PhyStat-ν Workshop on Statistical Issues in Experimental Neutrino Physics

from 30 May 2016 to 01 June 2016 (Asia/Tokyo)
Asia/Tokyo timezone

The 3 Reactor ν Experiments

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Reactor ν Experiments

- Very short baseline: O(1 m ~ 10 m)
  DANSS, NEOS, Neutrino 4, Nucifer, NuLat, Poseidon, Prospect, SoLid, Stereo etc.

See Ko's talk (Today)

- Short baseline: ~ 1 to 2 km
  Daya Bay, Double Chooz, RENO

- Medium baseline: ~ 50 km
  Juno, RENO-50

See Li's talk (Wed. June 1st)

Bob Cousins: "2 independent experiments each with 3.5σ better than one experiment with 5σ"

Outline

- **Status of Double Chooz, RENO, Daya Bay**

  1. **Introduction**
  2. **θ_{13} & $|\Delta m^2_{ee}|$ measurements**
  3. **χ^2 fitting & uncertainties**

- **Discussion**

  How to combine the results from the 3 reactor ν experiments ?

First θ_{13} measurements in 2012

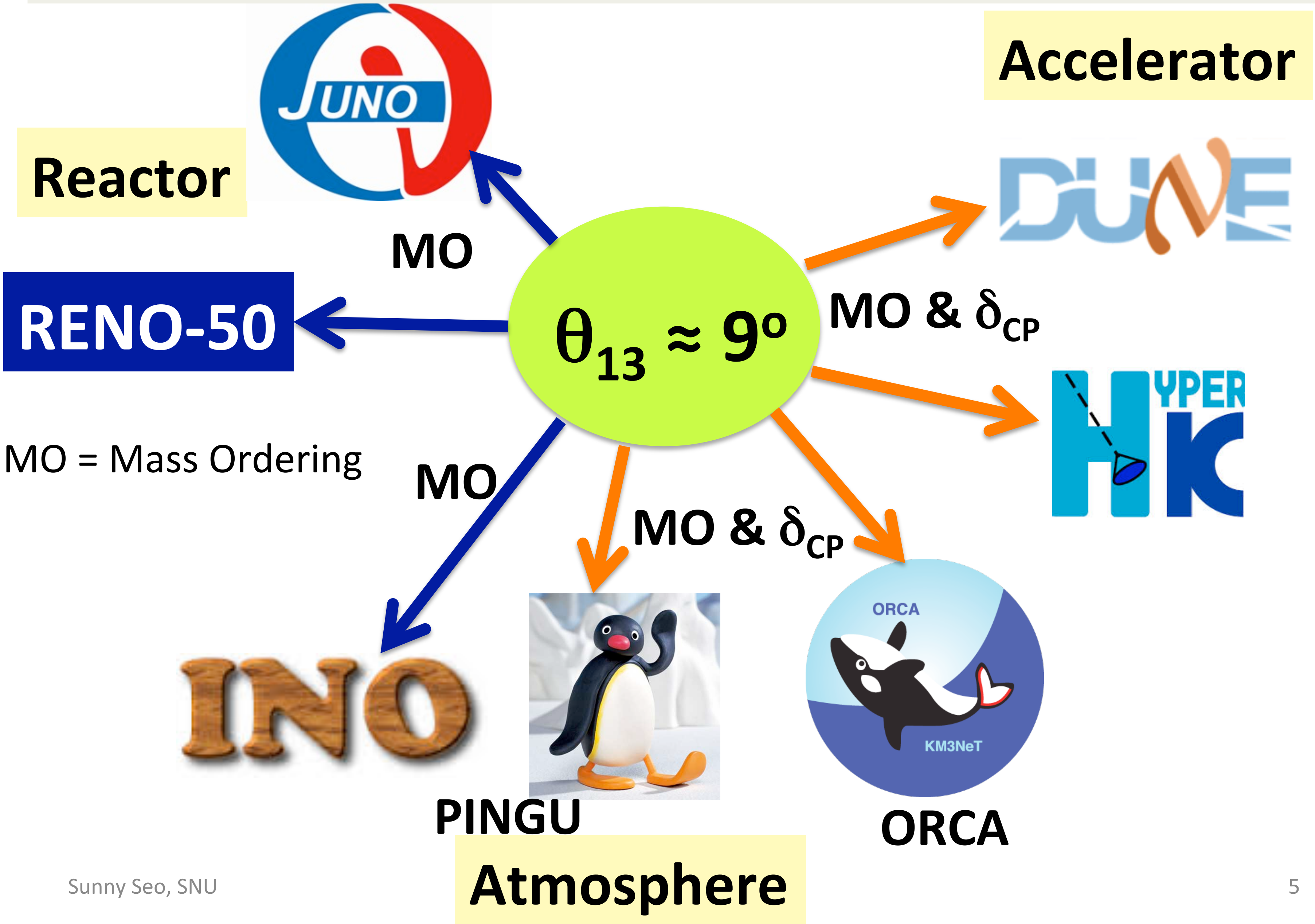
~ 4 years ago

	Double Chooz	Daya Bay	RENO
Publication	PRL 108, 131801 (Mar. 30, 2012)	PRL 108, 171803 (Apr.27, 2012)	PRL 108, 191802 (May 11, 2012)
$\sin^2(2\theta_{13})$	0.086	0.092	0.113
Stat. error	0.041 (101 days)	0.016 (49 days)	0.013 (220 days)
Syst. error	0.030 (flux uncert.)	0.005 (MC driven)	0.019 (data driven)
Significance	1.7 σ	5.2 σ	4.9 σ

1 month

2 weeks

θ_{13} and Future Experiments



Why Precise θ_{13} ?

1. θ_{13} affects θ_{12} (θ_{23}) and δ_{CP} measurements.

2. θ_{13} is best measured in short (1~2 km) baseline reactor ν experiments. → legacy measurement

Thus, we need to measure it
as precise as possible
with the currently operating detectors.

Reactor θ_{13} Experiments

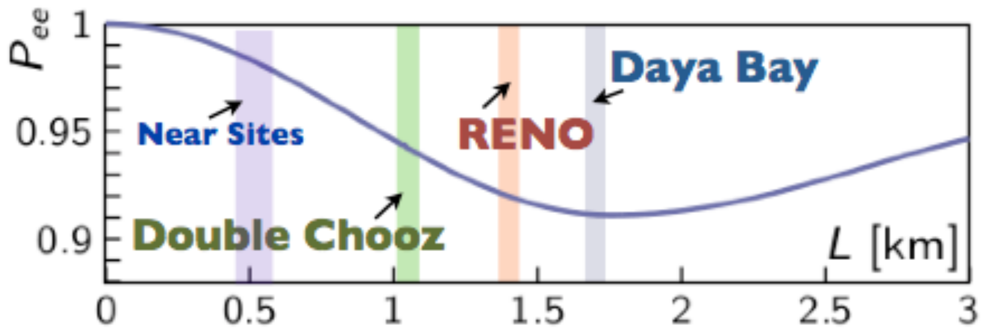
RENO

Double Chooz

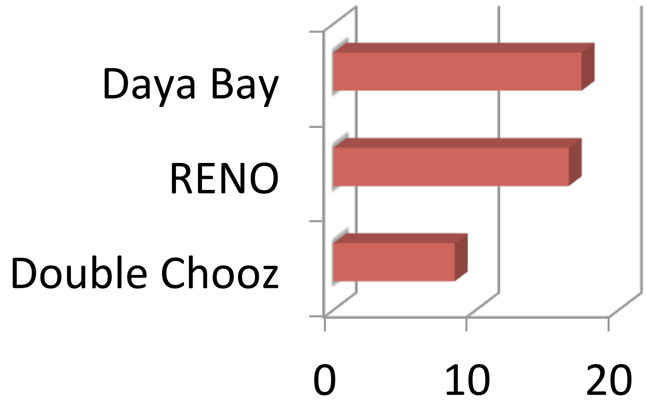
Daya Bay

Comparisons

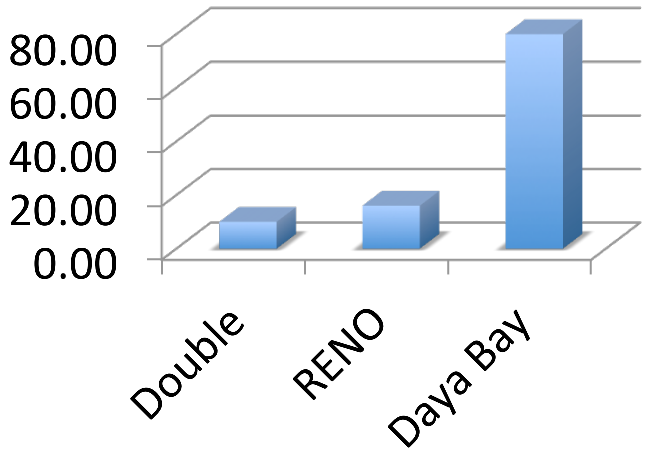
Baselines



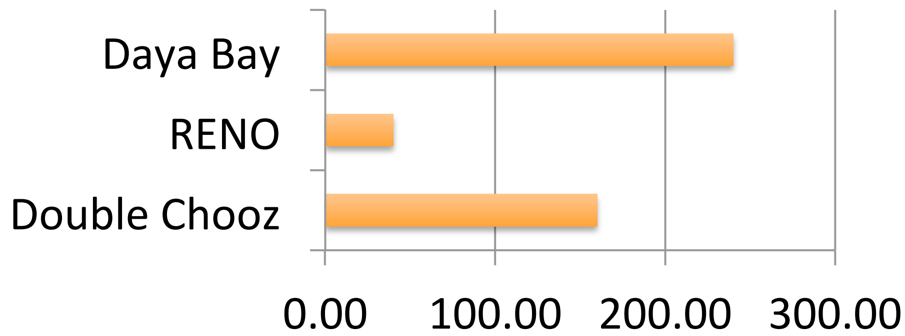
Reactor Thermal Power (GW_{th})



Target (ton)



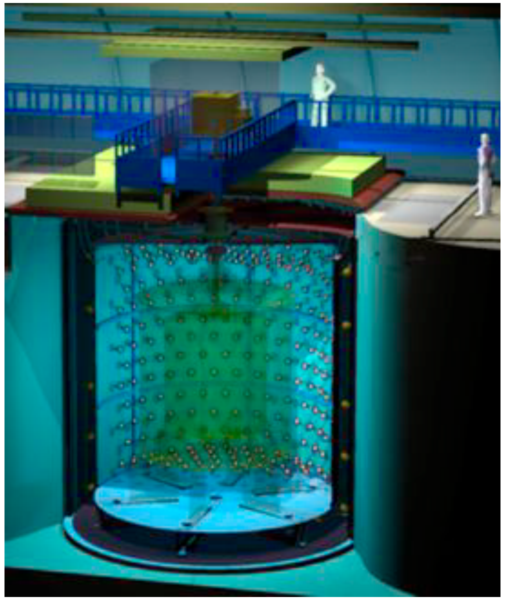
Manpower

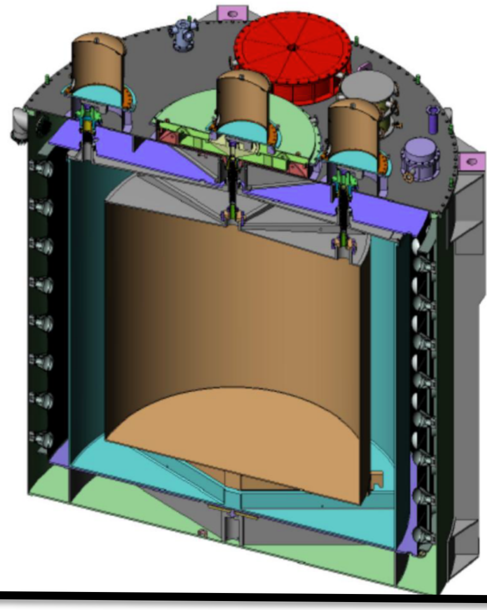


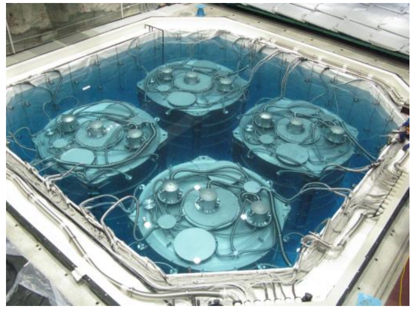
Reactor ν Experiments

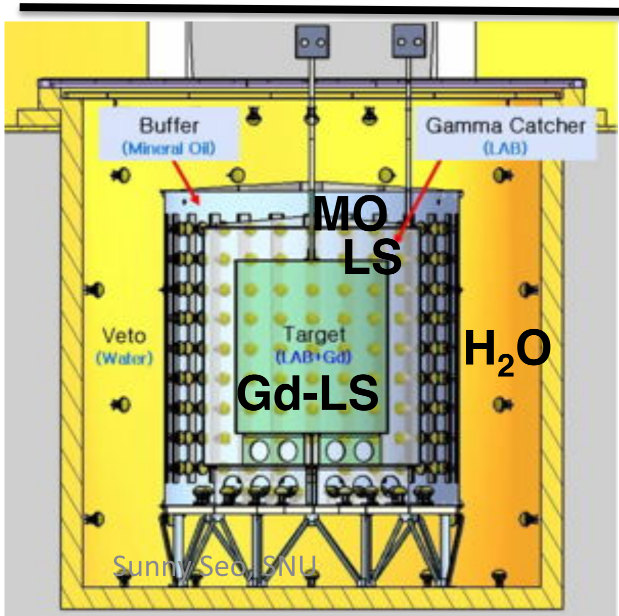
Experiment (location)	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)	Cost (US $)	# of members
Double Chooz (France)	8.5	400/ 1050	120/ 300	10/ 10	?	> 160
RENO (Korea)	16.8	290/ 1380	120/ 450	16/ 16	~10 M	< 30
Daya Bay (China)	17.4	360(500)/ 1985(1613)	260/ 860	40x2/ 80	?	~ 230

