Measuring the neutrino mixing angle θ_{13} in reactor experiments

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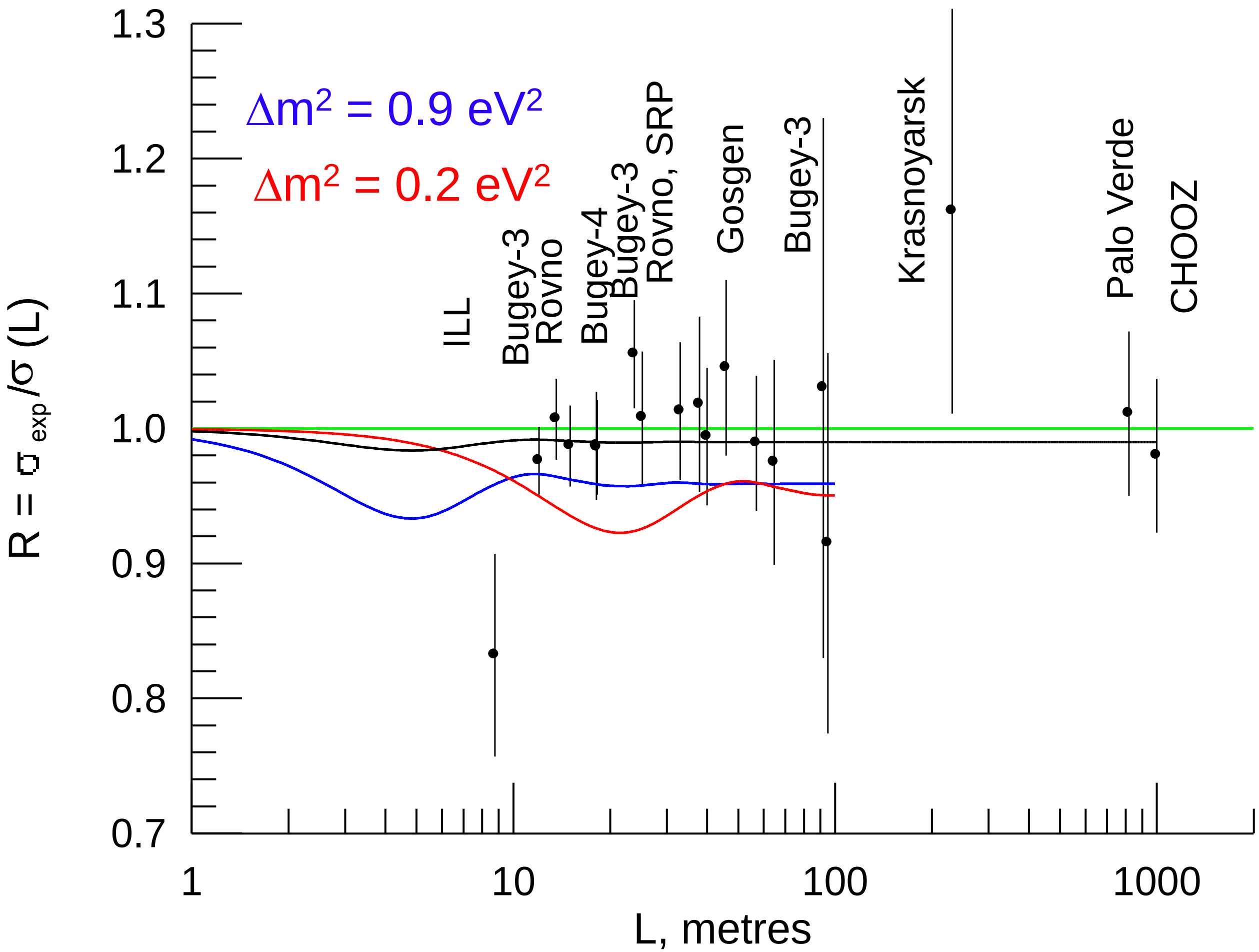
Plan of the talk

- Background for θ_{13} measurement. Before KamLAND data.
- Neutrino mixing matrix
- How the measurement of θ_{13} was prepared
- Double Chooz
- RENO
- Daya Bay
- Conclusions and outlook

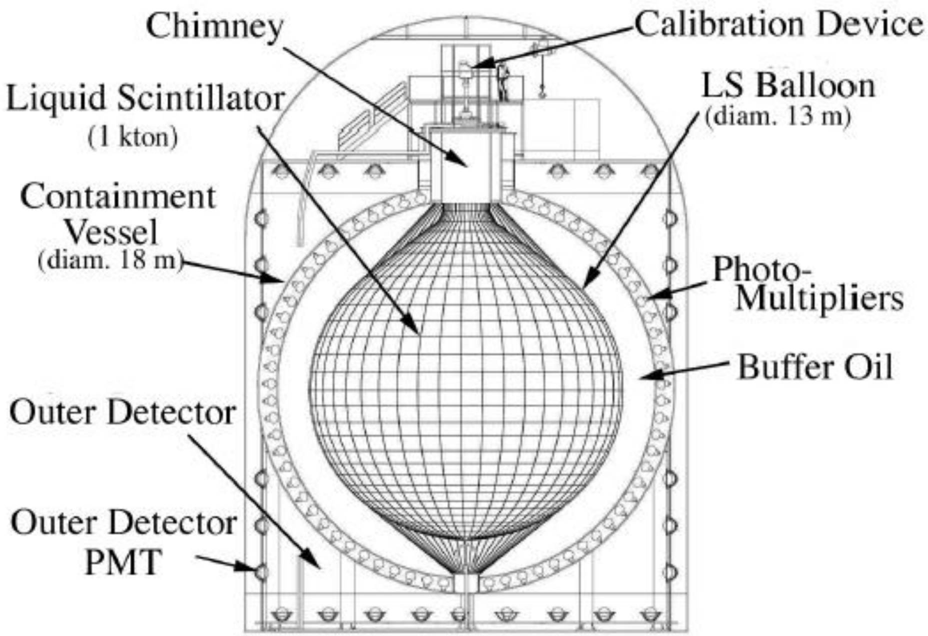
Looking for neutrino oscillations at nuclear reactors at 80th and 90th

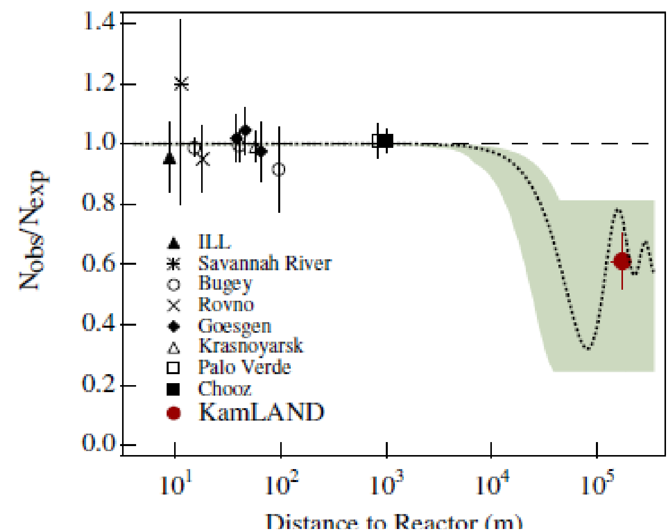
- Goesgen (37, 46, 65 m), 1984
- Bugey (18, 23 m), 1984
- ILL (8.5 m) 1983
- Bugey-3 (15,40,95 m), 1994
- Savannah River (18, 24 m), 1994
- Rovno, 1984-1986 (18-25-18 m), 1987-1990
- Krasnoyarsk (57, 230 m) 1984-1990
- Palo Verde (750 m) 1997-98
- CHOOZ (1050 m) 1997

