The International Neutrino Summer School

INSS2013

August 6-16, 2013, Beijing, China

Solar, Reactor and Atmospheric Neutrinos

Lecture 3

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Overall Outline

Lecture 1:

Δm_{23}^2 and θ_{23}:

Atmospheric neutrino experiments

Lecture 2:

Δm_{12}^2 and θ_{12}:

Solar neutrino and reactor experiments

Lecture 3:

θ_{13} and beyond:

Reactor and atmospheric neutrino exps

Outline – Lecture 3 -

- Introduction
- Neutrino oscillation experiments on θ_{13}
  - Status of θ_{13} before 2012
  - Reactor θ_{13} experiments
- Beyond θ_{13}
  - Future reactor experiments
  - Atmospheric ν experiments for MH
  - Future atmospheric neutrino experiments (MH)
  - Future atmospheric neutrino experiments(θ_{23} and CP)
- Summary

Introduction: 3 flavor oscillation

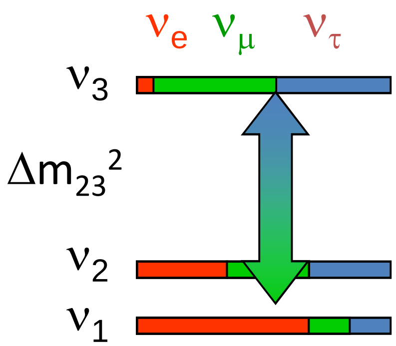
Most data are explained within the 3-flavor neutrino oscillation framework !

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Various experiments

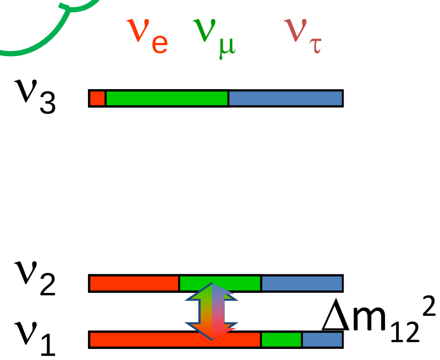
This lecture

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Atmospheric
LBL

Solar
KamLAND

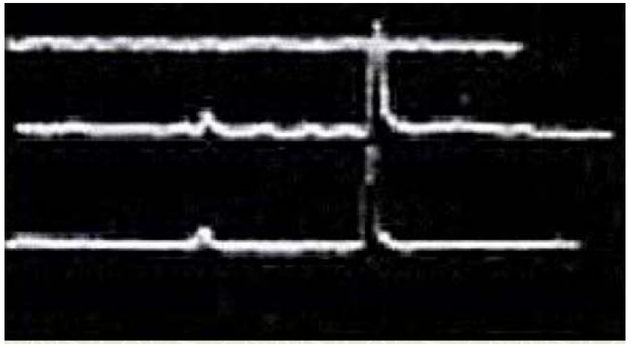


Introduction: neutrino discovery by reactor neutrino experiments

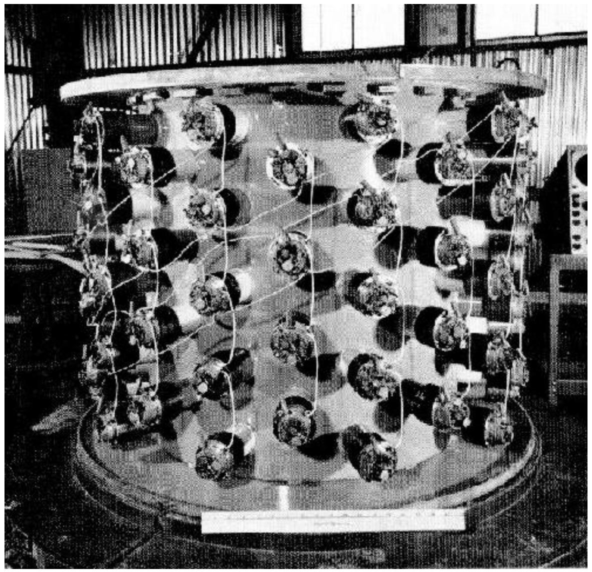
C. Cowan Jr.

F. Reines

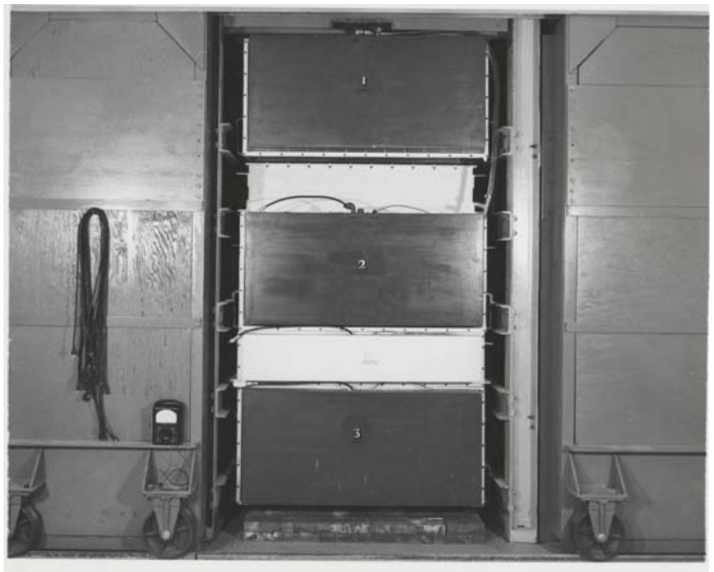
Reines & Cowan, Phys. Rev. 92, 830 (1953)
C. L. Cowan et al., Science 124, 103 (1956)
Also, H. Kruse, talk at neutrino 2006



Delayed coincidence!



@Hanford exp (1953)



@Savannah River (1956)

Neutrino oscillation experiments on θ_{13}

Searches for non-zero θ_{13}

acclerator experiments

- $\langle E_\nu \rangle$ ~ O(GeV) ➔ appearance experiments

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$

+ many terms (matter effect: important)

➔ Appearance measurement of θ_{13}.

➔ $P(\nu_\mu \rightarrow \nu_e) = F(\theta_{13}, \text{CP } \delta, \text{mass hierarchy}, \theta_{23})$

atmospheric ν experiments

- $\langle E_\nu \rangle$ ~ O(5-10 GeV) ➔ appearance experiments (matter resonance)

(These experiments are not discussed in detail in this lecture.)

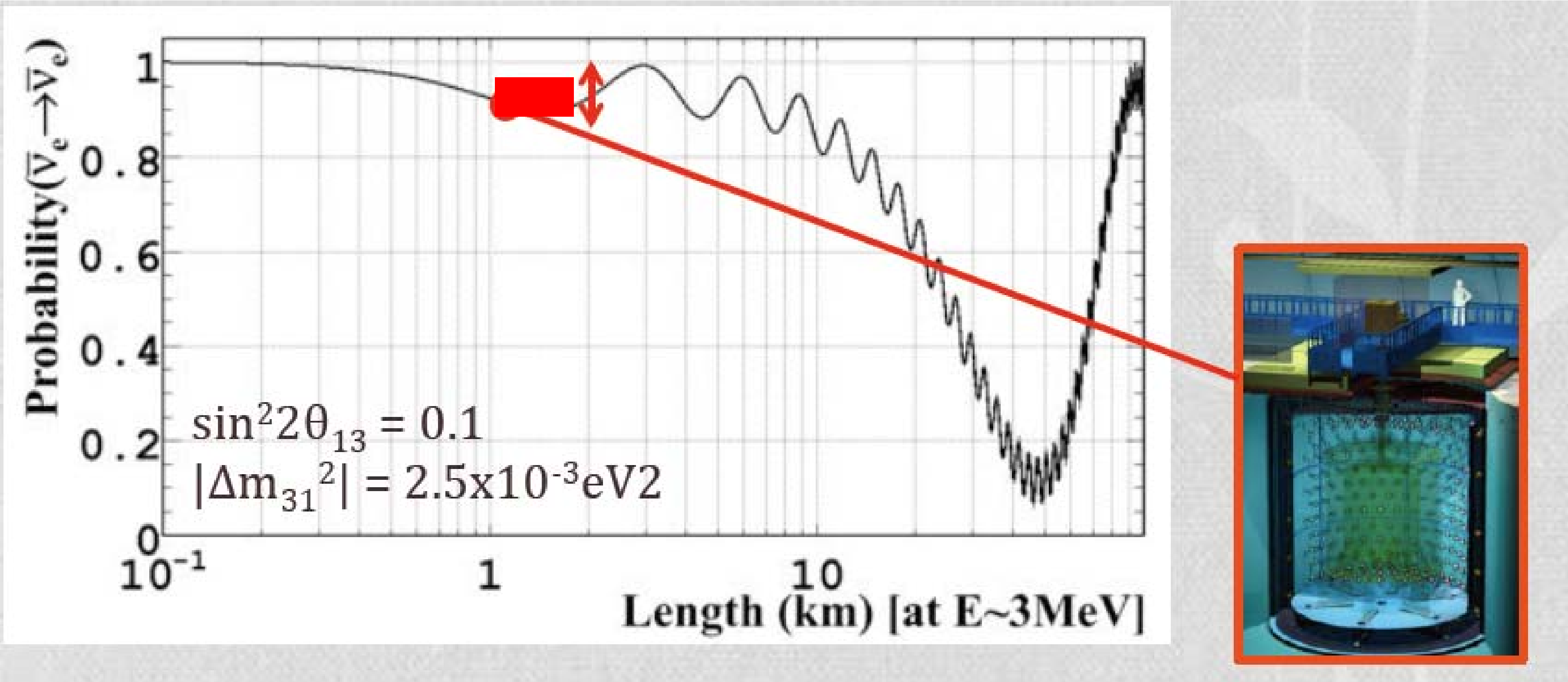
reactor experiments

Reactor θ_{13} experiments

- <E_ν> ~ a few MeV ➔ only disappearance experiments

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$ + (small solar effect)

➔ Almost pure measurement of θ_{13} with negligible matter effect.