θ_{13} Reactor Neutrino Detectors



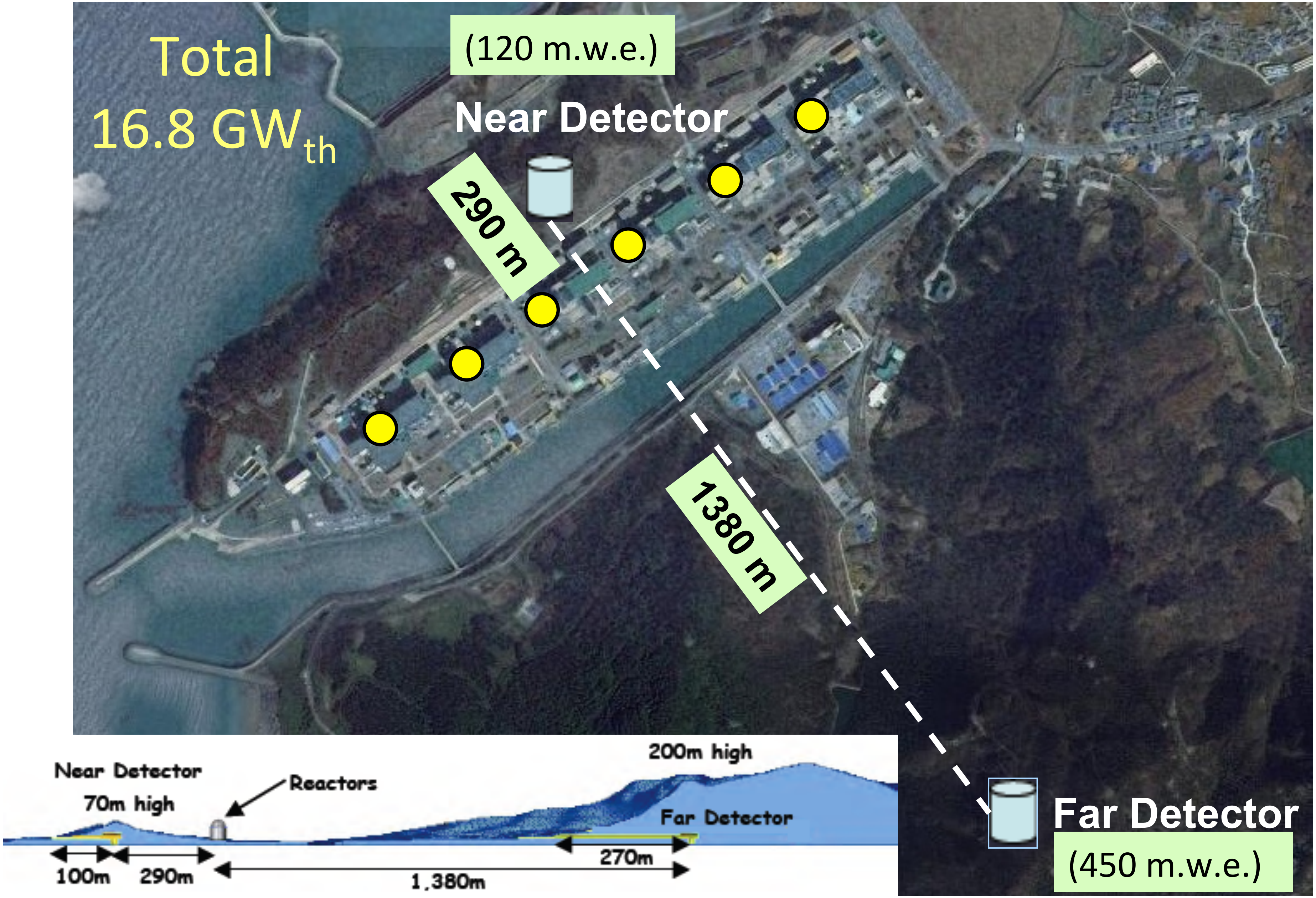






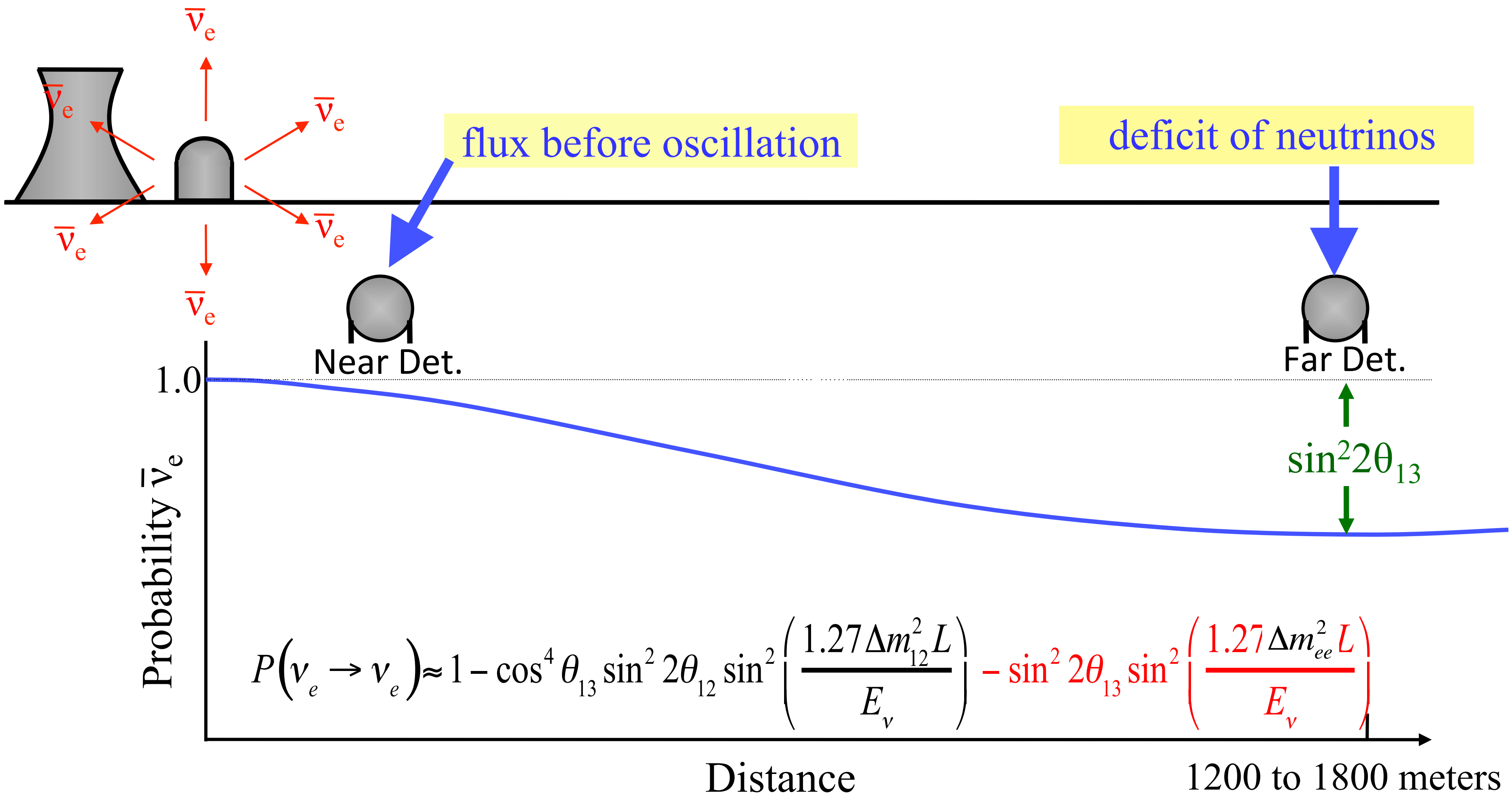
1. Cylindrical structure (four layers)
2. Neutrino Target: liquid scintillator with 0.1 % Gd doping

RENO



Total
16.8 GW$_{th}$
(120 m.w.e.)
Near Detector
290 m
1380 m
Far Detector
(450 m.w.e.)
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
1,380m
270m

Reactor Neutrino Disappearance



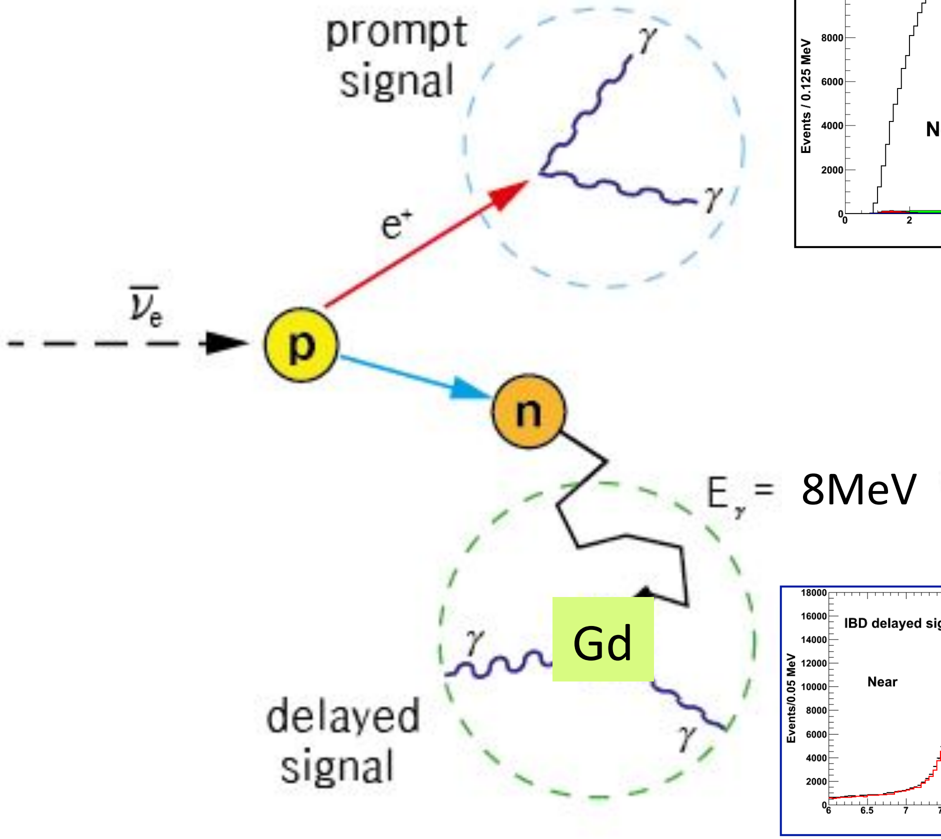
$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{ee}L}{E_\nu}\right)$$

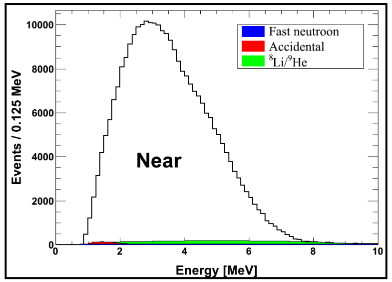
$$|\Delta m^2_{ee}| \equiv \cos^2\theta_{12}\,|\Delta m^2_{31}| + \sin^2\theta_{12}\,|\Delta m^2_{32}|$$

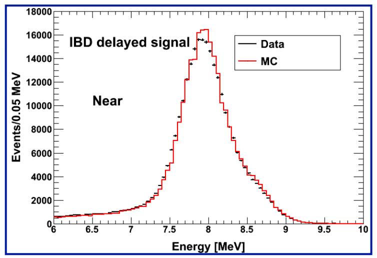
Nunokawa, Parke, Funchal, PRD 72, 013009 (2015)

Using multiple, identical detectors will reduce the systematic errors in 1%.

Detection Principle of Reactor Neutrinos







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

Inverse Beta Decay (IBD)

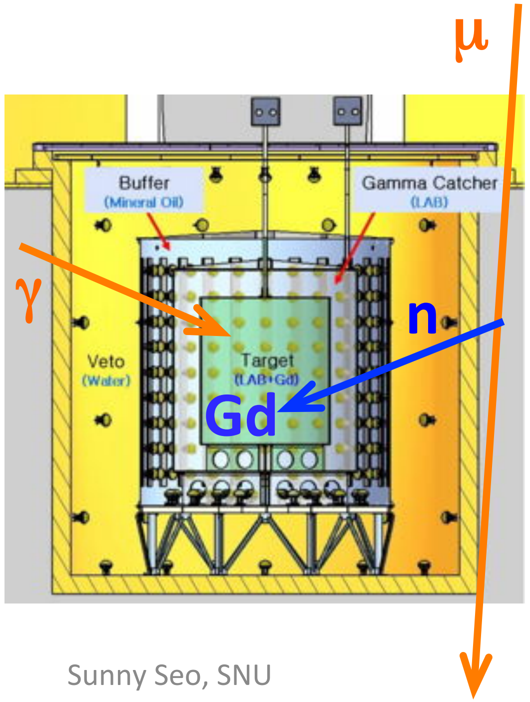
Gd capture		**H capture**
Delayed signal		**Delayed signal**
~30 μs	**or**	**~200 μs**
~8 MeV		**~2.2** MeV

- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** in ~30 μs
  or 2.2 MeV 〃 by H in ~200 μs

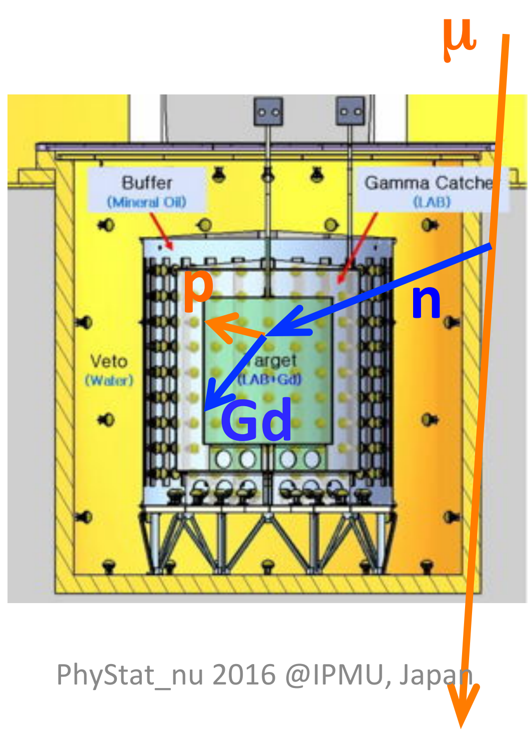
Backgrounds

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- ^{9}Li/^{8}He β-n followers produced by cosmic muon spallation