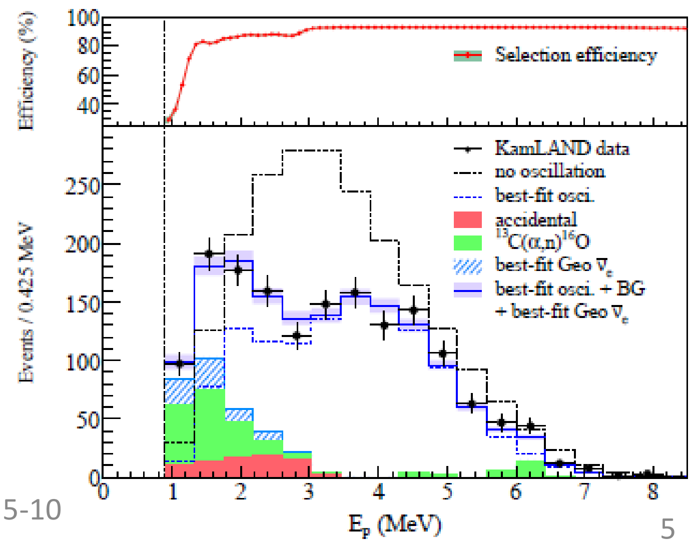
Ratio of measured rate to expected one



Reactor experiment proves solar neutrino oscillations (KamLAND), 2005







180 km – mean distance to reactor

$\Delta m^2 = (7.58^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.15}_{-0.15}\,(\text{syst.}))10^{-5}$ эВ^2,

$\text{tg}^2\theta = 0.56^{+0.10}_{-0.07}\,(\text{stat.})\,^{+0.10}_{-0.06}\,(\text{syst.})$,

$\sin^2 2\theta = 0.857 \pm 0.024$

Three neutrino flavors

- Neutrino flavor: ν_e, ν_μ, ν_τ N = 3 (2.9840±0.0082, PDG2012)
- Mass eigenstates: ν_1, ν_2, ν_3
- Mixing: $|\nu_k> = \Sigma\, U_{ki}\, |\nu_i>$

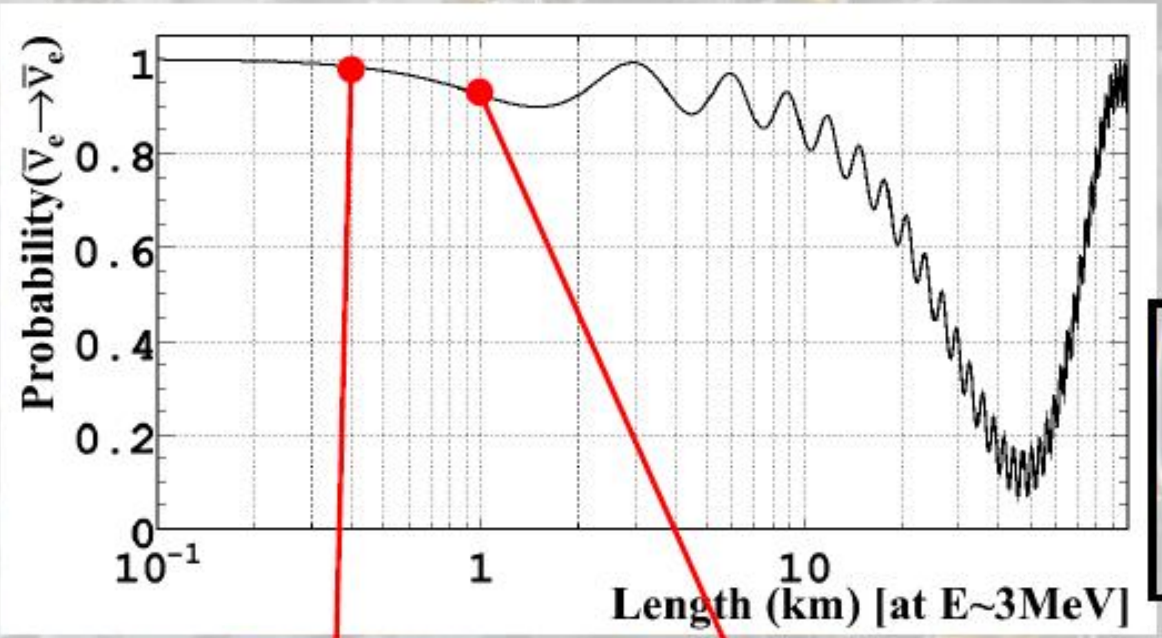
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{1e} & U_{2e} & U_{3e} \\ U_{1\mu} & U_{2\mu} & U_{3\mu} \\ U_{1\tau} & U_{2\tau} & U_{3\tau} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\Delta_{13} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21} - \text{etc}, \quad \Delta_{ij} = \frac{\Delta m^2_{ij}\, L}{4E}$$

Double Chooz: θ_{13} measurements with reactor neutrinos

Survival probability:

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



FD-only phase: Double Chooz uses Bugey4 as effective ND

Measure reactor $\overline{\nu}_e$ flux and spectrum **before** oscillation
reduce systematic uncertainties

