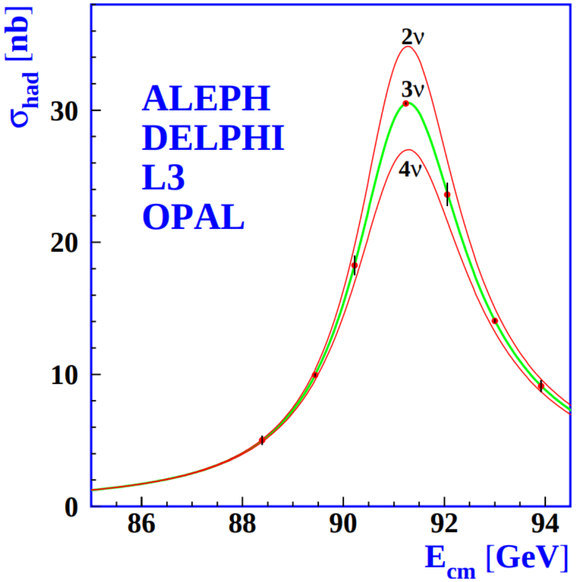
The 3ν paradigm





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

$$\downarrow$$

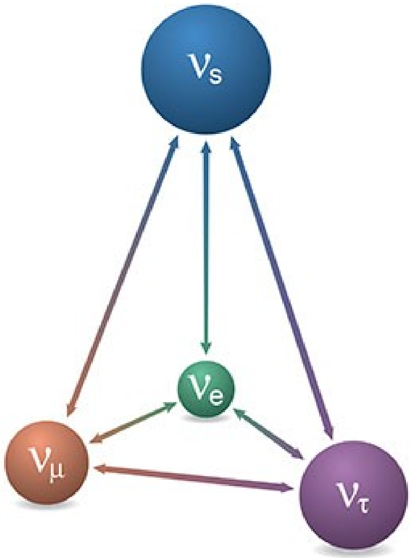
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

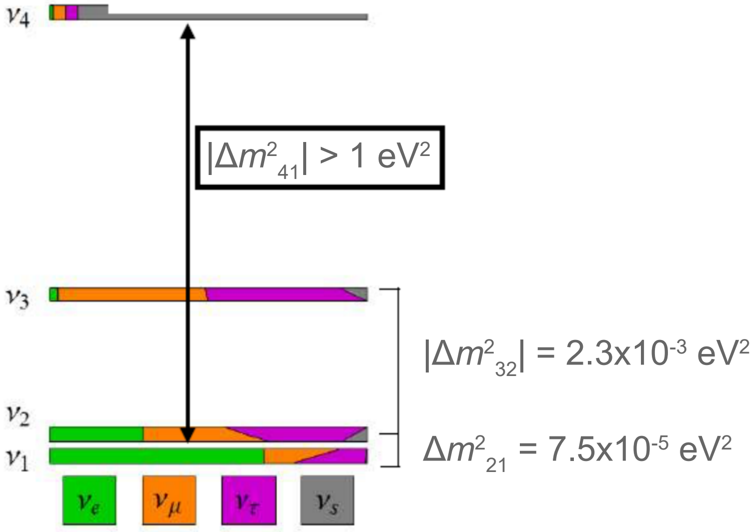
Solar / Long baseline reactor	Short baseline reactor / Long baseline accelerator	Atmospheric / Long baseline accelerator	Neutrinoless double beta decay

Sterile neutrino motivation

Why consider sterile neutrinos?

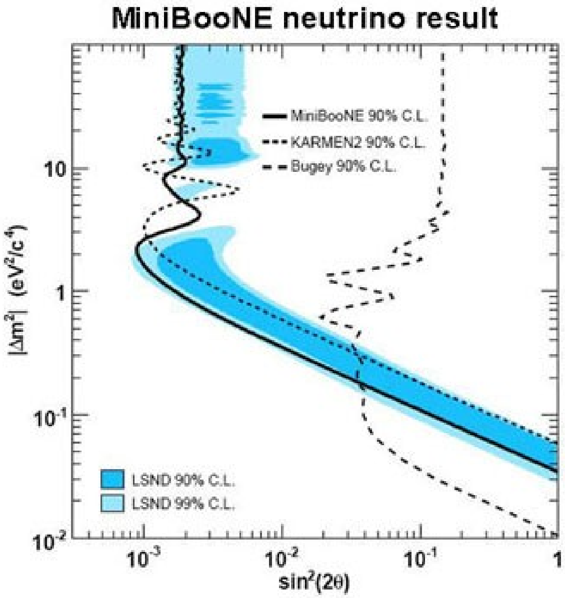
- **GUT scale:** RH sterile neutrinos generate light *ν* masses via seesaw mechanism
- **keV scale:** Dark matter candidate
- **eV scale (this talk):** Explain various experimental anomalies