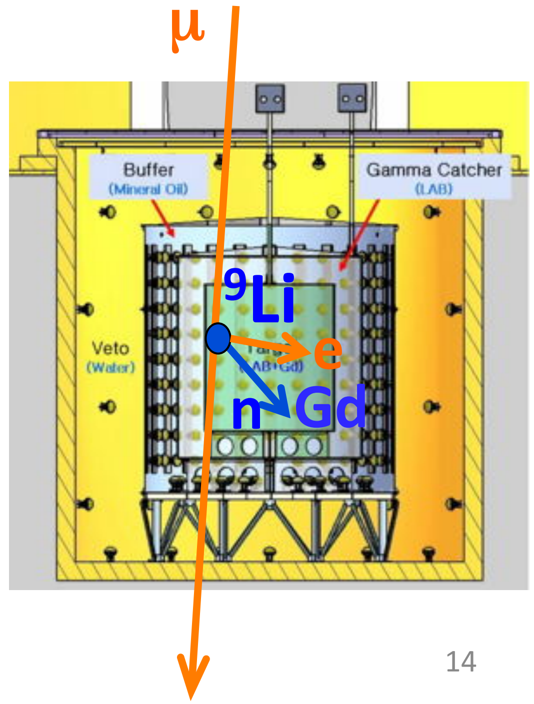
Accidentals



Fast neutrons



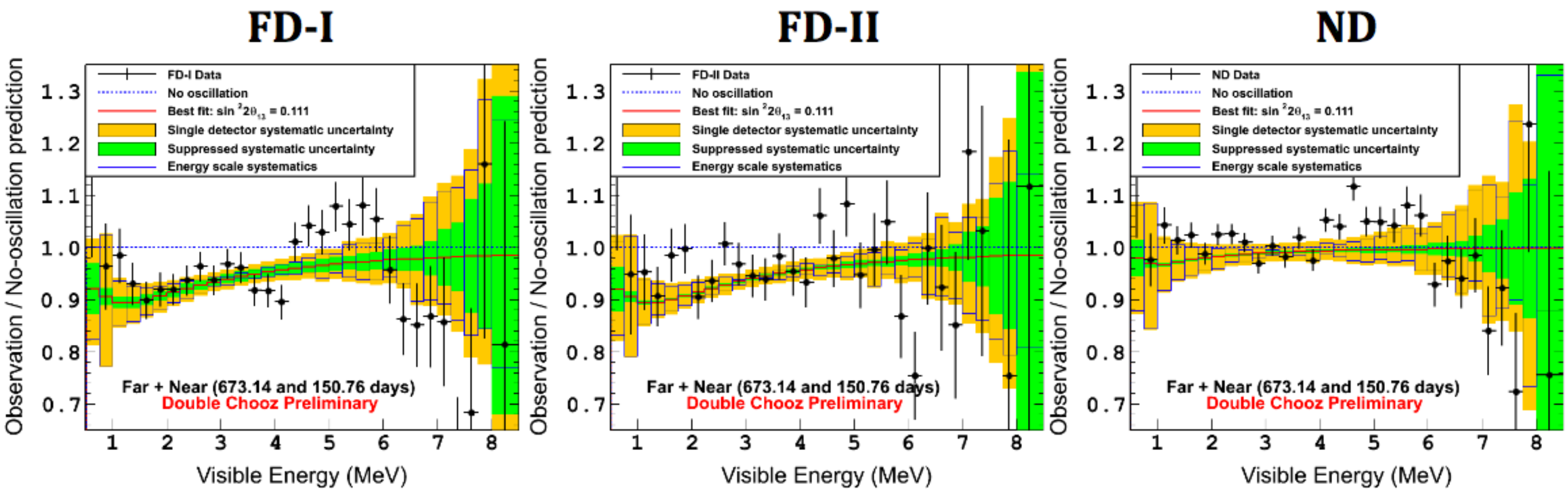
^{9}Li/^{8}He β-n followers



θ_{13}: Double Chooz

Fit results

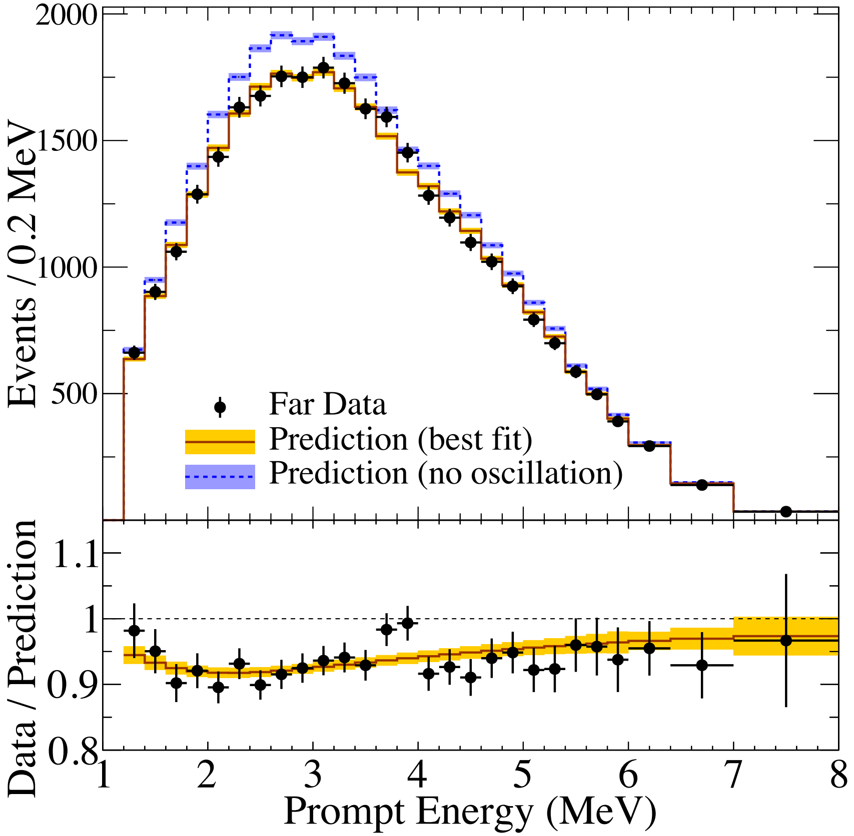
@ Moriond 2016

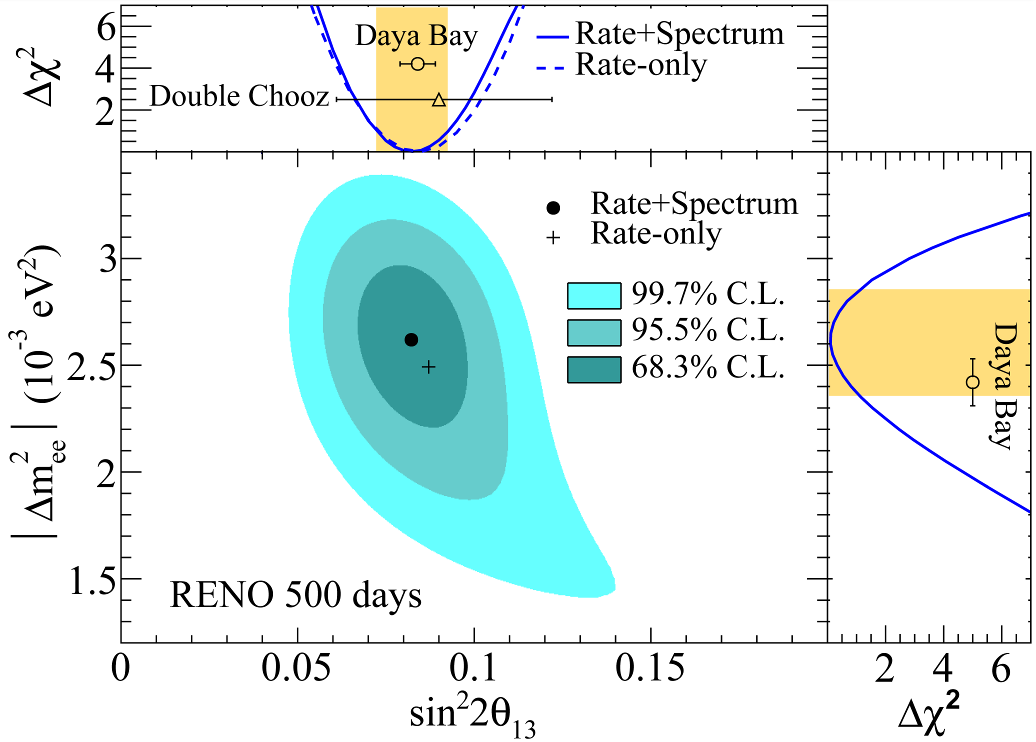


- Best-fit: $\mathbf{\sin^2 2\theta_{13} = 0.111 \pm 0.018}$ (stat.+syst.) (χ^2/dof = 128.8/120)
  - **Non-zero θ_{13} observation at 5.8σ C.L.**

    Double Chooz Preliminary
  - Cosmogenic ^{9}Li BG: 0.75±0.14 d^{-1}(FD), 4.89±0.78 d^{-1}(ND)
  - Fast-n+stop-μ BG: 0.535±0.035 d^{-1}(FD), 3.53±0.16 d^{-1}(ND)
  - Energy non-linearity: consistent across data sets and with calibration

θ_{13} & $|\Delta m^2_{ee}|$ in RENO





PRL 116, 211801 (2016)

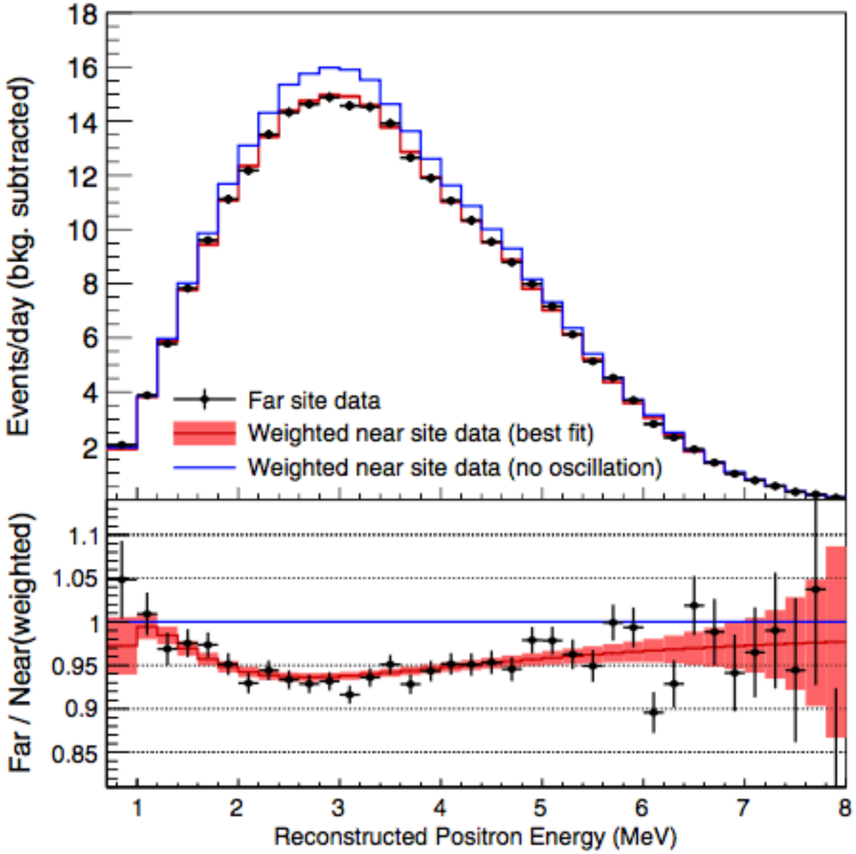
500 days

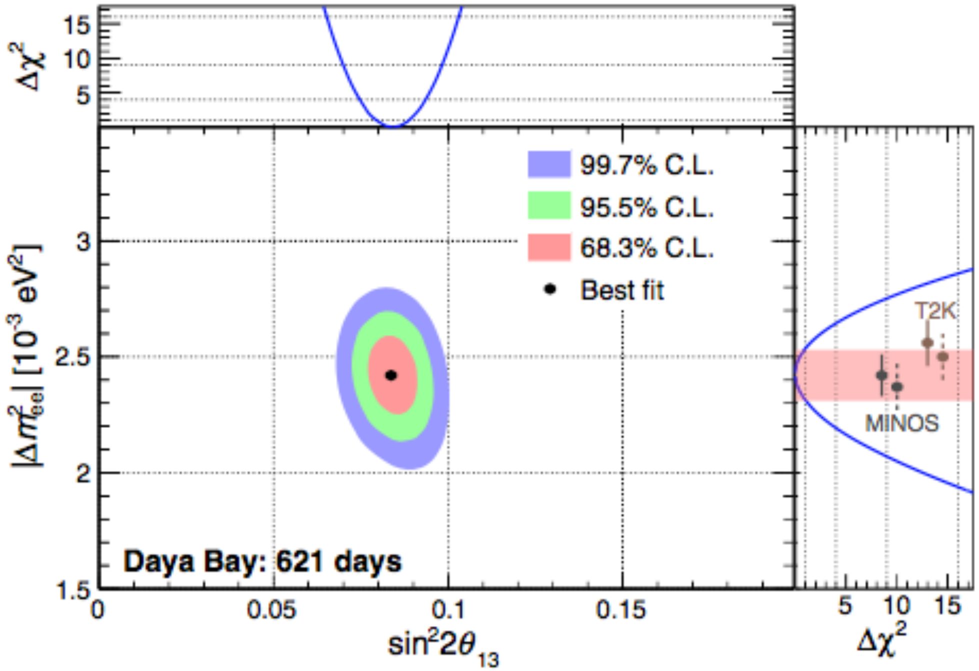
$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$$

RENO's 1st $|\Delta m^2_{ee}|$ measurement !

$$\left|\Delta m^2_{ee}\right| = 2.62\,^{+0.21}_{-0.23}(\text{stat.})\,^{+0.12}_{-0.13}(\text{syst.})\ \ (\times 10^{-3}\,eV^2)$$

θ_{13} & $|\Delta m^2_{ee}|$ in Daya Bay



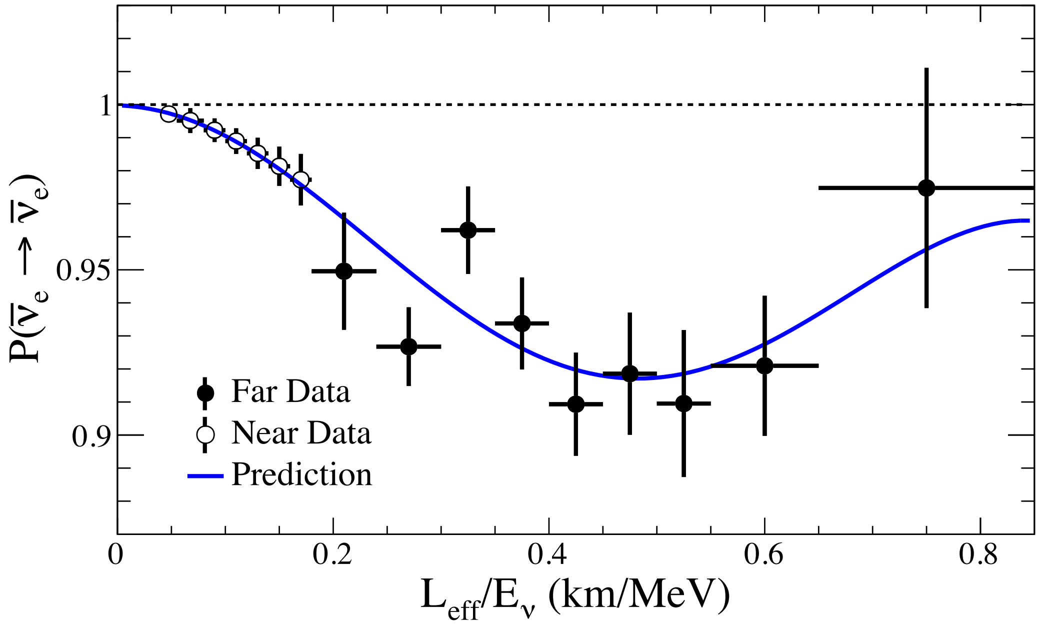


PRL 115, 111802 (2015)

621 days

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

Reactor Neutrino Disappearance on L/E



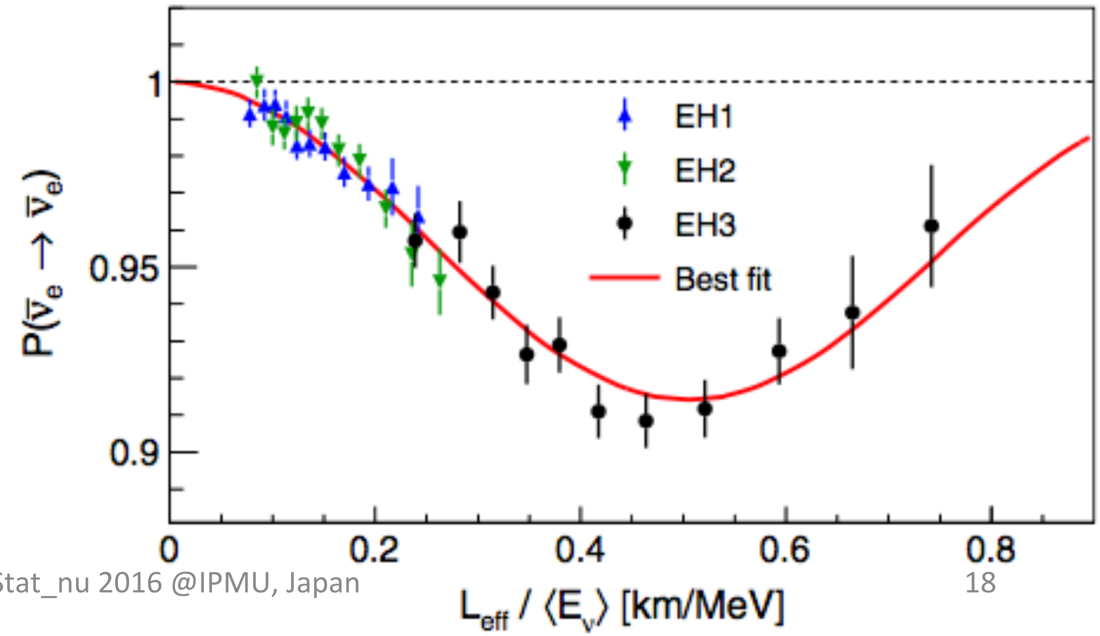
RENO

PRL 116, 211801 (2016)

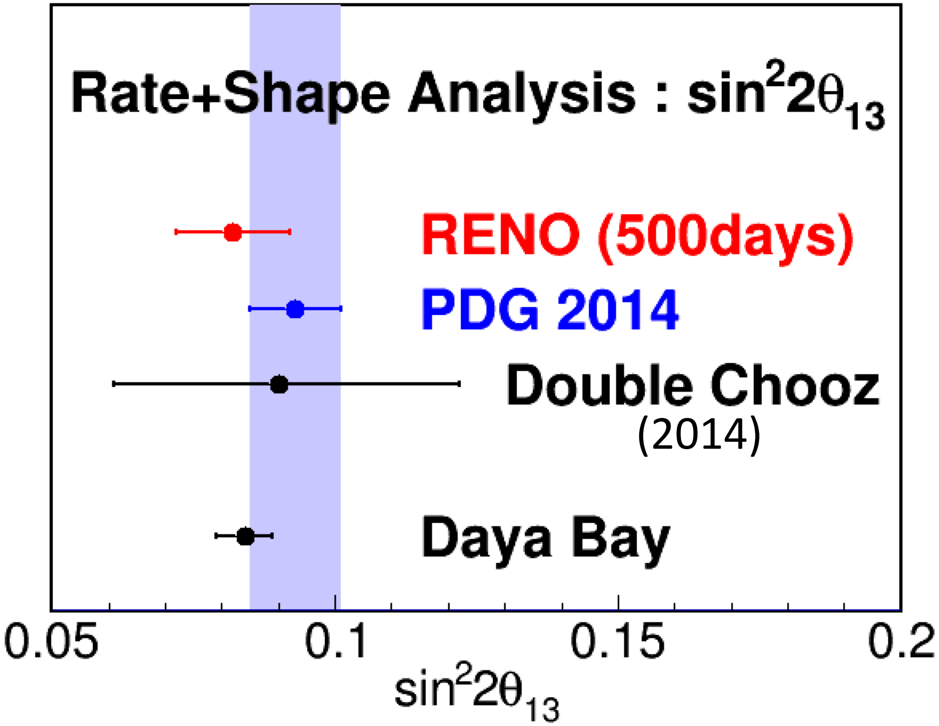
Daya Bay

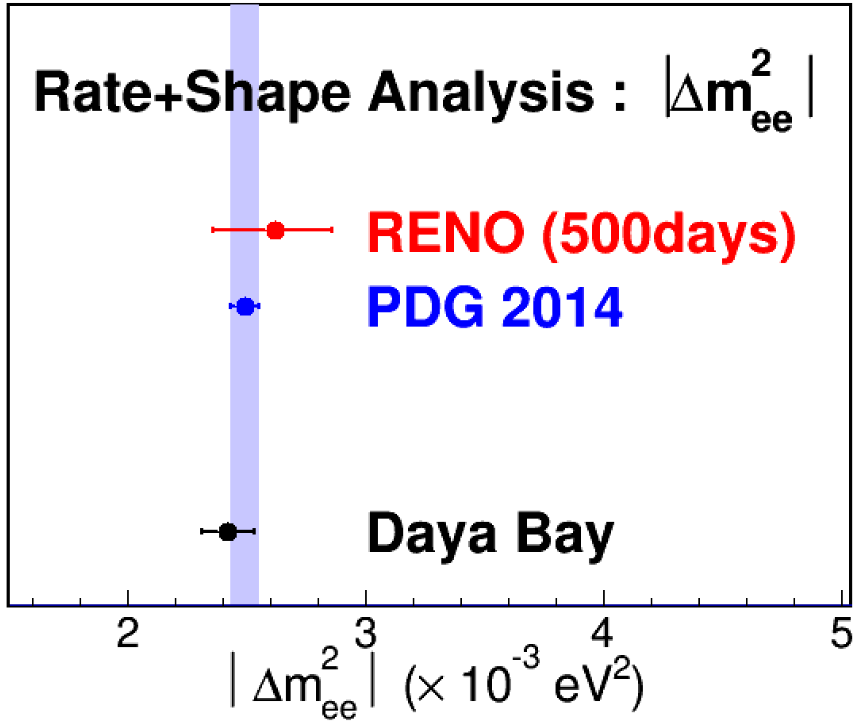
PRL 115, 111802 (2015)