Status of θ_{13}: before 2012

Reactor neutrinos

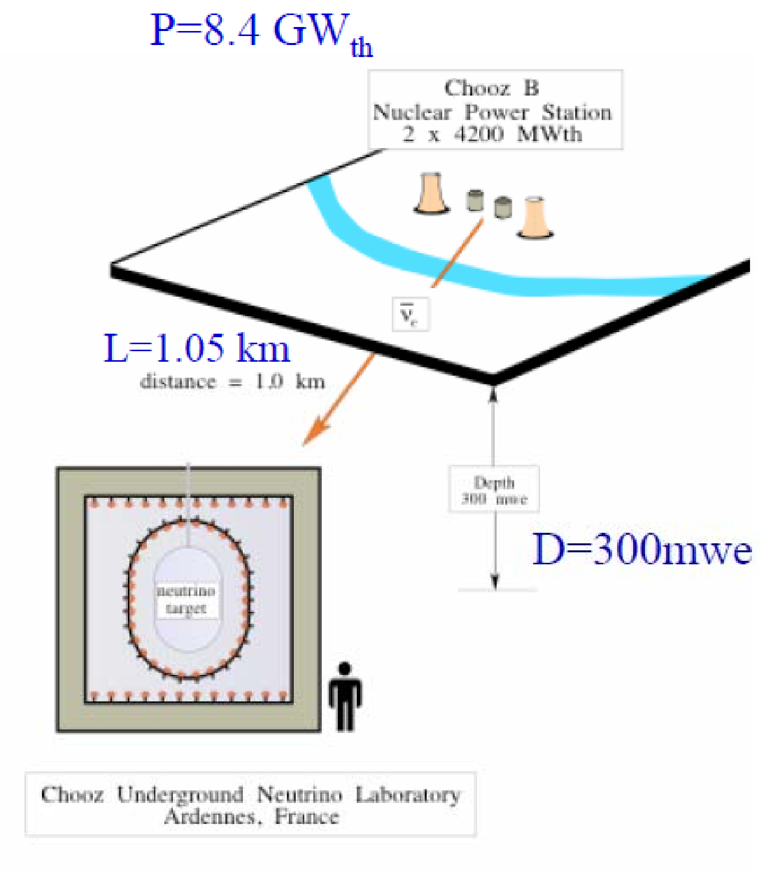
Solar neutrinos

Long baseline Experiments

Most sensitive experiment before 2011: CHOOZ

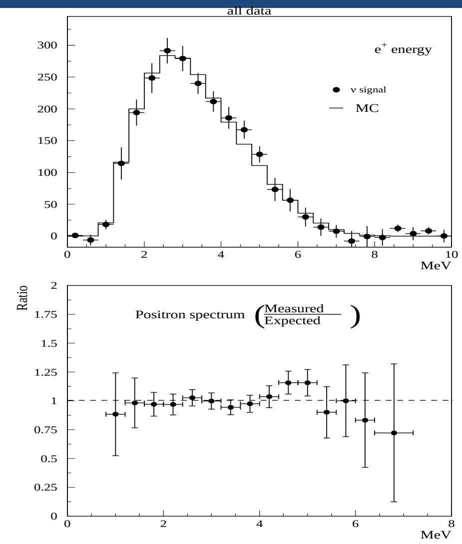
hep-ex/9907037
hep-ex/0301017

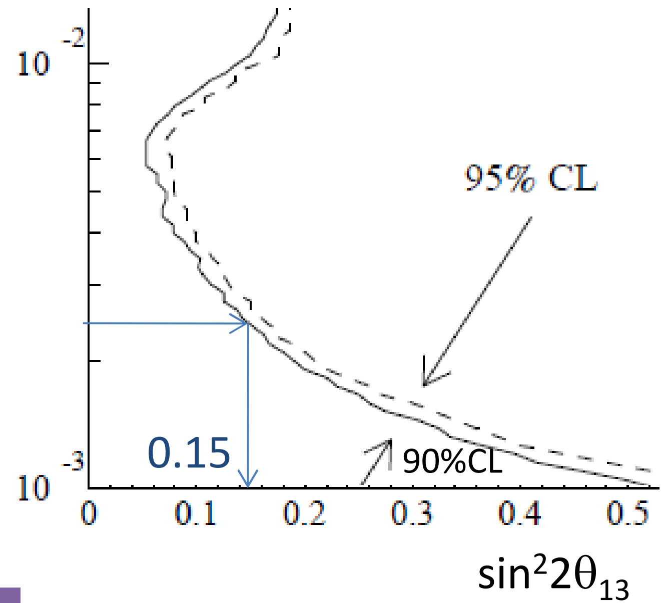
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right)$$



m = 5 tons, Gd-loaded liquid scintillator

Data/Expectation = 1.01±0.028(stat)±0.027(syst)



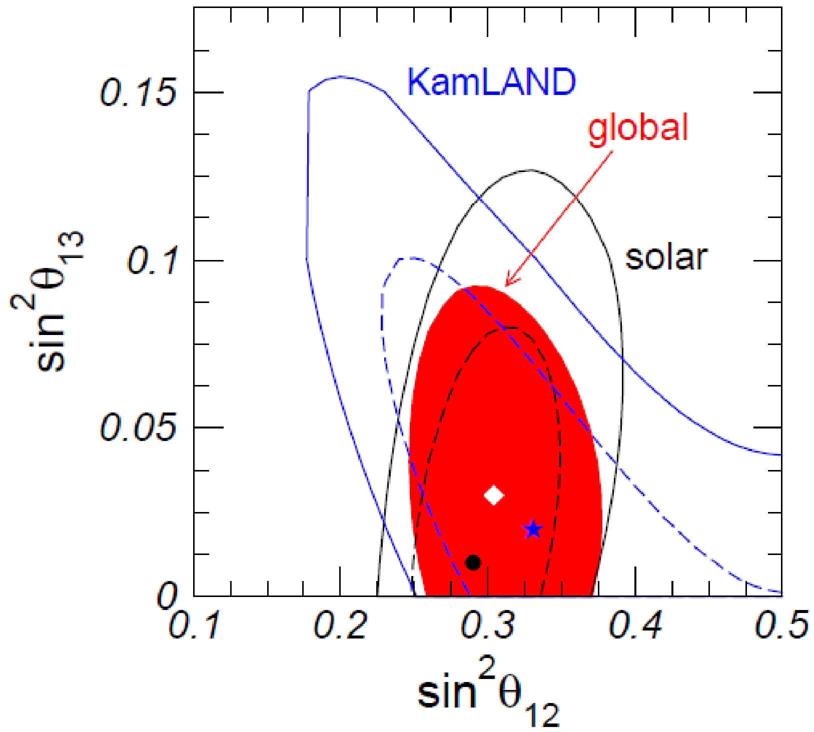


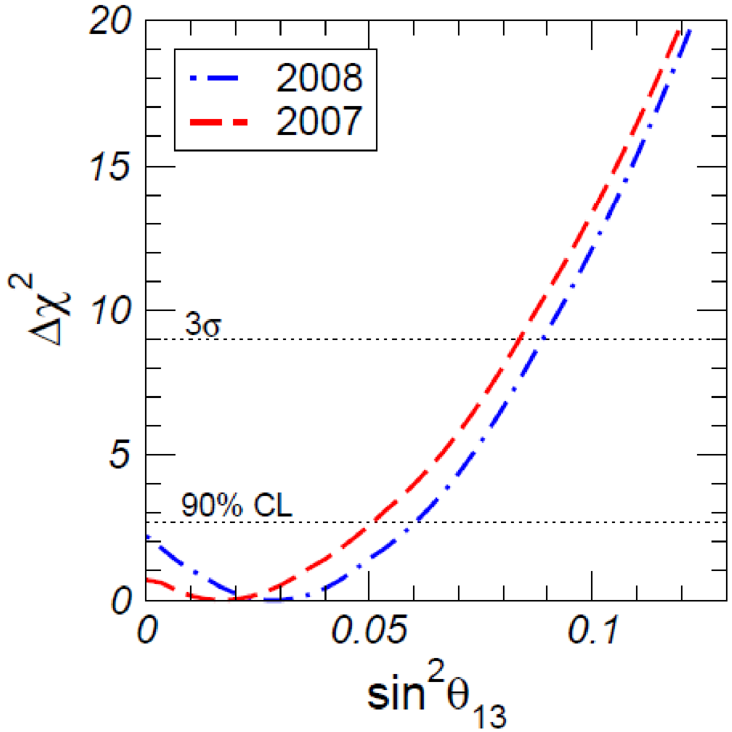
Some hints before 2012: solar + KamLAND

$$P(\nu_e \to \nu_e)[SNO] = \frac{CC}{NC} \approx \cos^4\theta_{13} \cdot \sin^2\theta_{12}$$ $\cdots\cdots \theta_{13} \nearrow \;\to \sin^2\theta_{12} \nearrow$ for SNO

$$P(\nu_e \to \nu_e)[KL] \approx \cos^4\theta_{13} \cdot \left(1 - \sin^2 2\theta_{12} \cdot \sin^2(f[\Delta m^2_{12}])\right)$$ $\cdots \theta_{13} \nearrow \;\to \sin^2\theta_{12} \searrow$ for KL

T.Schwets, M. Tortola, J.W.F.Valle arXiv: 0808.2016v3 (Feb.2010)
and several more references



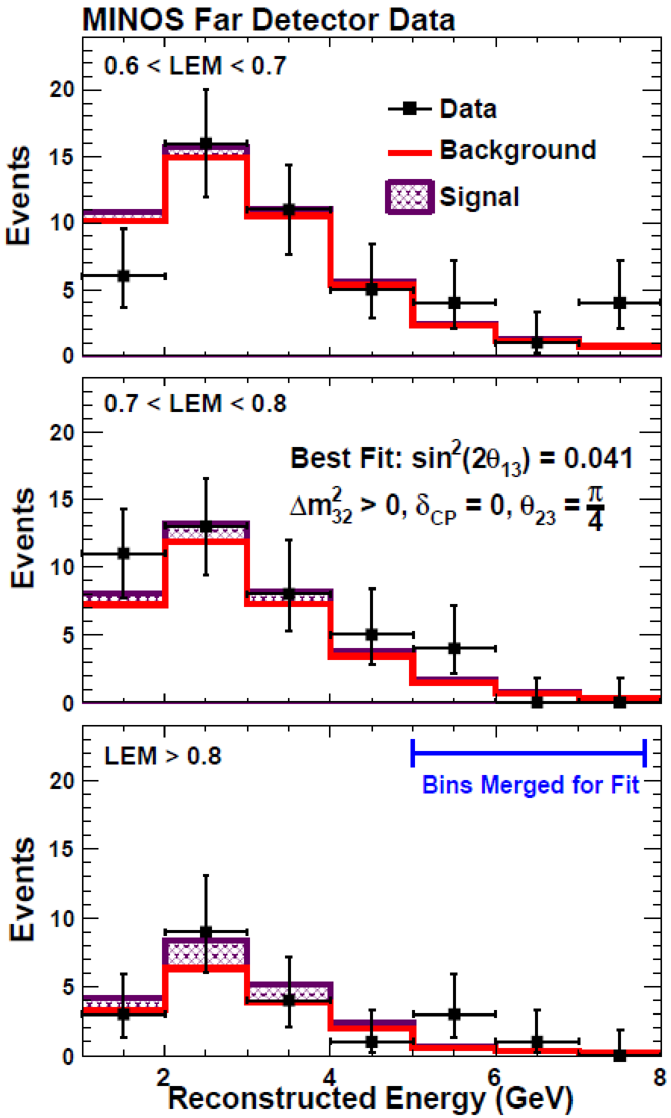


Small tension in $\sin^2\theta_{12}$ with θ_{13}=0. The tension disappears if $\sin^2\theta_{13}$~0.025.

