Recent Results From Reactor Neutrino Experiments

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Neutrino Oscillations

A short reminder

Neutrino flavors are a superposition of mass eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\Delta m^2_{31}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\Delta m^2_{31}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\Delta m^2_{21}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\sin^2 2\theta_{23} \approx 1$ atmospheric ν

$\sin^2 2\theta_{13} \approx 0.1$ accelerator+reactor

$\sin^2 2\theta_{12} \approx 0.8$ solar ν

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Propagation of states leads to oscillation phenomenon

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$
$$+ \sin^2(2\theta_{13})\sin^2(\theta_{12})\left[\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2\left(\frac{\left(\Delta m^2_{31} - \Delta m^2_{21}\right) L}{4E}\right)\right]$$

Neutrino Oscillations

Reactor neutrino experiments predestined for measuring θ_{13}

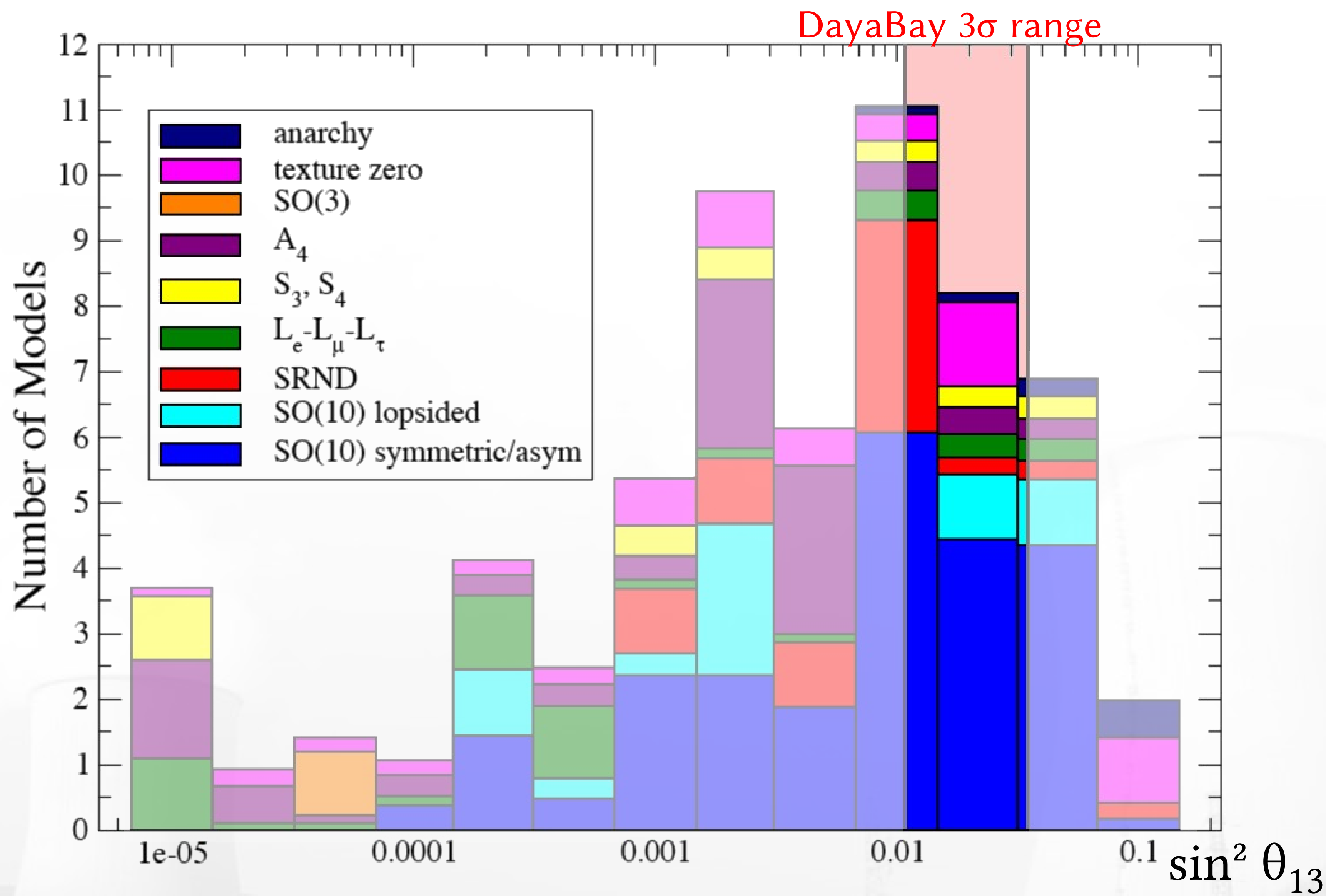
- Strongest man-made neutrino sources (good statistics)
- Pure source of antineutrinos (no flavor contaminations)
- Antineutrinos rather than neutrinos (no matter effects)

Tremendous effort: θ_{13} from unknown to best known in a few years

Why are we interested in θ_{13}?

- Measure CP violation in lepton sector (matter asymmetry in the universe)
- Determine mass hierarchy ($\longrightarrow$ future experiments; understanding of ν mass)
- Understand the structure of mixing matrix (guide development of new theories)

Theories of θ_{13}



Reactor ν experiments efficiently cleaned up the neutrino theory landscape!

From hep-ph:0608137 (2006)