Near Detector

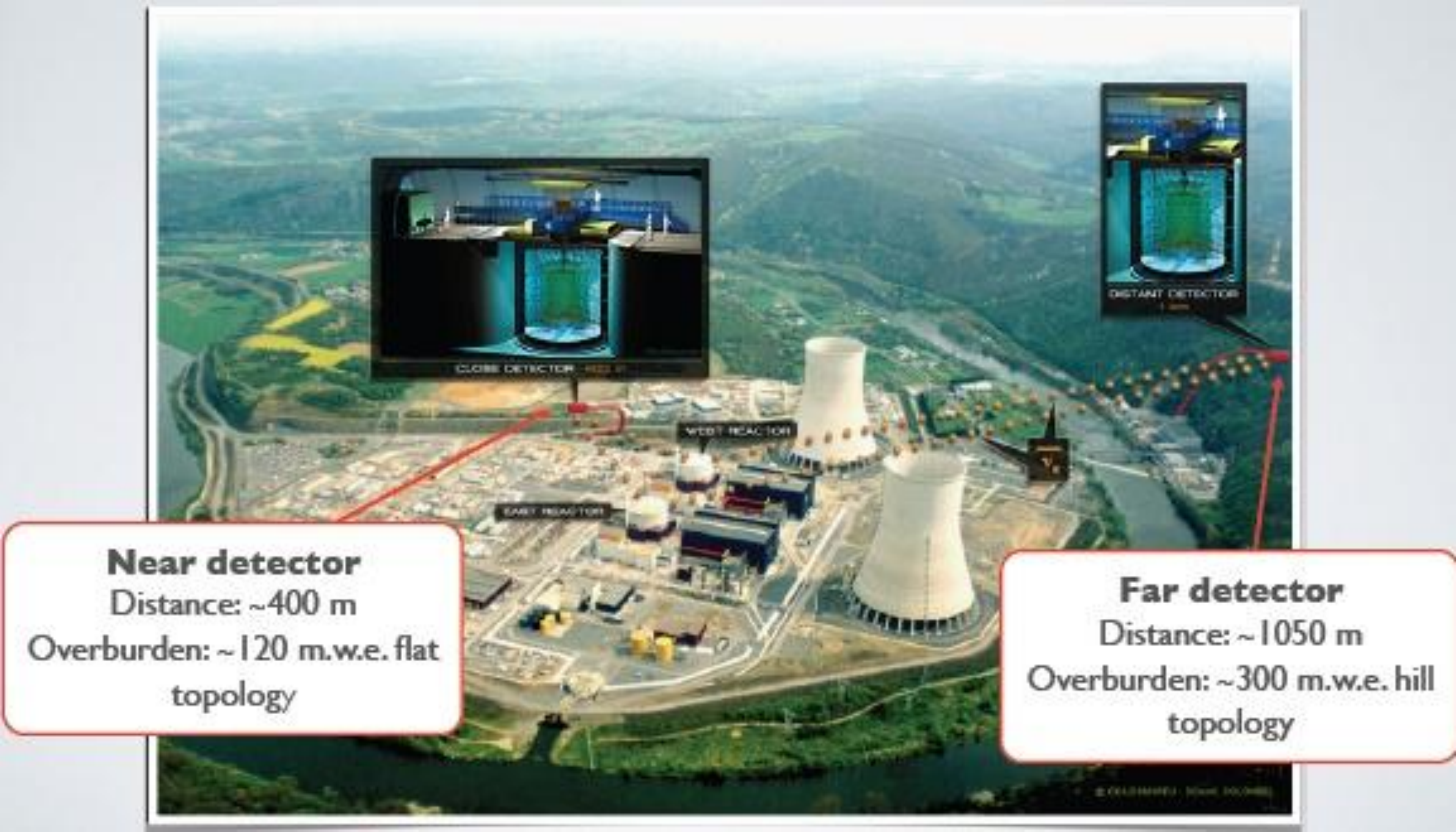
Far Detector

Measure oscillated $\overline{\nu}_e$ flux and spectrum
determine θ_{13}

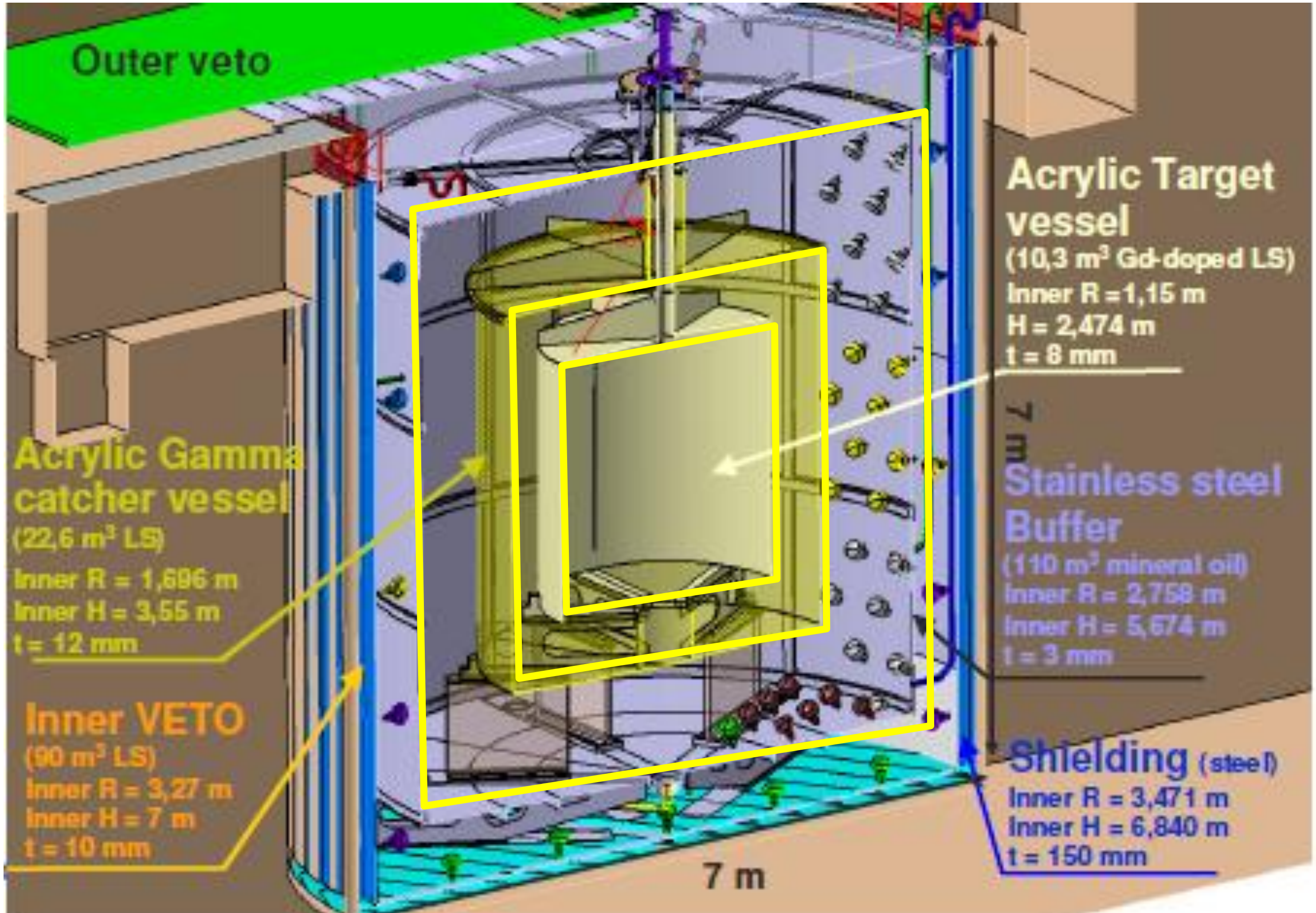
Discovering of third neutrino mixing angle, 2012

- At the beginning of 2000^{th} there was appeared a proposal to use two identical detectors (near and far) for measuring θ_{13}.
- After several Workshops a number of projects and sites were proposed for realization the proposal. Finally three of them were realized: Double Chooz, Daya Bay, RENO. Double Chooz is still ongoing.

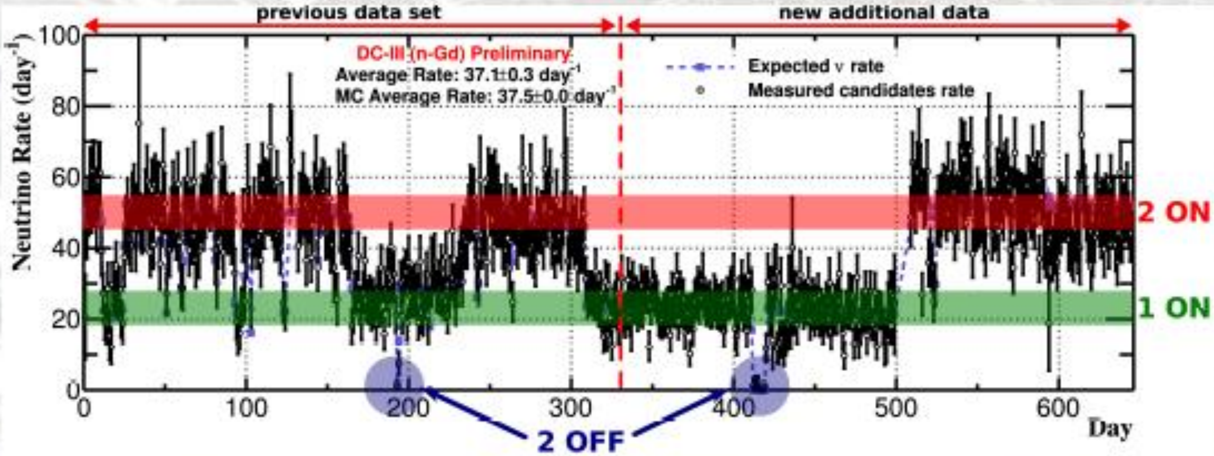
Double Chooz (France)

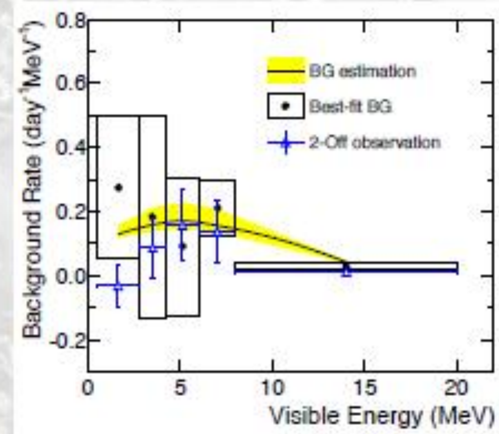


Detector scheme



Neutrino Candidates and Uncertainties



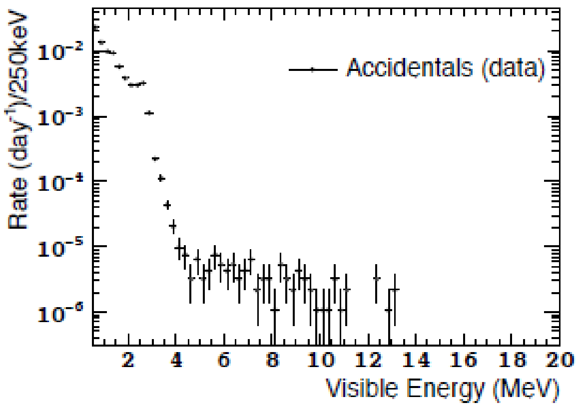


- Extended livetime
  - 17351 IBD candidates in 460.67 days
  - x2 statistics wrt last publication (Gd-II)
- -20% uncertainties wrt last publication
- Reactor 0ff-off period
  - Unique in Double Chooz
  - 7 IBD candidates in 7.24 days, in agreement with bkg model ($12.9^{+31}_{-1.4}$ events)