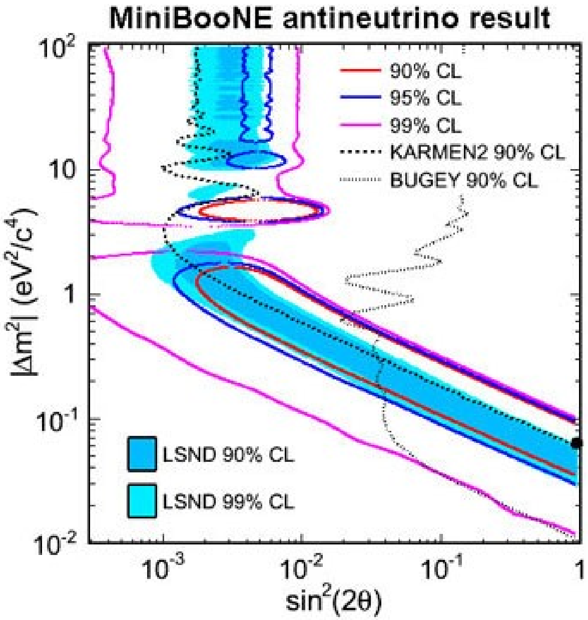




	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Sterile neutrino evidence

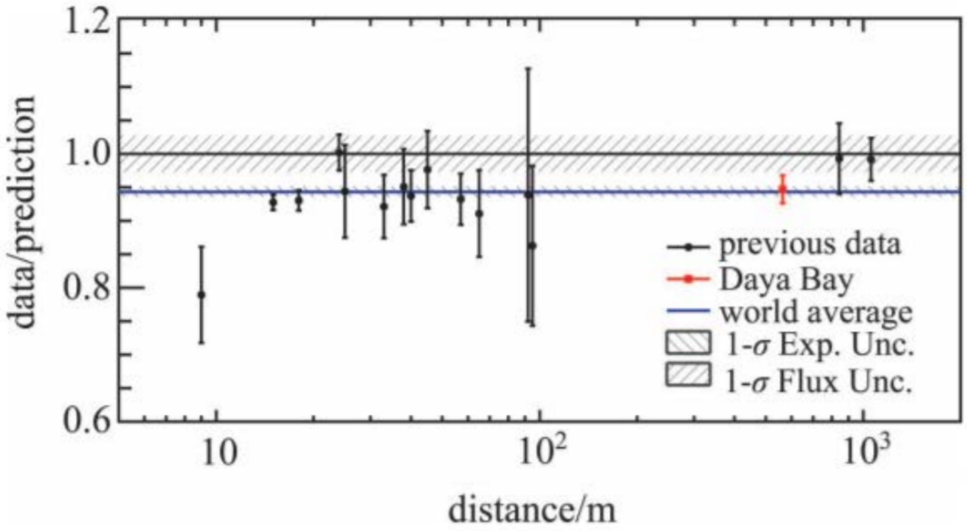

MiniBooNE neutrino result

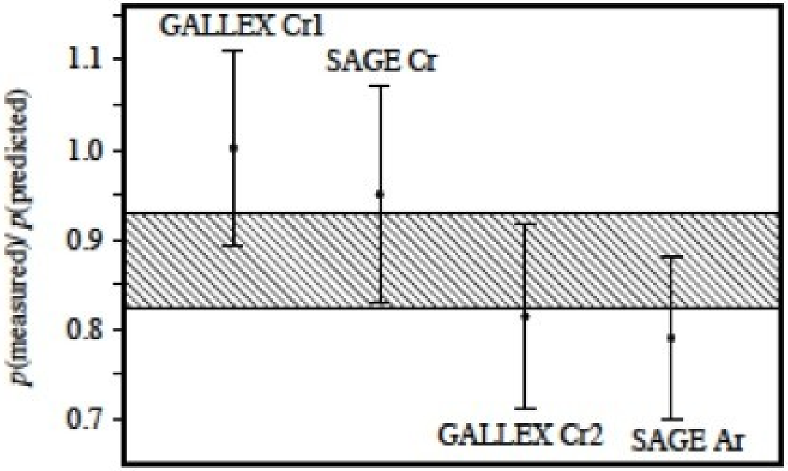

MiniBooNE antineutrino result

Accelerator: Anomalous $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam (LSND, MiniBooNE)

Reactor: 6% deficit in observed flux vs. latest calculations (Huber-Mueller model)

Isotopes: Disappearance of $\bar{\nu}_e$ from gallium decays

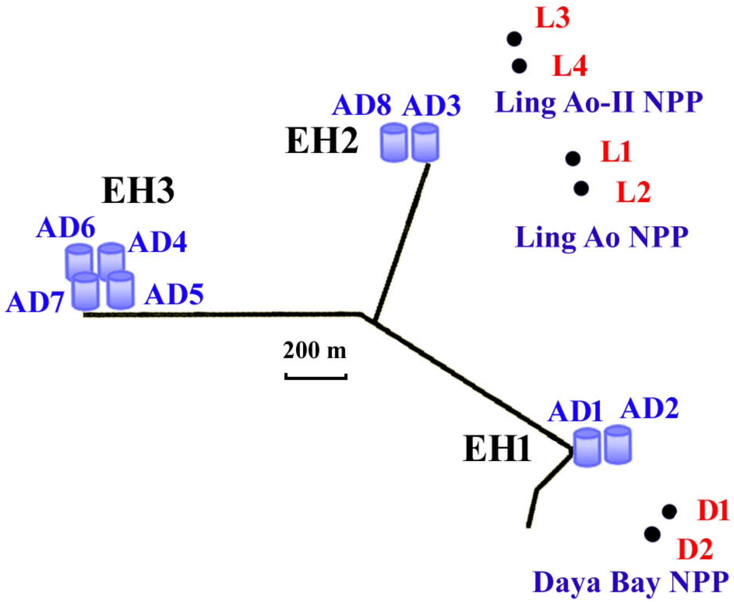


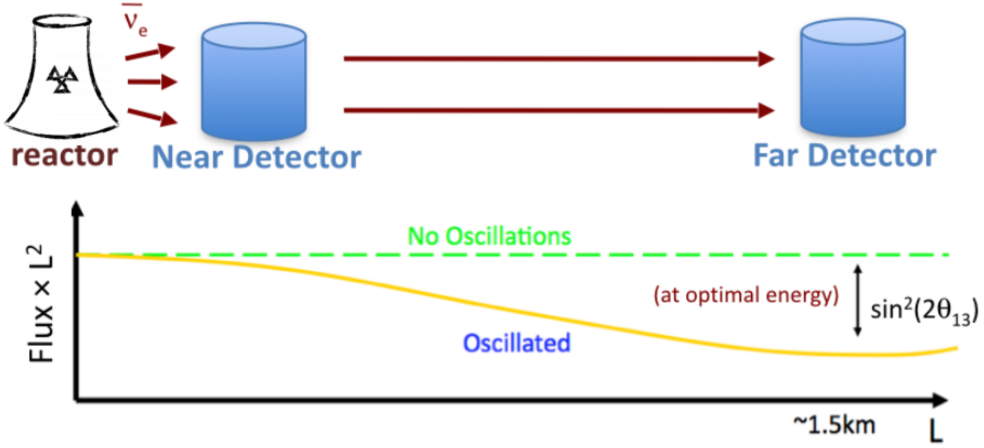


Daya Bay experiment

An optimized design:

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





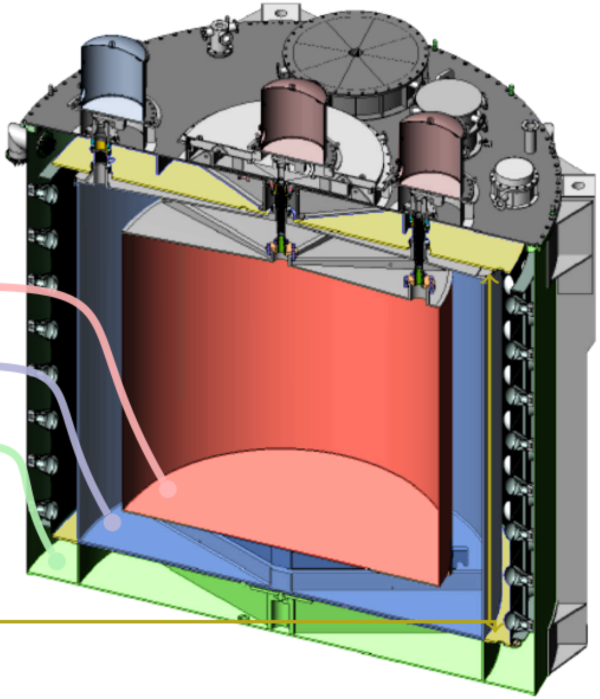
Detecting antineutrinos

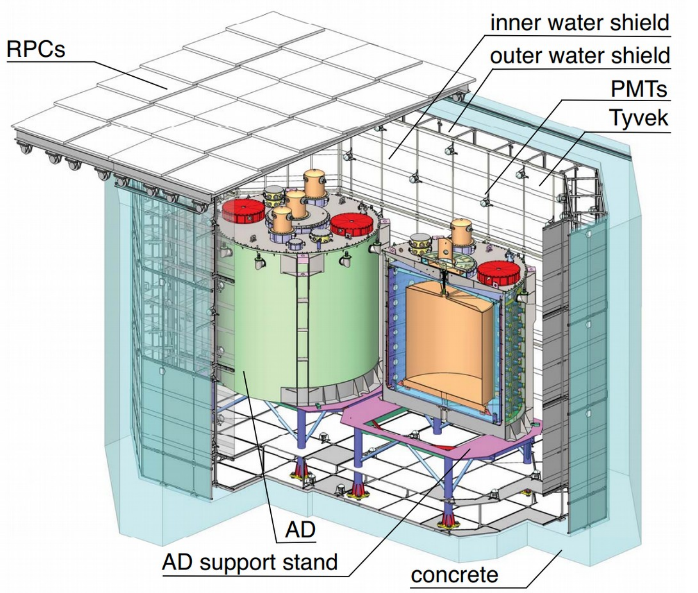
8 functionally identical detectors reduce systematic uncertainties