The Reactor Neutrino Experiments

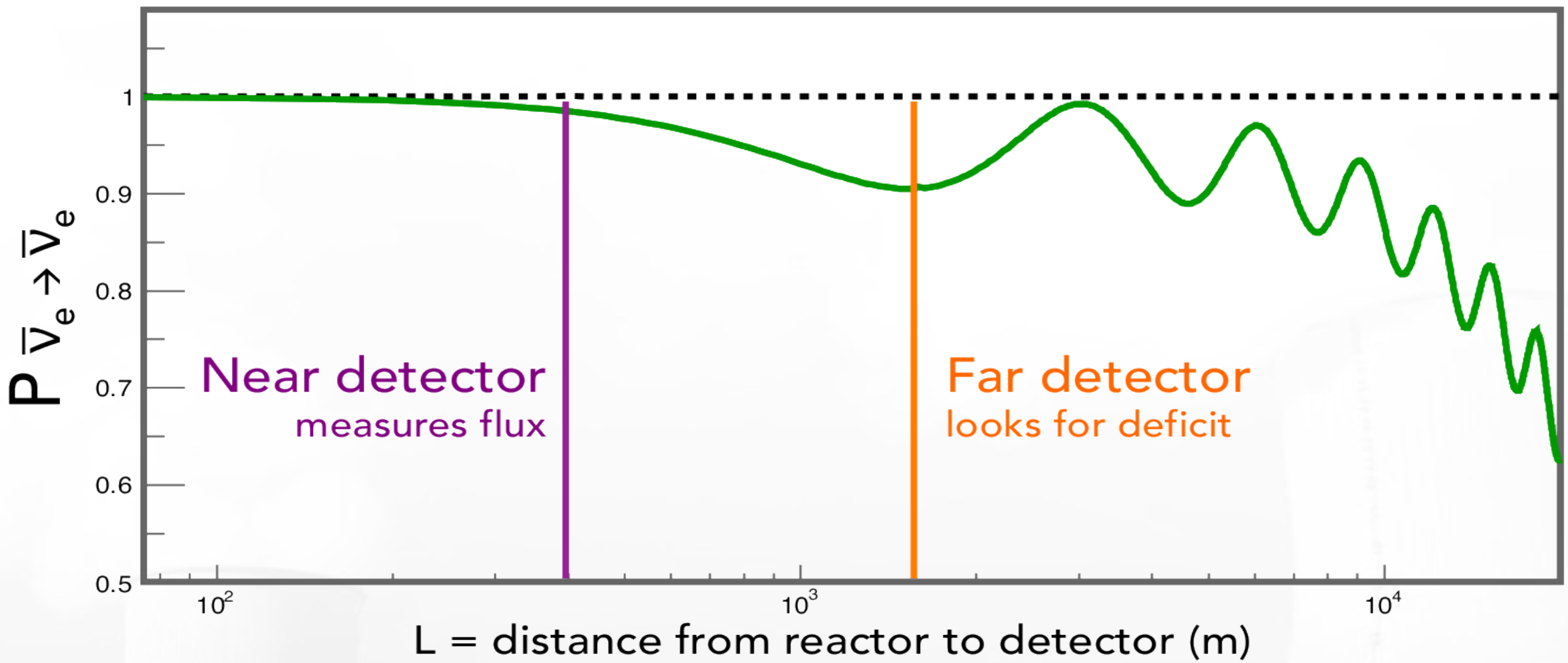
Daya Bay

Double Chooz

RENO

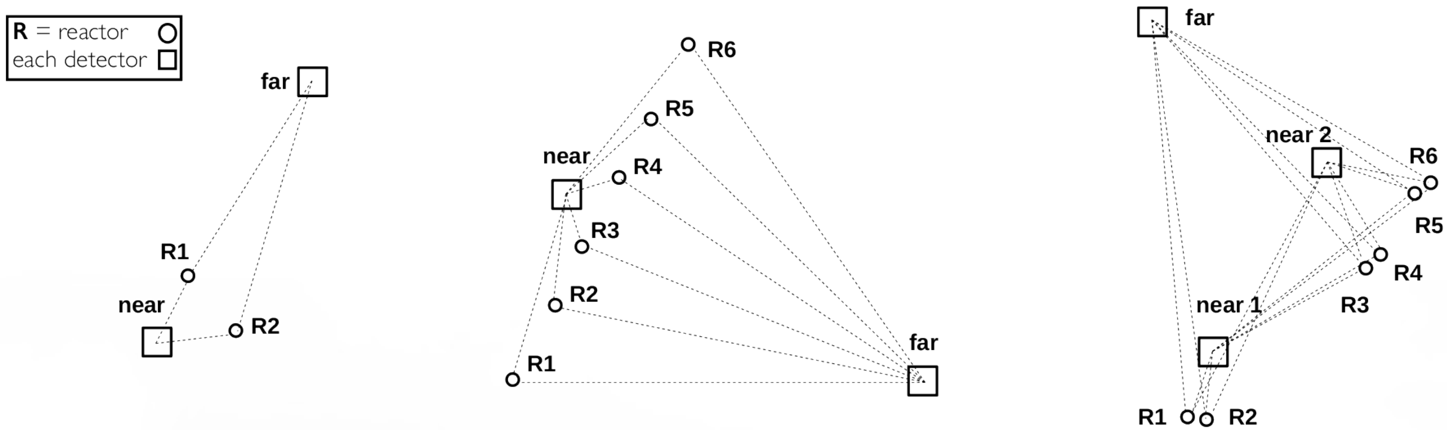
Experimental Concept

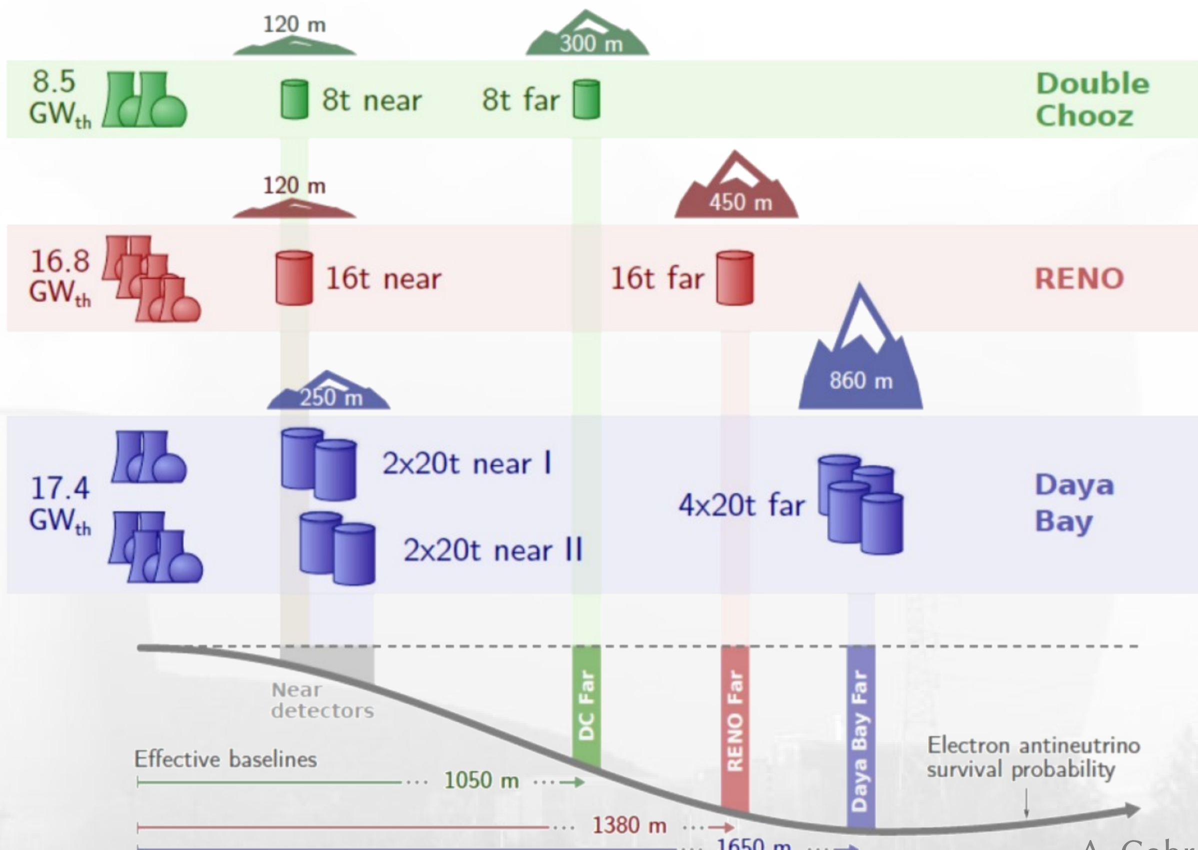
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \ \sin^2 \left(1.27 \ \Delta m^2_{23}(\text{eV}^2) \ \frac{L(\text{m})}{E(\text{MeV})} \right)$$



- **Short baseline:** reduce parameter correlations
- **Two-detector-concept:** reduction of systematics

Experimental Geometries





A. Cabrera

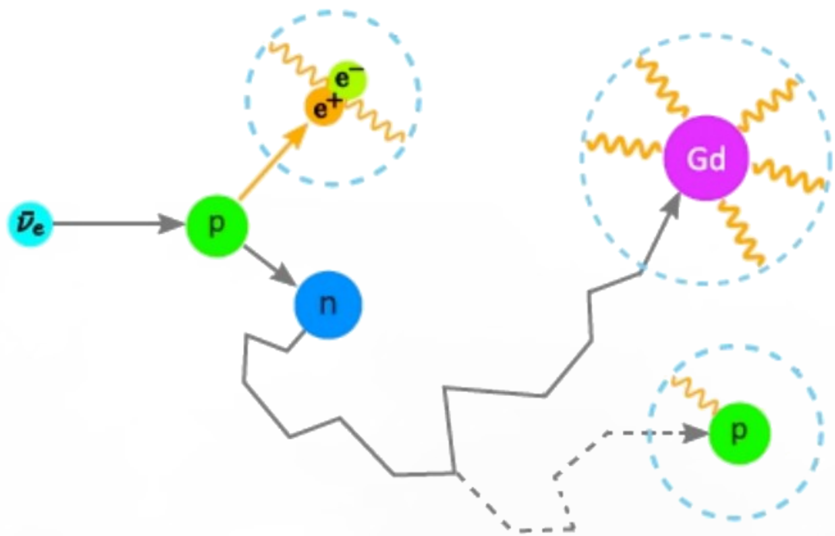
Isoflux lines

Various baselines

Various baselines

Many detectors

Detection Principle



Inverse Beta Decay (IBD):

$$\overline{\nu}_e + H \longrightarrow e^+ + n_0$$

Coincidence signature:

- Prompt: e^+ energy deposition + annihilation
- Delayed: n thermalization + capture

Gd-loaded scintillator:

- High deexcitation energy (~8 MeV)
- Short coincidence window (~30 μs)
- ⟶ very clean signature

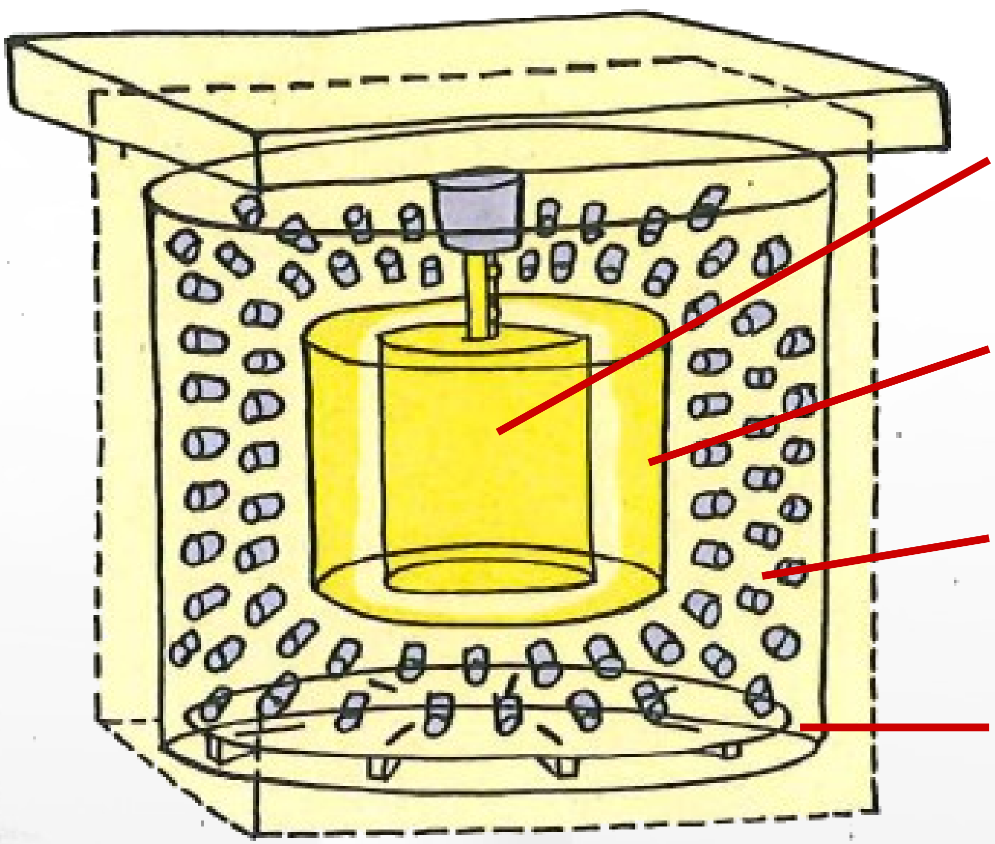
Also n-H channel available:

- Higher statistics
- But larger BG contribution (2.2 MeV, 200 μs)

Rate-only or also spectral analyses

Generic Detector Design

„Standard“ multi-volume organic liquid scintillators detector design



Spirou #3849, 2012

Outer Veto

- Plastic scintillator for muon detection + tracking

Neutrino Target

- Gd-loaded LS for neutrino detection (n-Gd)

Gamma Catcher

- Unloaded LS for γ containment (E-scale)