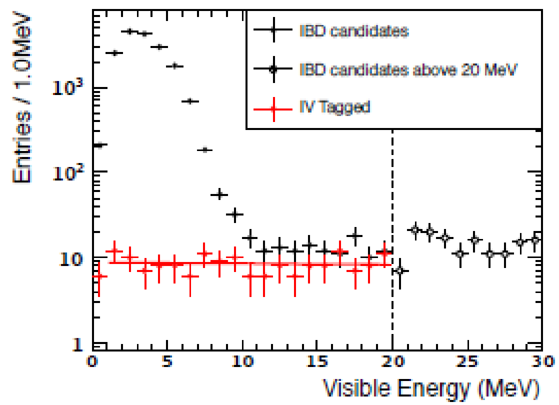
Uncertainty	Gd-II (%)	H-II (%)	Gd-III (%)	Gd-III/Gd-II
Reactor Flux	**1.7**	**1.7**	**1.7**	**-**
Detection ε	1.1	1.6	0.6	0.6
Cosmogenic bkg		1.2	+1.1/-0.4	0.5
Correlated bkg		0.5	0.1	0.2
Statistics	1.1	1.1	0.8	0.7
Total	**2.7**	**3.1**	**+2.3/-2.0**	**0.8**

Backgrounds in DC

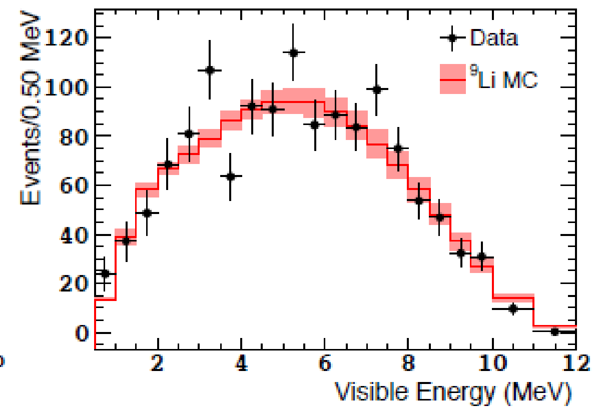
Accidentals



Correlated



Cosmogenic



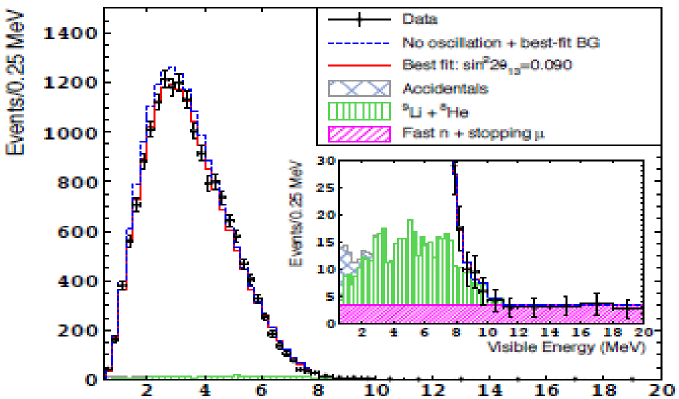
(Gd) $0.97^{+0.41}_{-0.16}$ per day
(H) 4.33 ± 0.01

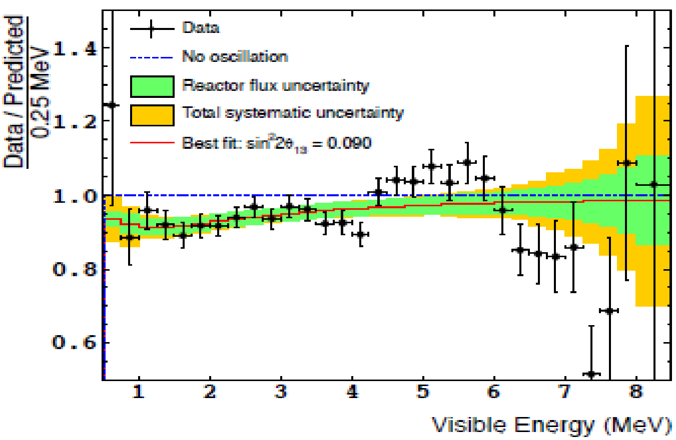
(Gd) 0.604 ± 0.051 per day
(H) 1.55 ± 0.15

(Gd) 0.070 ± 0.003 per day
(H) $0.95^{+0.57}_{-0.33}$

Data Analysis DC 2015

Rate + Shape (Gd)Analysis

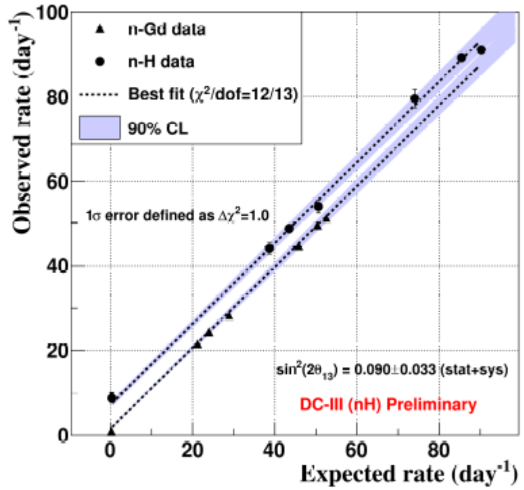




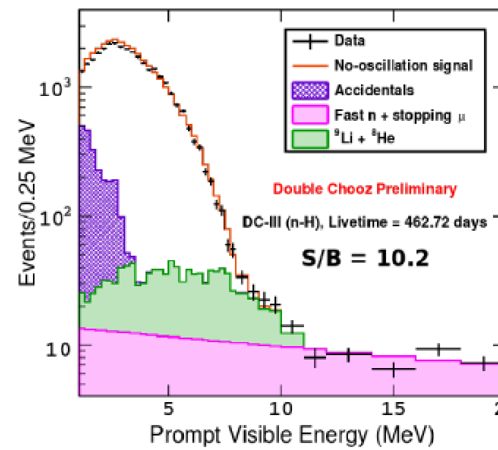
of n-Gd analysis.