MINOS

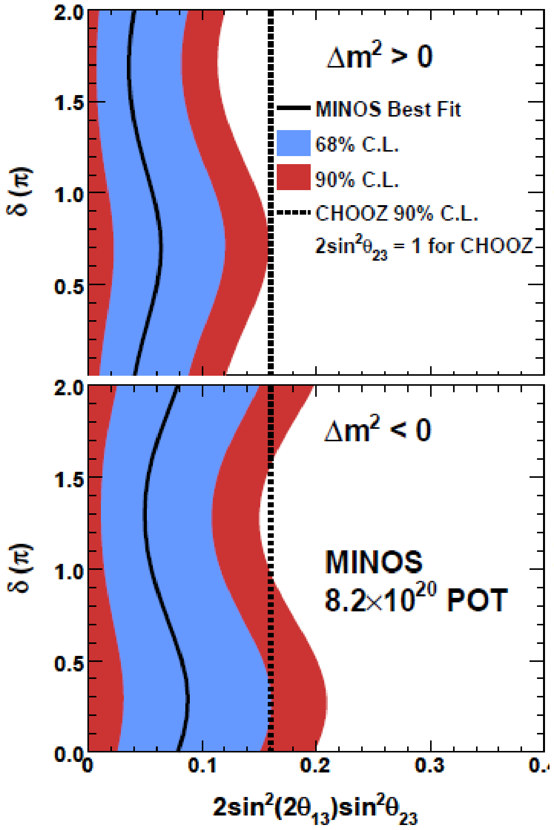
MINOS PRL 107, 181802 (2011)

R. Nichol (MINOS) nu2012



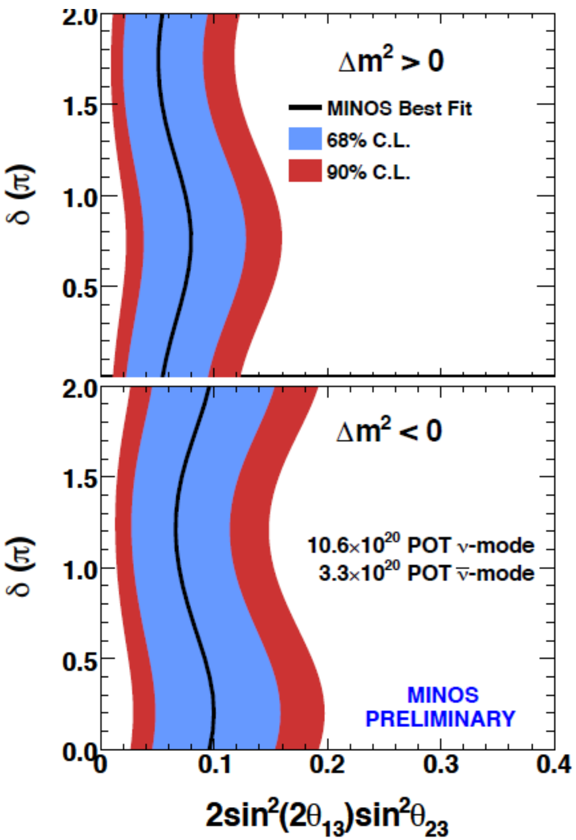
Better match to ν_e

2011



θ_{13}=0 disfavored at 89%CL (2011)

(2012)

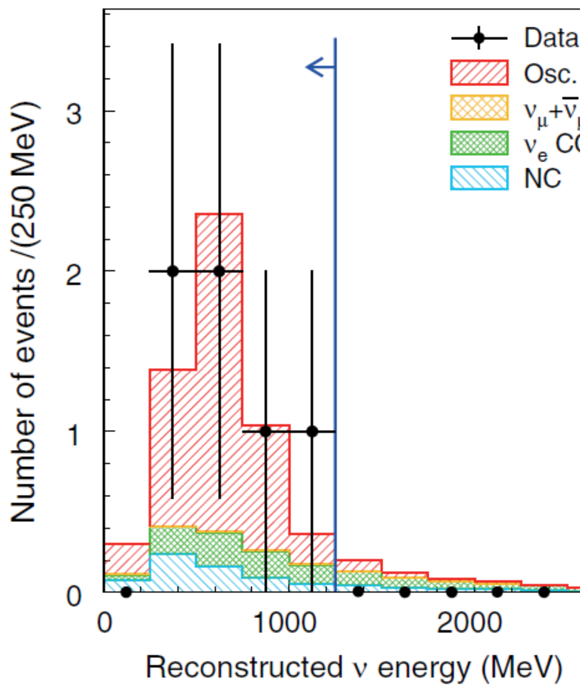


θ_{13}=0 disfavored at 96%CL (2012)

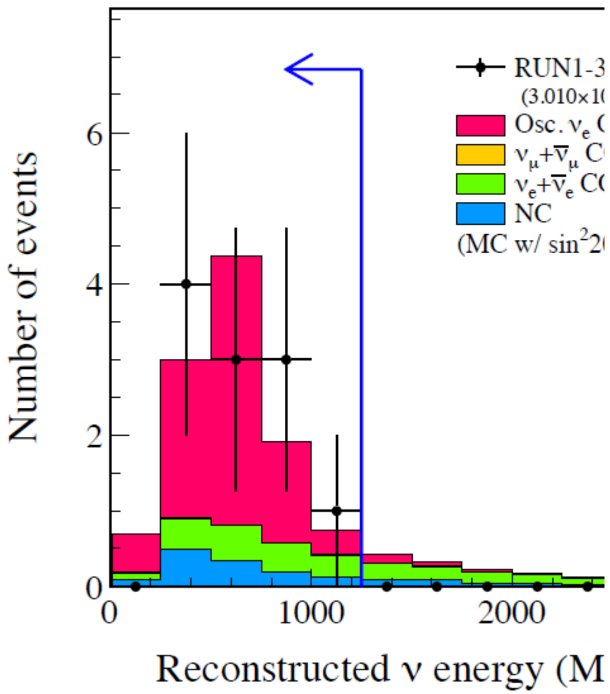
T2K

ν_e appearance search

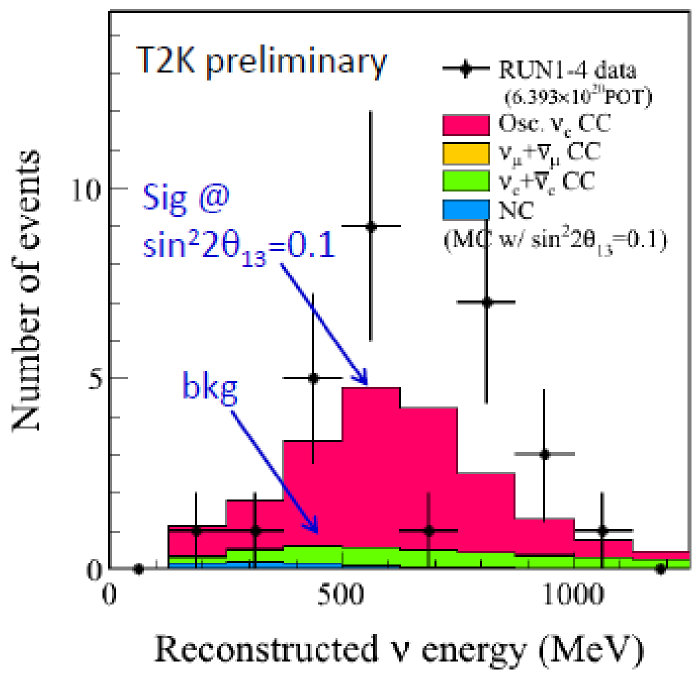
2011 T2K PRL 107, 041801 (2011)



(2012) T2K nu2012, arXiv: 1304.0841



(2013) T2K EPS2013



2011	2012	2013
Obs'd: 6	Obs'd: 11	Obs'd: 28
BG: 1.5±0.3(syst)	BG: 3.3±0.4(syst)	BG: 4.64±0.51(syst)
(2.5σ excess)	(3.1σ excess)	(7.5σ excess)

(Paul Soler's lecture)

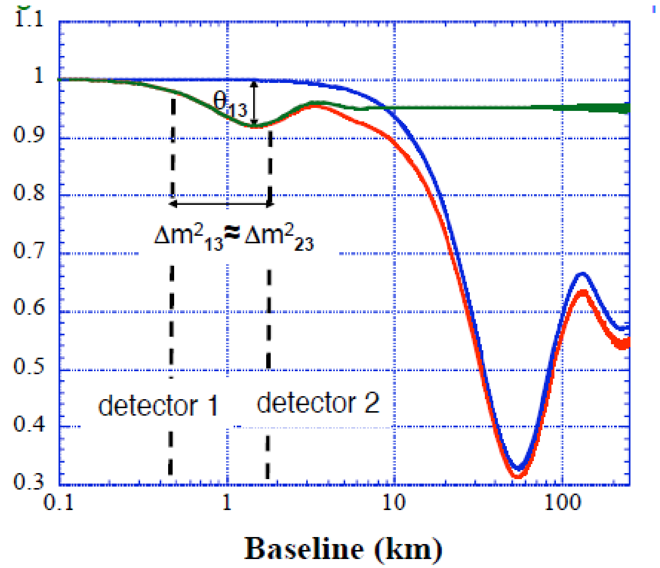
Reactor θ_{13} experiments

Reaching $\delta(\sin^2 2\theta_{13}) \sim 0.01$ in a reactor exp.

CHOOZ: Data/Expectation = 1.01±0.028(stat)±0.027(syst)

Increasing statistics:

- larger detector
- Longer run time
- Powerful reactor

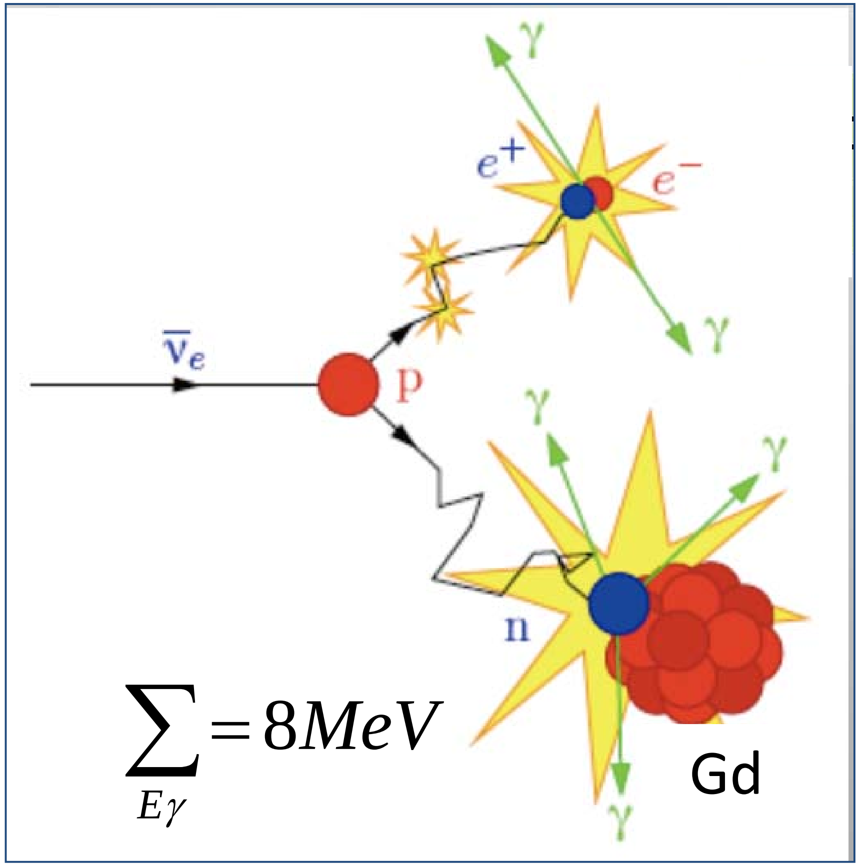


Reducing systematic errors:

- Near and far detectors to minimize the normalization errors
- Near and far detector should be identical
- Optimized baseline for best sensitivity
- Deep enough to reduce the cosmic-ray induced backgrounds
- Enough shielding, clean scintillator
- Good (inter) calibration and monitoring

Detecting reactor neutrinos in reactor θ_{13} experiments

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



Neutron capture time ~ 30μsec for typical θ_{13} experiments

Neutrino capture on Gd have advantages (compared with that on hydrogen):