	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

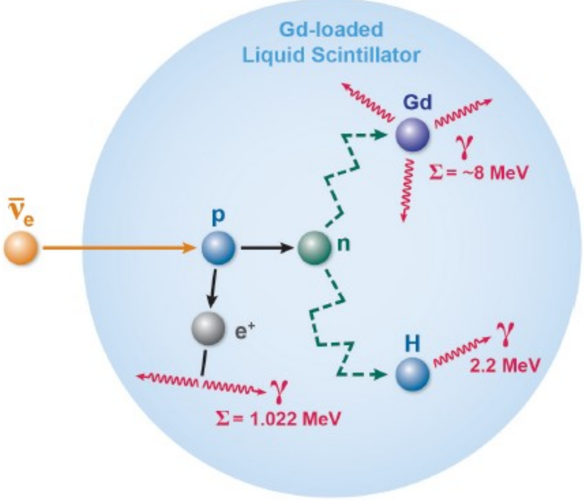




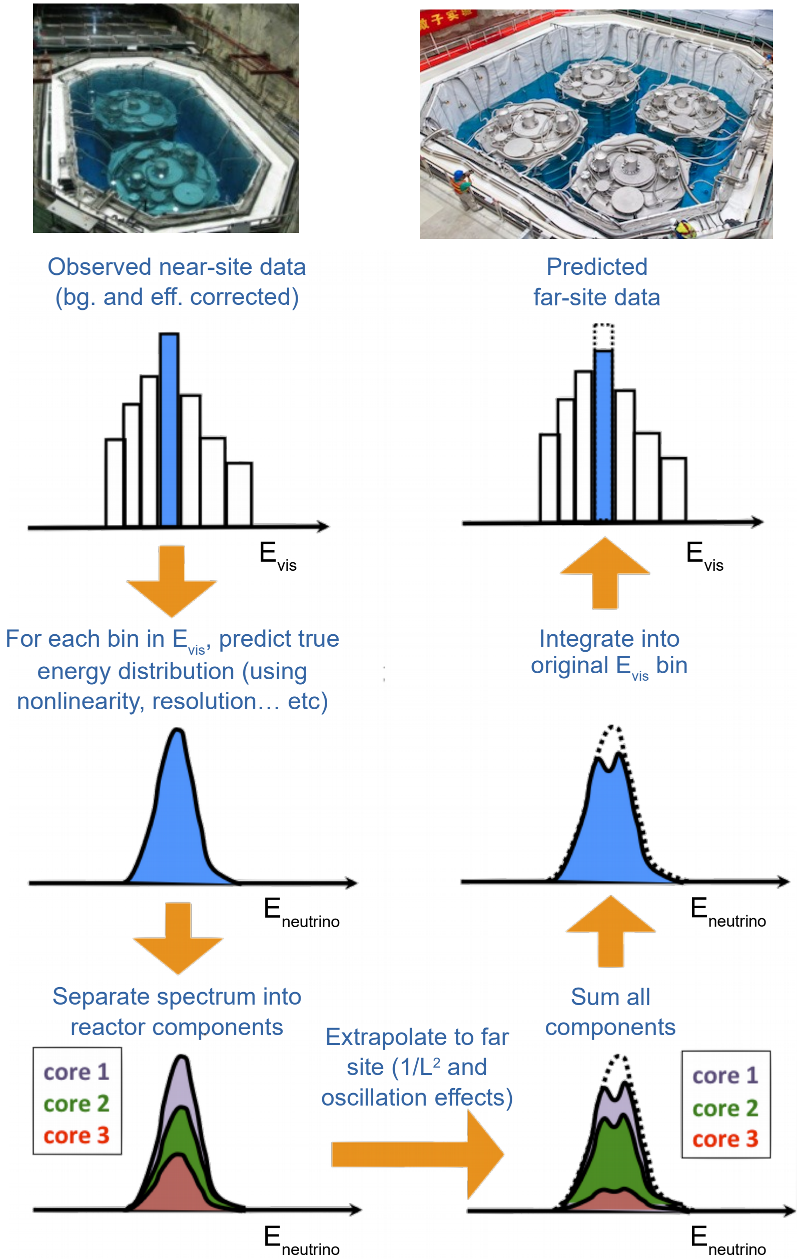
Antineutrinos are detected via **inverse β decay:**

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

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



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)

Integrate into original E_{vis} bin

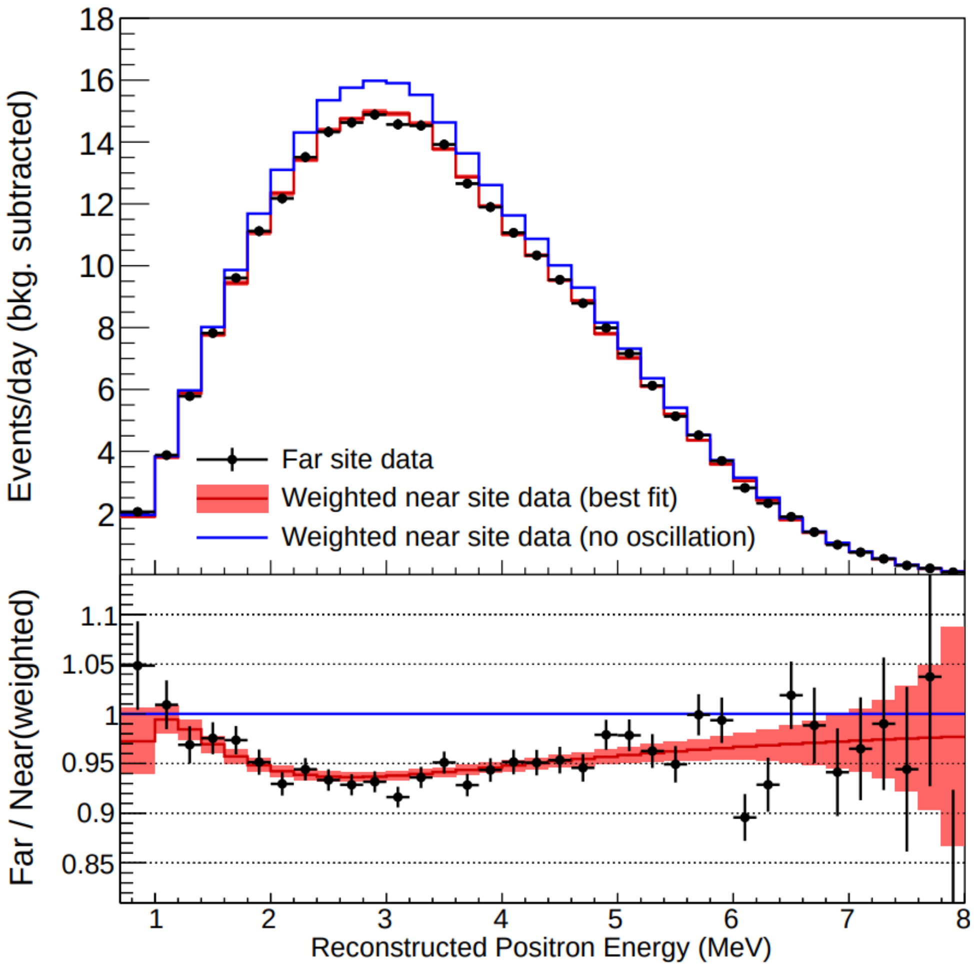
Separate spectrum into reactor components