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



Summary: Latest n-Gd Results





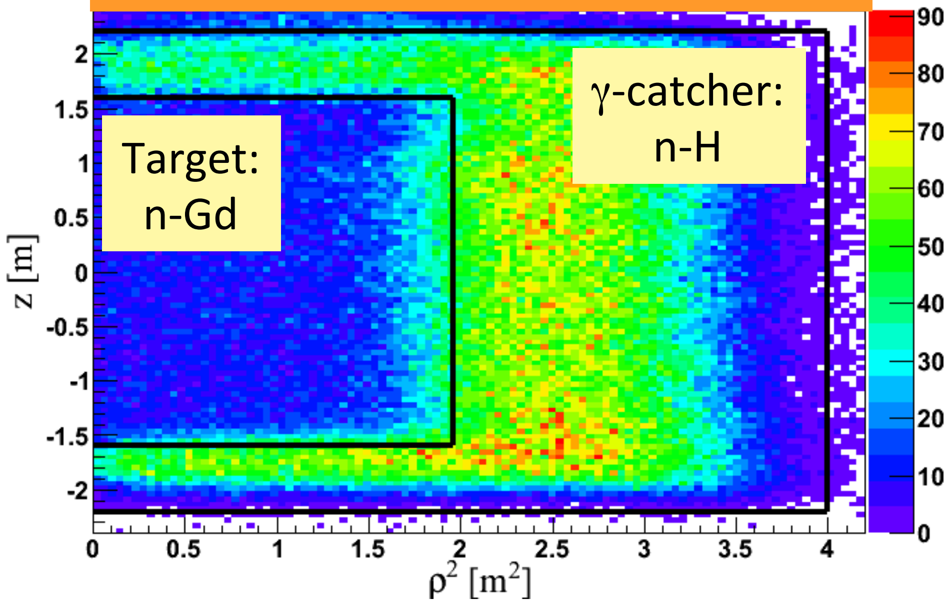
Rate + Shape [$\chi 2$/NDF]	$\sin^2 2\theta_{13}$ ± Total Error	$\lvert\Delta m_{ee}\rvert^2$ ($\times 10^3$ eV^2) ± Total Error
RENO [58.9 / 66]	0.082 ± 0.010	$2.62^{+0.24}_{-0.26}$
Daya Bay [134.6/146]	0.084 ± 0.005	2.42 ± 0.11
Double Chooz [52.2/40]	$0.090^{+0.032}_{-0.029}$	---

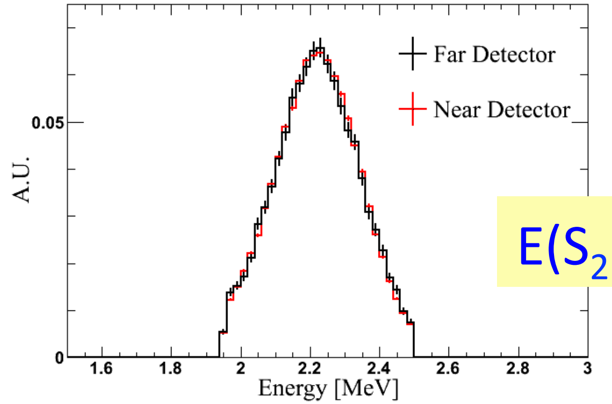
n-H Analysis

Motivation:

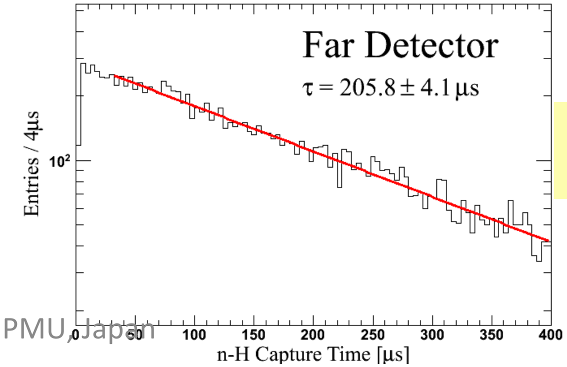
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

n-H IBD Event Vertex Distribution



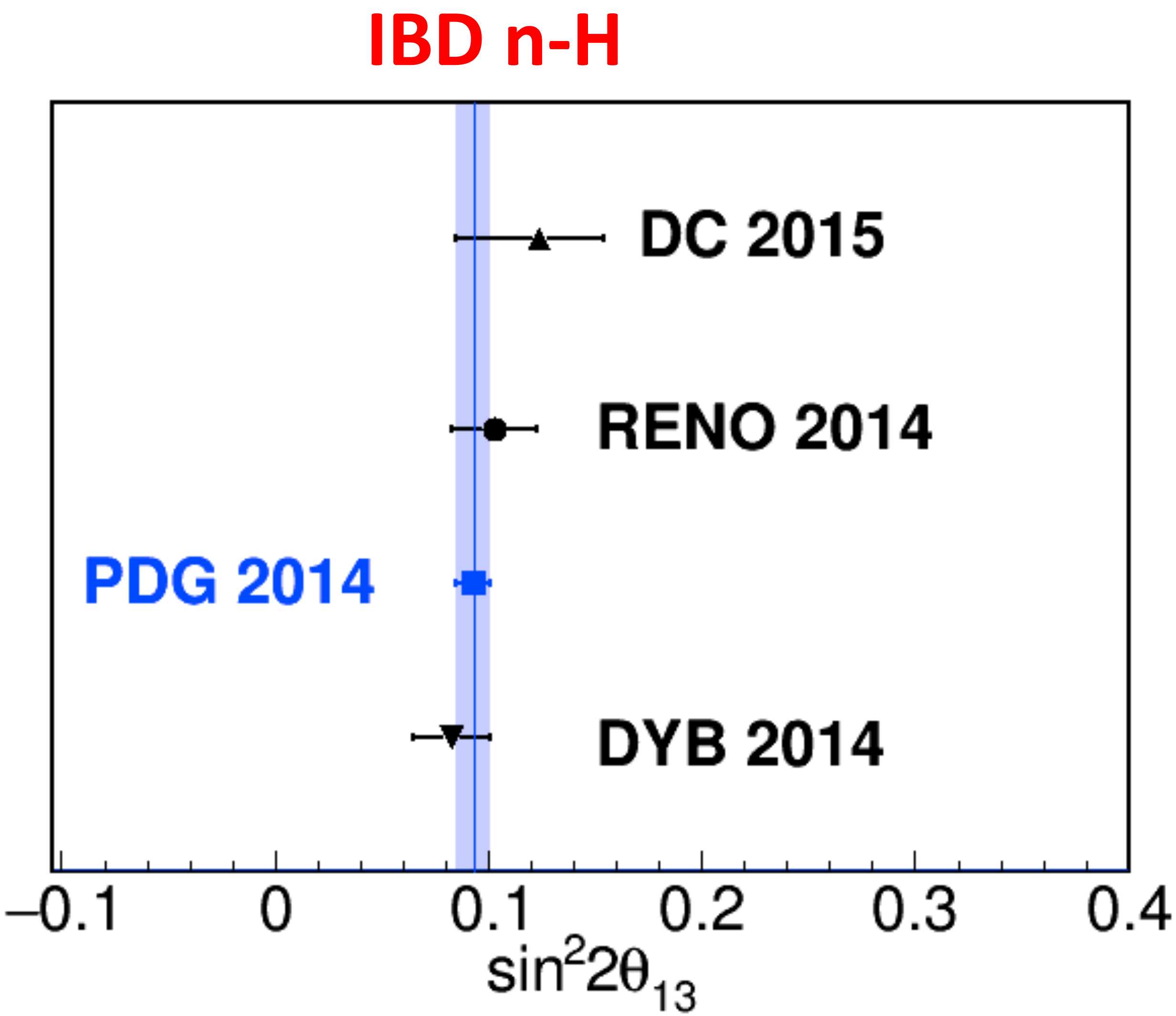


E(S_2): ~2.2 MeV



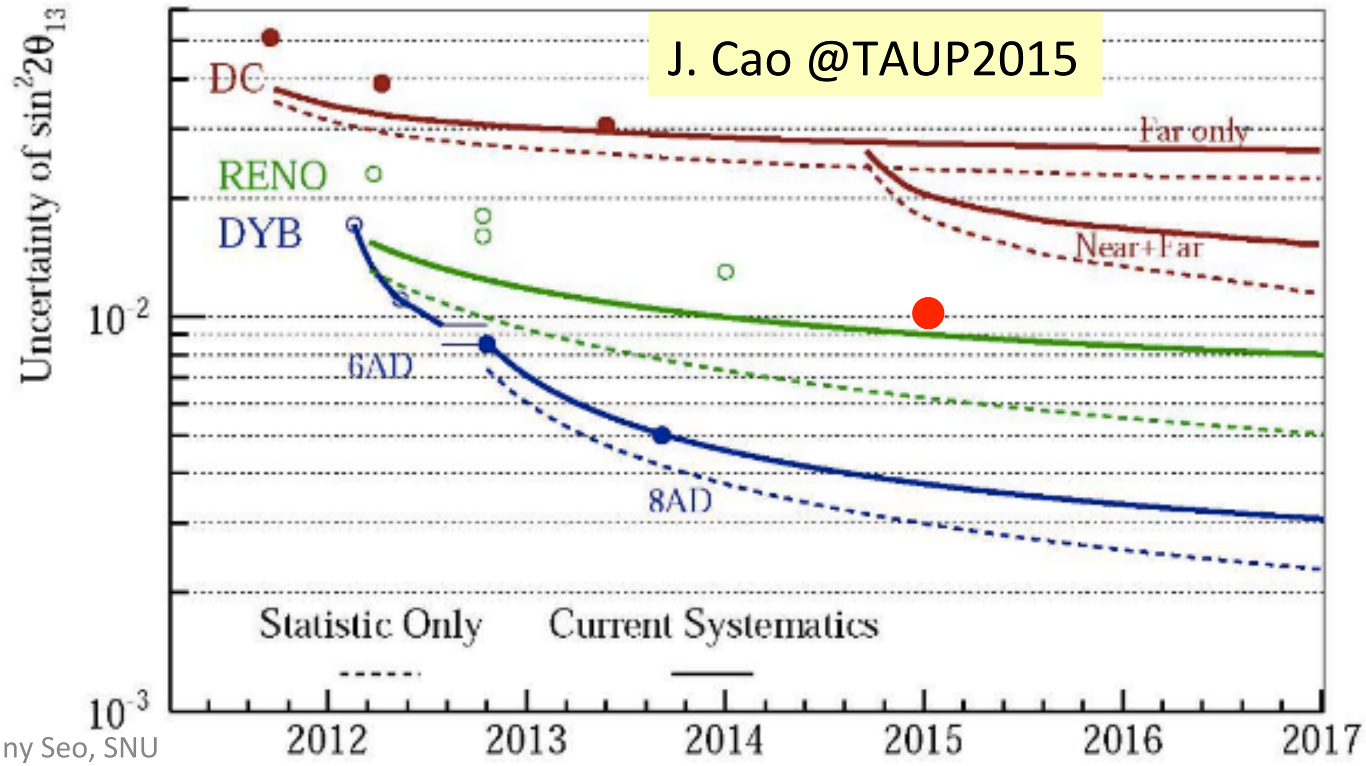
Δt: ~200 μs

Summary: Latest n-H Results



Future Prospects on θ_{13}

	Double Chooz	RENO	Daya Bay
Data	3 yrs Near&Far	5 yrs	6 yrs
$\Delta(\sin^2 2\theta_{13})$	~10 %	~5 %	~3 %
$\Delta(\lvert m^2_{ee}\rvert)$	---	~5 %	~3 %



θ_{13} & $|\Delta m^2_{ee}|$ measurements

This is a “Parameter estimation”.

→ Find minimum χ^2 by varying θ_{13} & $|\Delta m^2_{ee}|$

θ_{13} & $|\Delta m^2_{ee}|$ measurements

Survival prob.

$$
\begin{aligned}
1 - P &= \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\
&\quad + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\
&\approx \sin^2 2\theta_{13}\sin^2\Delta_{ee} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \quad (1)
\end{aligned}
$$

"Approx. Osc. Prob. accurate to 1 part in 10^4"

Where, $\boxed{\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}}$ (*i,j* = 1,2,3) $\boxed{\Delta_{ee} \equiv \frac{\Delta m^2_{ee} L}{4E}}$

$$\boxed{\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}}$$

Parke arXiv:1601.07464

→ Find minimum χ^2 by varying θ_{13} & $|\Delta m^2_{ee}|$

Parameter estimation

X^2 Fit Methods

- Covariance matrix method: ← Daya Bay

  → more traditional in HEP in the past

  → could be more difficult when # of sys. error increases.

- Pull method: Stump et al, PRD65, 014012 (2002)

  → reduces error ← RENO

  → easier to code up

The two methods are exactly identical mathematically. Fogli et al, PRD66, 053010 (2002)

General X^2 Fit with Pull Method

Fogli et al, PRD 66, 053010 (2002)

Correlated error

$$\chi^2_{\text{pull}} = \min_{\{\xi_k\}} \left[\sum_{n=1}^{N} \left(\frac{R_n^{\text{expt}} - R_n^{\text{theor}} - \sum_{k=1}^{K} \xi_k c_n^k}{u_n} \right)^2 + \sum_{k=1}^{K} \xi_k^2 \right]$$

Pull parameters

Uncorrelated Error

Pull method is more practical when
K (#. sys. error sources) << N (#. observables)

RENO: X² fit

$$\chi^2 = \sum_{i=1}^{N_{bins}} \frac{(O_i^{F/N} - T_i^{F/N})^2}{U_i^{F/N}} + \sum_{d=N,F} \left(\frac{b^d}{\sigma_{bkg}^d}\right)^2 + \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_{flux}^r}\right)^2 + \left(\frac{\epsilon}{\sigma_{eff}}\right)^2 + \left(\frac{e}{\sigma_{scale}}\right)^2$$

PRL 116, 211801 (2016)

(Pull method)

$$T_i^{F/N} = T_i^{F/N}(b^d, f_r, \epsilon, e; \theta_{13}, |\Delta m_{ee}^2|)$$

❖ Expected events term ($T_i^{F/N}$) contains energy dependent BKG uncertainties.