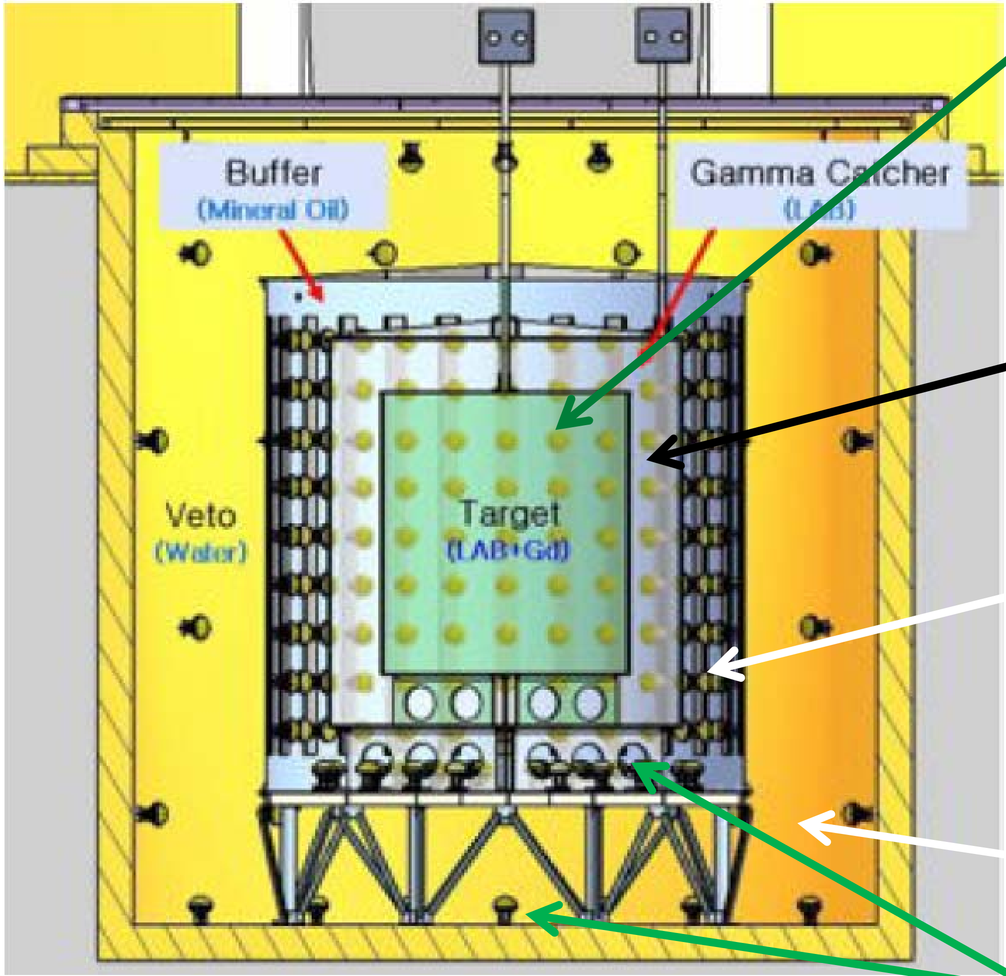
✓Higher total gamma ray energy (8 MeV vs. 2.2 MeV)

✓Shorter neutron capture time (~30 μsec vs. ~200 μsec)

➔Better signal to noise ratio

Detector design

Example: RENO (Other experiments have the similar designs)



ν-target: Volume for ν-interaction
0.1% Gd loaded liquid scintillator (to detect neutrons)

γ-catcher: Extra-volume with pure liquid scintillator

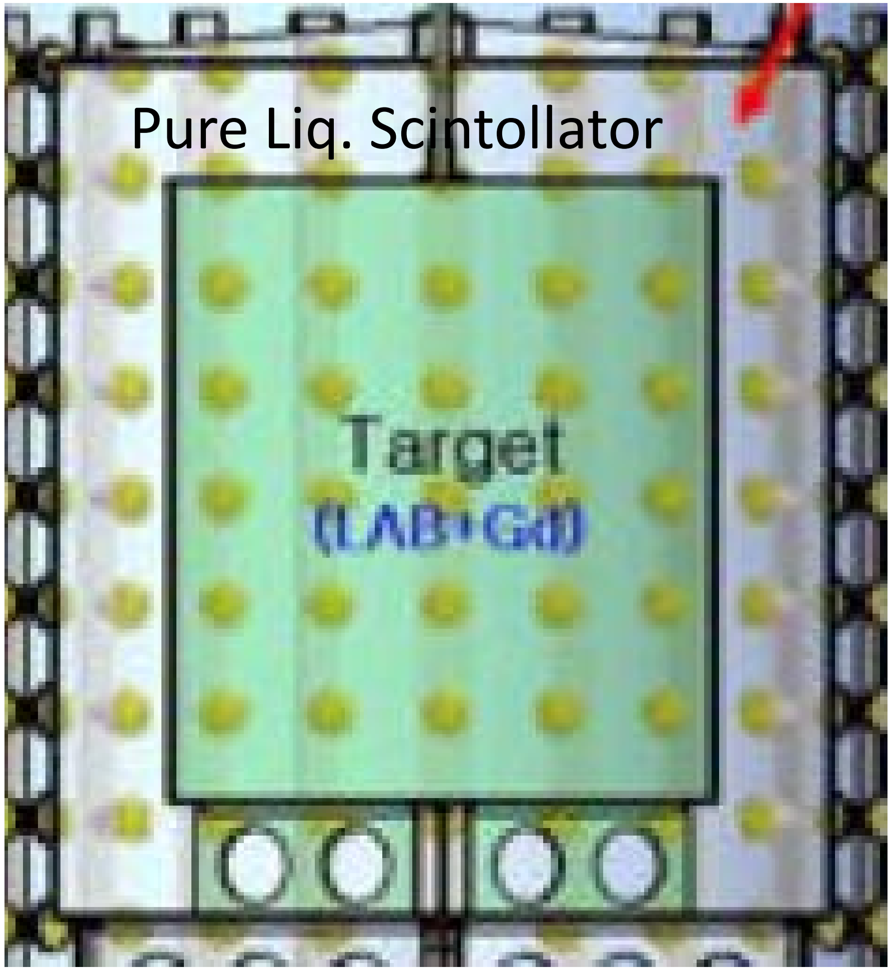
Non-scintillating buffer: Mineral Oil to Isolate PMTs from target area

Veto region (water)

PMTs

Detector design

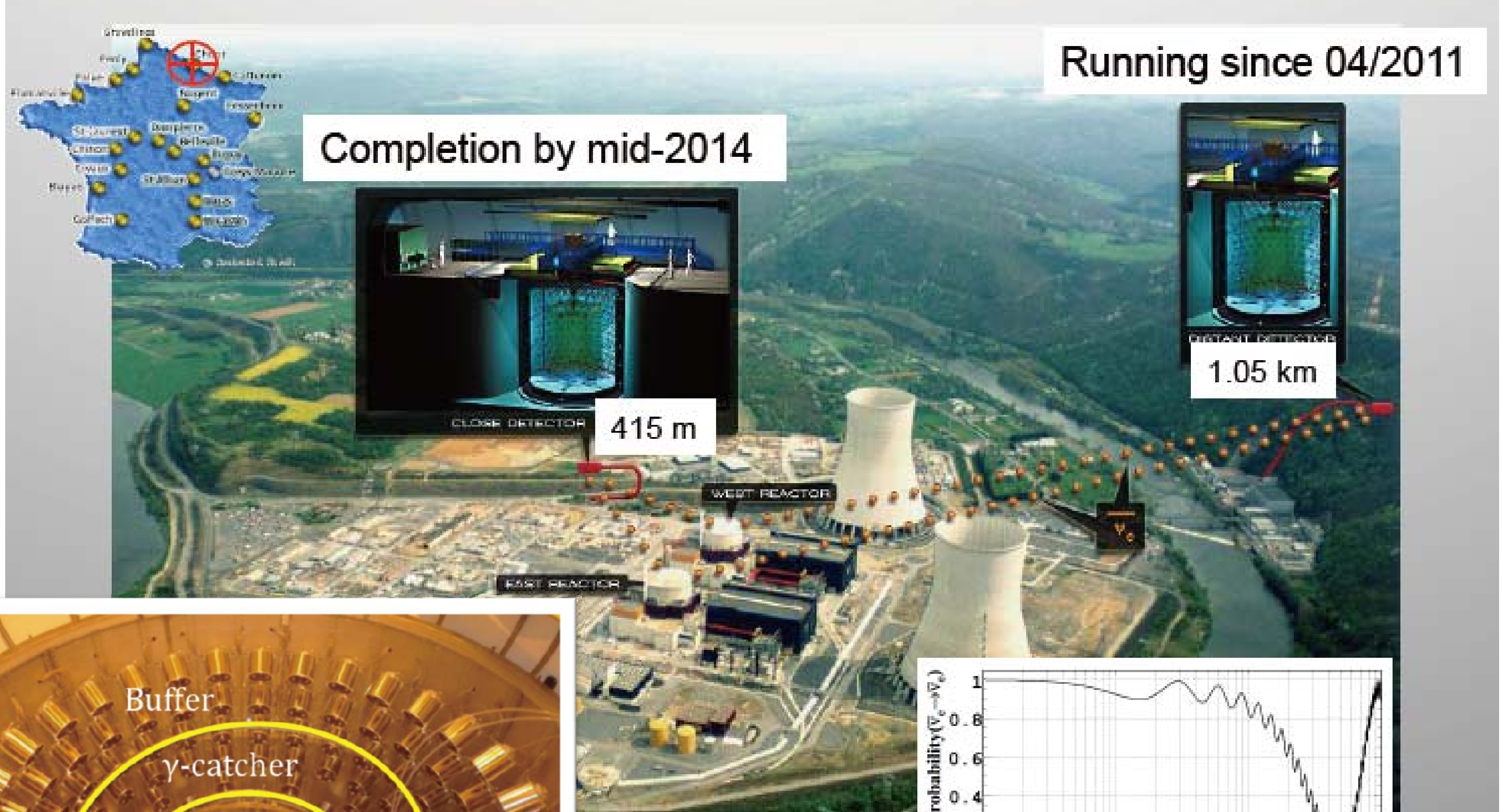
Example: RENO (Other experiments have the similar designs)

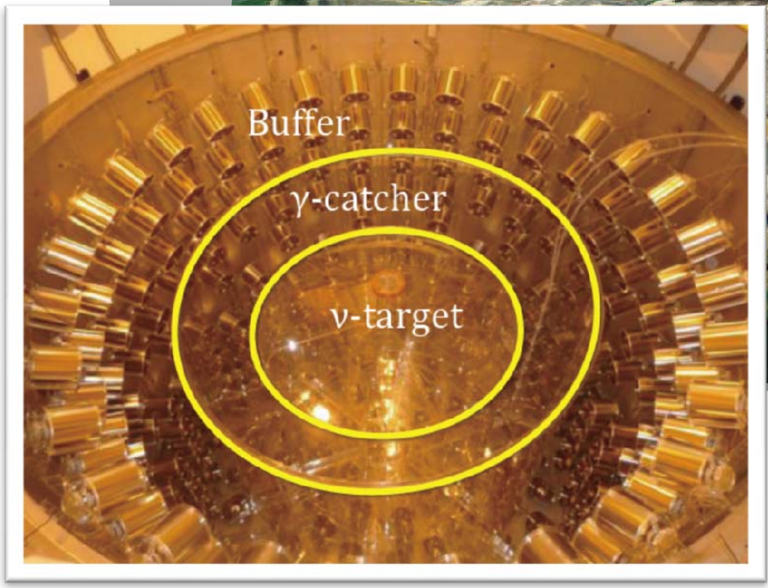


➔The 2 layer configuration (Gd loaded Liq. Scintillator + pure Liq. Scintillator) is very important for the software (vertex position reconstruction) independent determination of the fiducial volume.

➔8MeV neutron capture signals indicate the fiducial volume whose mass is measured very precisely.