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

Sum all components

All 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 reactor systematics.



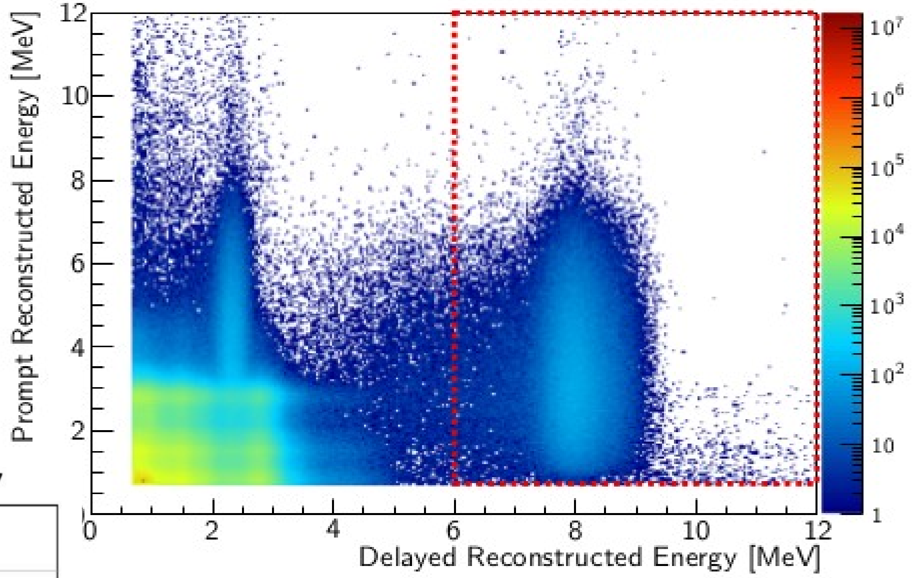
Dataset

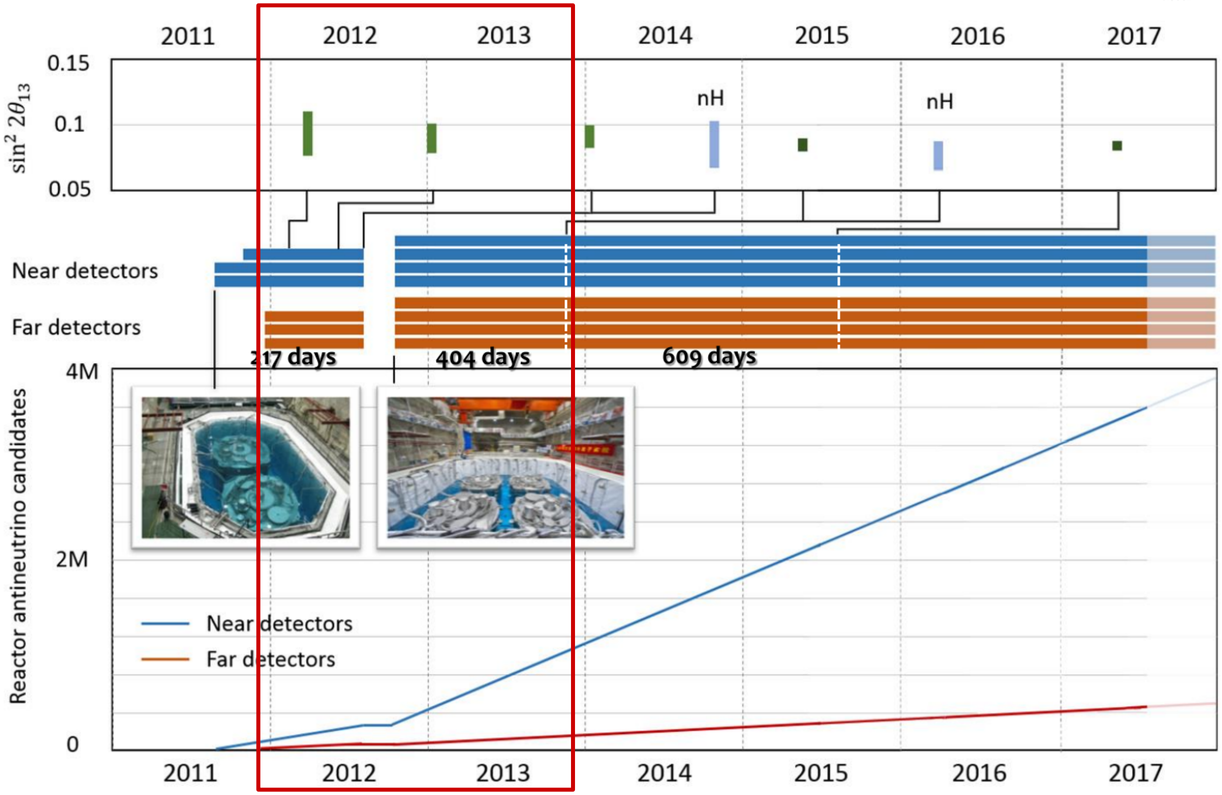
This analysis [**PRL 117, 151802 (2016)**]:

217 (404) days of 6-AD (8-AD) data
→ 3.6x statistics vs. previous publication

Improved energy calibration, background reduction

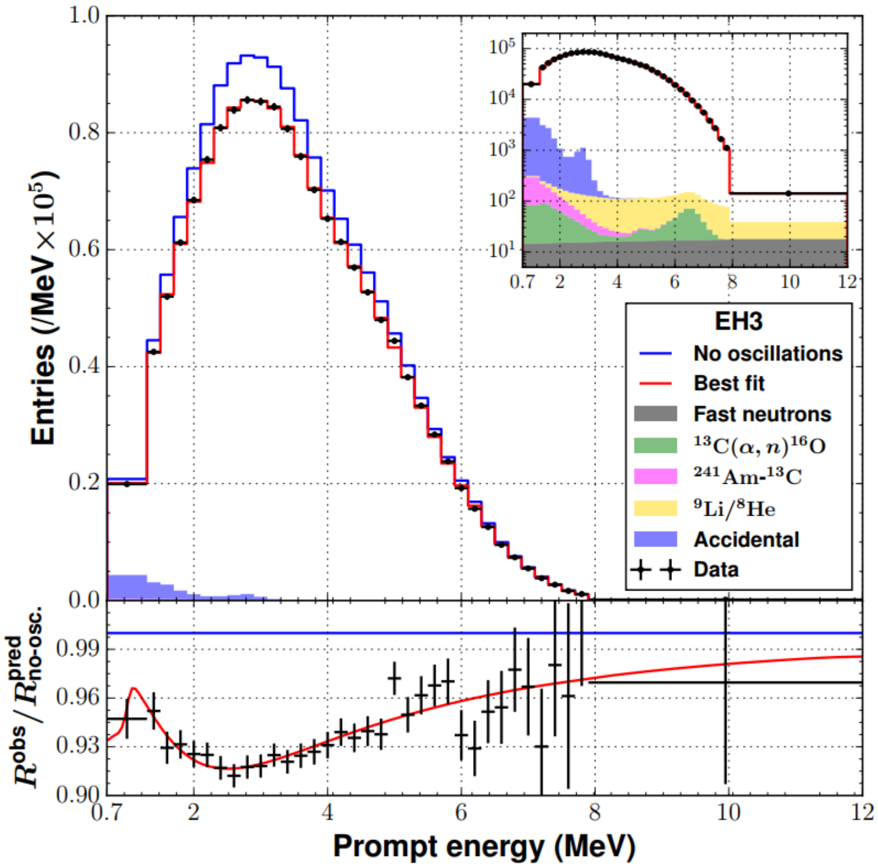
Neutron capture on Gd (lowest systematics)

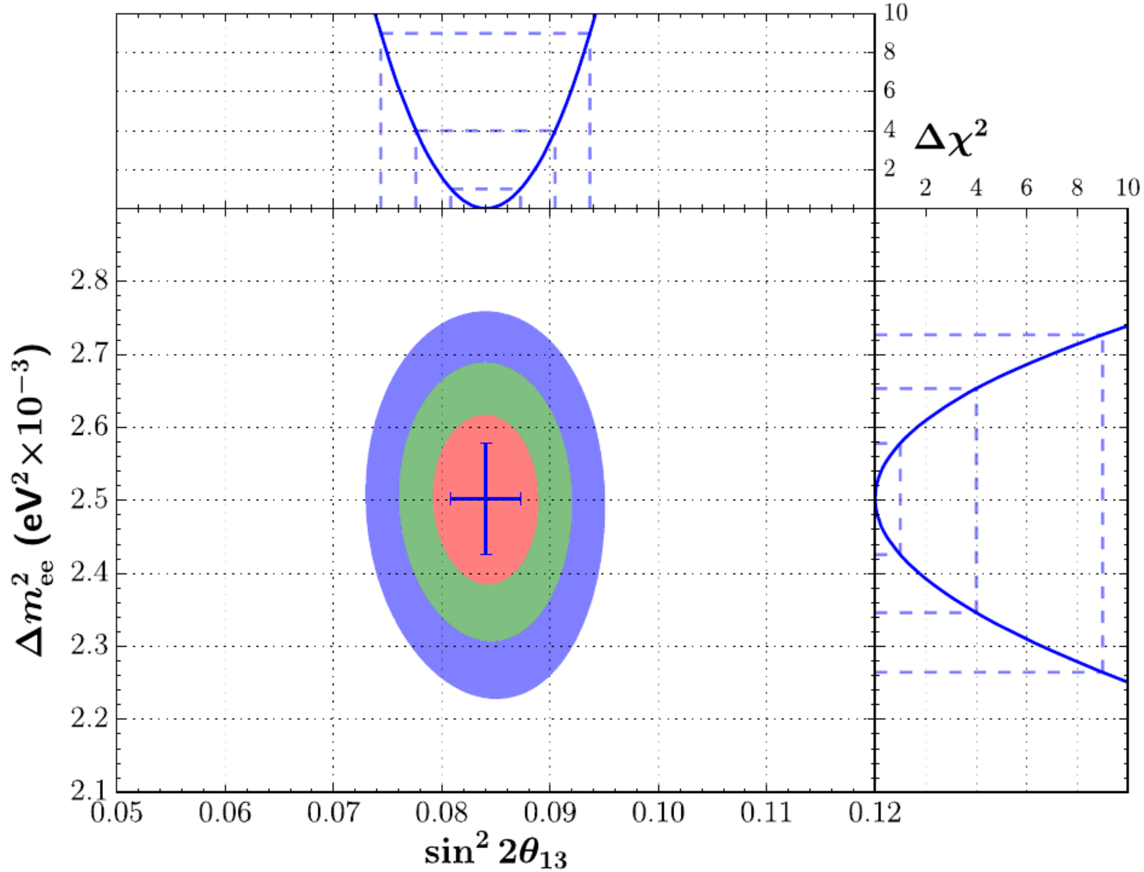




Pool muon veto [μs]	600
AD muon (>20MeV) veto [μs]	1000
Shower muon (>2.5GeV) veto	1s
Prompt Energy [MeV]	[0.7,12]
Delayed Energy [MeV]	[6,12]
Capture time [μs]	[1,200]
Distance Cut [mm]	N/A

3ν oscillation results





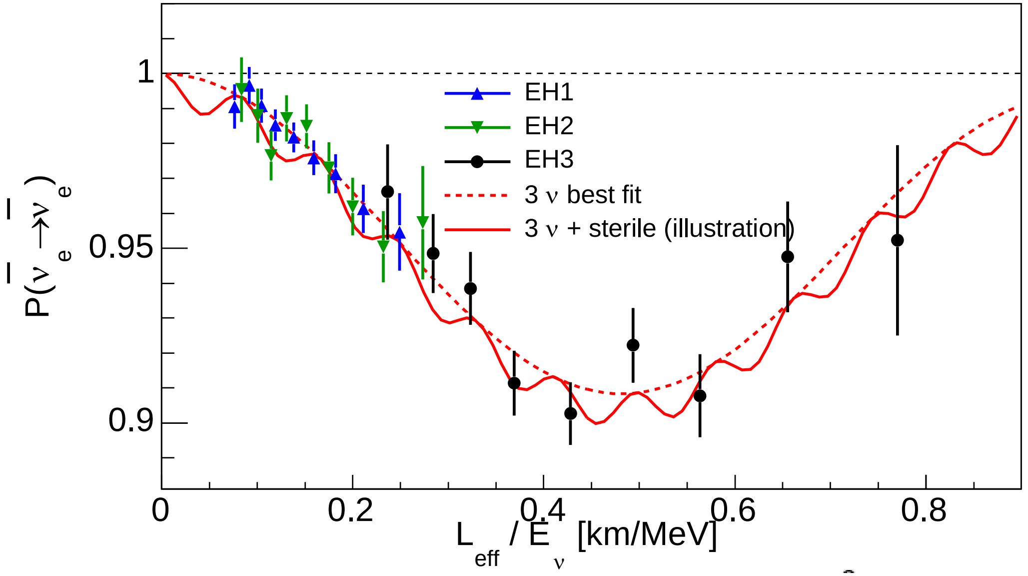
By comparing the far site (EH3) to the two near sites (EH1, EH2), we perform a 2D rate+shape fit to determine θ_{13} and Δm^2_{ee}