68 bins = **34** energy bins **x 2** periods

Daya Bay: X^2 fit

(Covariance Matrix method)

PRL 115, 111802 (2015)

$$\chi^2 = \sum_{i,j} (N_j^f - w_j N_j^n)(V^{-1})_{ij}(N_i^f - w_i N_i^n)$$

Weight

$$w_i = \frac{N_i^f}{N_i^n} = \left(\frac{T^f}{T^n}\right)\left(\frac{\epsilon^f}{\epsilon^n}\right)\sum_j \mathcal{P}(E_j^{\text{true}}|E_i^{\text{rec}})r_j$$

Extrapolation factor

$$r_j = \frac{\sum_k^{\text{cores}} P(E_j^{\text{true}}, L_k^f)\phi_{jk}/(L_k^f)^2}{\sum_k^{\text{cores}} P(E_j^{\text{true}}, L_k^n)\phi_{jk}/(L_k^n)^2}$$

Cov. Matrix element

$$V_{ij} = \frac{1}{N}\sum^{N}(S_i^f - w_i S_i^n)(S_j^f - w_j S_j^n)$$

148 bins = **37** energy bins **x 2** N-F pair **x 2** periods

Double Chooz: X² fit

$$\chi^2 = \sum_{i=1}^{40}\sum_{j=1}^{40}(N_i^{\rm obs} - N_i^{\rm exp})M_{ij}^{-1}(N_j^{\rm obs} - N_j^{\rm exp}) + \sum_{k=1}^{5}\frac{\epsilon_k^2}{\sigma_k^2}$$
$$+(\epsilon_a, \epsilon_b, \epsilon_c)\begin{pmatrix} \sigma_a^2 & \rho_{ab}\sigma_a\sigma_b & \rho_{ac}\sigma_a\sigma_c \\ \rho_{ab}\sigma_a\sigma_b & \sigma_b^2 & \rho_{bc}\sigma_b\sigma_c \\ \rho_{ac}\sigma_a\sigma_c & \rho_{bc}\sigma_b\sigma_c & \sigma_c^2 \end{pmatrix}^{-1}\begin{pmatrix}\epsilon_a \\ \epsilon_b \\ \epsilon_c\end{pmatrix} + 2\left[N_{\rm off}^{\rm obs}\cdot\ln\left(\frac{N_{\rm off}^{\rm obs}}{N_{\rm off}^{\rm exp}}\right) + N_{\rm off}^{\rm exp} - N_{\rm off}^{\rm obs}\right]$$

(Hybrid method)

Cov. Matrix element

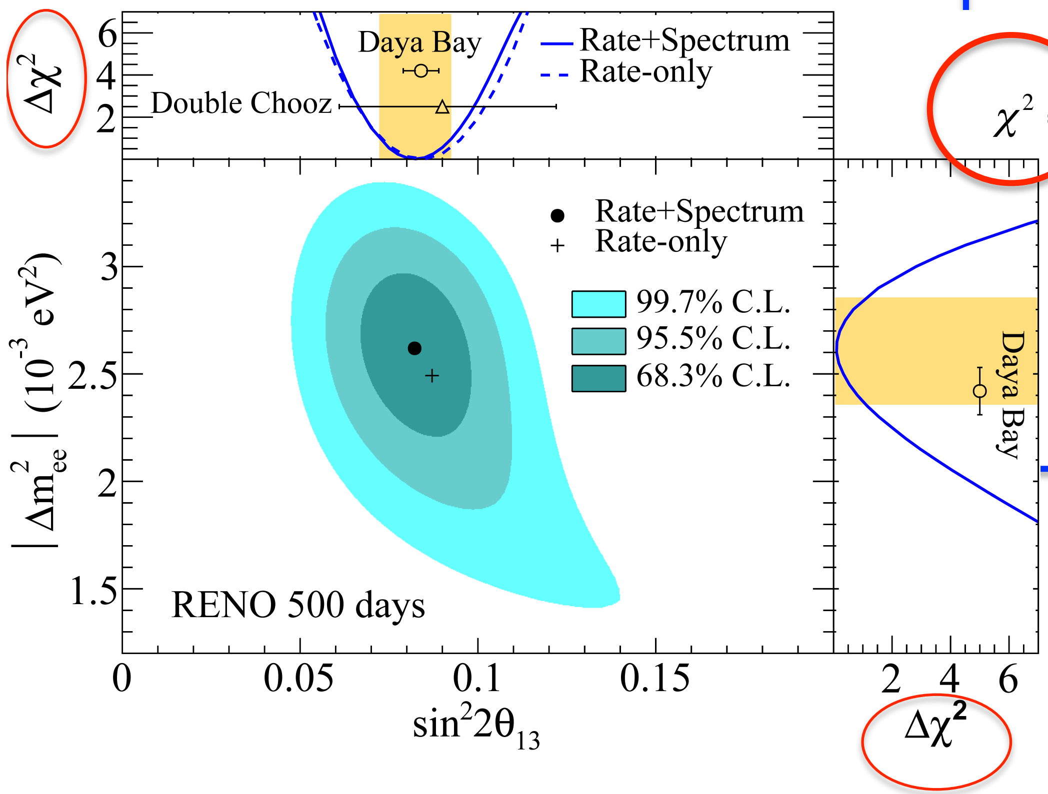
$$M_{ij} = M_{ij}^{\rm stat} + M_{ij}^{\rm flux} + M_{ij}^{\rm eff} + M_{ij}^{\rm Li/He(shape)} + M_{ij}^{\rm acc(stat)}$$

JHEP 10, 086 (2014)

Source	Uncertainty (%)
Reactor flux	1.7
Detection efficiency	0.6
^{9}Li + ^{8}He BG	+1.1 / −0.4
Fast-n and stop-μ BG	0.1
Statistics	0.8
Total	+2.3 / −2.0

Fit Parameter	Input Value	Best-Fit Value
Li+He bkg. (d^{-1})	$0.97^{+0.41}_{-0.16}$	0.74 ± 0.13
Fast-n + stop-μ bkg. (d^{-1})	0.604 ± 0.051	$0.568^{+0.038}_{-0.037}$
Accidental bkg. (d^{-1})	0.0701 ± 0.0026	0.0703 ± 0.0026
Residual $\bar{\nu}_e$	1.57 ± 0.47	1.48 ± 0.47
Δm^2 (10^{-3} eV^2)	$2.44^{+0.09}_{-0.10}$	$2.44^{+0.09}_{-0.10}$
E-scale ϵ_a	0 ± 0.006	$0.001^{+0.006}_{-0.005}$
E-scale ϵ_b	0 ± 0.008	$-0.001^{+0.004}_{-0.006}$
E-scale ϵ_c	0 ± 0.0006	$-0.0005^{+0.0007}_{-0.0005}$

θ_{13} & $|\Delta m^2_{ee}|$ uncertainties



$$\chi^2 = \sum_{P=before,After} \left\{ \sum_{i=1\sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{(U_i)^2} \right\} + Pull\_Terms$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

$$\Delta\chi^2 = \chi^2 - \chi^2_{min}$$

PRL 116, 211801 (2016)

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\mathrm{stat}) \pm 0.006(\mathrm{syst})$$

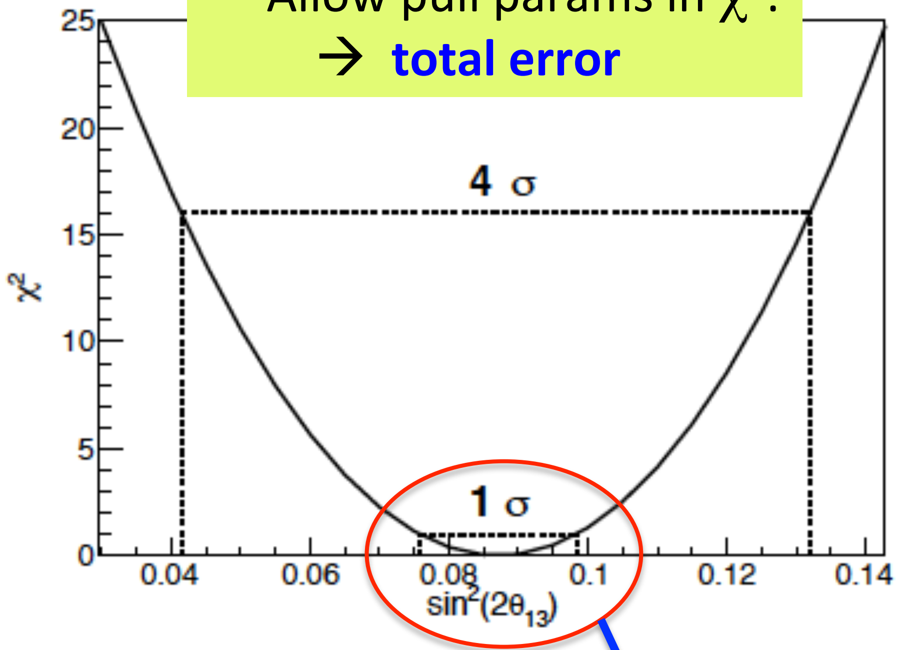
$$\left|\Delta m^2_{ee}\right| = 2.62\,^{+0.21}_{-0.23}(\mathrm{stat.})\,^{+0.12}_{-0.13}(\mathrm{syst.}) \;\; (\times 10^{-3} eV^2)$$

1 σ uncertainty: $\Delta\chi^2 = 1$

- Allow pull params in χ^2:
  → **total error**
- Remove pull params in χ^2:
  → **stat. error**

Example: Rate-only Analysis

- Allow pull params in χ^2:
  → **total error**



$$\sin^2 2\theta_{13} = 0.087 \pm 0.011(\text{total})$$

$$\chi^2 = \sum_{P=SetA,SetB} \left\{ \frac{\frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} - \frac{N_{exp}^{F,P}}{N_{exp}^{N,P}}}{U^P} \right\}^2 + \chi^2_{penalty}$$

where

$$N_{exp}^{F,P} = \sum_{r=1}^{6} \left[(1 + \xi + \xi_F^{SetB} + f_r) \cdot N_{exp}^{F,P,r} \right] - b_F^P - \beta_F^P \cdot S_{LH}^F$$

$$N_{exp}^{N,P} = \sum_{r=1}^{6} \left[(1 + \xi_N^{SetB} + f_r) \cdot N_{exp}^{N,P,r} \right] - b_N^P - \beta_N^P \cdot S_{LH}^N$$

$$U^P = \frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} \sqrt{\frac{N_{obs}^{F,P} + N_{bkg}^{F,P}}{\left(N_{obs}^{F,P}\right)^2} + \frac{N_{obs}^{N,P} + N_{bkg}^{N,P}}{\left(N_{obs}^{N,P}\right)^2}}$$

and

$$\chi^2_{penalty} = \left(\frac{\xi}{\sigma_\xi}\right)^2 + \sum_{d=F,N} \left(\frac{\xi_d^{SetB}}{\sigma_{\xi_d}}\right)^2 + \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_{f_r}}\right)^2 + \sum_{P,d} \left(\frac{b_d^P}{\sigma_{b_d}^P}\right)^2 + \sum_{d} \left(\frac{S_{LH}^d}{\sigma_{LH}^d}\right)^2$$

Example: Rate-only Analysis

$$\chi^2 = \sum_{P=SetA,SetB} \left\{ \frac{\frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} - \frac{N_{exp}^{F,P}}{N_{exp}^{N,P}}}{U^P} \right\}^2 + \cancel{\chi^2_{penalty}}$$

where

$$N_{exp}^{F,P} = \sum_{r=1}^{6} \left[(1 + \cancel{\xi} + \cancel{\xi_F^{SetB}} + \cancel{f_r}) \cdot N_{exp}^{F,P,r} \right] - \cancel{b_F^P} - \cancel{\beta_F^P} \cdot S_{LH}^F$$

$$N_{exp}^{N,P} = \sum_{r=1}^{6} \left[(1 + \cancel{\xi_N^{SetB}} + \cancel{f_r}) \cdot N_{exp}^{N,P,r} \right] - \cancel{b_N^P} - \cancel{\beta_N^P} \cdot S_{LH}^N$$

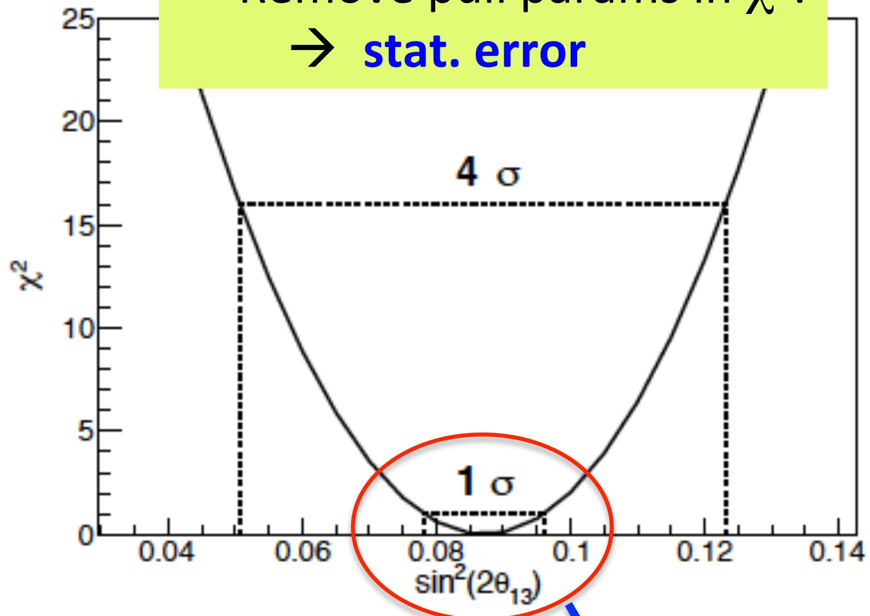
$$U^P = \frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} \sqrt{\frac{N_{obs}^{F,P} + N_{bkg}^{F,P}}{\left(N_{obs}^{F,P}\right)^2} + \frac{N_{obs}^{N,P} + N_{bkg}^{N,P}}{\left(N_{obs}^{N,P}\right)^2}}$$

and

$$\cancel{\chi^2_{penalty} = \left(\frac{\xi}{\sigma_\xi}\right)^2 + \sum_{d=F,N} \left(\frac{\xi_d^{SetB}}{\sigma_{\xi_d}}\right)^2}$$

$$\cancel{+ \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_{f_r}}\right)^2 + \sum_{P,d} \left(\frac{b_d^P}{\sigma_{b_d}^P}\right)^2 + \sum_{d} \left(\frac{S_{LH}^d}{\sigma_{LH}^d}\right)^2}$$

- Remove pull params in χ^2:
  → **stat. error**



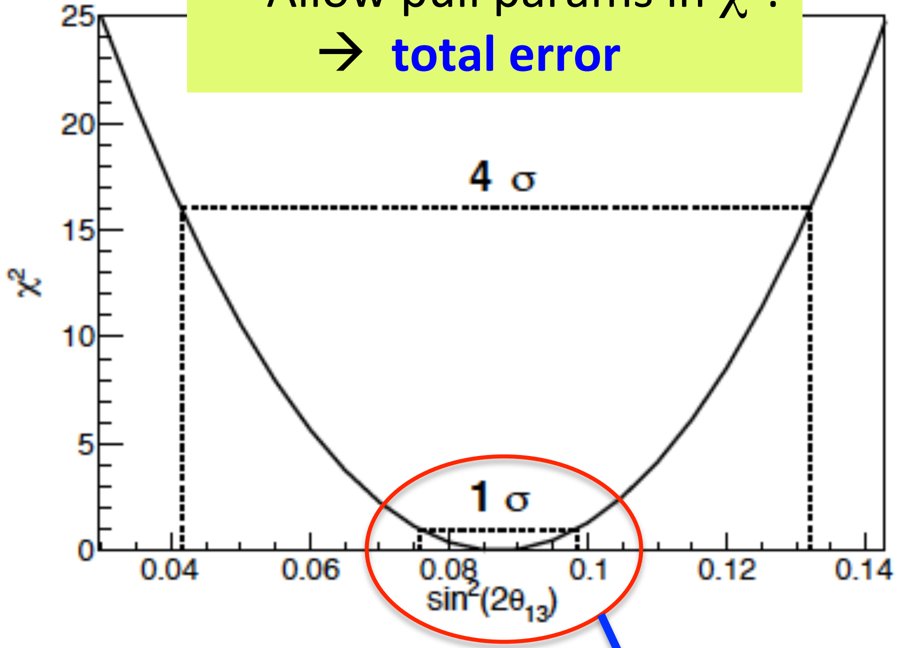
$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat})$$

$$\boxed{\delta^2_{syst.} = \delta^2_{total} - \delta^2_{stat.}}$$

$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})$$

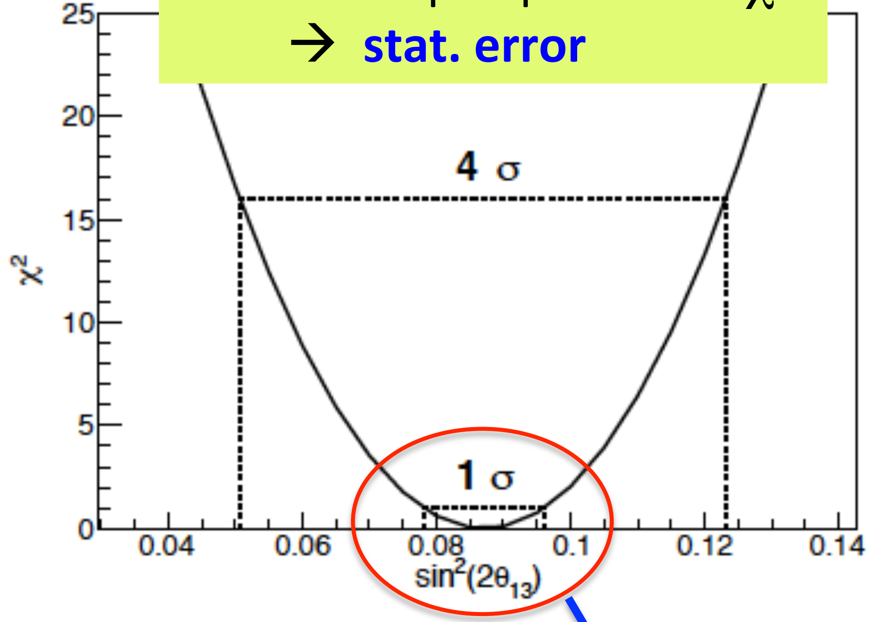
Example: Rate-only Analysis

- Allow pull params in χ^2:
  → **total error**



$$\sin^2 2\theta_{13} = 0.087 \pm 0.011(\text{total})$$

- Remove pull params in χ^2:
  → **stat. error**



$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat})$$

$$\boxed{\delta^2_{syst.} = \delta^2_{total} - \delta^2_{stat.}}$$

RENO Rate-only result →

$$\boxed{\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})}$$

Summary before discussion

1. Neutrino mixing angle θ_{13} was measured in 2012 using reactor neutrinos: ~ 5 σ

→ Open a wide window to future ν physics

2. Precise θ_{13} measurement is still necessary.
3 exp. combined analysis: better than 3 % precision

(Current Daya Bay: 6 %, RENO: 12 %, Double Chooz: 33 % → 16%)