Reactor θ_{13} experiment: Double CHOOZ





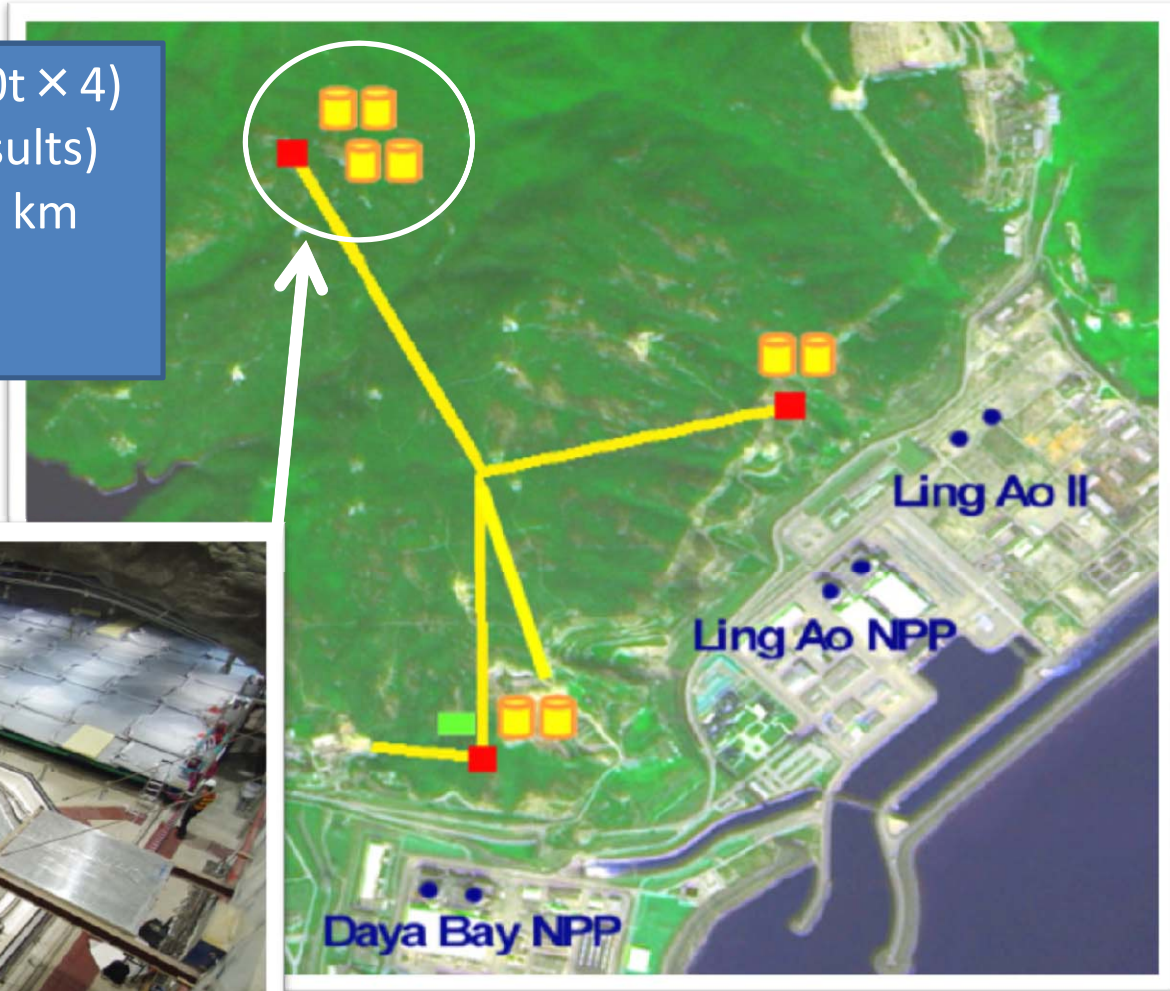
Far detector mass = 10 tons
Baseline length (far) = 1.05 km
Overburden = 300 m.w.e.
Power = 8.5 GW

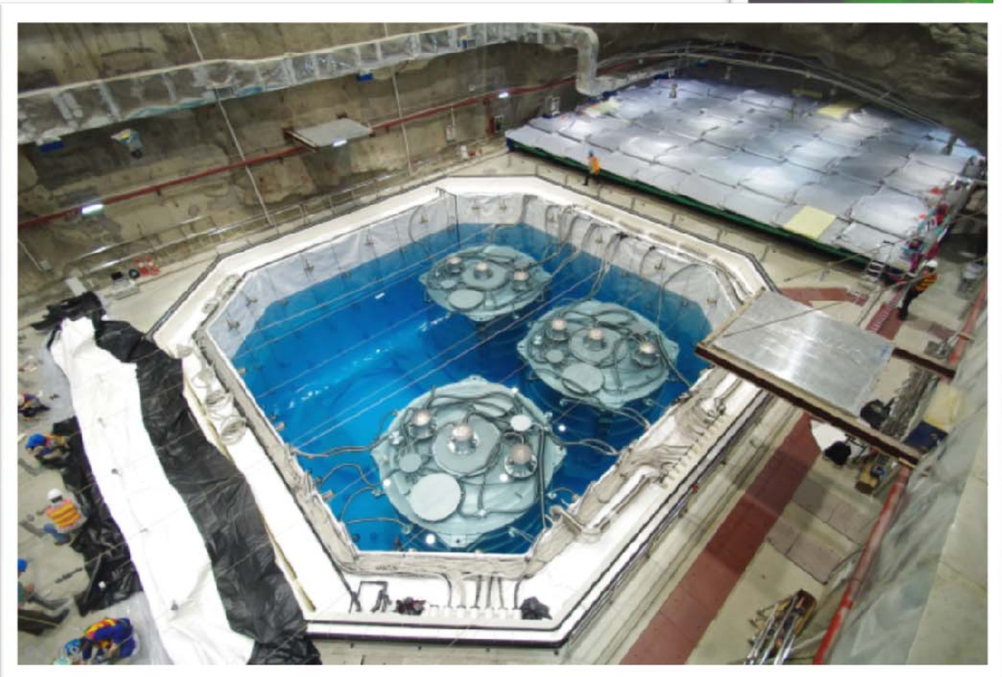
Reactor θ_{13} experiments: RENO

Far detector mass = 16.5 tons
Baseline length (far) = 1.38 km
Overburden = 440 m.w.e.
Power = 17GW

Reactor θ_{13} experiments: Daya Bay

Far detector mass = 80 tons (20t × 4)
(60 tons for initial results)
Baseline length (far) = 1.55, 1.9 km
Overburden = 860 m w.e.
Power = 17.4 GW





Full detector (8 detectors) operation started in Oct. 2012.

Reactor θ_{13} experiments: comparison

Y. Wang, EPS 2013

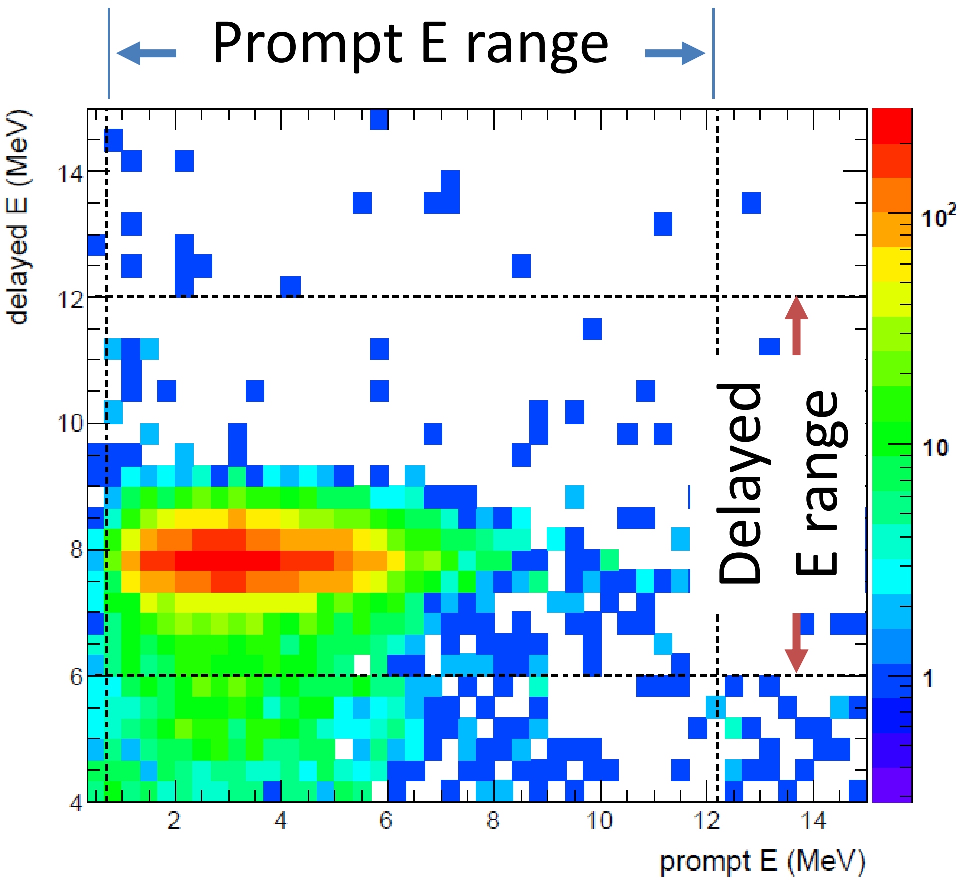
Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

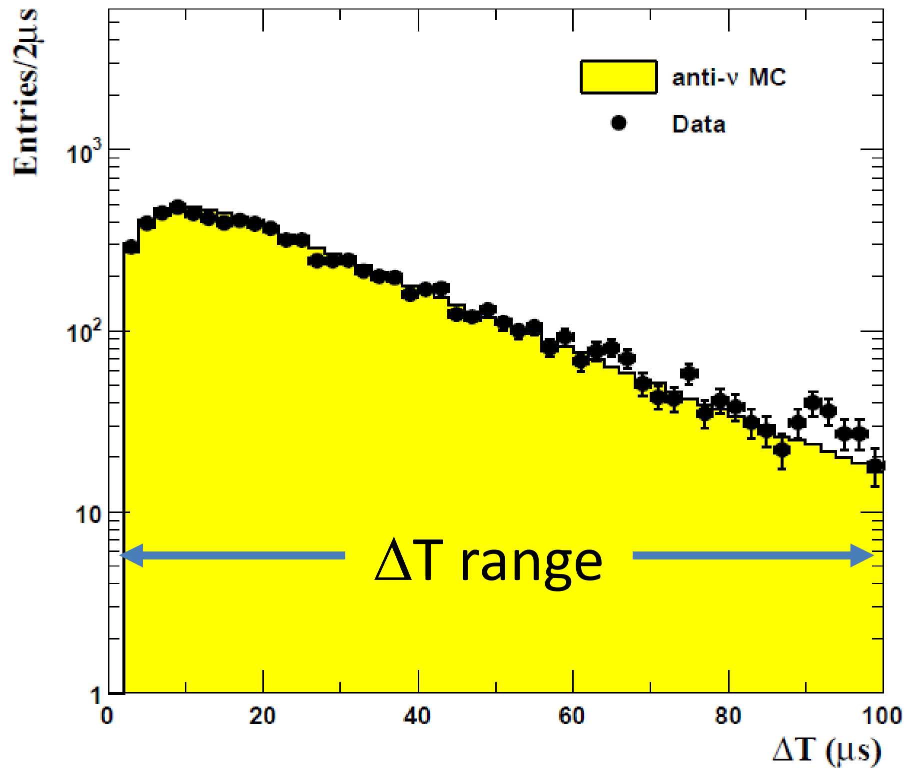
✓For Double Chooz, the near detector still to be installed in 2014
✓For Daya Bay, results for far presented are based on 6 (out of 8) detector configurations.