Buffer Volume

- Mineral oil to shield inner volumes; PMTs

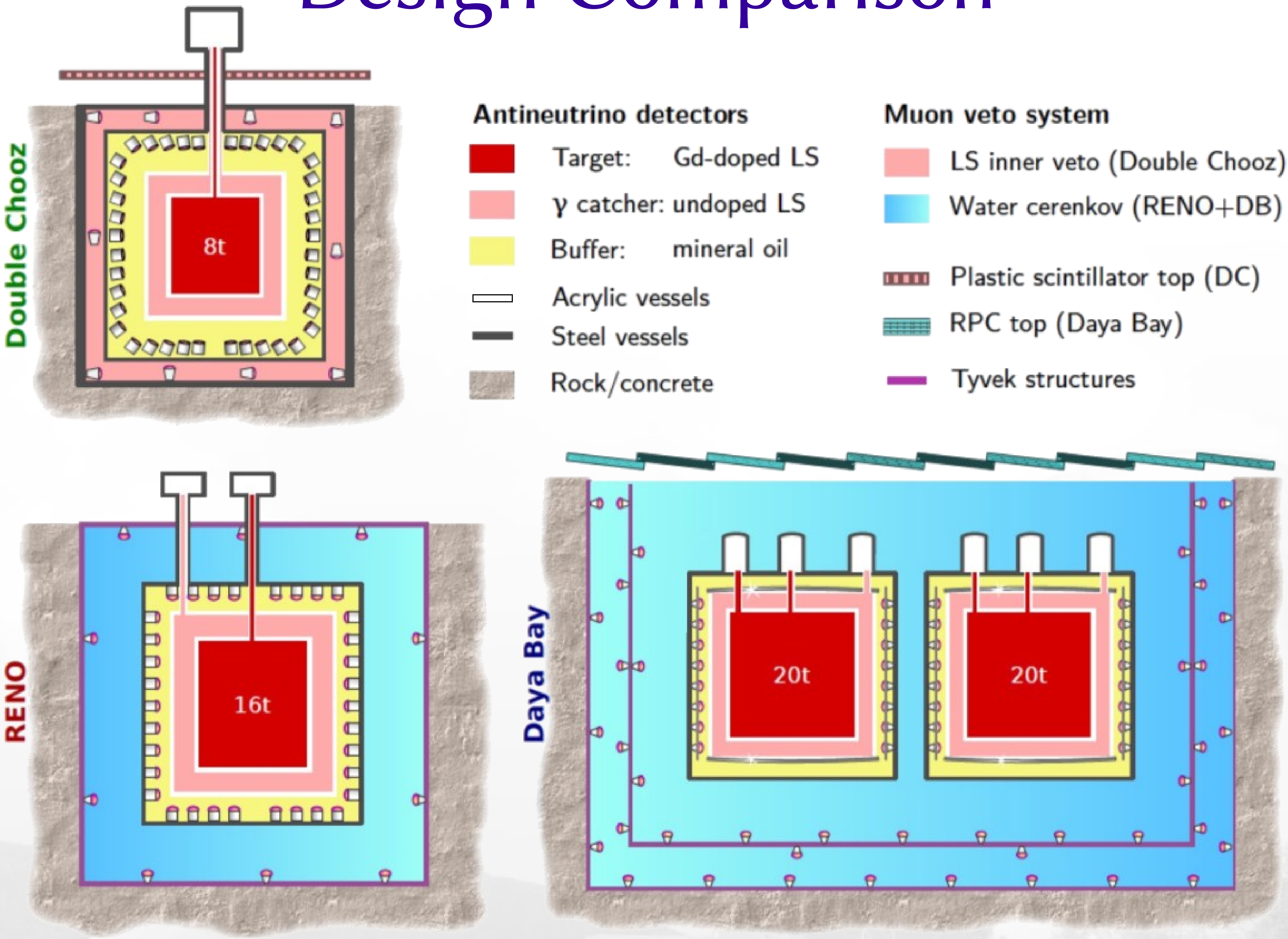
Inner Veto

- Rejection of muons and external radioactivity

Passive Shielding

- Overburden + shielding

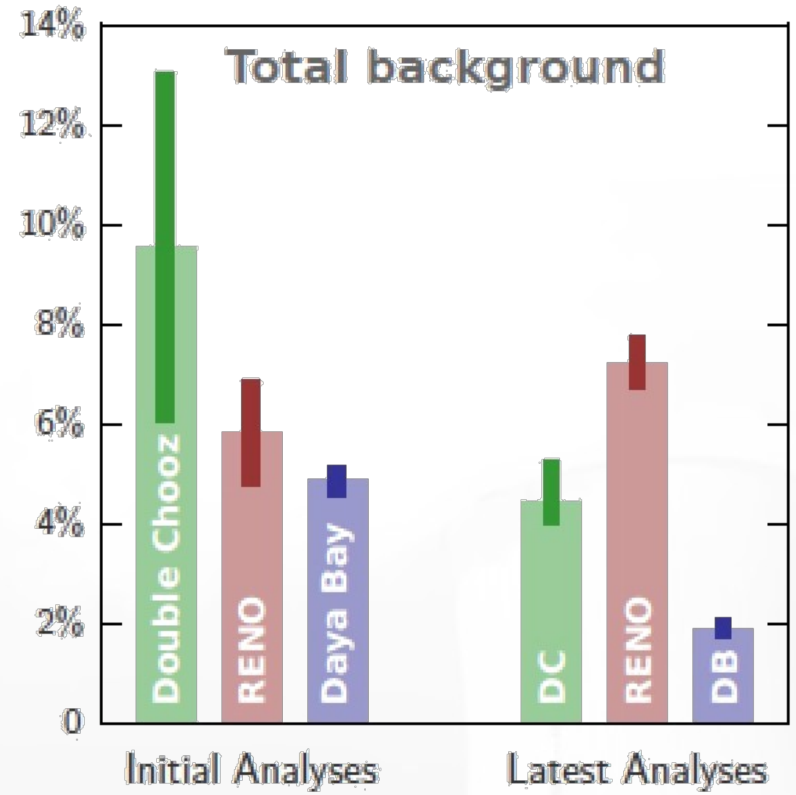
Design Comparison



A. Cabrera

Background Contributions

- **Accidentals:** negligible for n-Gd, still important for n-H
- **Correlated (stopping-μ, fast n):** μ-induced, reduced with increasing overburden
- **Cosmogenic β-n emitters (^{9}Li, ^{8}He):** concern to all experiments
- **Other backgrounds:** Daya Bay removed calibration sources, RENO suffers from 252Cf contamination in post-2012 data (under control)
- All experiments significantly improved their BG understanding
- New methods developed to reject BG



@ Far Detector sites, n-Gd analyses

New θ_{13} Results

Daya Bay

Double Chooz

RENO

Daya Bay θ_{13} Results

n-Gd analysis

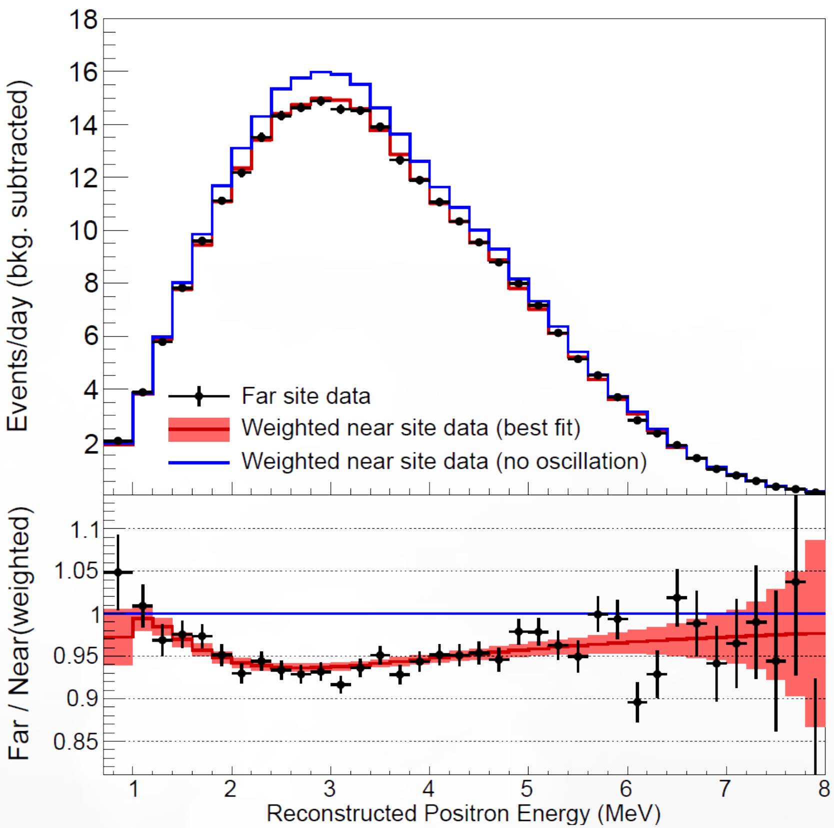
Improvements over last result:

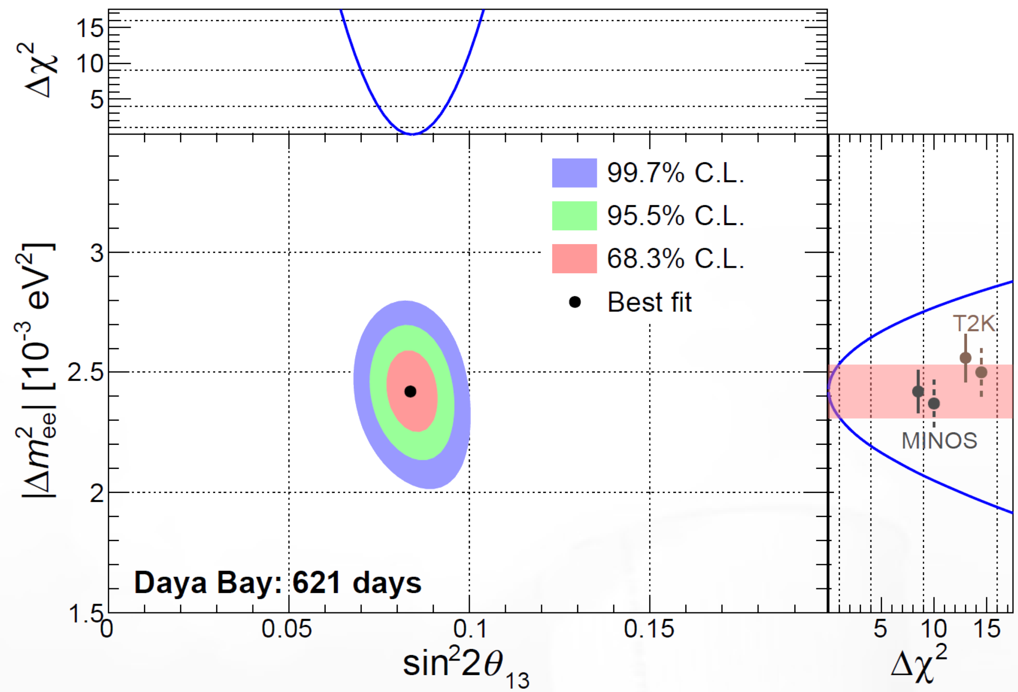
- 621 days of data
- Last 2 detectors operational (total exposure larger by factor of 3.6)
- Improved energy calibration
- Improved BG understanding

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	0.4%	0.4%	~50%	Measured with after-muon events	Extend to larger data set
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics

Z. Wang, TAUP 2015

Daya Bay θ_{13} Results





- Far/near relative measurement
- Precision of $\sin^2 2\,\theta_{13}$: 10% ⟶ 6%
- Precision of $|\Delta m^2_{ee}|$: 8% ⟶ 4%

n-Gd analysis

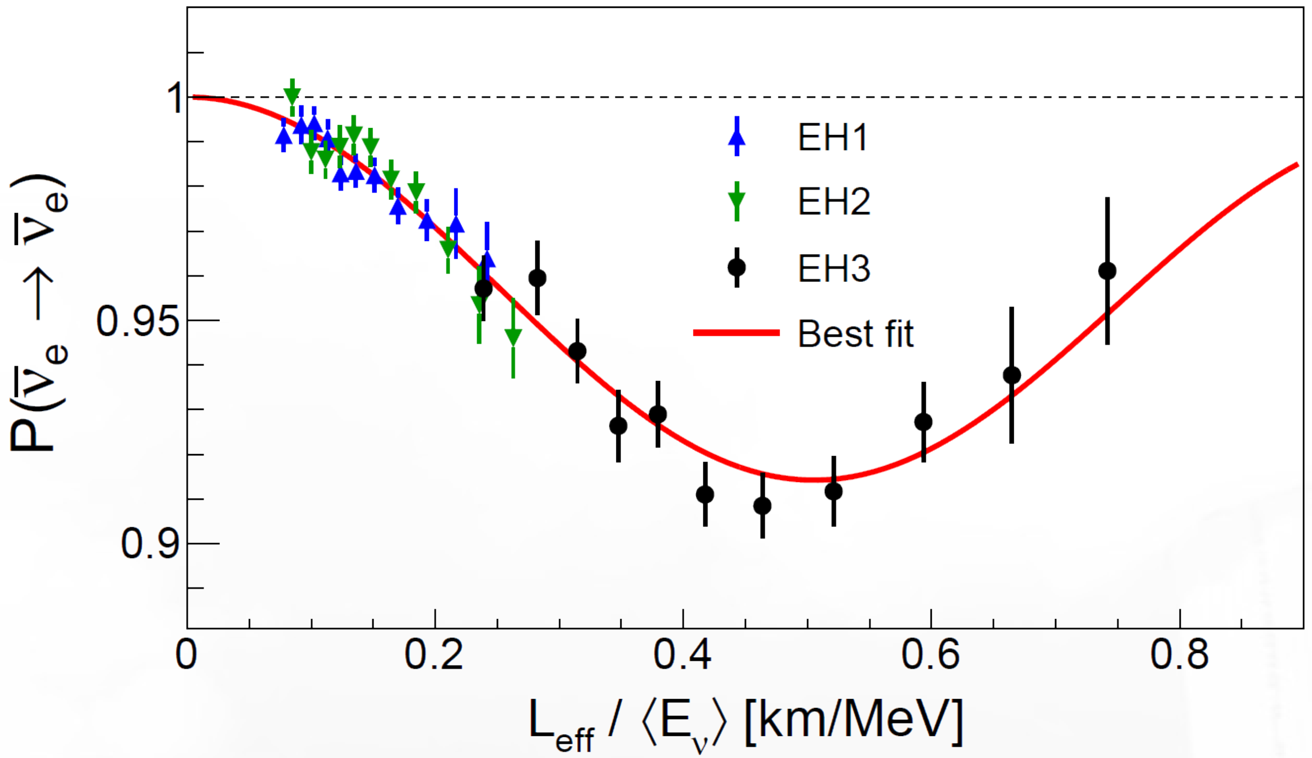
Rate+Shape analysis:

$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

$|\Delta m^2_{ee}| = [2.42 \pm 0.11] \cdot 10^{-3}\ \mathrm{eV}^2$

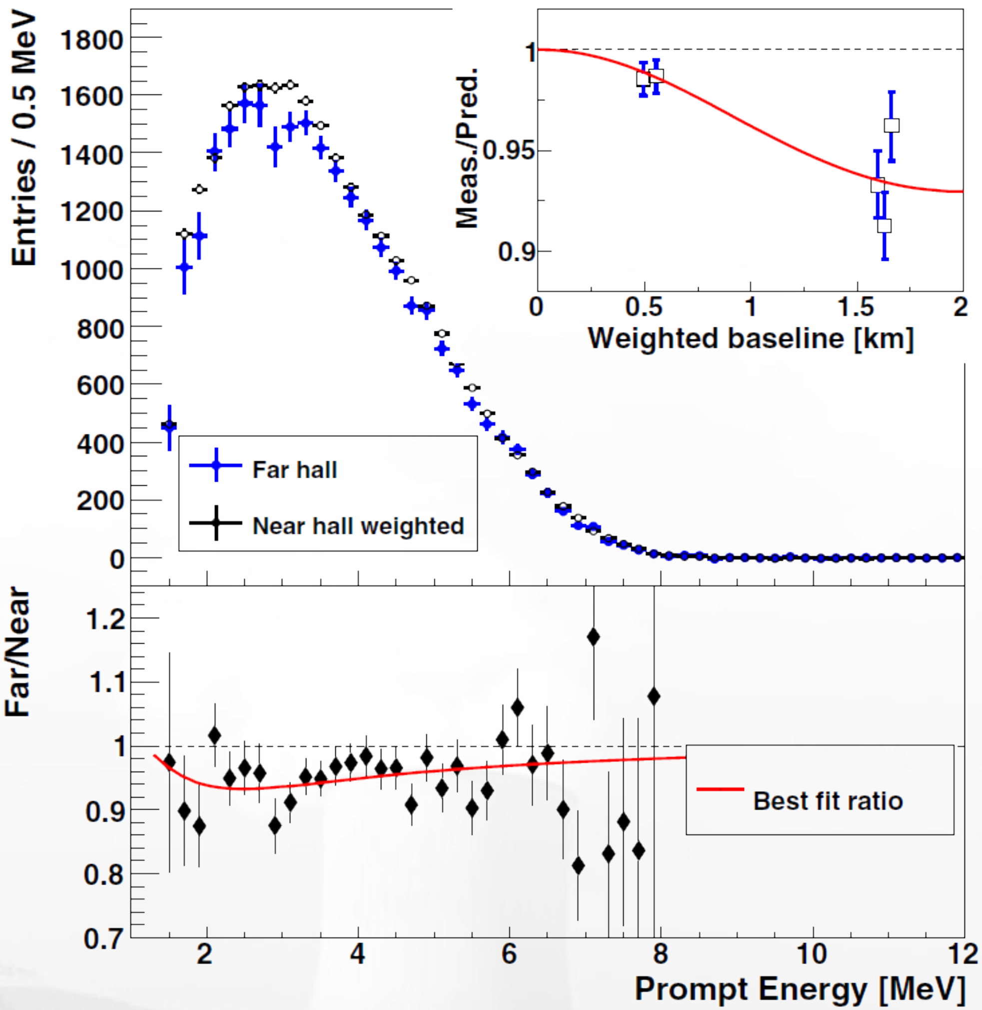
[arXiv:1505.03456]

Daya Bay θ_{13} Results



- L/E plot produced with n-Gd data
- Due to many different baselines in the setup
- Beautiful confirmation of oscillation interpretation

Daya Bay θ_{13} Results



n-H analysis

BG reduction strategy:

- Prompt energy cut >1.5 MeV
- Prompt-delayed distance cut <0.5 m

217 days with 6 detectors

Rate-only analysis:

$\sin^2 2\theta_{13} = 0.083 \pm 0.018$

[PRD 90, 071101 R (2014)]

New θ_{13} Results

Daya Bay

Double Chooz

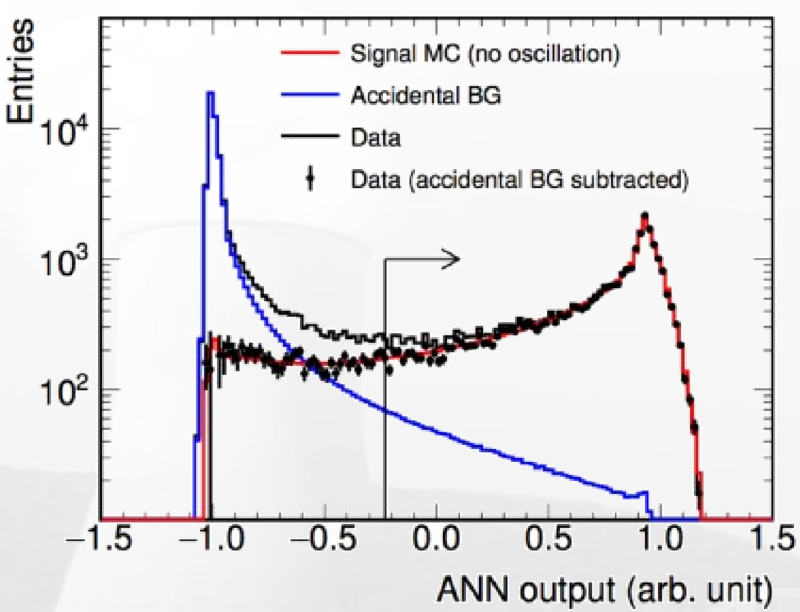
RENO

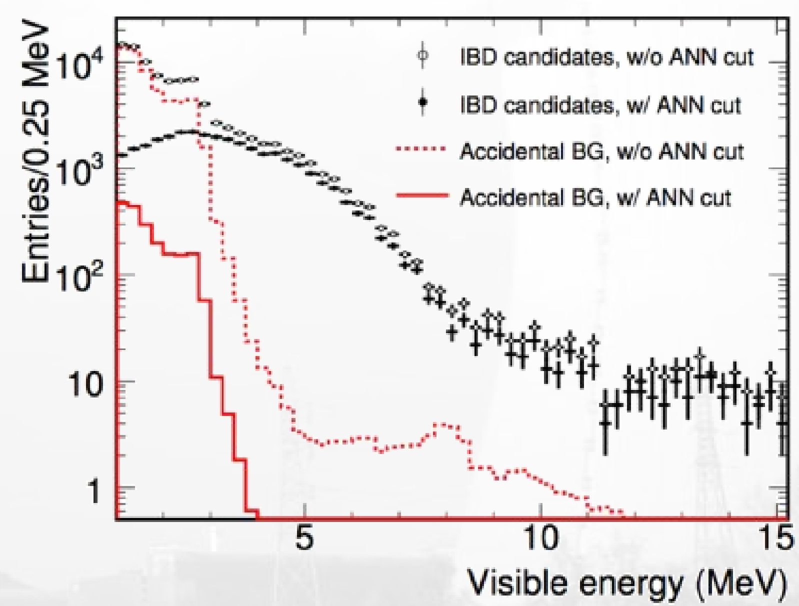
Double Chooz θ_{13} Results

n-H analysis

Improvements over last nH result:

- Significantly larger data set (~240 days ⟶ ~460 days)
- Multivariate BG rejection (ANN-based)
- Multiplicity Pulse Shape veto against FN





T. Lasserre, TAUP 2015

Double Chooz θ_{13} Results

n-H analysis

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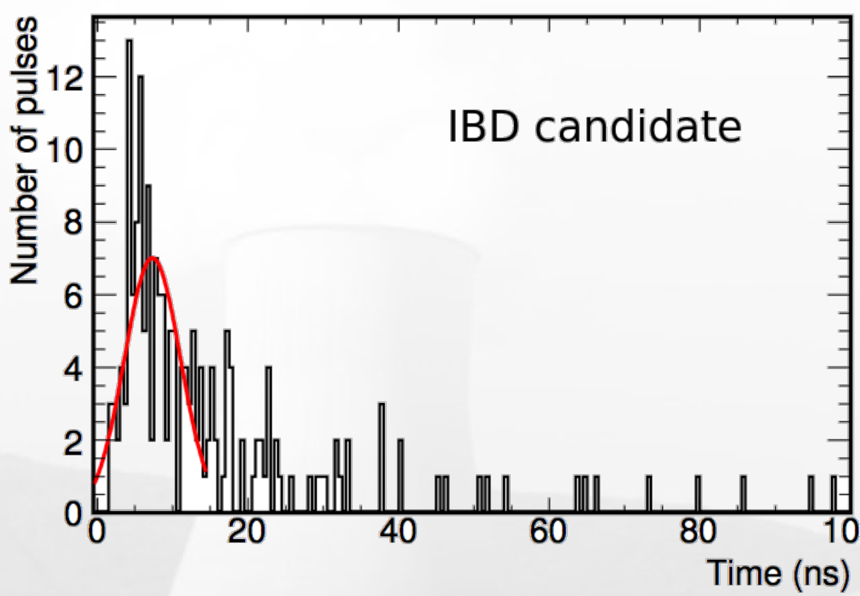