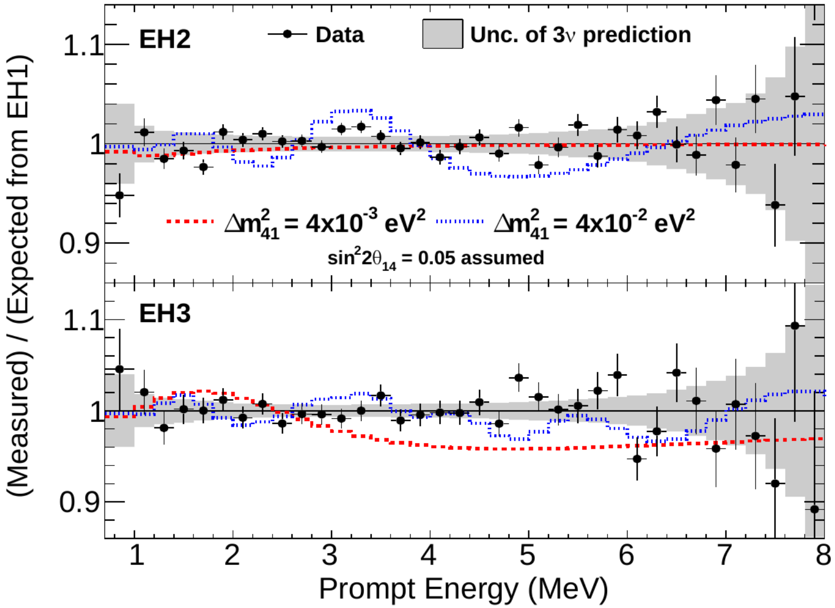
Now, what happens if we include a fourth neutrino in the fit?...

Adding a fourth neutrino

Instead of using EH1+EH2 to predict EH3, we use EH1 to predict EH2 (for larger $|\Delta m^2|$) and EH1 to predict EH3 (for smaller $|\Delta m^2|$), while using a modified oscillation expression:

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





Under 3*ν* hypothesis, *p*-value for observed $\Delta\chi^2$ is 0.4

No apparent sterile neutrino signature

Sterile neutrino limits

Two independent analyses:

1) Near/far analysis. Calculate χ^2 using covariance matrix derived from toy MC.

   Set limits using Feldman-Cousins

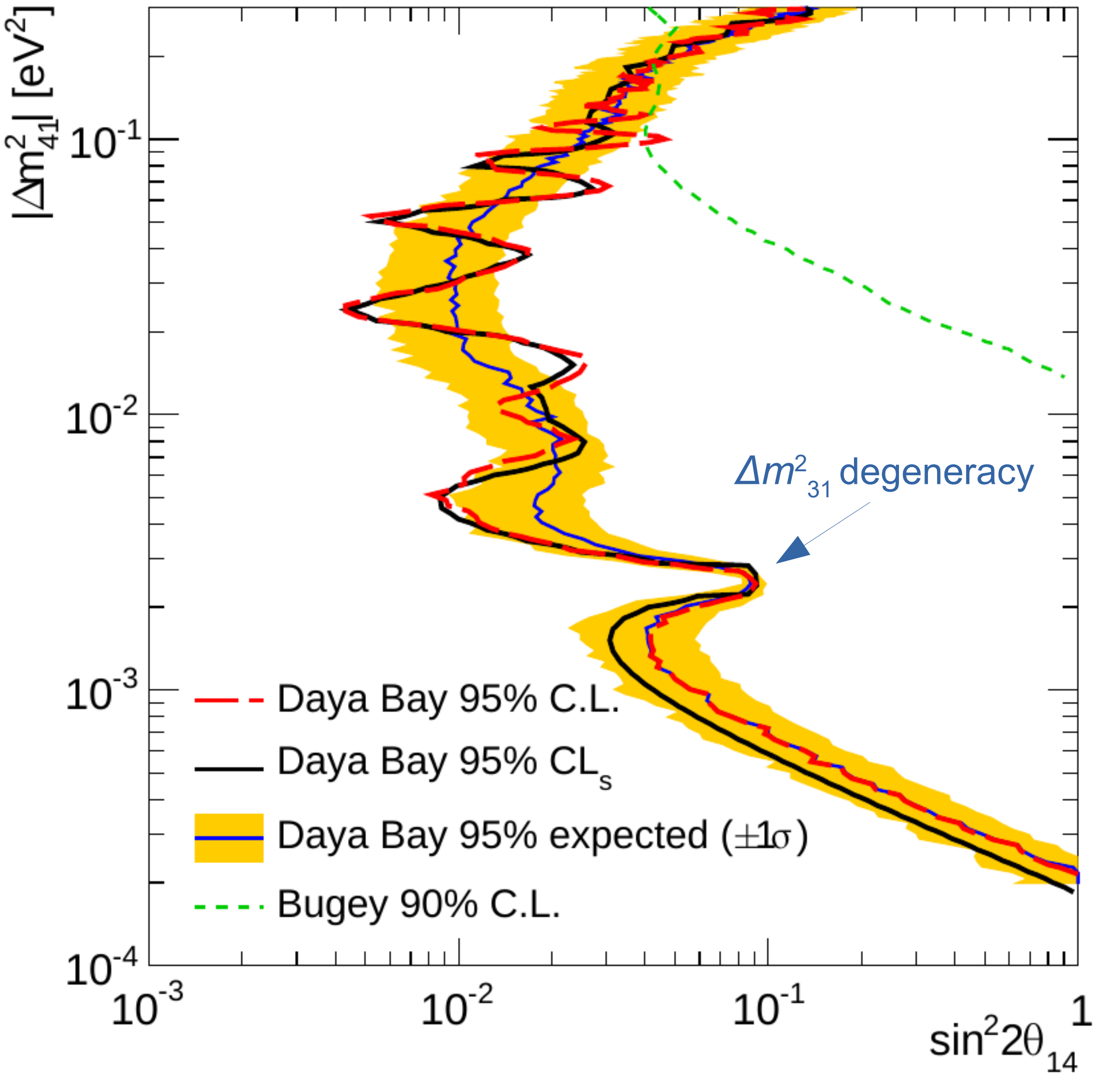
2) Use reactor model for all predictions. Calculate χ^2 using explicit nuisance parameters.

   Set limits using Gaussian CL_s

Results consistent with each other and with MC expectation!