$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

Reactor Rate Modulation Analysis



Rate + Shape (H)Analysis



n-H analysis

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

RRM analysis

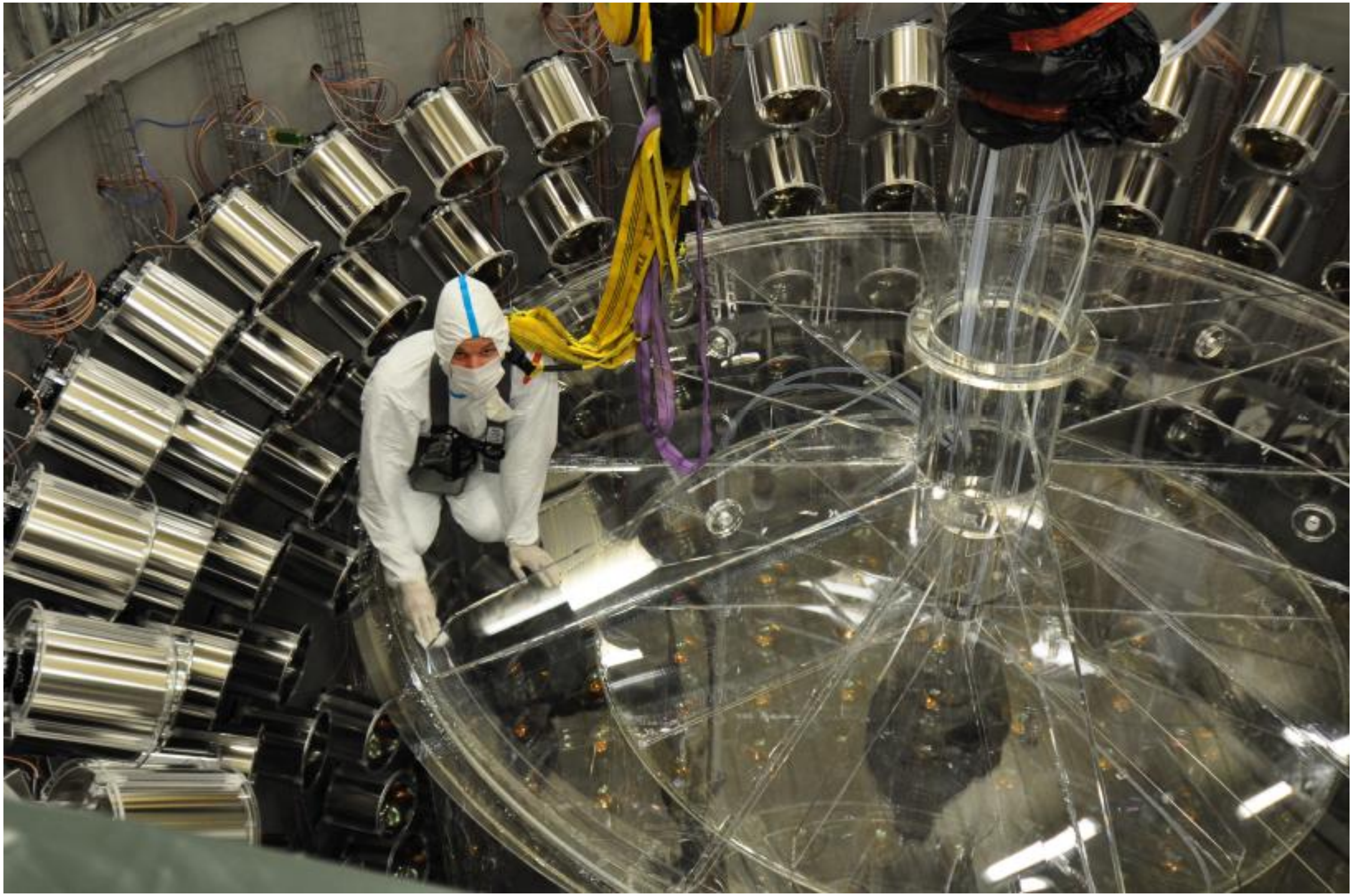
(n-H) $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$

(Gd) $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

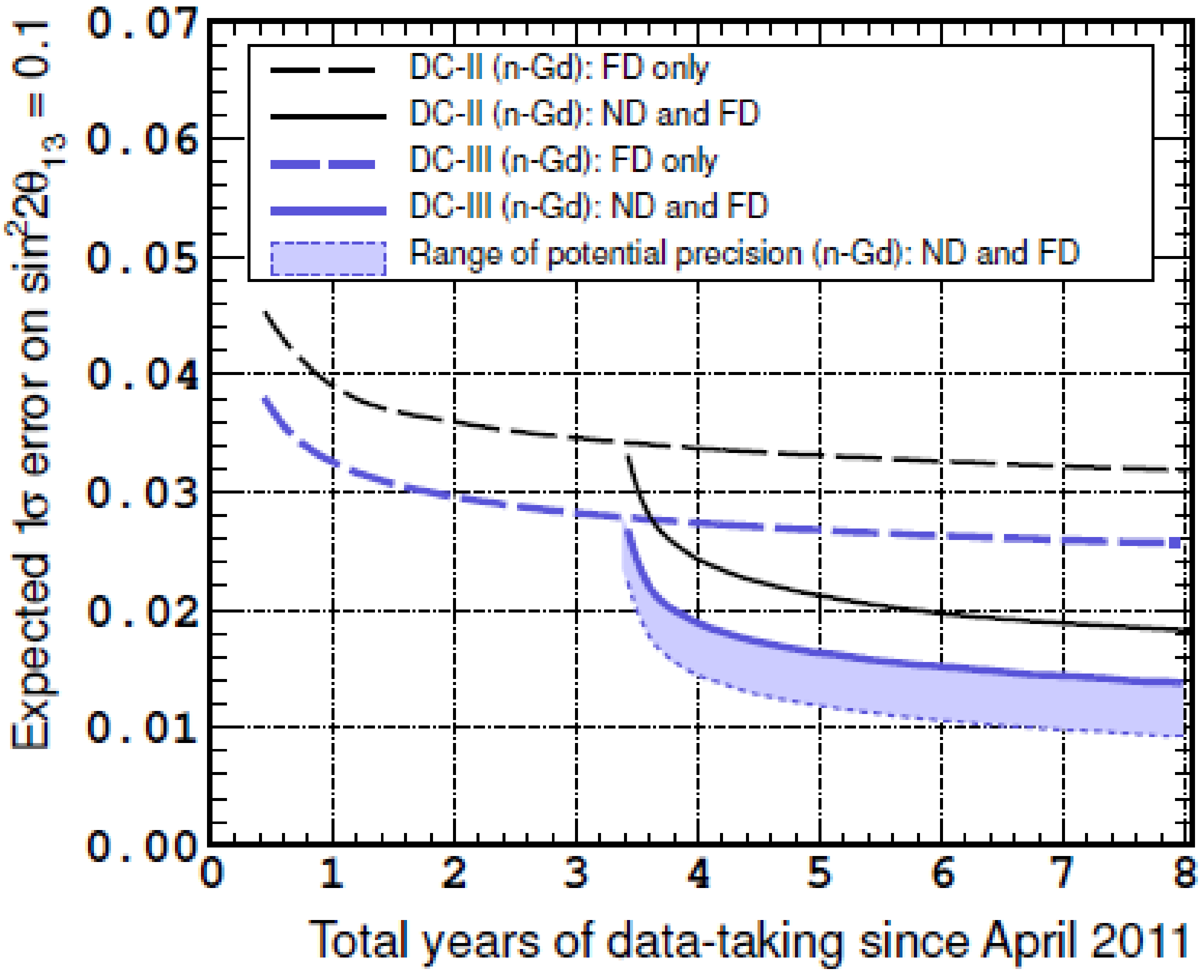
Combined analysis $\sin^2 2\theta_{13} = 0.090 \pm 0.33$ with

$\Delta m^2 = 2.44$ eV^2 (MINOS)

Data taking from 2015 are ongoing with the use of two detectors



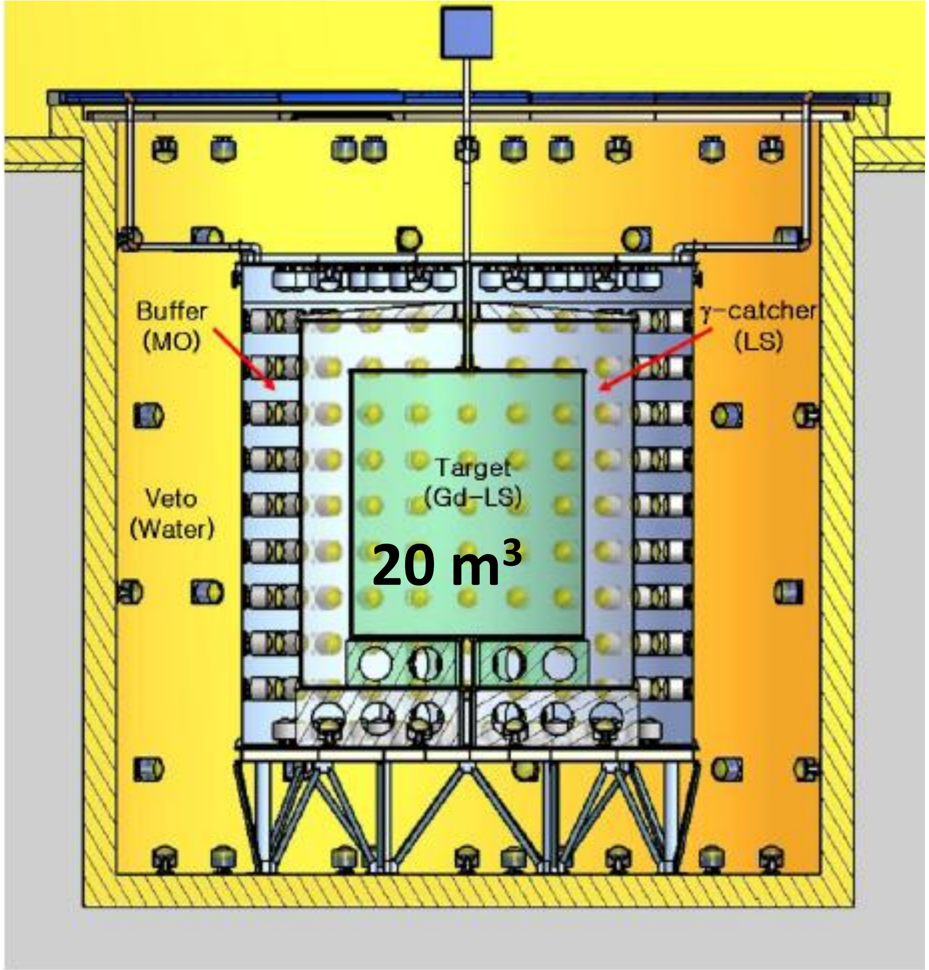
Precision that we expect to have from using both detectors