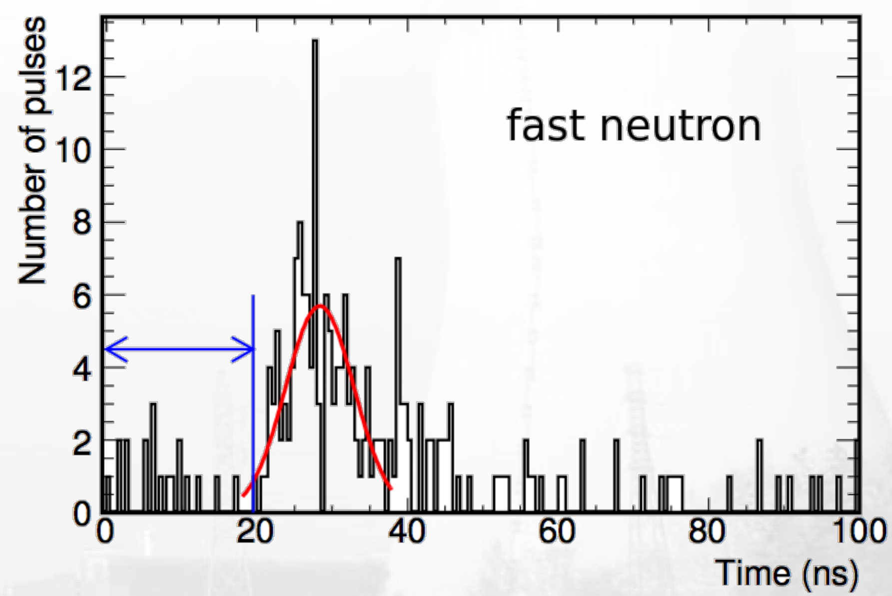

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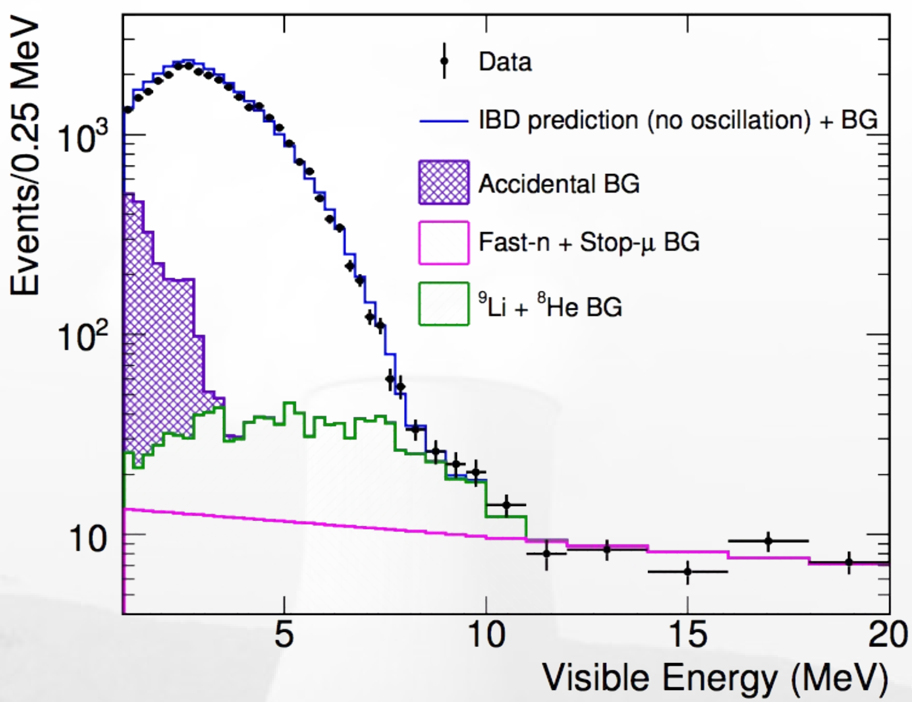
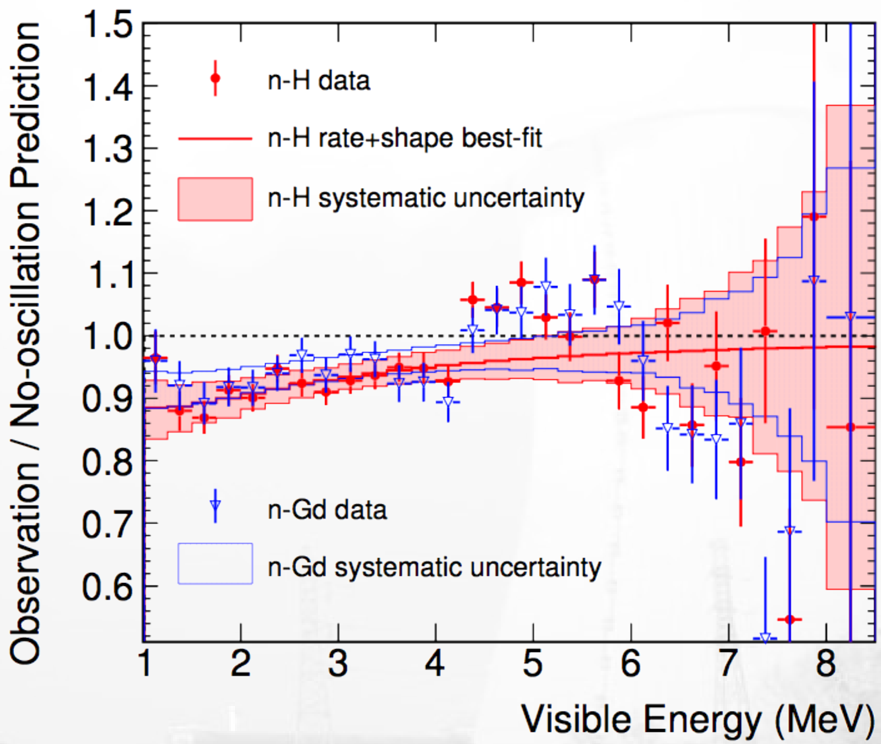
Double Chooz θ_{13} Results

n-H analysis

⟹ S/BG ratio improved by factor of ~20!

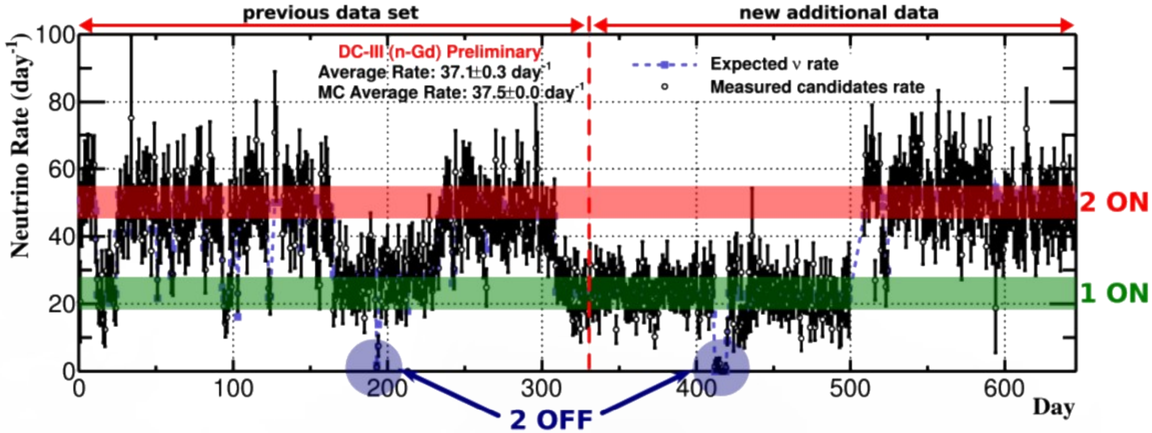
Rate+shape analysis: $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$





J. Castaño, WIN 2015

Double Chooz θ_{13} Results

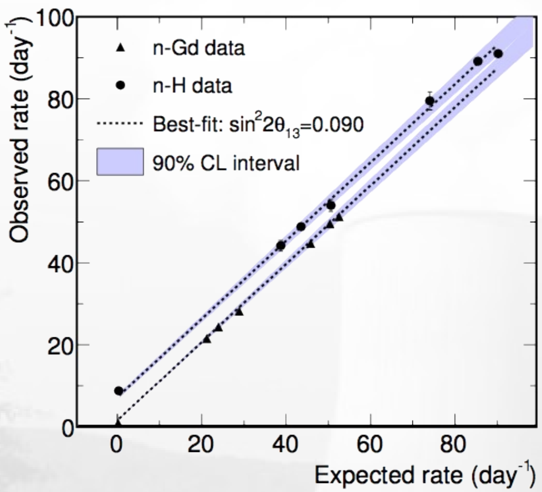


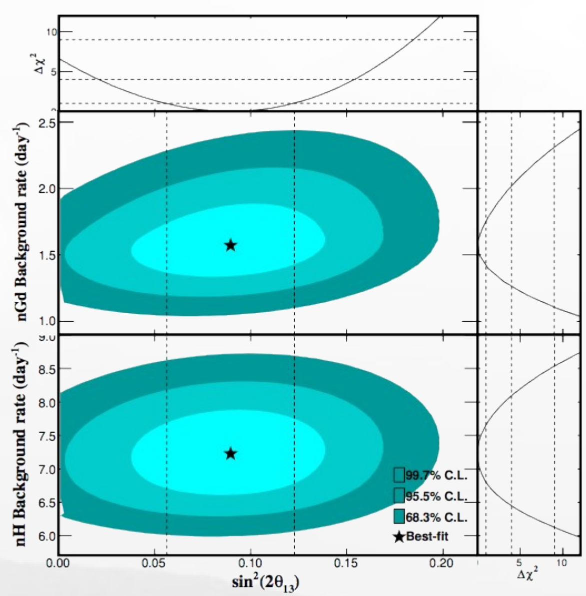
Reactor-rate-modulation

- Compares IBD rates for different reactor powers
- Measurement of θ_{13} and BG rate at the same time
- Independent of neutrino energy distribution
- BG model independent measurement or using BG model to increase precision
- Combined Gd-III + H-III fit:

$\sin^2 2\theta_{13} = 0.090 \pm 0.033$

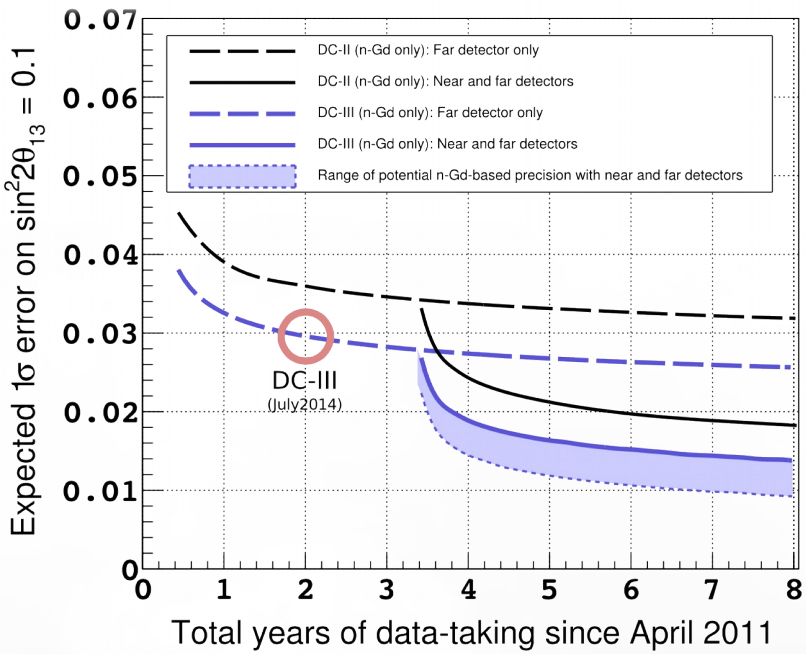
BG rate = 7.29 ± 0.49 d^{-1}





T. Lasserre, TAUP 2015

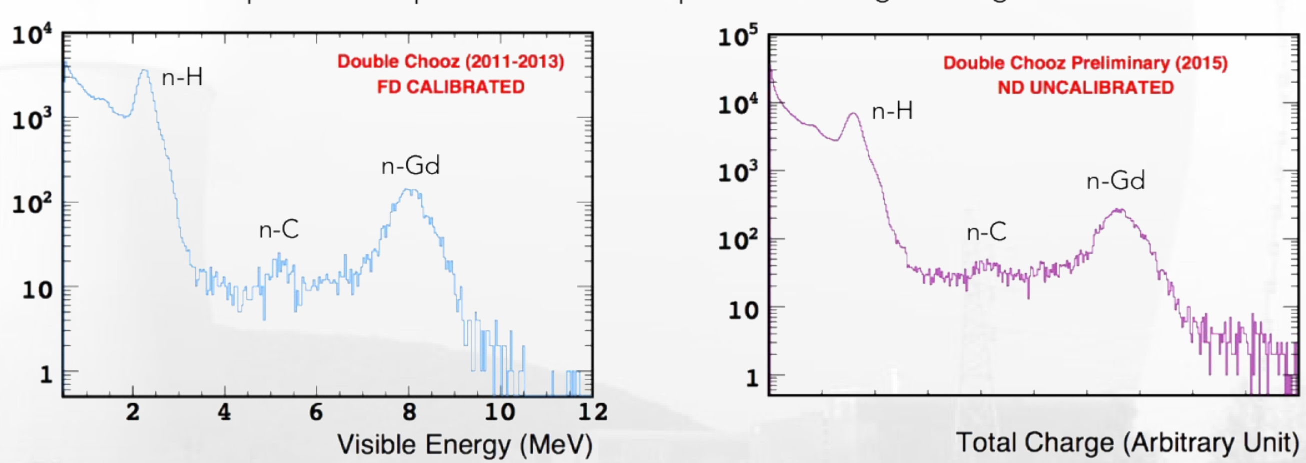
Double Chooz θ_{13} Results



2-detector phase

- Near detector completed
- Taking data since January 2015
- Prospect to lower 1σ-uncertainty to below 10%