World-leading limits for $|\Delta m^2_{41}| \in [0.0002, 0.2]$ eV²

PRL 117, 151802 (2016)

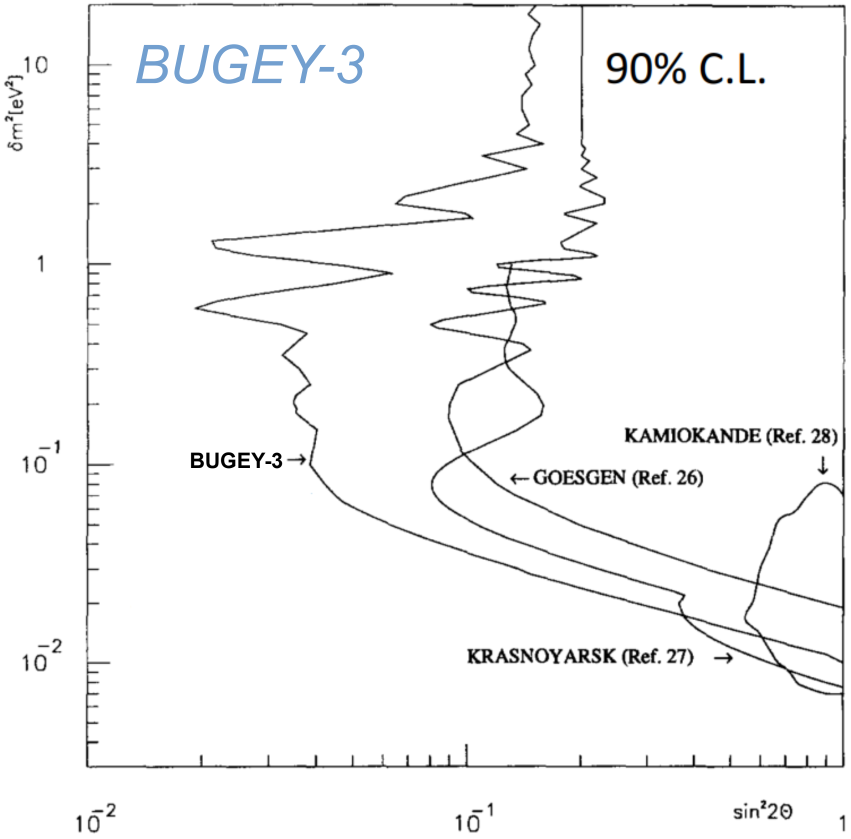


Δm^2_{31} degeneracy

MINOS and Bugey-3

Complementary datasets: Synergy in combination with Daya Bay!

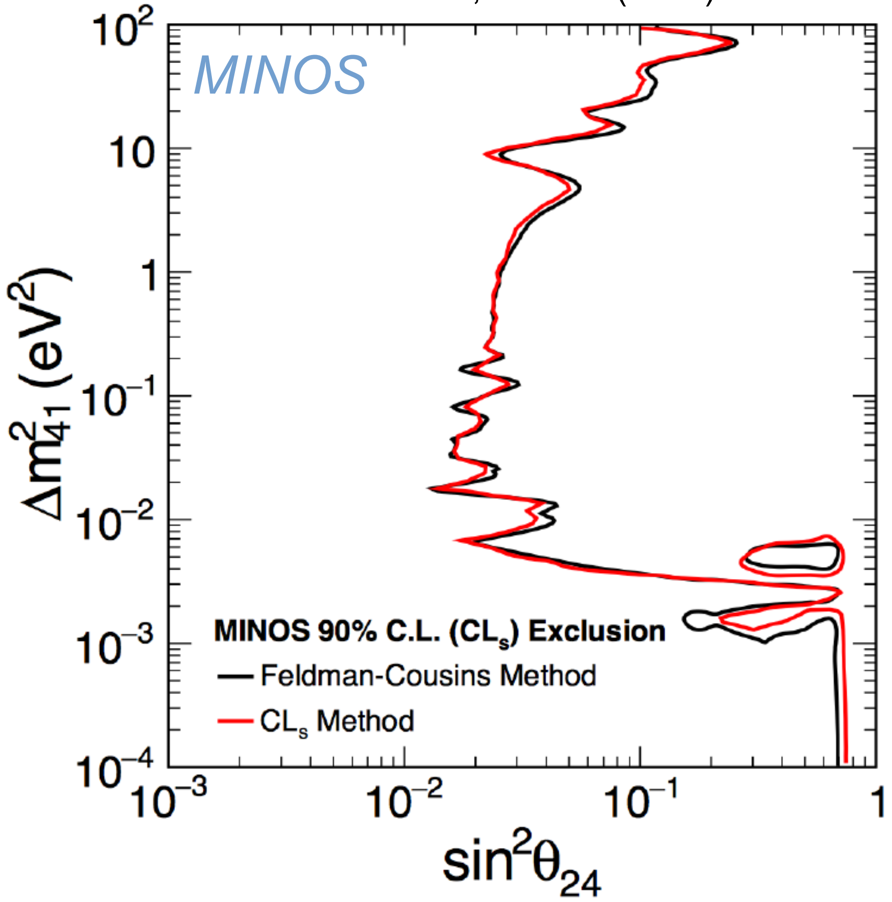
Nucl. Phys. B 434, 503 (1995)



Reactor $\bar{\nu}_e$, short baseline (15/40/95 m)

Sensitivity to 0.3 – 3 eV^2

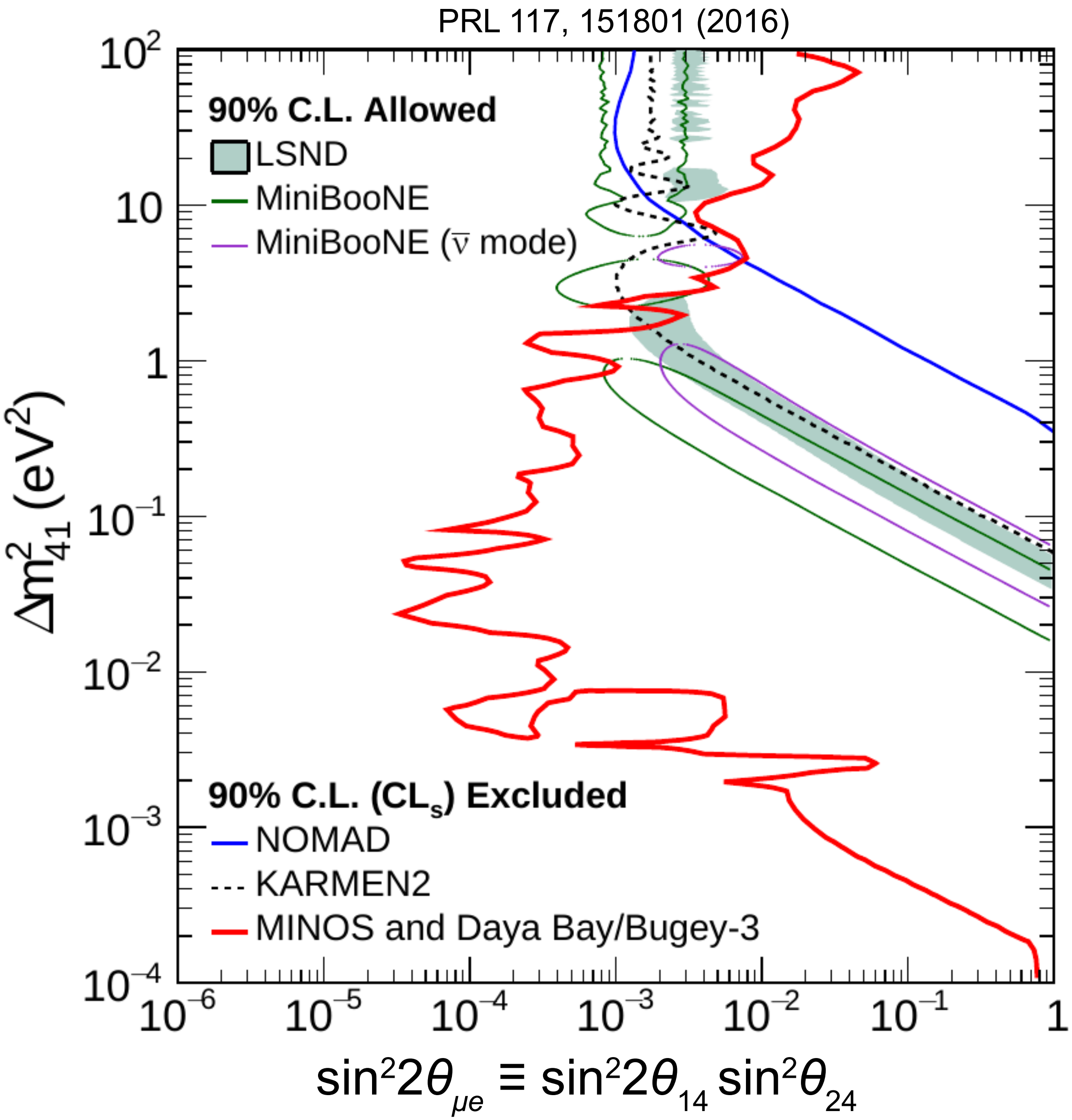
PRL 117, 151801 (2016)