Some distributions

Double Chooz arXiv: 1207.6632

Double Chooz





Importance of near and far detectors

Daya Bay

Tables from Daya Bay arXiv: 1210.6327

Correlated and uncorrelated syst. errors among the reactors

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Reactor-to –reactor uncorrelated uncertainty.
➔ After taking far/near ratio, the final uncertainty in the far/near is 0.04%.

Correlated and uncorrelated syst. errors among the detectors

	Efficiency	Correlated	Uncorrelated
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture fraction	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

If w/o near detector, the systematic error to the far detector event rate relative to the no-osci. prediction: ~sqrt($3\%^2+0.8\%^2+1.9\%^2+\Delta(BG)^2$) **~3.6%** ($\Delta$BG neglected)

If with near detector; ~sqrt($0.04\%^2+0.2\%^2+\Delta(BG)^2$) **~0.2%** ($\Delta$BG neglected)

Importance of BG understanding and depth

Daya Bay arXiv: 1210.6327

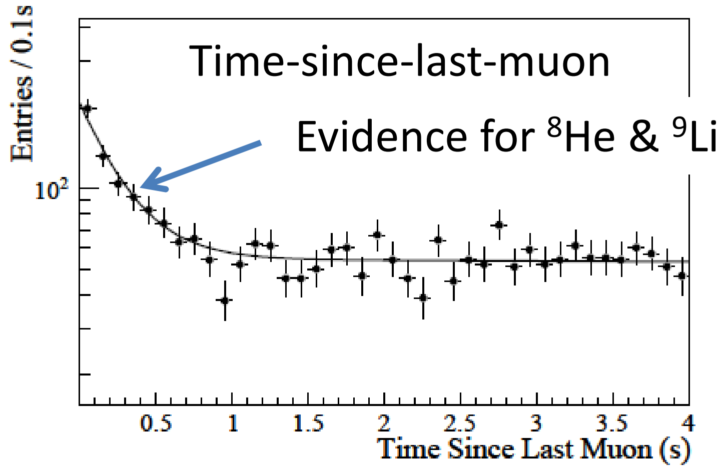
Daya Bay

Daya Bay	*Near detectors* (250mwe)		(265mwe)	*Far detectors* (860mwe)		
	AD1	AD2	AD3	AD4	AD5	AD6
signal: IBD candidates	69121	69714	66473	9788	9669	9452
Expected IBDs	68613	69595	66402	9922.9	9940.2	9837.7
DAQ livetime (days)	127.5470		127.3763	126.2646		
ϵ_μ	0.8231	0.8198	0.8576	0.9813	0.9813	0.9810
$\bar{\epsilon}_m$	0.9738	0.9742	0.9753	0.9737	0.9734	0.9732
BG: Accidentals (per day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05 ±0.04	3.04 ± 0.04	2.93 ±0.03
Fast-neutron (per day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{9}Li/^{8}He (per AD per day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C correlated (per AD per day)	0.2±0.2					
(α, n) background (per day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (per day)	662.47±3.00	670.87±3.01	613.53±2.69	77.57±0.85	76.62±0.85	74.97±0.84

$$\mu + {}^{12}C \rightarrow \mu + X$$

$$^{8}He \rightarrow {}^{7}Li + e^{-} + \bar{\nu}_e + n$$

$$^{9}Li \rightarrow {}^{8}Be + e^{-} + \bar{\nu}_e + n$$

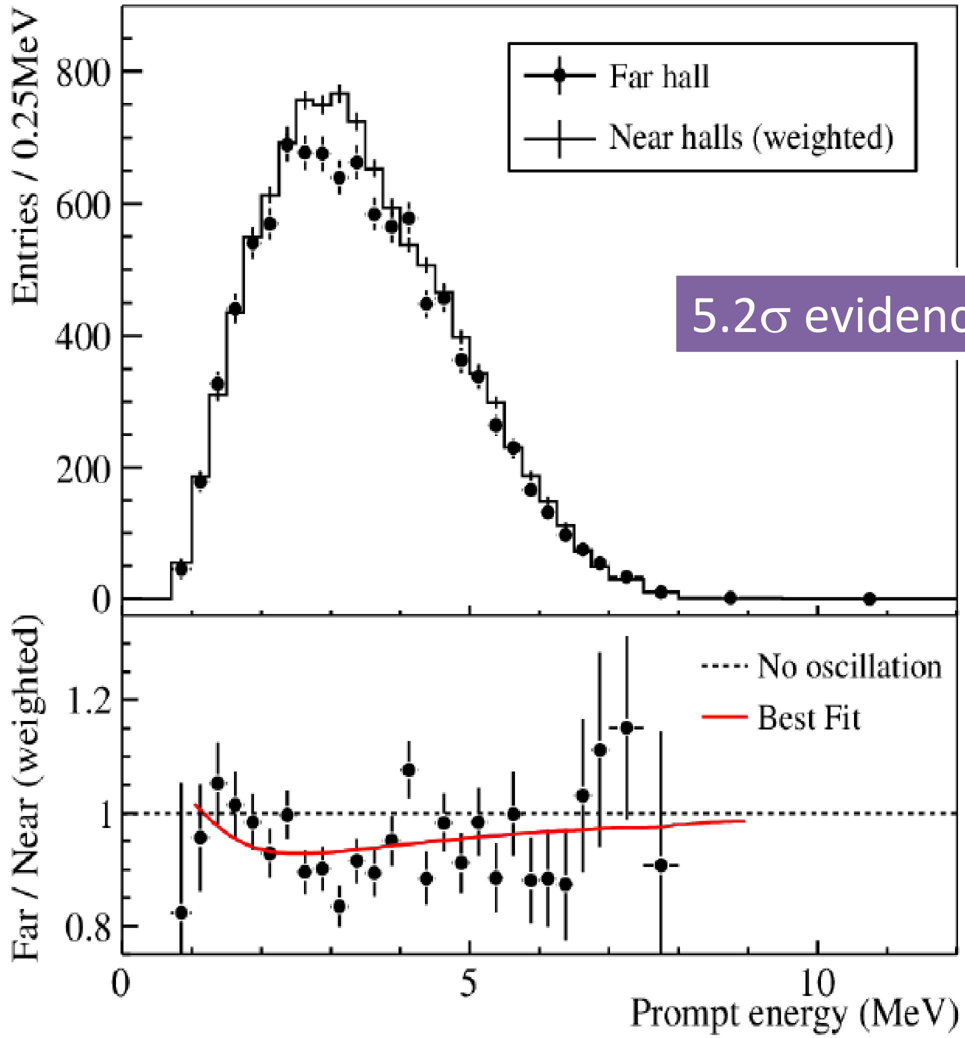


Reactor θ_{13} experiments: Results

Example: Daya Bay

Daya Bay: arXiv: 1203.1669

March 2012



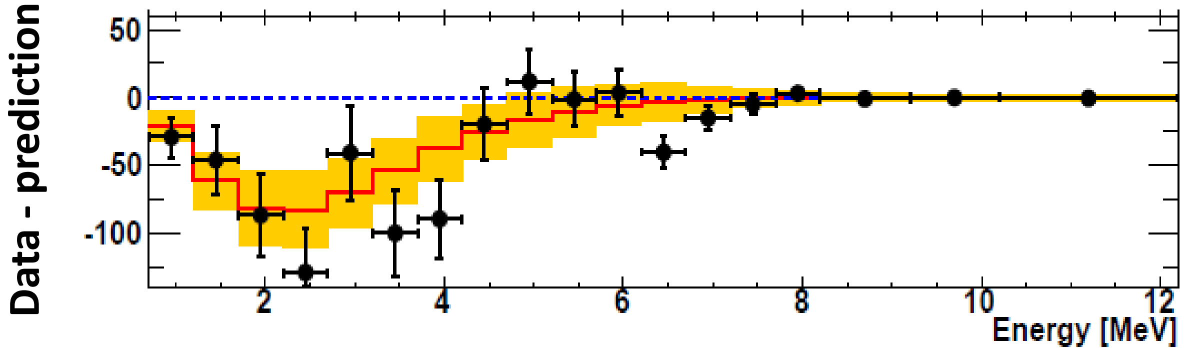
5.2σ evidence

Within a month, RENO also published their first results.