Spectrum of spallation neutron captures following crossing muons



J. Castaño, WIN 2015

New θ_{13} Results

Daya Bay

Double Chooz

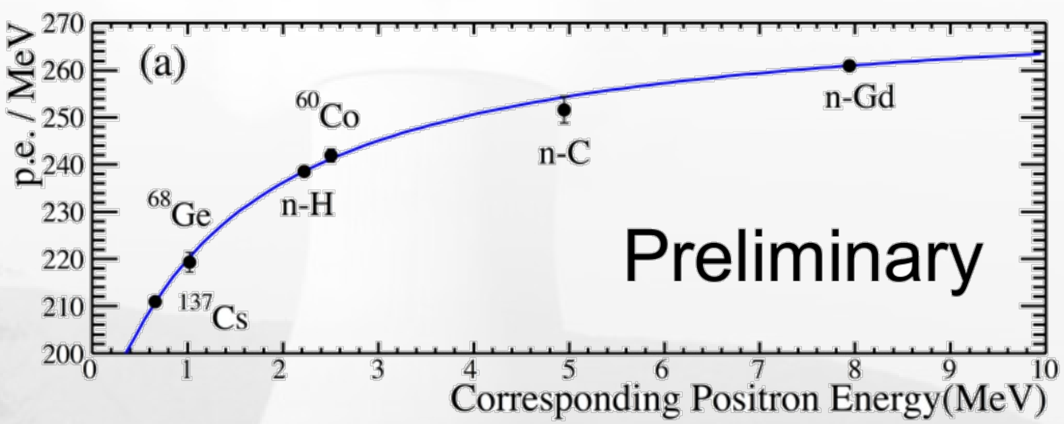
RENO

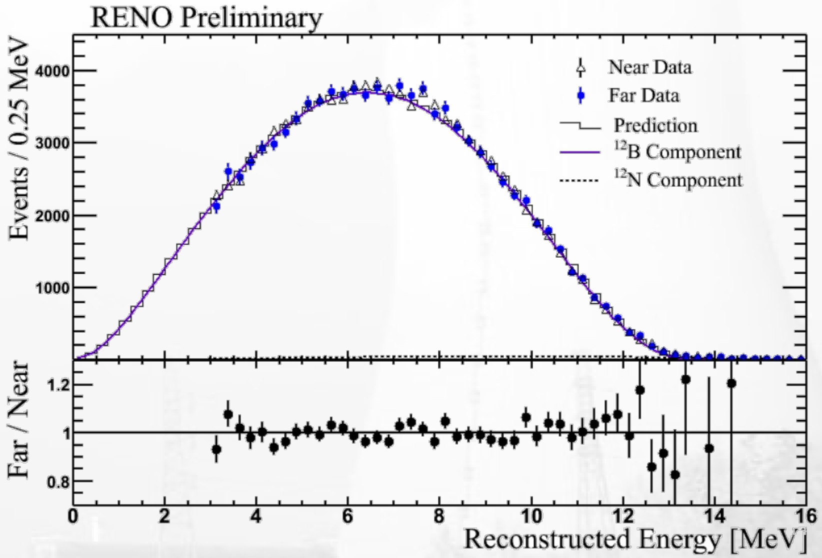
RENO θ_{13} Results

n-Gd analysis

Improvements over last result

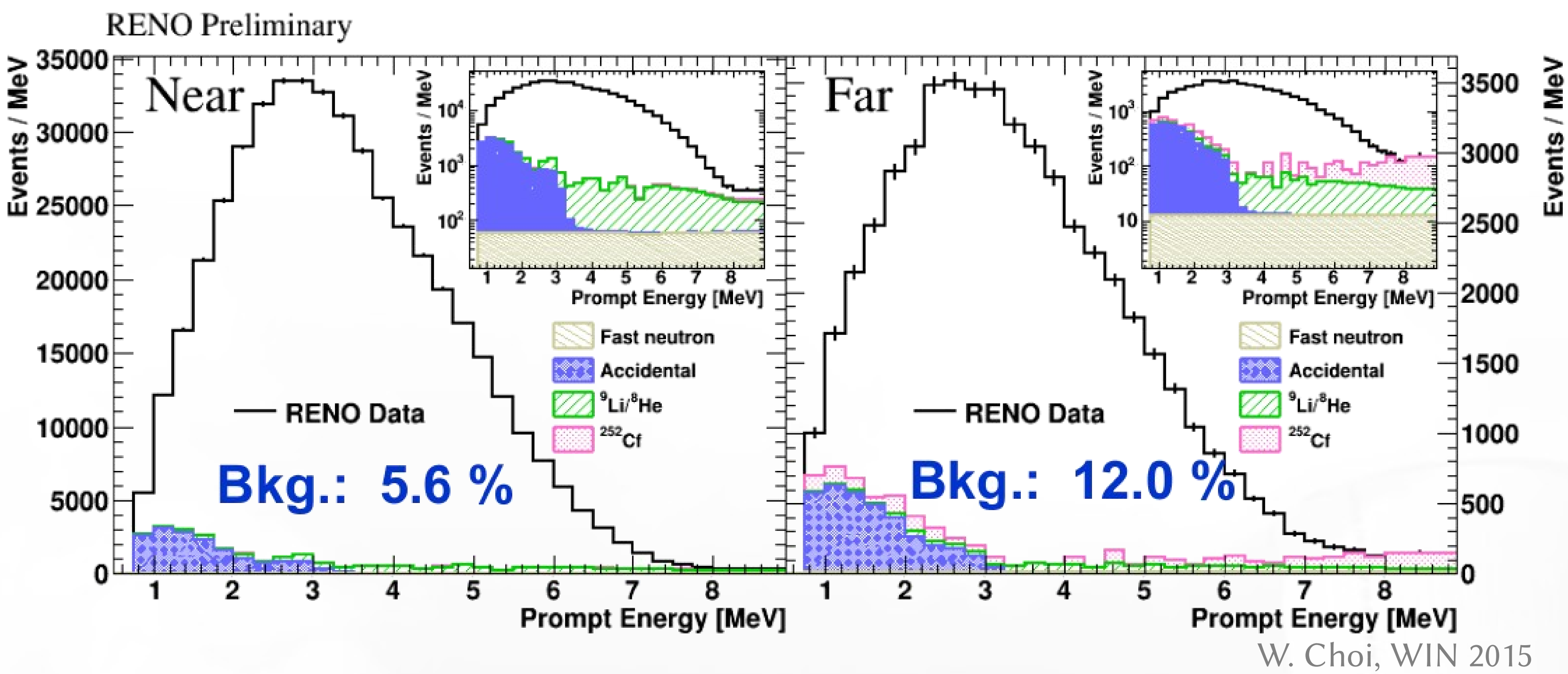
- Significantly larger data set (~400 days ⟶ ~800 days)
- Relaxed Q_{max}/Q_{tot} cut: increases statistics, reduces shape uncertainty, more BG
- Improved energy scale and BG spectra (esp. important for R+S)





W. Choi, WIN 2015

RENO θ_{13} Results

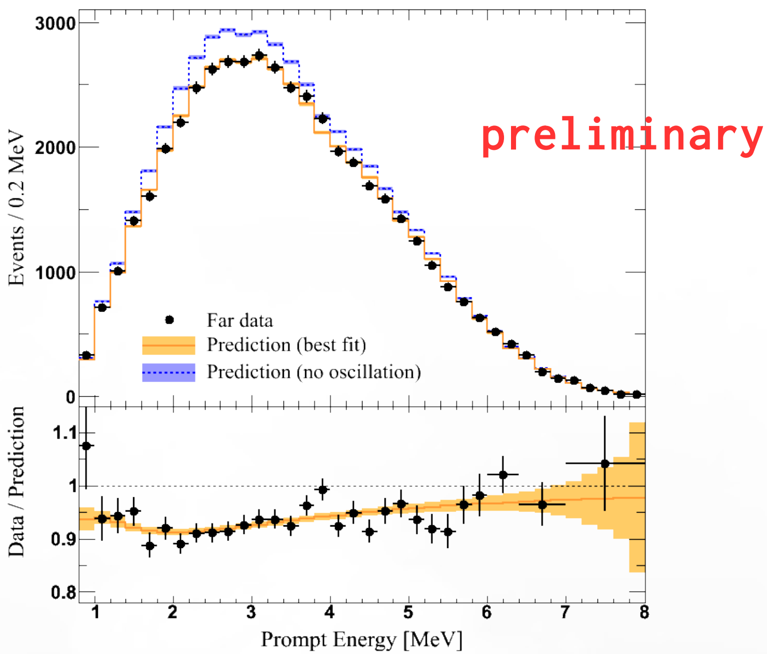


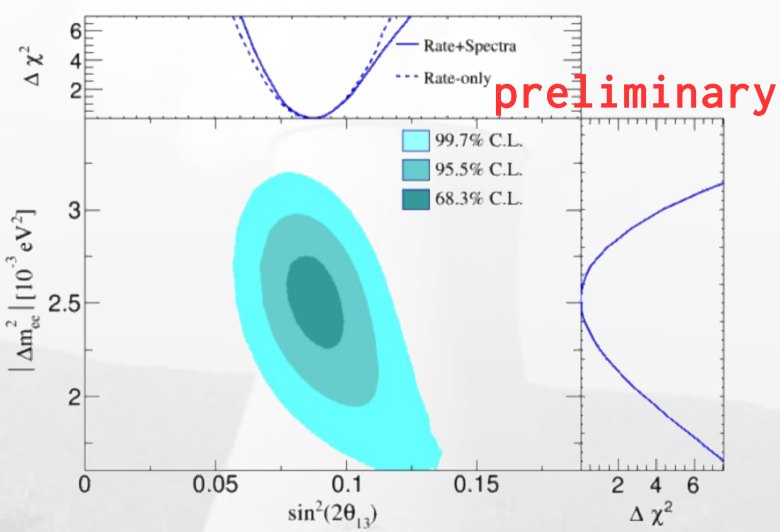
n-Gd analysis

Rate-only analysis: $\sin^2 2\theta_{13} = 0.087 \pm 0.008_{stat} \pm 0.008_{sys}$

Uncertainty dominated by background contribution

RENO θ_{13} Results





W. Choi, WIN 2015

Spectral analysis in progress

- Combined fit of $|\Delta m^2_{ee}|$ and θ_{13}
- BG spectra are leading uncertainty