RENO (Hanbit (Yeongwang) PP, Korea)

250 km direction south-west from Seoul
Distance to the nearest detector from the line of reactors – 294 m, to the far one – 1380 m

Детектор



target 140 cm radius,
320 cm hight

60 cm gamma-catcher

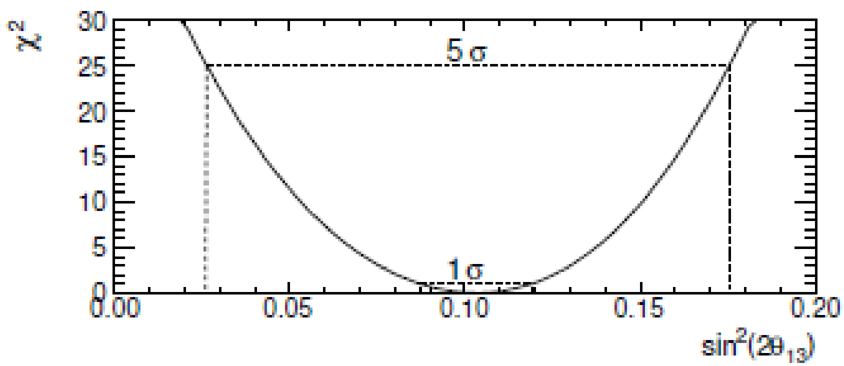
70 cm buffer

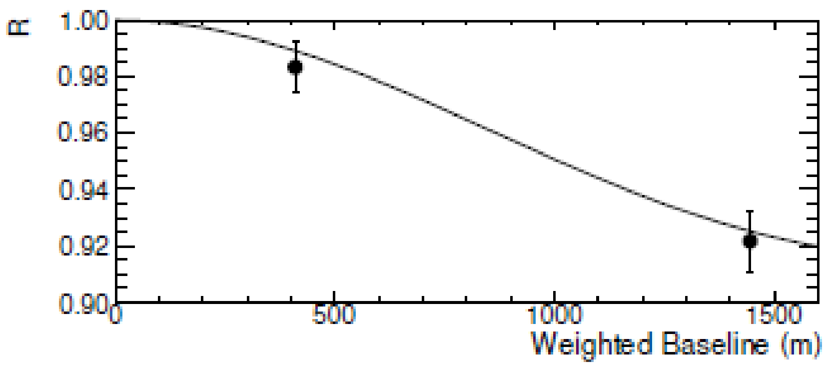
150 cm muon veto

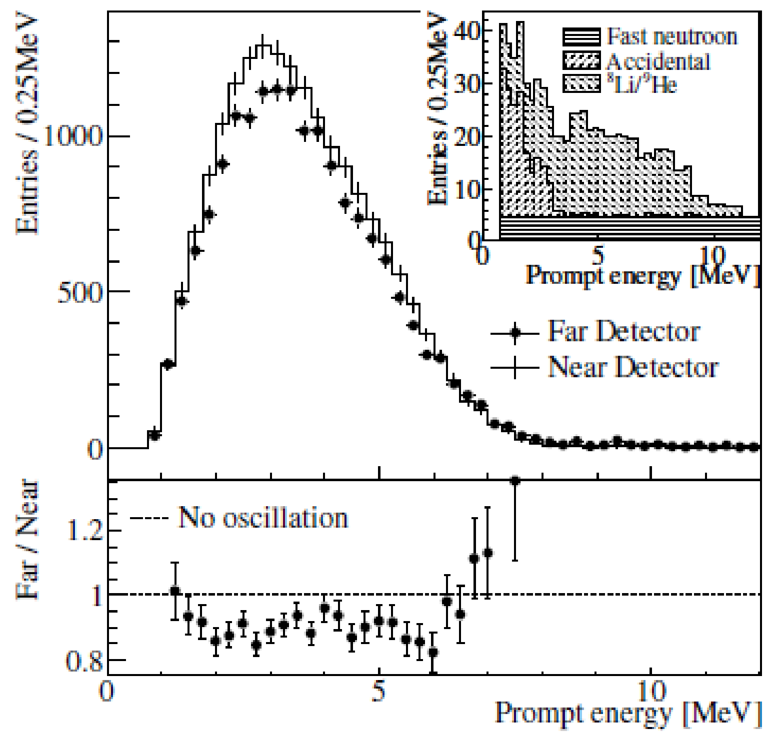
TABLE 1. Event rates of the observed IBD candidates and the estimated background.

Detector	Near	Far
Selected events	433,196	50,750
Total background rate (per day)	12.48±0.68	4.62± 0.28
IBD rate after background subtraction (per day)	569.16±0.87	63.86±0.28
Live time (days)	761.11	794.72
Accidental rate (per day)	1.82±0.11	0.36±0.01
$^{9}Li/^{8}He$ rate (per day)	8.28±0.66	1.85±0.20
Fast neutron rate (per day)	2.09±0.06	0.44±0.02
^{252}Cf rate (per day)	0.28±0.05	1.98±0.27