Reactor θ_{13} experiments: Results @nu2012

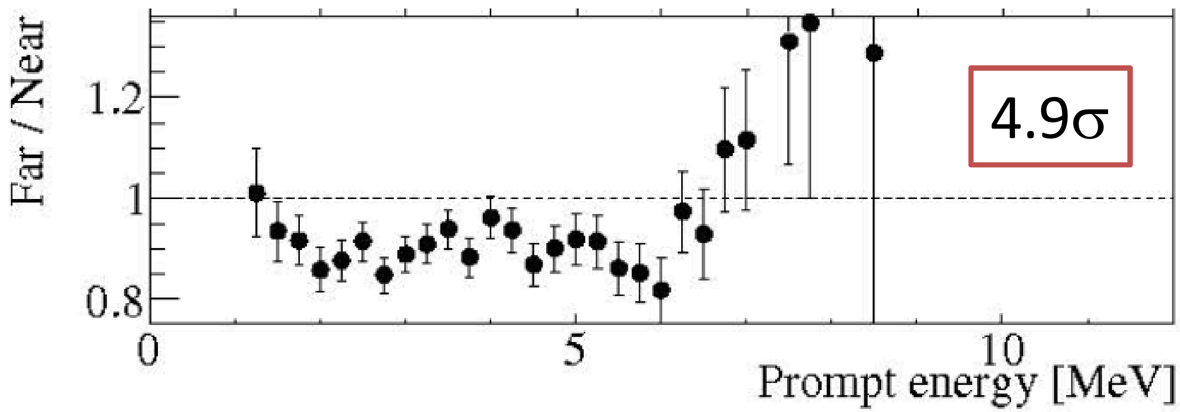
Double CHOOZ

M. Ishitsuka (DC) nu2012
arXiv: 1207.6632



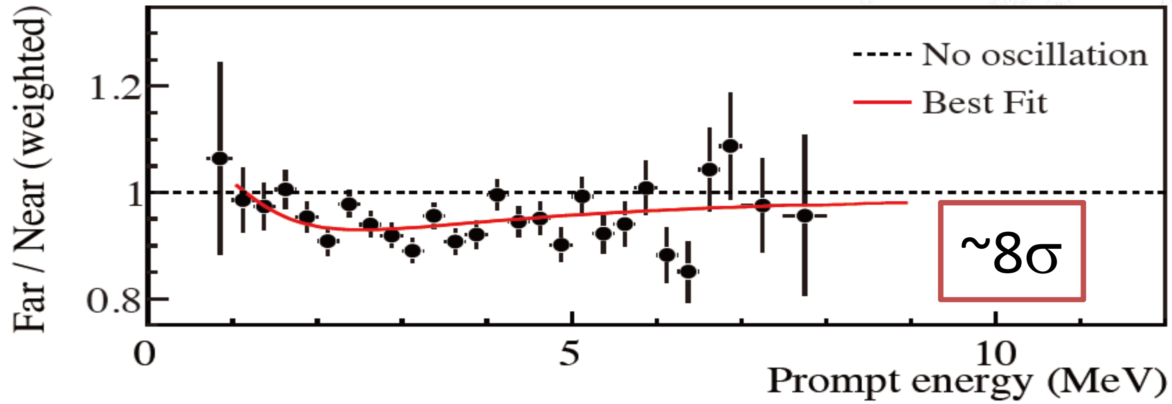
RENO

M.B.Kim (RENO) nu2012
arXiv: 1204.0626



Daya Bay

D. Dwyer (DB) nu2012
arXiv: 1203.1669



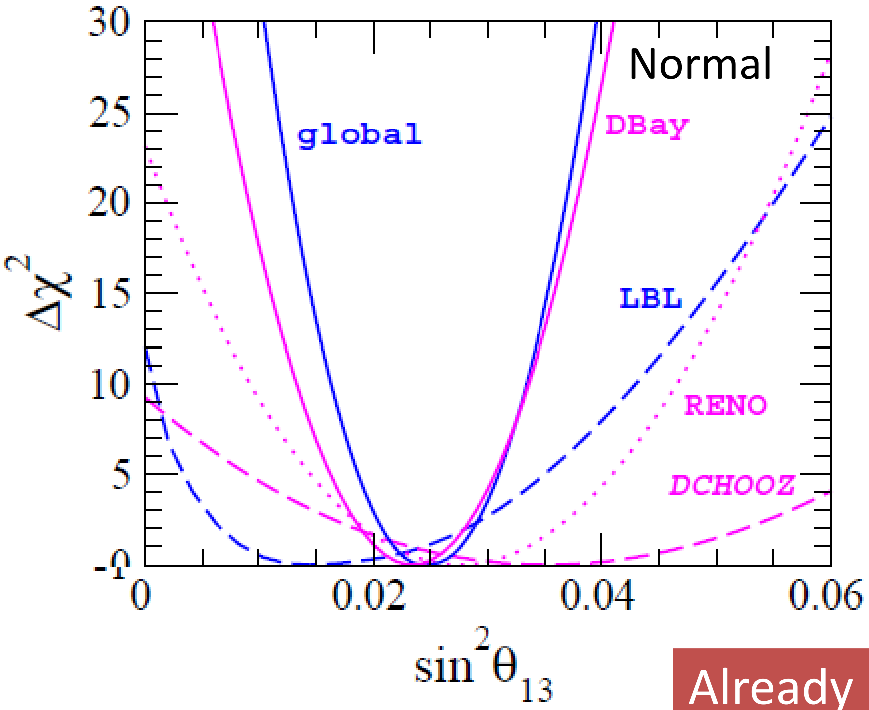
(Updated/new analyses from DC and DB are available.)

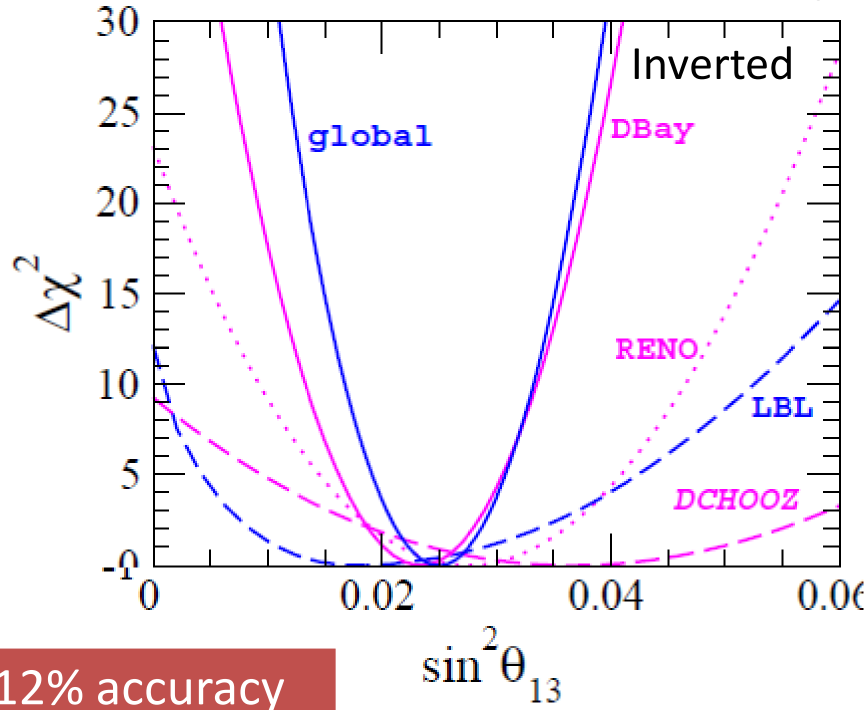
Reactor θ_{13} experiments: θ_{13} value

	$\sin^2 2\theta_{13}$
Double CHOOZ	0.109±0.030(stat)±0.025(syst)
RENO	0.113±0.013(stat)±0.019(syst)
Daya Bay	0.089±0.010(stat)±0.005(syst)

✓In good agreement!
✓Also in good agreement with T2K and MINOS

Forero, Tortola, Valle arXiv: 1205.4018 (Aug.2012)

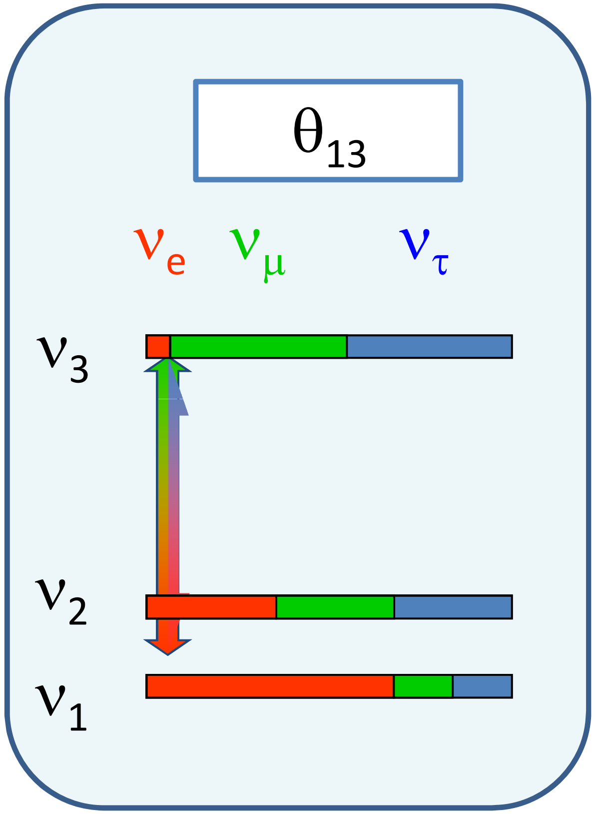




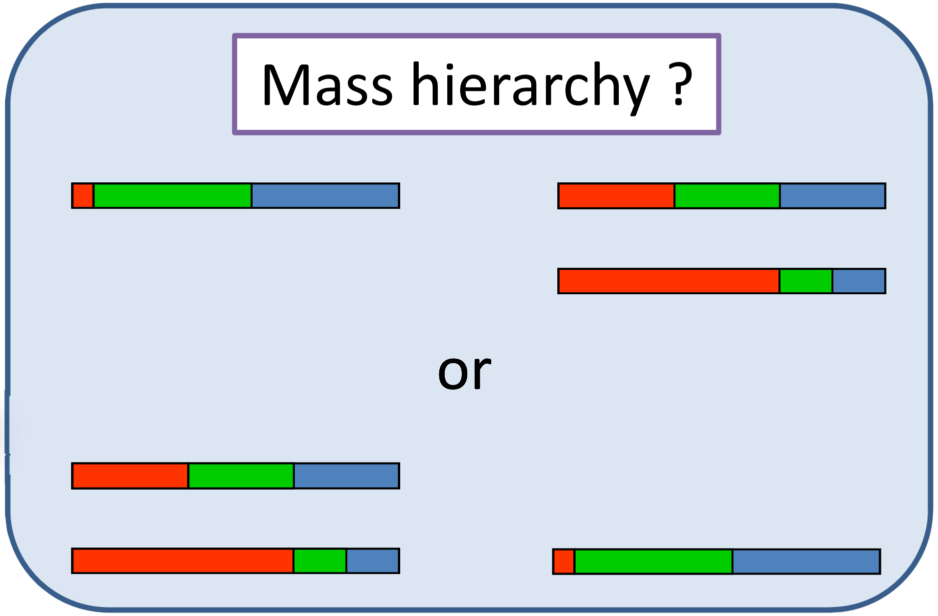
Already 12% accuracy

Beyond θ_{13}

Beyond θ_{13}



θ_{13} is not very small



Is the mass pattern of neutrinos similar to those of quarks and charged leptons?

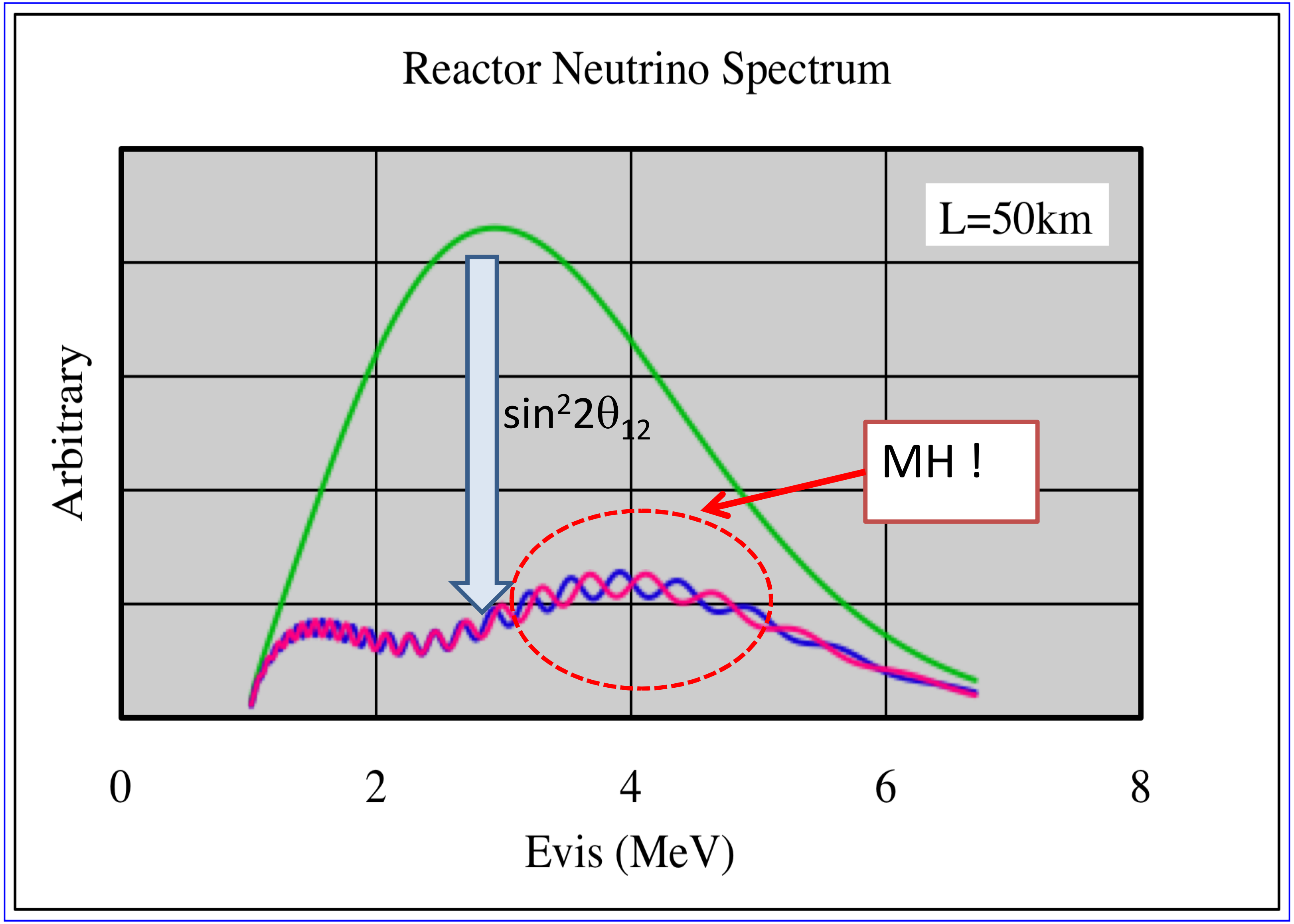
CP violation ?