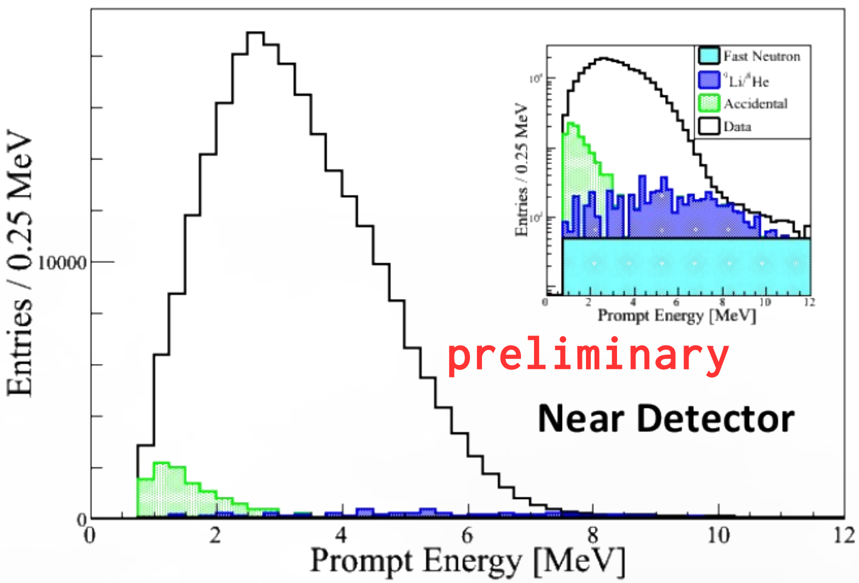
$$\sin^2 2\theta_{13} = 0.088 \pm 0.008_{stat} \pm 0.007_{sys}$$

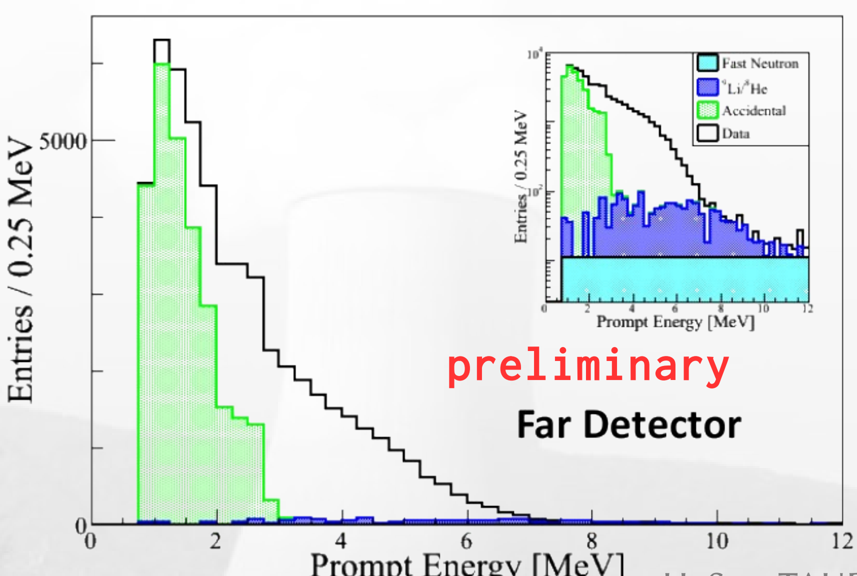
$$|\Delta m^2_{ee}| = [2.52 \pm 0.19_{stat} \pm 0.17_{sys}] \cdot 10^{-3}\ eV^2$$

Envisaged accuracy goals:

- $\sin^2 2\theta_{13}$: 5%
- $|\Delta m^2 ee|$: 4% (within two years)

RENO θ_{13} Results





H. Seo, TAUP 2015

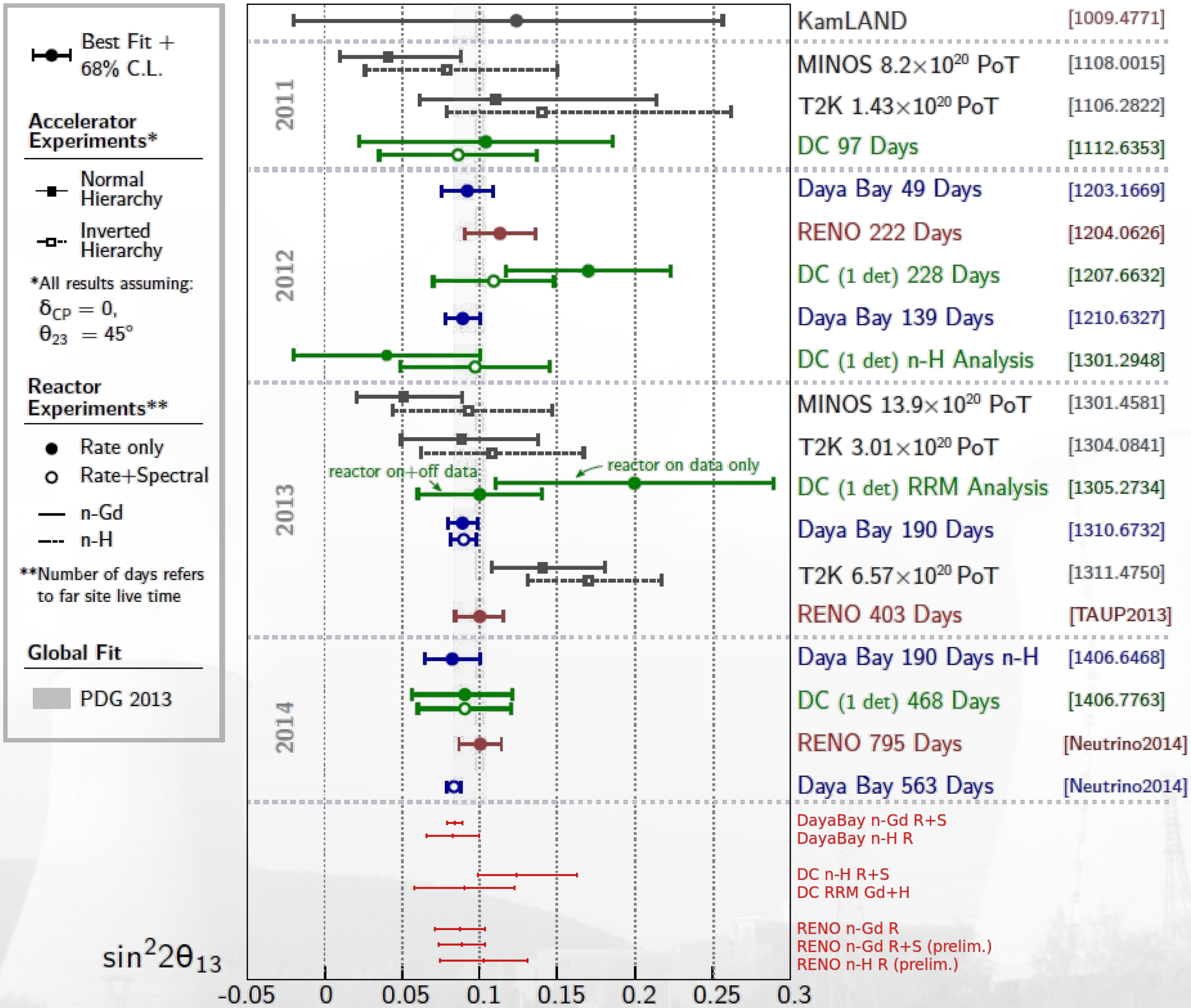
n-H analysis in progress

- Reduction of the uncertainty of accidental BG
- ≈400 days of data

Rate-only analysis:

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014_{stat} \pm 0.014_{sys}$$

θ13 Summary



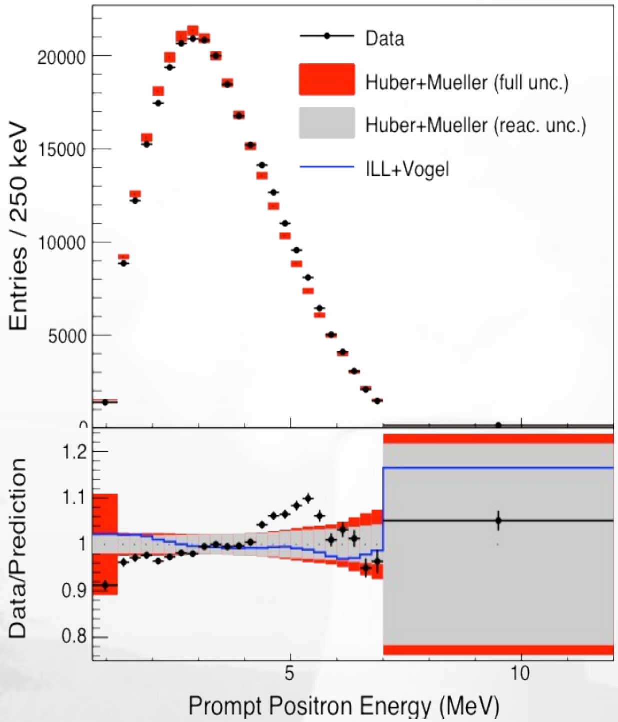
Best Fit + 68% C.L.
Accelerator Experiments*
Normal Hierarchy
Inverted Hierarchy
*All results assuming: δCP = 0, θ23 = 45°
Reactor Experiments**
Rate only
Rate+Spectral
n-Gd
n-H
**Number of days refers to far site live time
Global Fit
PDG 2013
2011
2012
2013
2014
KamLAND [1009.4771]
MINOS 8.2×10^20 PoT [1108.0015]
T2K 1.43×10^20 PoT [1106.2822]
DC 97 Days [1112.6353]
Daya Bay 49 Days [1203.1669]
RENO 222 Days [1204.0626]
DC (1 det) 228 Days [1207.6632]
Daya Bay 139 Days [1210.6327]
DC (1 det) n-H Analysis [1301.2948]
MINOS 13.9×10^20 PoT [1301.4581]
T2K 3.01×10^20 PoT [1304.0841]
reactor on+off data
reactor on data only
DC (1 det) RRM Analysis [1305.2734]
Daya Bay 190 Days [1310.6732]
T2K 6.57×10^20 PoT [1311.4750]
RENO 403 Days [TAUP2013]
Daya Bay 190 Days n-H [1406.6468]
DC (1 det) 468 Days [1406.7763]
RENO 795 Days [Neutrino2014]
Daya Bay 563 Days [Neutrino2014]
DayaBay n-Gd R+S
DayaBay n-H R
DC n-H R+S
DC RRM Gd+H
RENO n-Gd R
RENO n-Gd R+S (prelim.)
RENO n-H R (prelim.)
sin²2θ13
-0.05 0 0.05 0.1 0.15 0.2 0.25 0.3

New Results Beyond θ_{13}

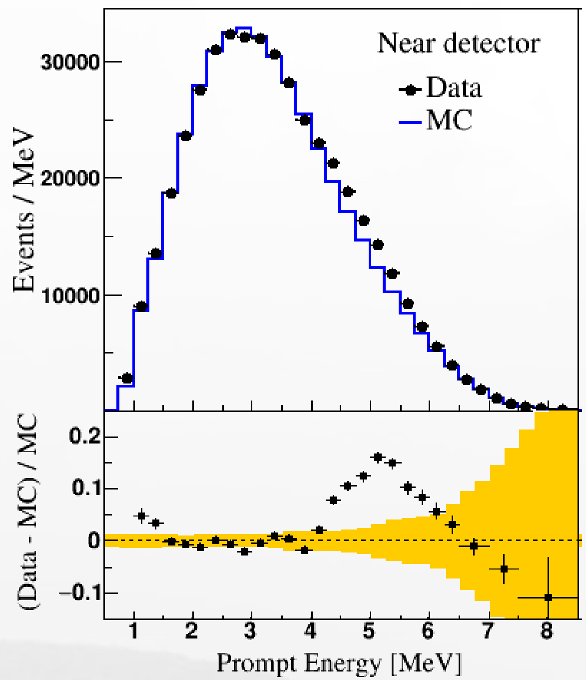
Spectral Distortion

„5 MeV bump“ observed in all three experiments (in ND and FD)