RENO announced their 1st $|\Delta m^2_{ee}|$ measurement. PRL 116, 211801 (2016)

3. θ_{13} & $|\Delta m^2_{ee}|$ are obtained from χ^2_{min} by varying θ_{13} & $|\Delta m^2_{ee}|$.
→ parameter determination

Daya Bay/ D. Chooz / RENO

- **Technology**:   similar

-- GdLS: similar but not identical
-- Acrylic vessel: different thickness
-- PMTs: DC & RENO have same PMTs

- **Analysis technique**:

-- three exp. use pretty much the same technique.

❑ **Future plans**:

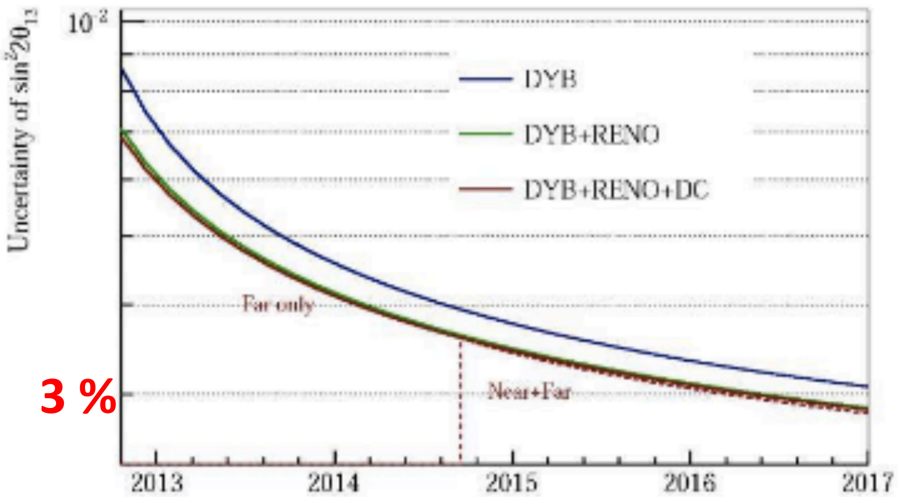
-- common workshop is needed for understanding better,
and may come up with combined analysis ?
→ better than 3% precision

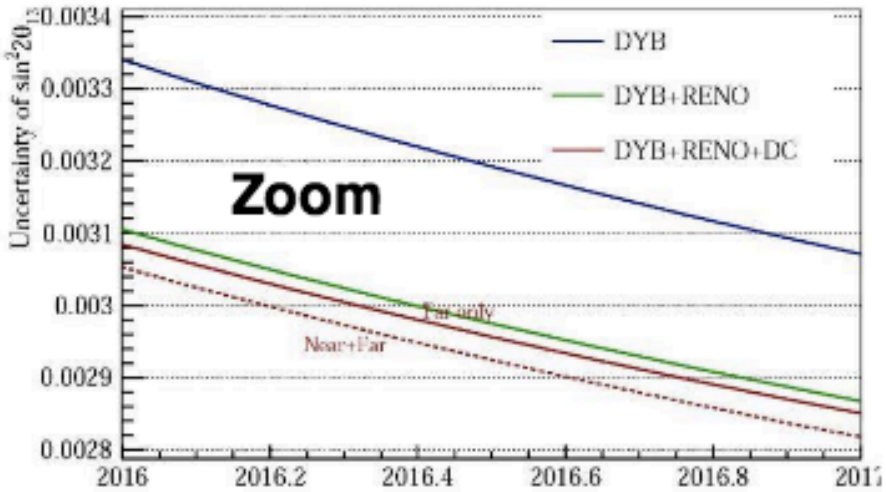
Combination Prospects

J. Cao @TAUP2015

- The 3 experiments started to discuss combination.
- To the end of 2016 (by J. Zhao)
  - Daya Bay: 0.00307
  - Daya Bay + RENO: 0.00287 → improve by 6.5%
  - Daya Bay + RENO + DC: 0.00282 → improve by 8.2%
- Assumed uncorrelated
  - Reactor, detector, background
  - Cosmogenic bkg correlation → worse
  - Cosmogenic bkg (50% systematic uncer.) reduction → better

3 %





Discussion (I)

- **Combining results from 3 reactor experiments**

$$\chi^2 = \chi^2_{DB} + \chi^2_{RENO} + \chi^2_{DC}$$

→ This will require unification of χ^2 formalism
→ Could be little (?) complicated…
→ Any other technical problems ?

Any good idea to get the best result ?

Discussion (II)

- **Combining n-Gd & n-H** analysis result

$$\chi^2 = \chi^2_{n\text{-}Gd} + \chi^2_{n\text{-}H}$$

→ This might be relatively easy within the same exp. ?
→ Any technical problems ?

PhyStat-ν Workshop on Statistical Issues in Experimental Neutrino Physics

from 30 May 2016 to 01 June 2016 (Asia/Tokyo)

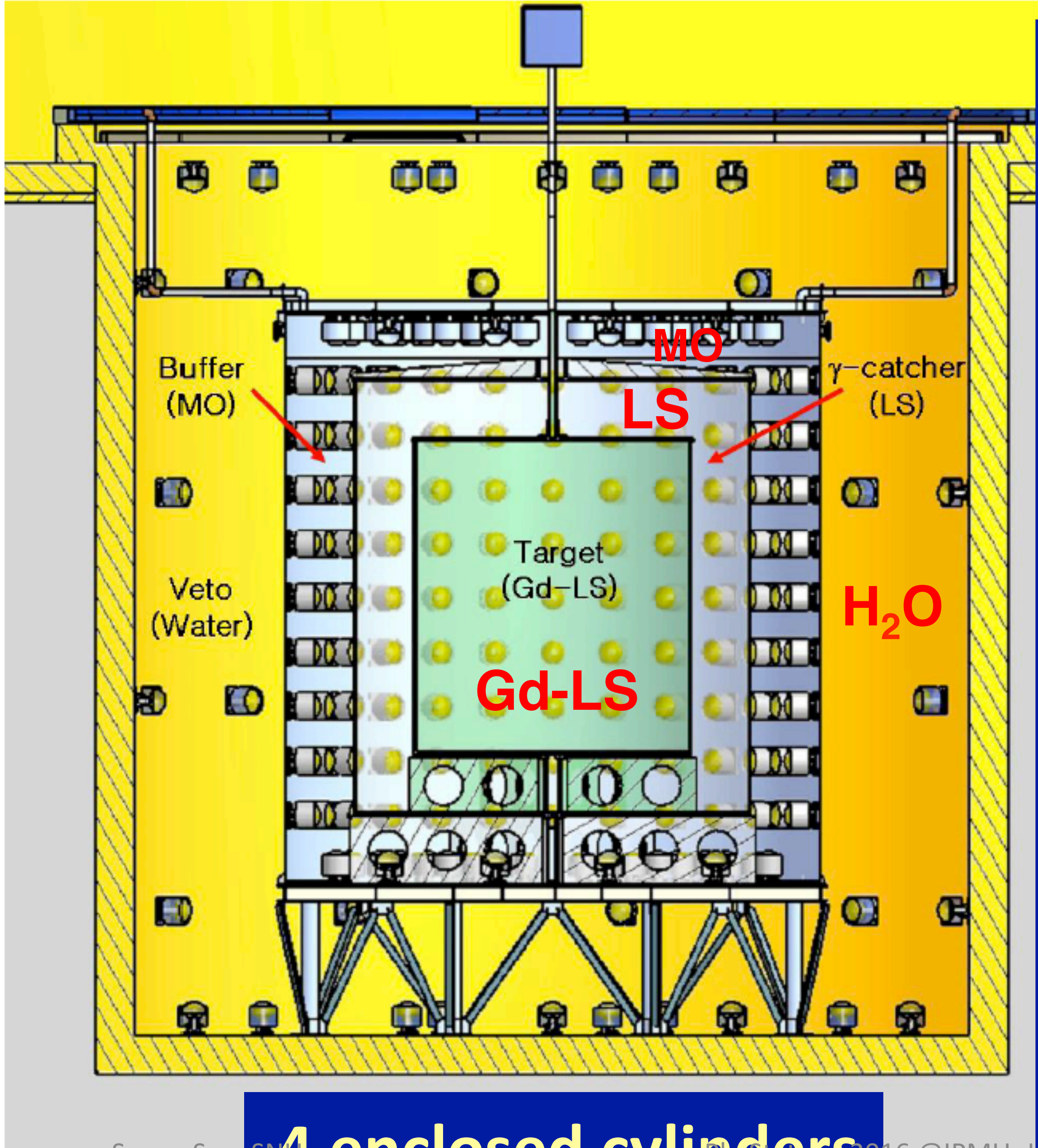
Asia/Tokyo timezone

Thank you !

감사합니다 !

ありがとう！

The RENO Detector



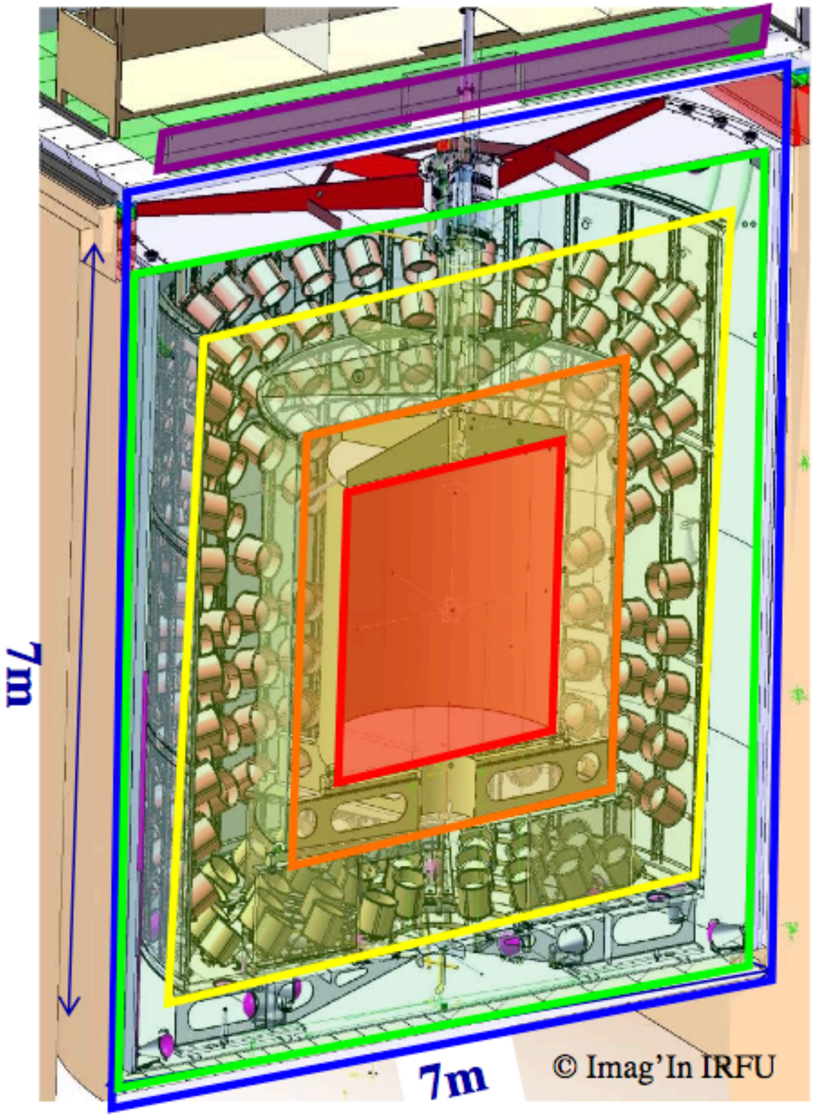
4 enclosed cylinders

- **Target : 16.5 ton Gd-LS**
  (R=1.4m, H=3.2m)
- **Gamma Catcher :**
  30 ton **LS**
  (R=2.0m, H=4.4m)
- **Buffer :** 65 ton **mineral oil**
  (R=2.7m, H=5.8m)
- **Veto : 350 ton water**
  (R=4.2m, H=8.8m)

-- 354 ID 10 " PMTs

-- 67 OD 10" PMTs

Detector: Double Chooz



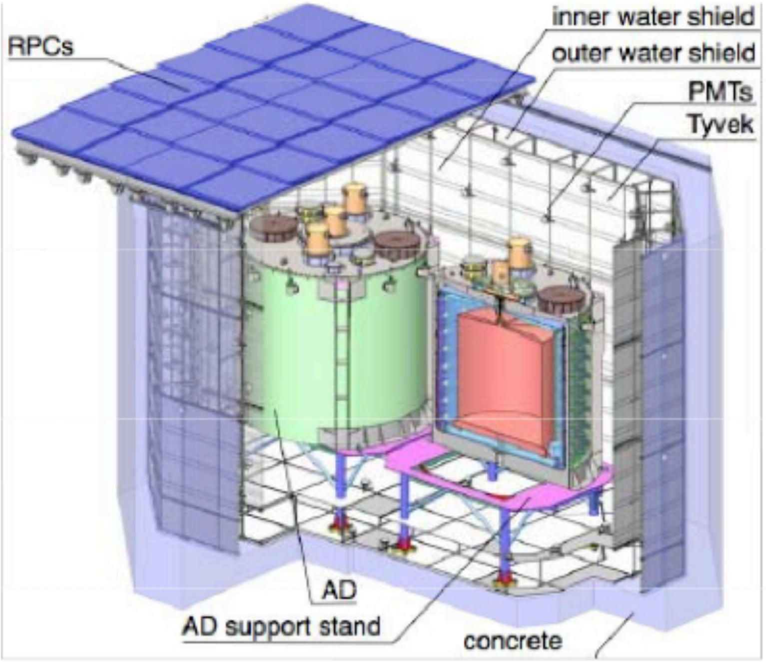
Inner detector:

- **Neutrino target:** acrylic vessel (8 mm) with 10.3 m^3 **Gd-loaded** (1 g/l) **liquid scintillator**.
- **Gamma-catcher:** acrylic (12 mm) vessel with 22.3 m^3 of **liquid scintillator**.
- **Buffer:** stainless steel (3 mm) vessel supporting **390 10" PMTs**, with 110 m^3 of **non-scintillating mineral oil**.

Outer detector:

- **Inner veto:** steel (10 mm) vessel supporting **78 8" PMTs**, with 90 m^3 of **liquid scintillator**.
- **Shielding:** 15 cm **steel**.
- **Outer veto:** **plastic scintillator** strips.