RENO experiment results



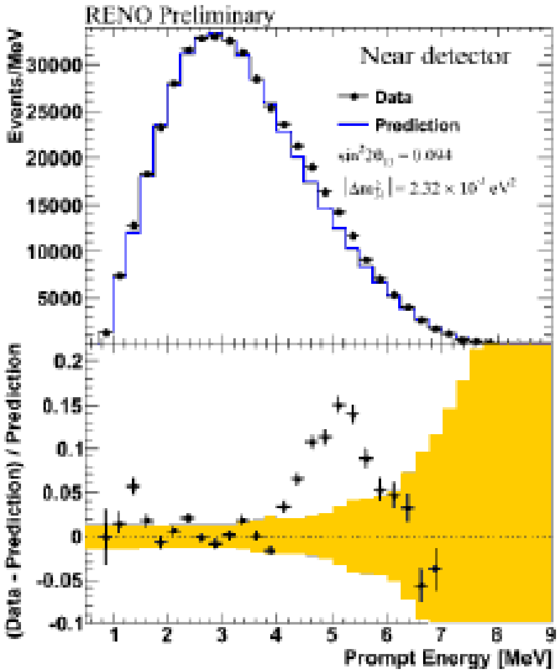


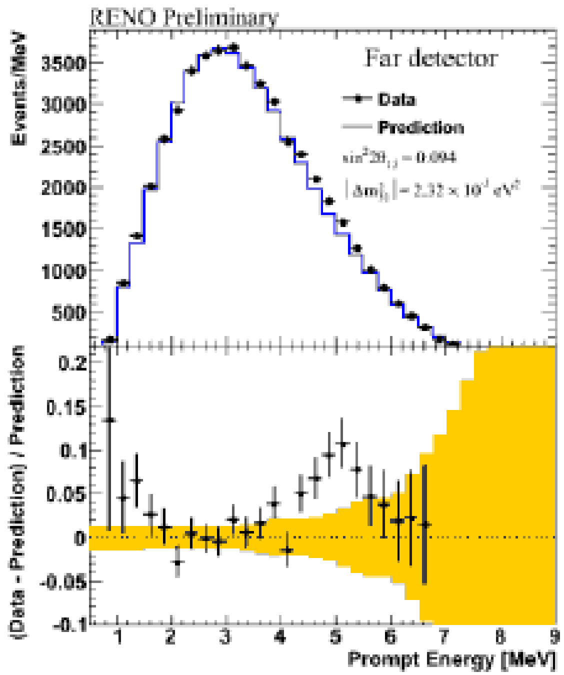


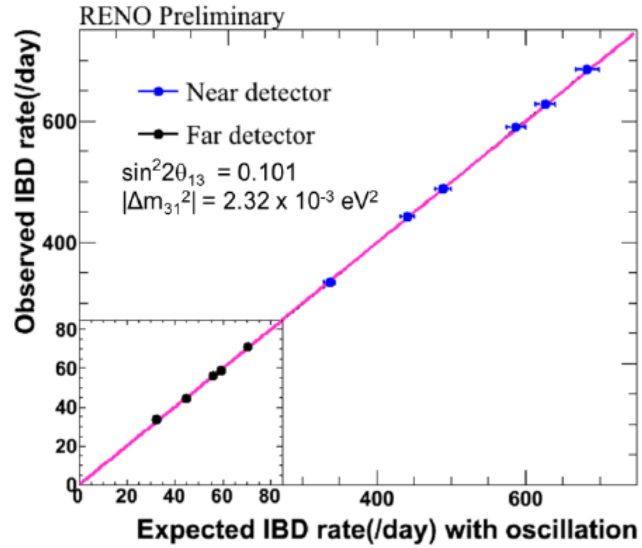
$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

From the Rate only analysis based on statistics 17102 events in far detector

New RENO result (2014)





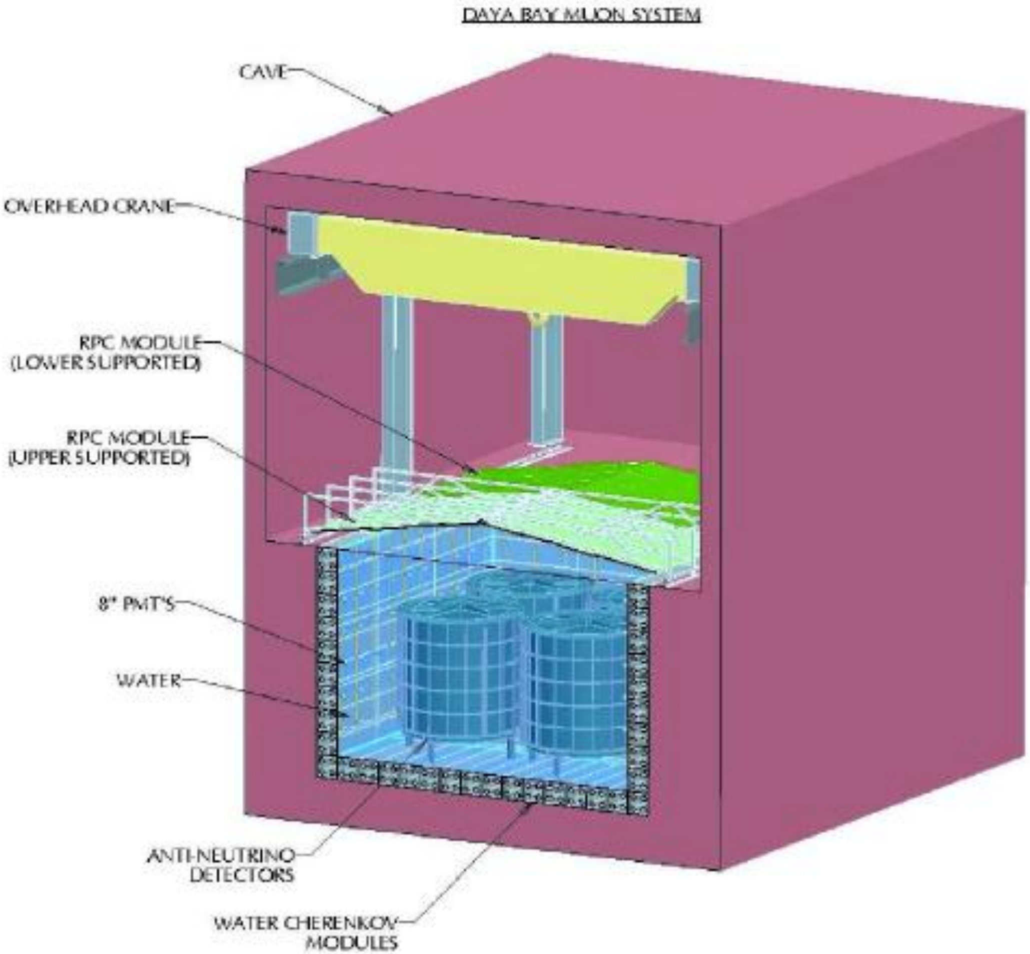


$\sin^2 2\theta_{13}$ = 0.101 ± 0.008 (stat) ± 0.010 (syst), with Δm^2_{31} = 2.32 × 10^{-3} eV^2

The result was crosschecked with data of n-H captures:
$\sin^2 2\theta_{13}$ = 0.103 ± 0.014 (stat) ± 0.014 (syst).

Daya Bay experiment
(Daya Bay & Ling Ao power plants)