3 GeV ν_μ, 1 + 734 km baseline

Sensitivity out to 10^2 eV^2

Combined results



Combine Daya Bay and Bugey-3* data to obtain $\Delta\chi^2$ across ($\sin^2 2\theta_{14}$, Δm^2_{41}) plane

* Updated due to change in measured neutron lifetime and latest reactor models

From MINOS, get $\Delta\chi^2$ across ($\sin^2\theta_{24}$, Δm^2_{41}) plane

For each point in ($\sin^2 2\theta_{14}$, $\sin^2\theta_{24}$, Δm^2_{41}) space, add the two $\Delta\chi^2$'s, calculate CL_s from simulation

Get CL_s in ($\sin^2 2\theta_{\mu e}$, Δm^2_{41}) plane by conservatively taking largest CL_s among possible combos of $\sin^2 2\theta_{14}$ and $\sin^2\theta_{24}$

→ Exclude LSND/MiniBooNE allowed region for $|\Delta m^2| < 0.8$ eV^2 at 95% CL_s!

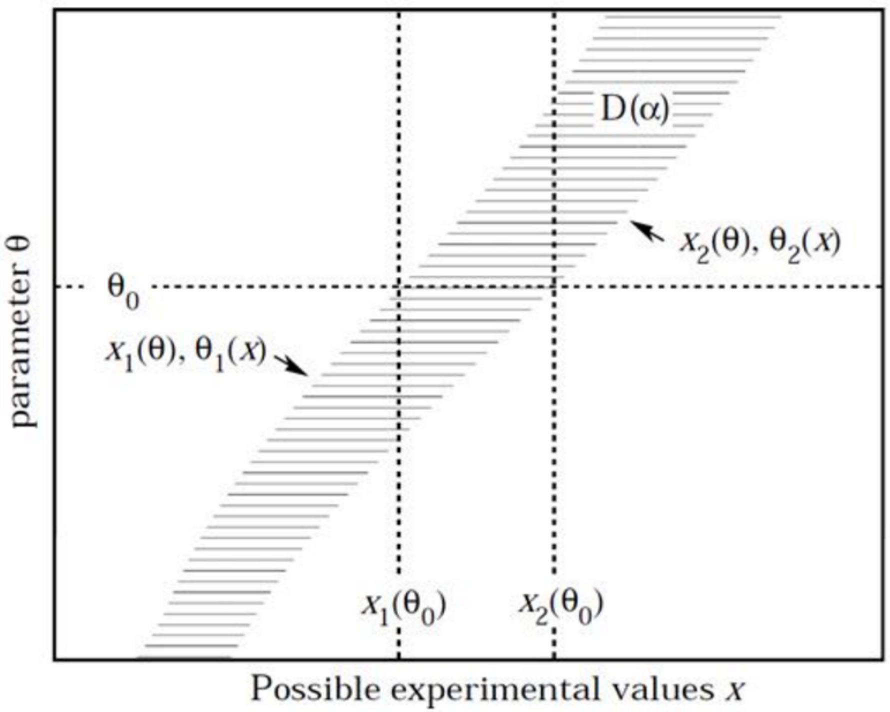
Conclusion

- Daya Bay finds no evidence of sterile neutrino mixing for $|\Delta m^2_{41}|$ ε [0.0002, 0.3] eV^2
  - Most stringent constraints to date below 0.2 eV^2
  - Another 2x in improvement in sensitivity using data up to 2017
- In combination with MINOS and Bugey-3, strong limits are set on $\sin^2 2\theta_{\mu e}$ for $|\Delta m^2_{41}|$ ε [0.0002, 100] eV^2
- LSND/MiniBooNE allowed regions for $|\Delta m^2_{41}| < 0.8$ eV^2 are excluded at 95% CL_s
- We've discussed a *relative* analysis. We also have an *absolute* analysis based on comparing flux to reactor predictions. Deficit is only seen for U-235 component, providing further evidence against an eV-scale sterile neutrino

Thanks!

Limit setting

Feldman-Cousins



- “Statistically rigorous” – Well-defined frequentist interpretation of limits/intervals
- Based on Neyman construction w/ FC ordering rule
- Computationally expensive – Many ToyMCs
- Can set overly aggressive limits in background-dominated situations

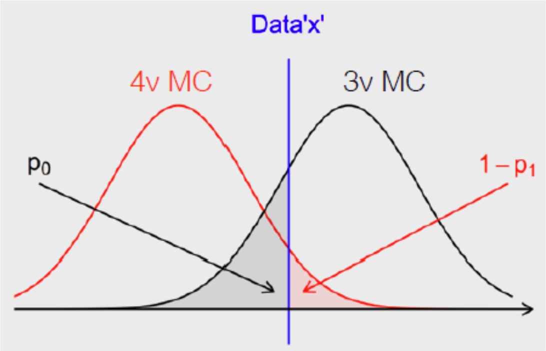
CL_s

CL_s Method*

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

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

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



For Gaussian CLs†, calculate

$\Delta\chi^2_{data}$ — data
$\Delta\chi^2_{3\nu}$ — 3ν Asimov data
$\Delta\chi^2_{4\nu}$ — 4ν 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)

- No well-defined frequentist interpretation
- Based on one-sided exclusion regions w/ “penalty” for overlap of background distribution
- Allows approximations for fast computation
- Easier for combining data from multiple experiments

Both methods are suitable for Daya Bay. Good for cross-checking.