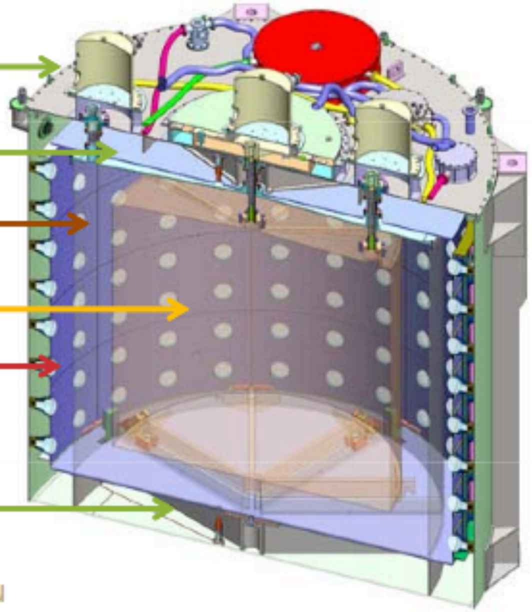
Detector: Daya Bay



Layout of the detectors

- Far-near relative measurement
- Eight identical antineutrino detectors (ADs)
- Multiple muon tagging system (RPC+IWS+OWS)

* Calibration unit
* 20t LS
* 20t Gd-LS
* 37t Mineral Oil
* Reflector

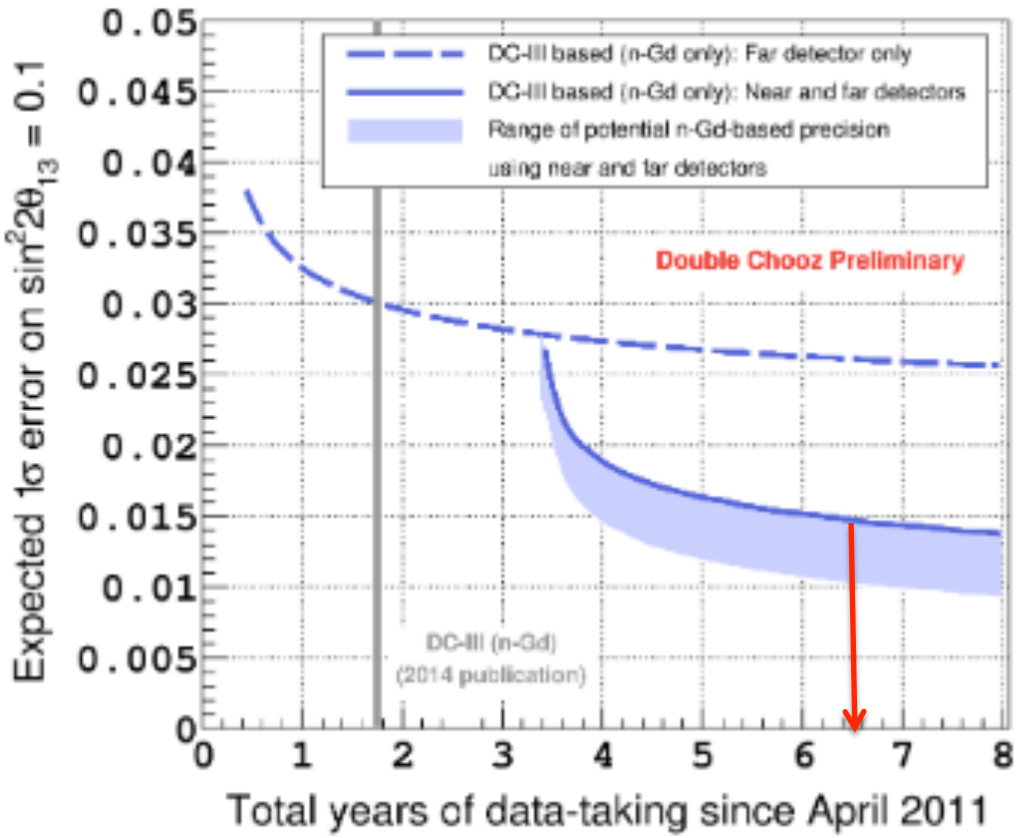


Nu 3

Future Prospects on θ_{13}

Double Chooz

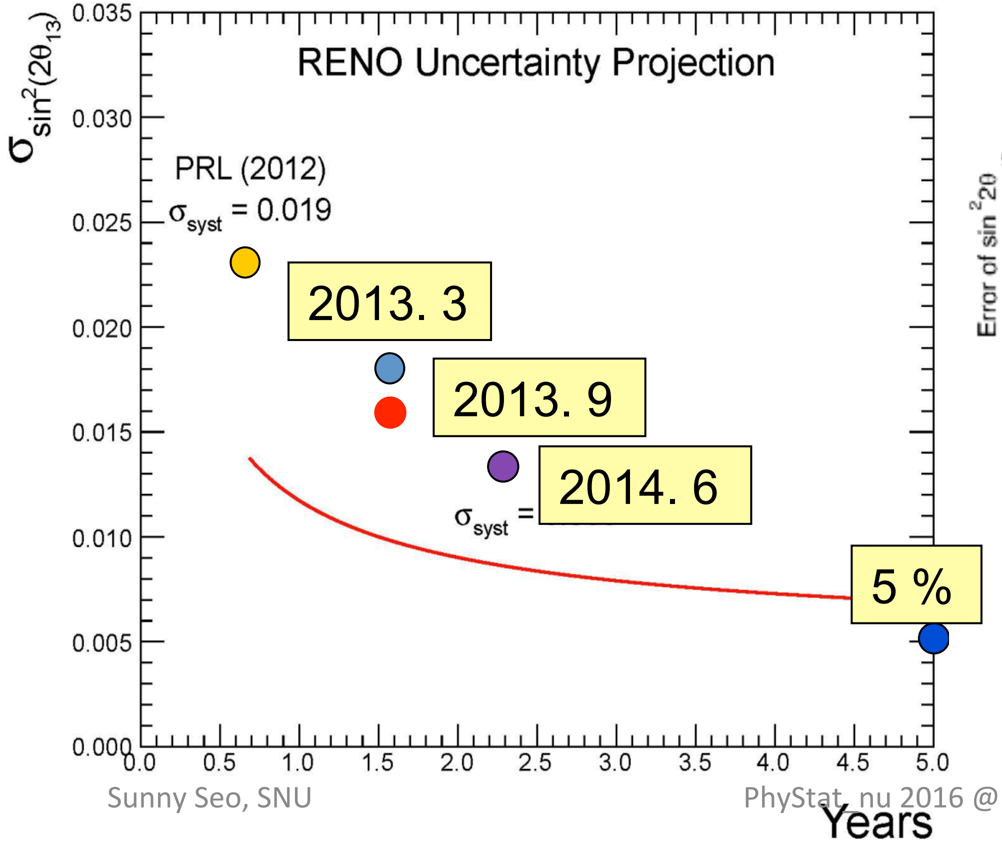
- 3 years of Far & Near data : 15 -10 %



Future Prospects on θ_{13}

RENO

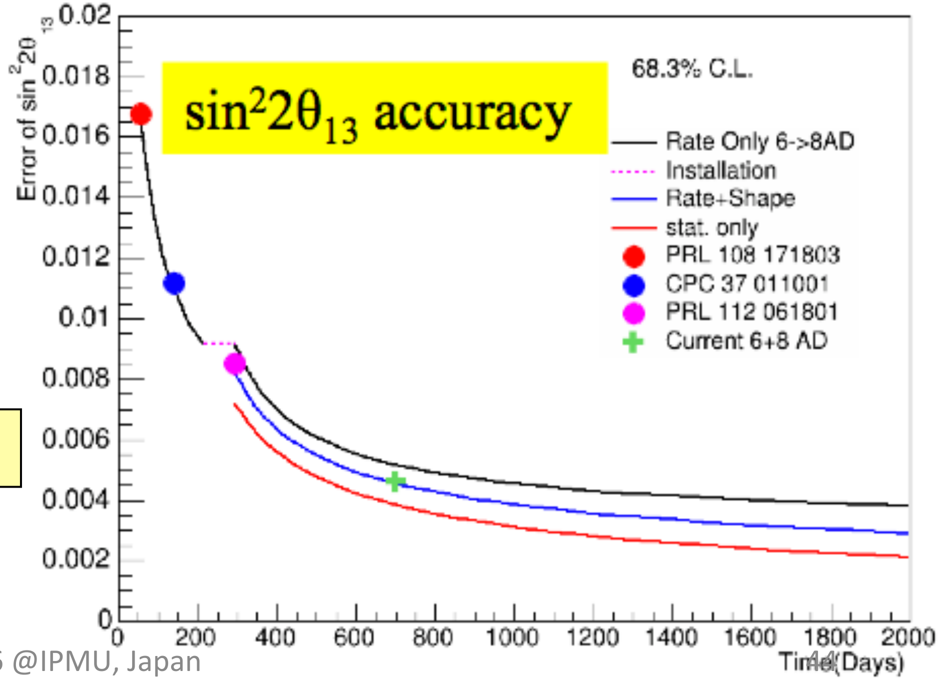
- 5 years of data : 5 %
  - stat. error : $\pm 0.008 \rightarrow \pm 0.005$
  - sys. error : $\pm 0.008 \rightarrow \pm 0.005$



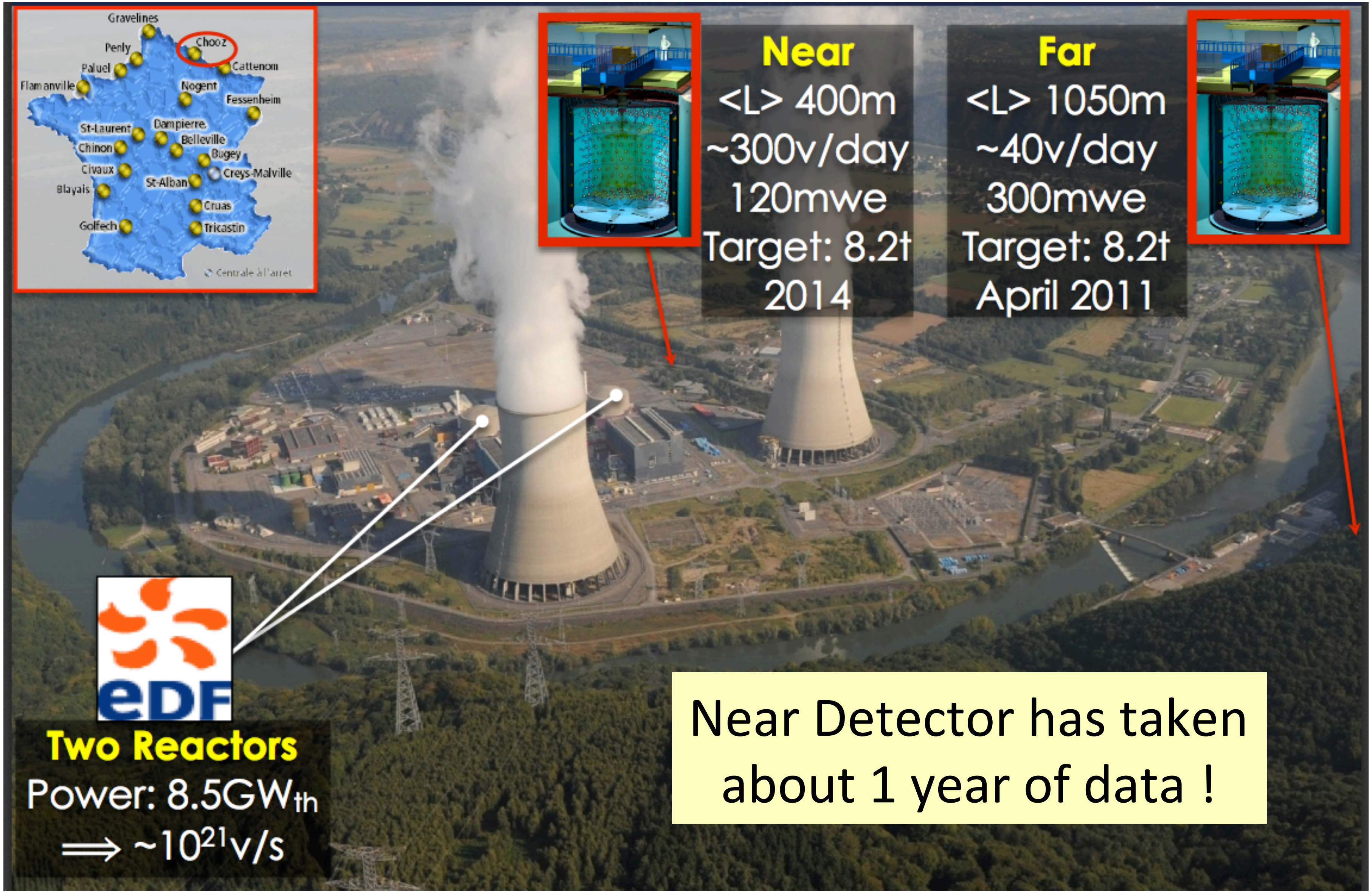
Daya Bay

- 2017 (6 years of data) : 3 %

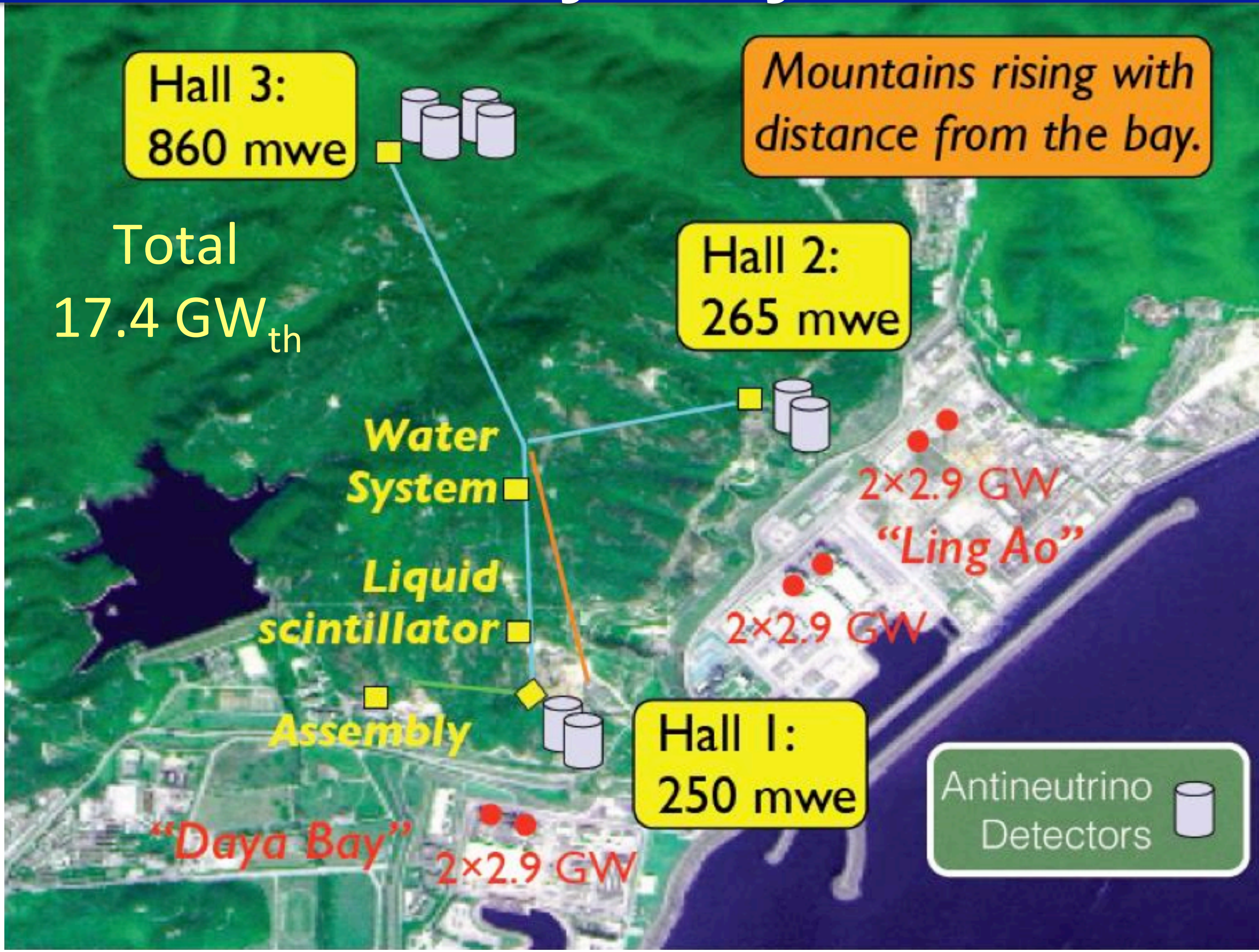
$\delta(\sin^2\theta_{13})\sim 0.003$, $\delta(\Delta m^2_{ee})\sim 0.07$