The detector and detectors hall

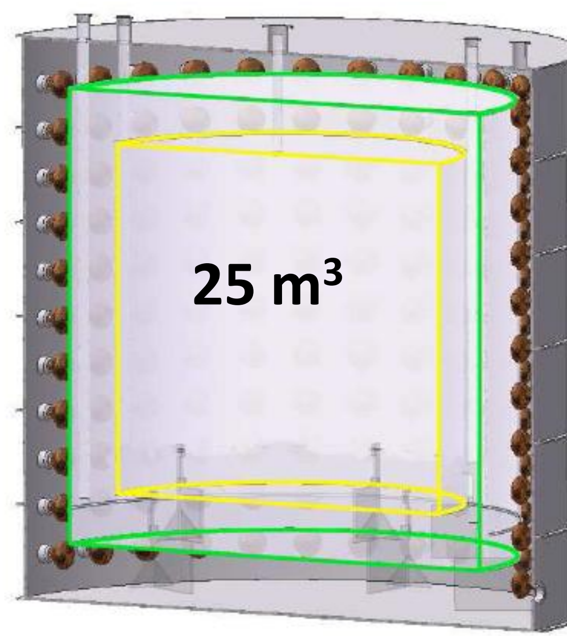


target 160 cm radius, 320 cm hight

45 cm gamma-catcher

45 cm buffer

150 cm water shielding

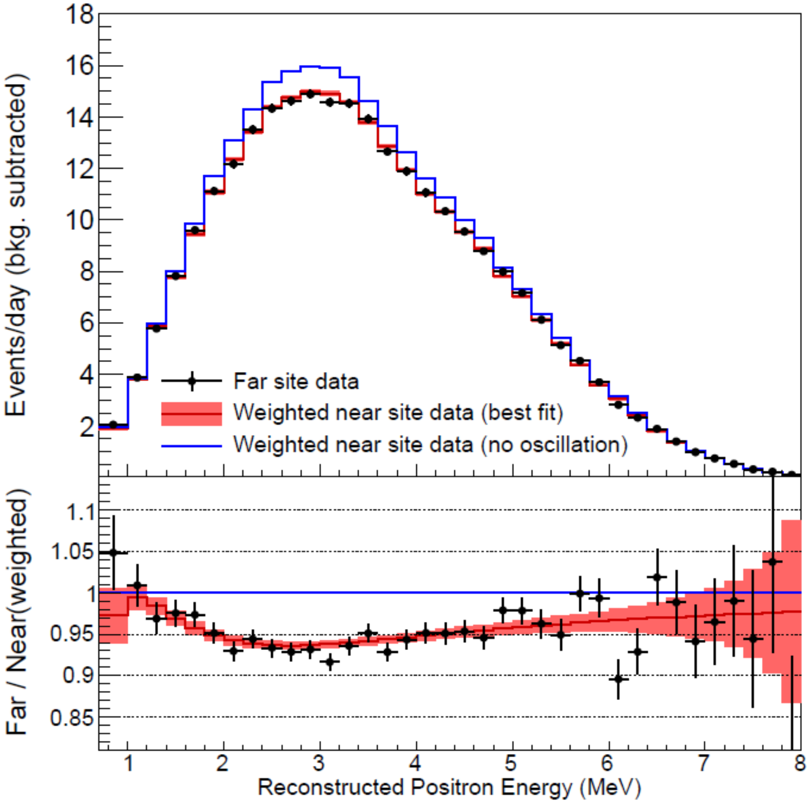


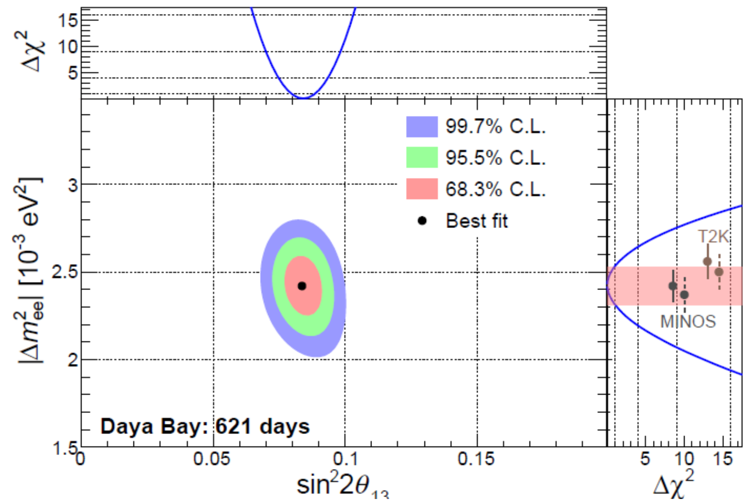
Signals and backgrounds

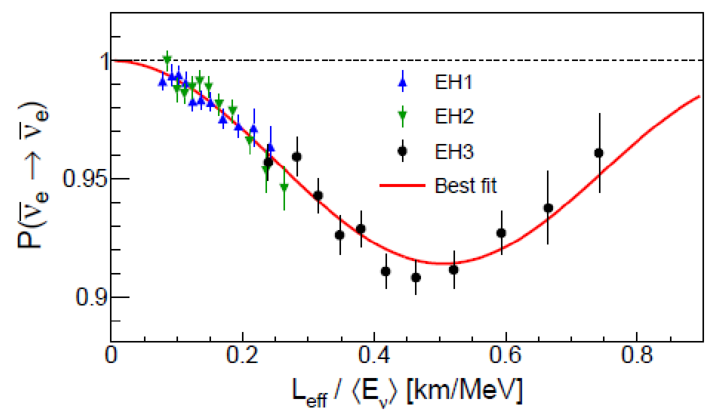
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	304459	309354	287098	190046	40956	41203	40677	27419
DAQ live time(days)	565.436	565.436	568.03	378.407	562.451	562.451	562.451	372.685
ε_μ	0.8248	0.8218	0.8575	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9744	0.9748	0.9758	0.9756	0.9756	0.9754	0.9751	0.9758
Accidentals(per day)	8.92 ± 0.09	8.94 ± 0.09	6.76 ± 0.07	6.86 ± 0.07	1.70 ± 0.02	1.59 ± 0.02	1.57 ± 0.02	1.26 ± 0.01
Fast neutron(per AD per day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
^{9}Li/^{8}He(per AD per day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C correlated 6-AD(per day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.09	
Am-C correlated 8-AD(per day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.03
^{13}C(α, n)^{16}O(per day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(per day)	657.18 ± 1.94	670.14 ± 1.95	594.78 ± 1.46	590.81 ± 1.66	73.90 ± 0.41	74.49 ± 0.41	73.58 ± 0.40	75.15 ± 0.49

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of the IBD rates in AD1 and AD2 (AD3 and AD8 in the 8-AD period) was 0.981±0.004 (1.019±0.004) while the expected ratio was 0.982 (1.012).

Daya Bay last results

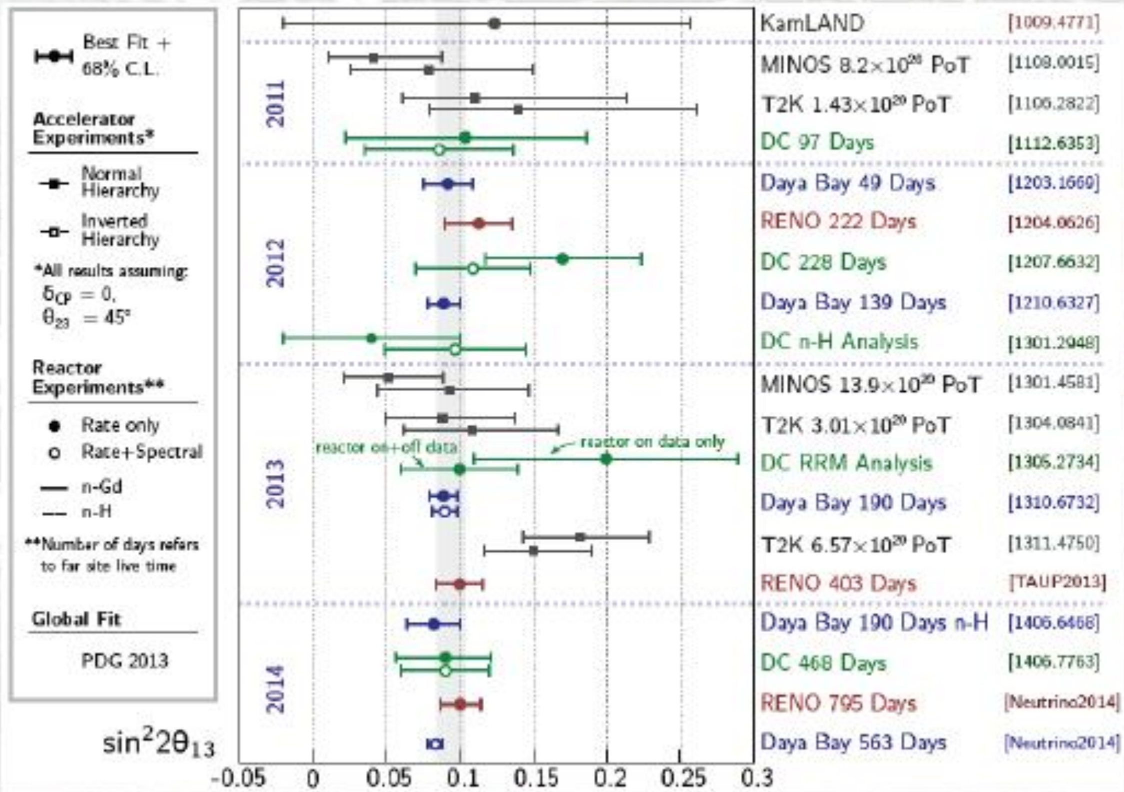






$\sin^2 2\theta_{13} = 0.084 \pm 0.005$, $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV^2

Double Chooz in the race for $\boldsymbol{\theta_{13}}$



- First hit of non-0 $\boldsymbol{\theta_{13}}$ and Rate+Shape analysis (2011)
  Phys.Rev.Lett. 108 (2012) 13180
- First n-H capture analysis (2012)
  Phys.Lett. B723 (2013) 66-70
- First (and only) Reactor Modulation oscillation alanysis RRM (2013)
  Phys.Lett. B735 (2014) 51-56
- First published results on the spectrum distortion (2014)
  JHEP 1410 (2014) 86

- Well understood detector
- Low background (improved reduction)
- Precise Energy estimation (<1% systematics, ~8%/√ E resolution)

- Low reactor power wrt competitor experiments
- Flux estimation systematics (no ND)

Conclusions and outlook

- The discovery of third neutrino mixing angle θ_{13} was made in the last three years, but prepared more than 10 years.
- The value of mixing angle θ_{13} is appeared unexpectedly high (about 9°).
- This opens the road for measuring CP-violation phase
- Also one should account its include in probability of flavor surviving or disappearing.
- Neutrino mass hierarchy may be observed in reactor experiments in nearest 10-15 years (JUNO and RENO-50).