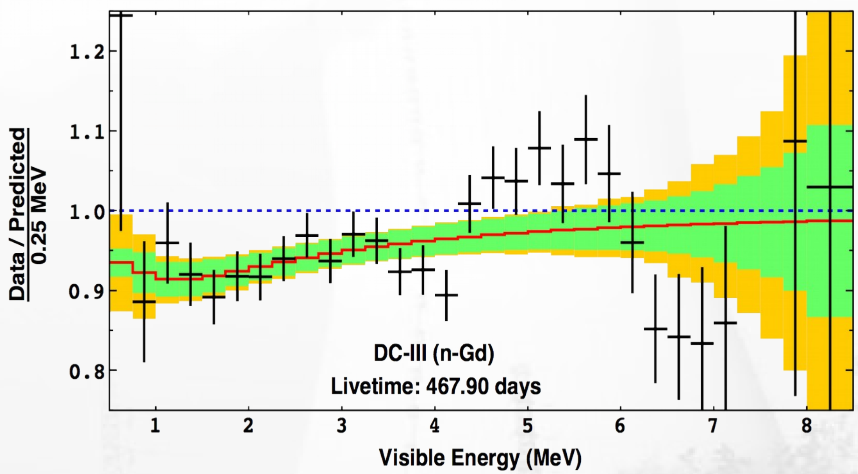
- Events have IBD characteristics
- Correlation with reactor power
- → consistent with feature in PWR neutrino spectra
- Appears in Gd and H analyses alike
- Measurement of θ_{13} is not affected!



Daya Bay ND



RENO ND



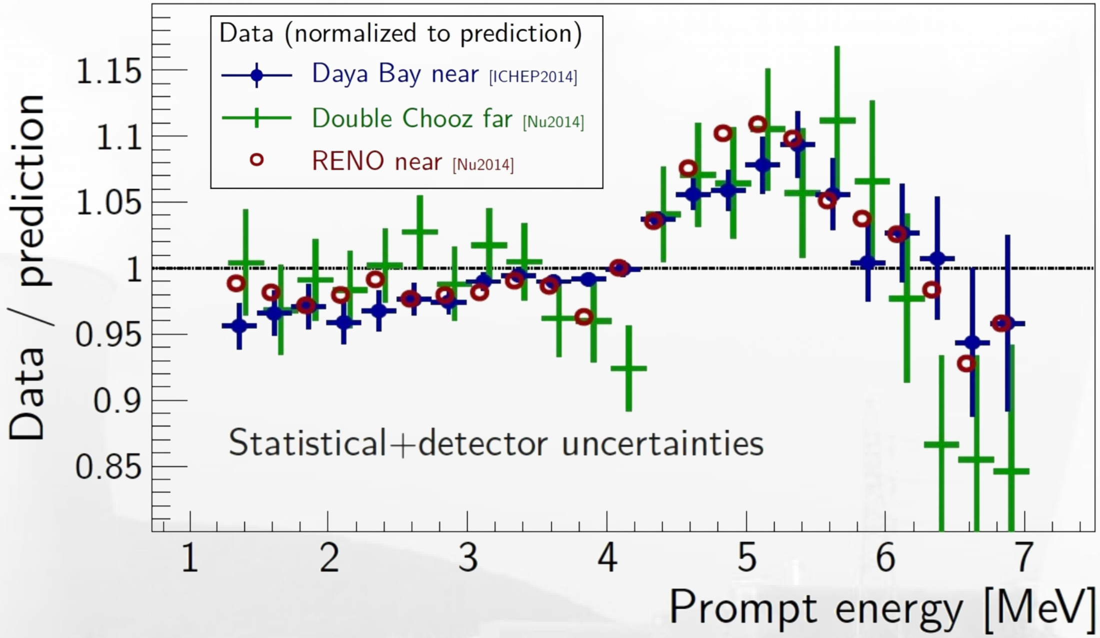
Double Chooz FD

Spectral Distortion

Possible SM explanations are available [e.g. PR D 92, 033015 (2015)]

- Non-fission contributions
- Forbidden transitions
- U-238 fission daughters
- PWR neutron spectrum
- Possible error in original measurement at ILL

Need for new reactor neutrino experiments with different reactor types

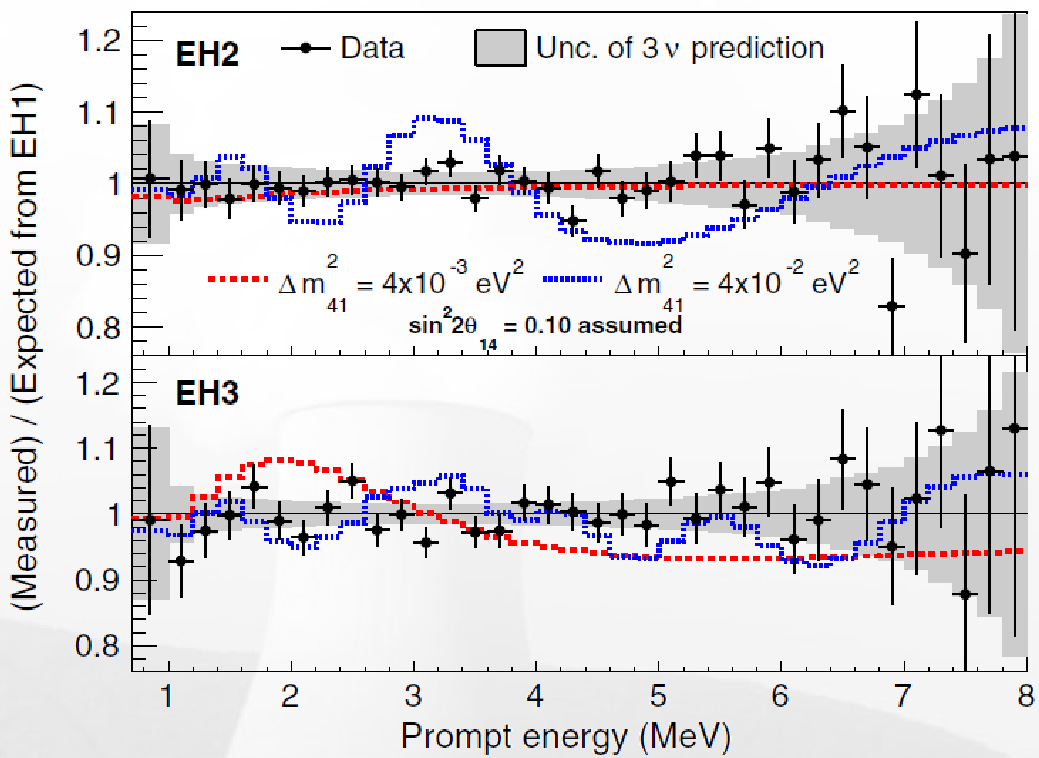


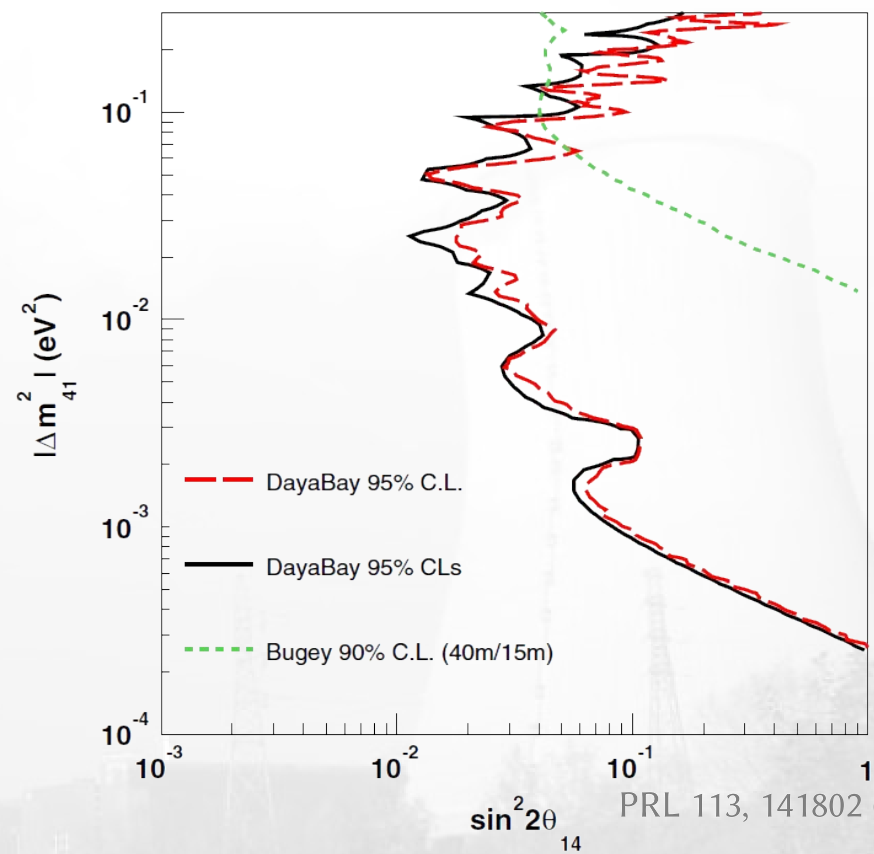
Sterile Neutrino Results

⟹ Talk by C. Giunti later this session

Search for light sterile νs performed by DB

- Relative measurements at various baselines (350, 500, 1600m)
- No signal observed, consistent with standard 3ν oscillation
- Most stringent limit for $0.001\ eV^2 < \Delta m^2_{41} < 0.1\ eV^2$





PRL 113, 141802 (2014)

Further Studies

Other physics results and development of analysis methods of general interest

- Background studies [1210.3748]
- Test of Lorentz violation [1209.5810]
- o-Positronium detection [1407.6913]
- Muon reconstruction [1405.6227, 1407.0275]
- Supernova neutrinos ?
- Nonstandard interactions
- Neutrino directionality
- Pulse shape analyses
- …

Conclusions

Improved results for θ_{13} (all compatible)

- Daya Bay: $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ (n-Gd R+S), also $|\Delta m^2_{ee}| = (2.42 \pm 0.11)\cdot 10^{-3}$ eV²
- Double Chooz: $\sin^2 2\theta_{13} = 0.090 \pm 0.033$ (RRM Gd+H)
- RENO: $\sin^2 2\theta_{13} = 0.087 \pm 0.016$ (n-Gd R)

Further improvements expected

- General improvements in data analysis and understanding of BG
- DC will start 2-detector phase
- RENO is preparing R+S analysis and n-H analysis

Physics beyond θ_{13}

- Discovery of spectral distortion by all three experiments
- No sterile neutrinos found in $0.001\ \text{eV}^2 < \Delta m^2_{41} < 0.1\ \text{eV}^2$ by DB
- Broad physics program possible

Thank you for your attention!