Double Chooz



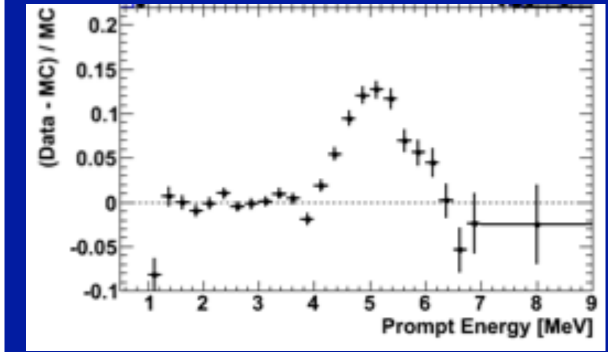
Daya Bay



Hall 3:
860 mwe
Mountains rising with
distance from the bay.
Total
17.4 GW$_{th}$
Hall 2:
265 mwe
Water
System
Liquid
scintillator
Assembly
2×2.9 GW
"Ling Ao"
2×2.9 GW
Hall 1:
250 mwe
Antineutrino
Detectors
"Daya Bay"
2×2.9 GW

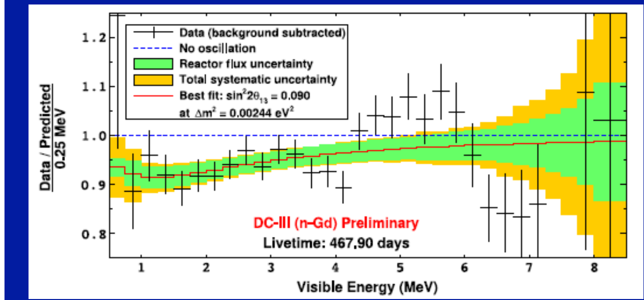
The 5 MeV Excess in 2014

RENO



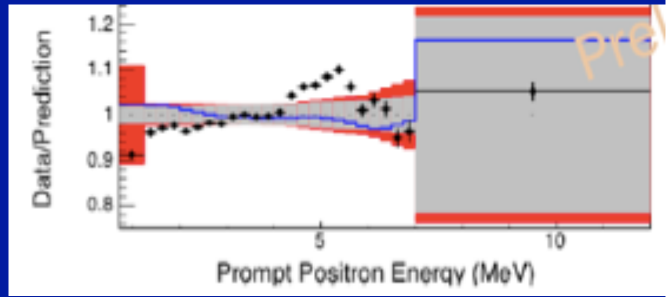
(In Neutrino 2014)

Double Chooz



(In Neutrino 2014)

Daya Bay



(In ICHEP 2014)

In 2012

-- **RENO**: excess (? σ)
in [3, 8] MeV region

(1) new background ?
(2) energy scale issue ?
(3) reactor ν model issue ?

(In Neutrino 2012)

In 2014

-- **RENO**: 5 MeV excess (**3.5 σ**)
correlation w/ reactor P_{th}.

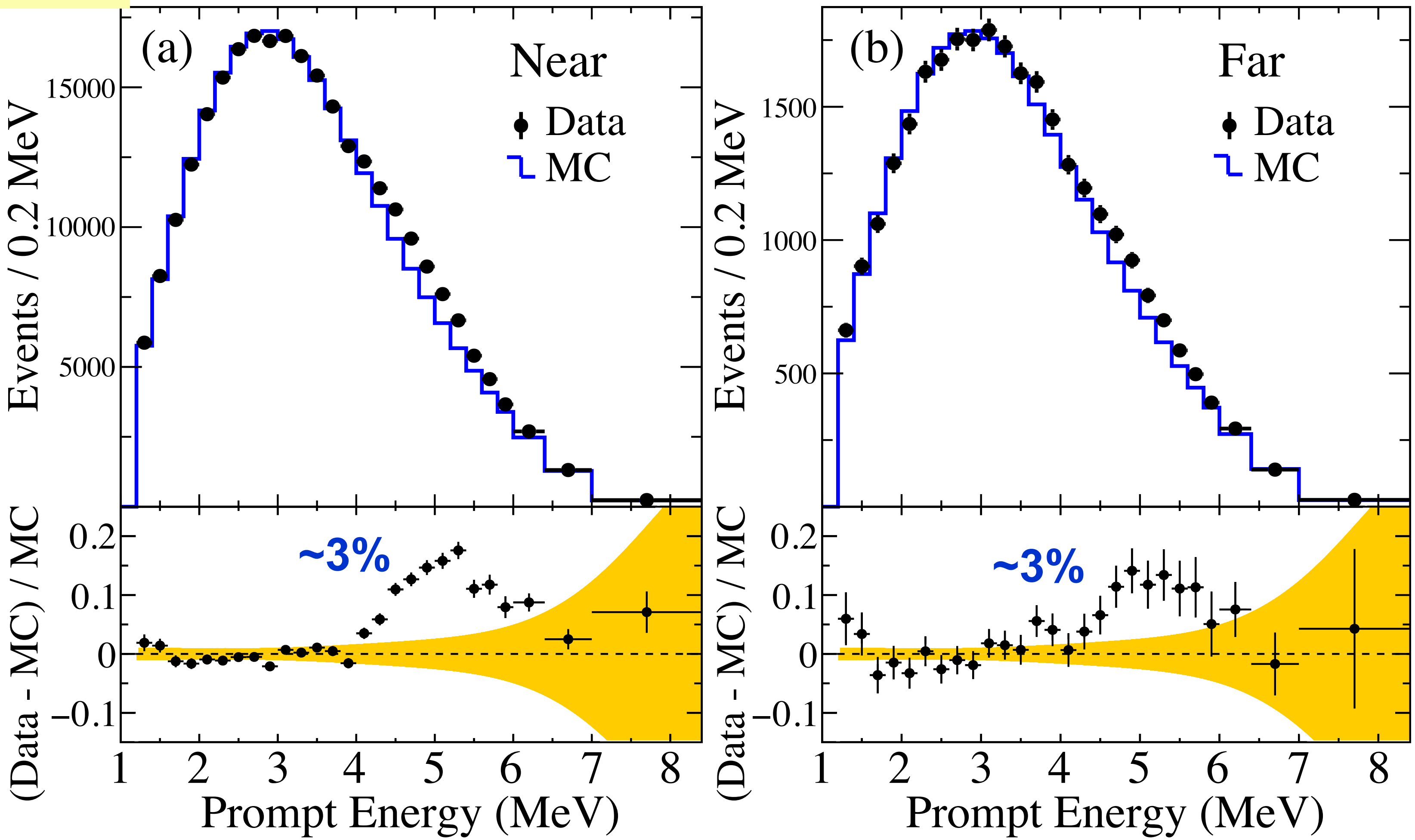
-- **DC**: 5 MeV excess (? σ)
correlation w/ reactor P_{th}.

-- **DB**: 5 MeV excess (? σ) → 4 σ in 2016

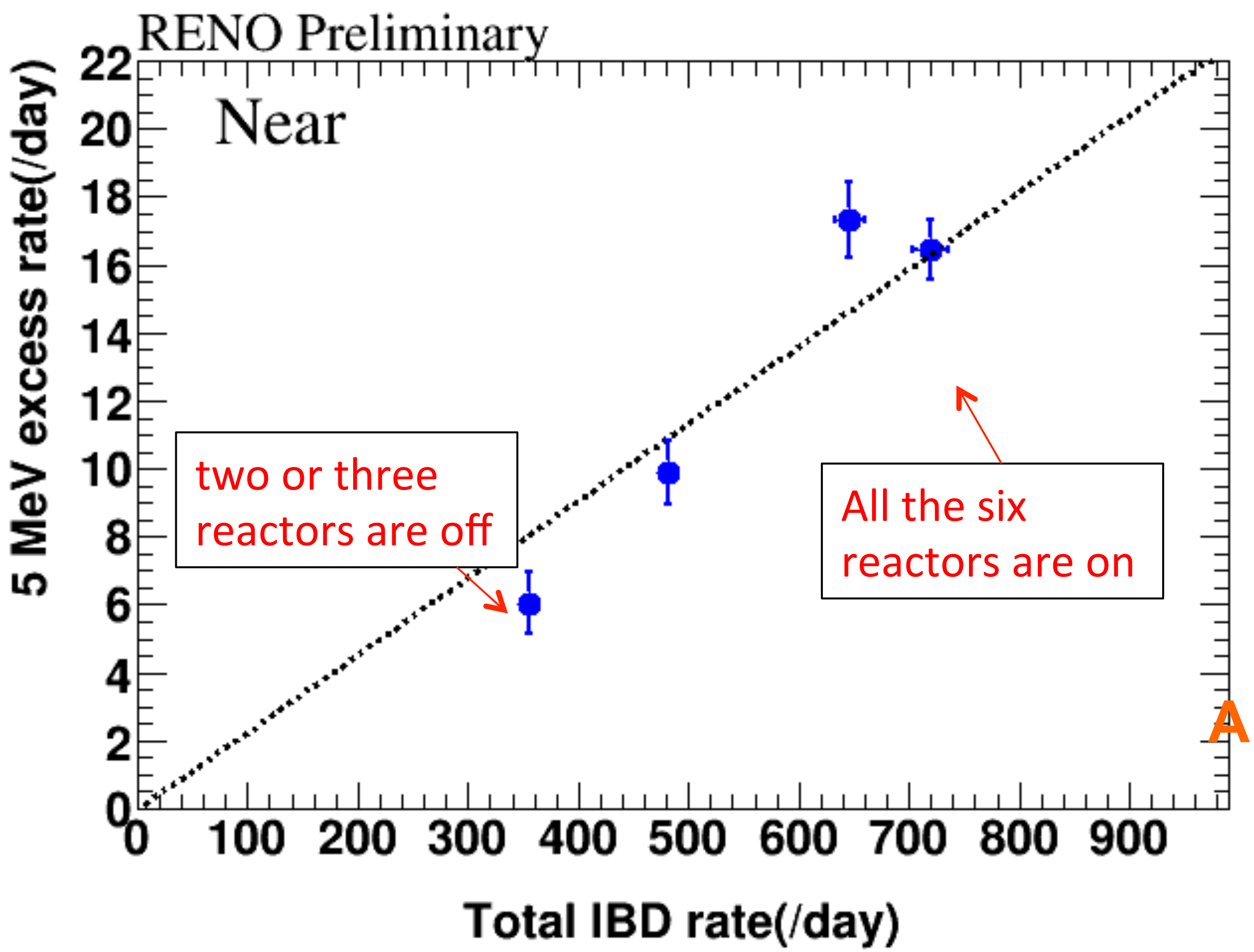
RENO: Excess at 5 MeV

RENO

arXiv:1511.05849.v2



Correlation of 5 MeV Excess with Reactor Power

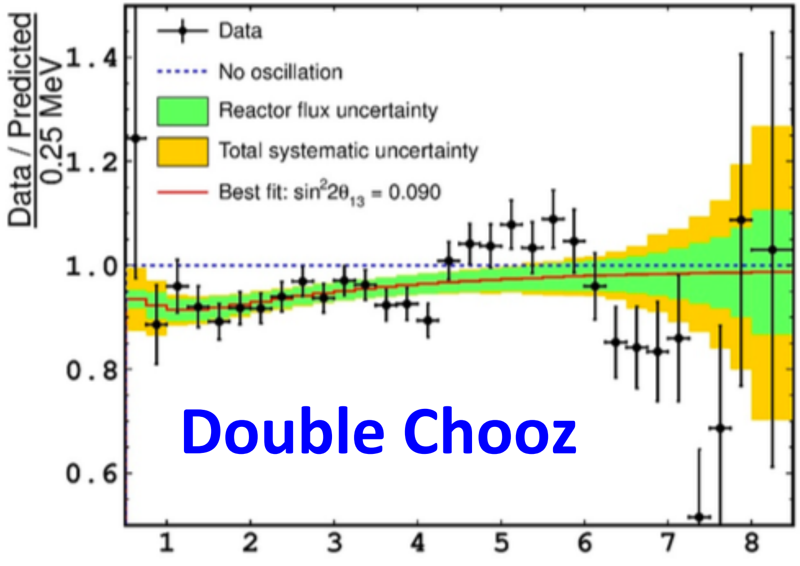


5 MeV excess has a clear correlation with reactor thermal power !

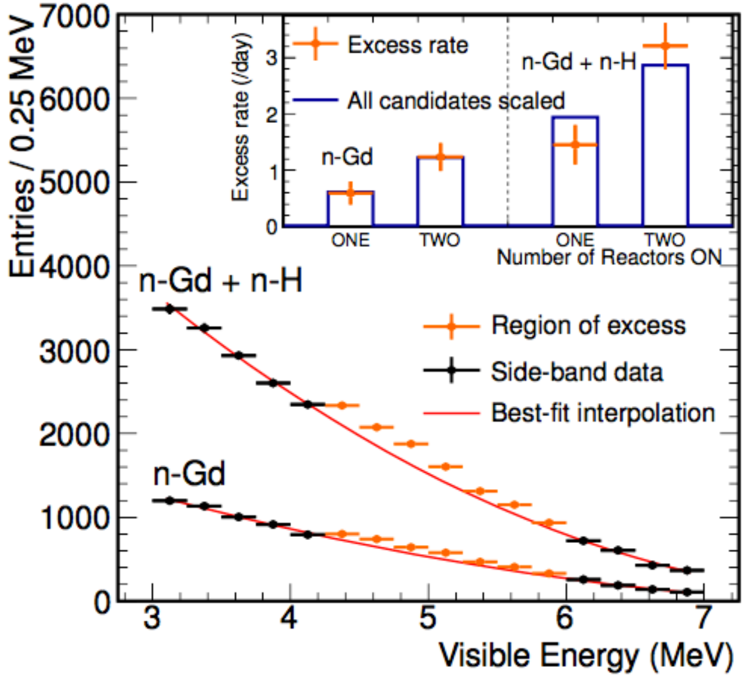
A new reactor neutrino component !!

** Recent ab initio calculation [D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)] :

- The excess may be explained by addition of eight isotopes, such as ^{96}Y and ^{92}Rb

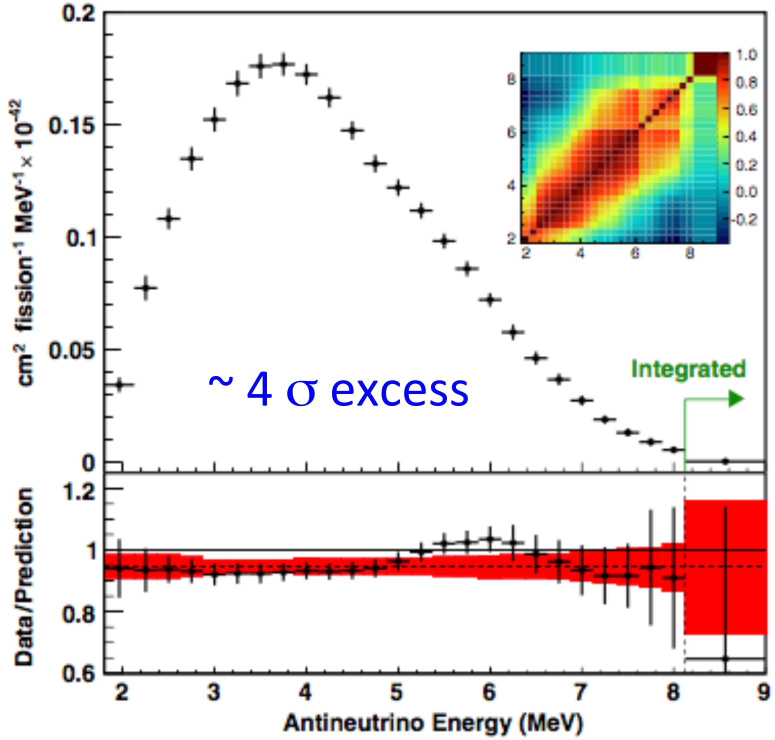


JHEP 10 (2014) 086



Daya Bay

PRL 116, 061801 (2016)



	$\delta\|\Delta m^2_{ee}\|$ ($\times 10^{-3}$ eV^2)	$\delta(\sin^2 2\theta_{13})$
Reactor	+0.018, −0.018	+0.0026, −0.0028
Detection efficiency	+0.020, −0.022	+0.0028, −0.0029
Energy scale	+0.081, −0.094	+0.0026, −0.0015
Backgrounds	+0.084, −0.106	+0.0030, −0.0028
Total	+0.115, −0.133	+0.0055, −0.0052