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

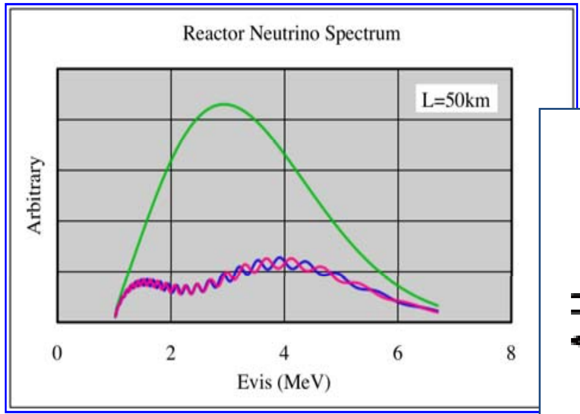
Future reactor experiments

Reactor experiments for MH

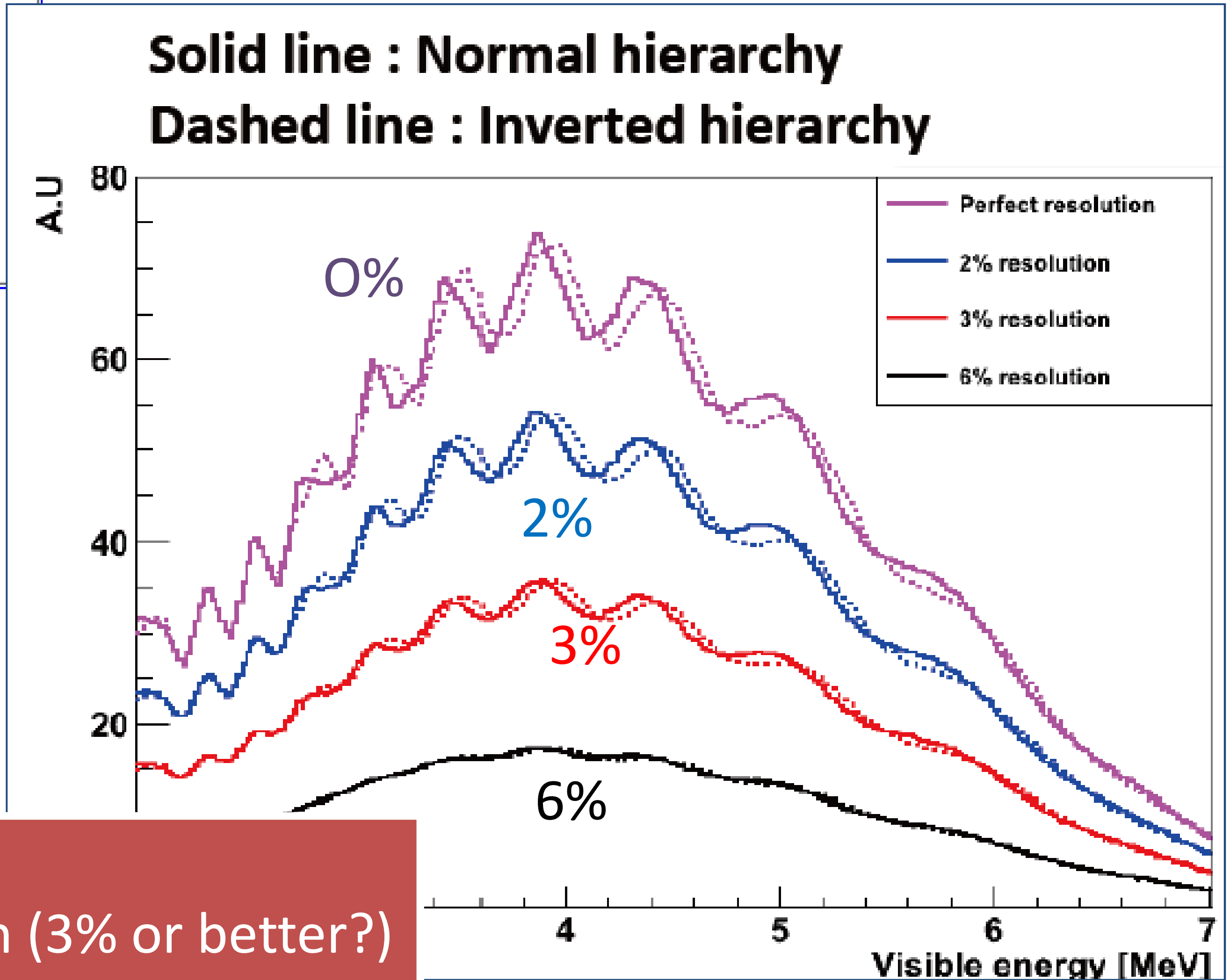


The keys for MH

Refs: RENO-50 workshop June 2013



Energy resolution



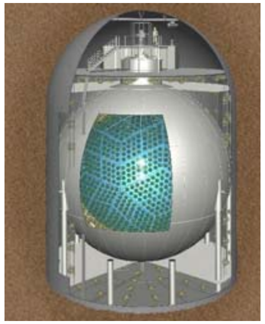
Keys:

✓Good E. resolution (3% or better?)

✓High stat. (large detector)

Energy resolution

Reference: KamLAND



1kton liq. scintillator
Viewed by 17inch PMTs (22% coverage)
→ 300 p.e. /MeV
→ Energy resolution = 6-7% / √E(MeV)

Needs > 1200 p.e./MeV with ~20kton fid. mass

L. Zhang RENO50 workshop (2013)

- Highly transparent LS
  - Attenuation length/D: 15m/16m → 30m/34m — X 0.9
- High light yield LS:
  - KamLAND: 1.5g/l PPO → 5g/l PPO
    Light Yield: 30% → 45% — X 1.5
- Photocathode coverage:
  - KamLAND: 34% → ~80% — X 2.3
- High QE "PMT":
  - 20'' SBA PMT QE: 25% → 35% — X 1.4
    or New PMT QE: 25% → 40% — X 1.6
    Both: 25% → 50% — X 2.0

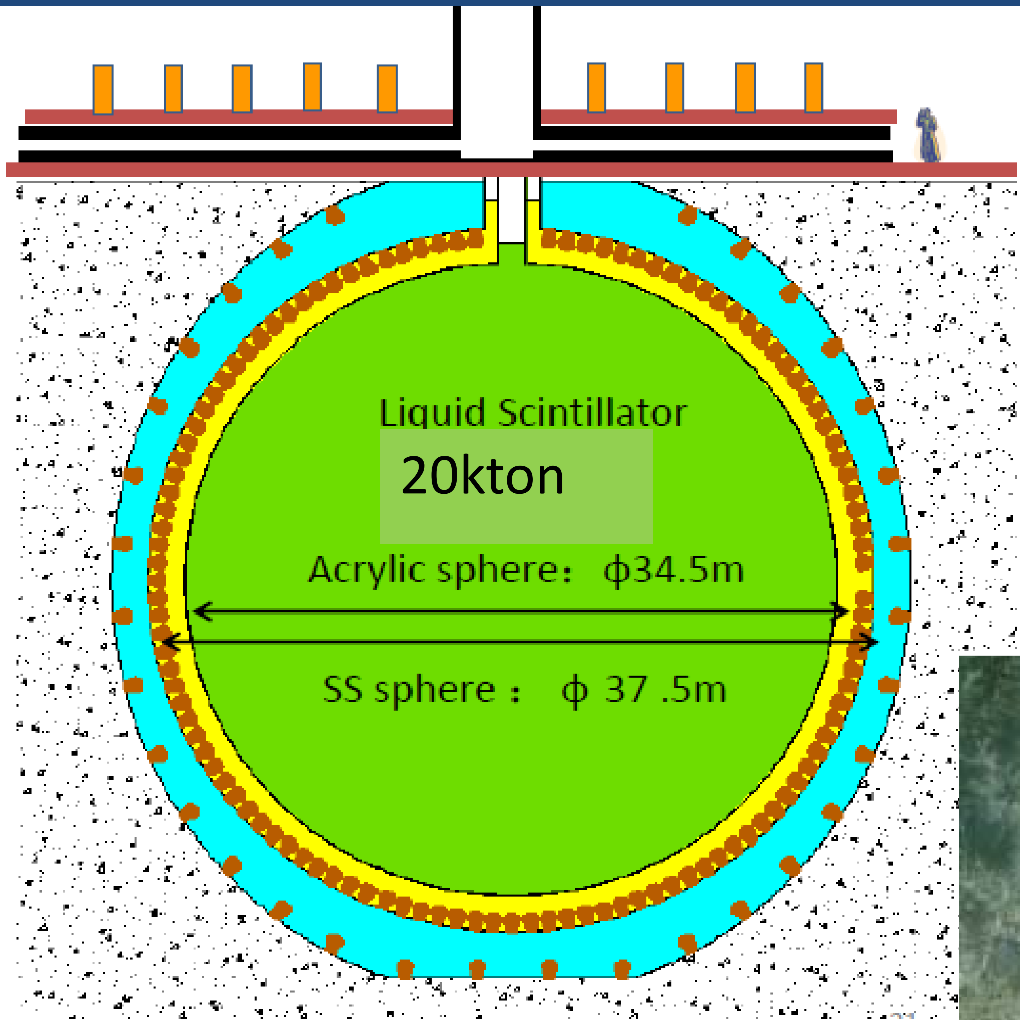
KamLAND
× (4.3 - 5.0)
might be possible

↓

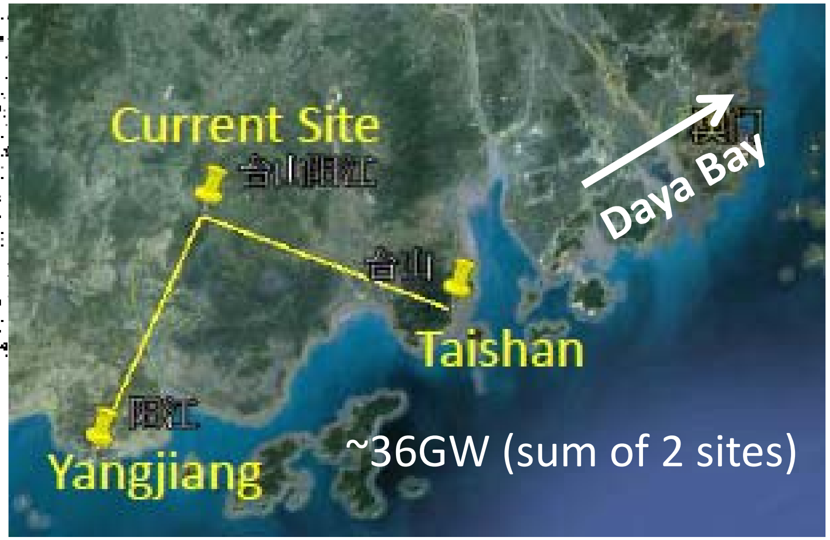
3% / √E(MeV)

Reactor experiments for MH

Refs: RENO-50 workshop June 2013

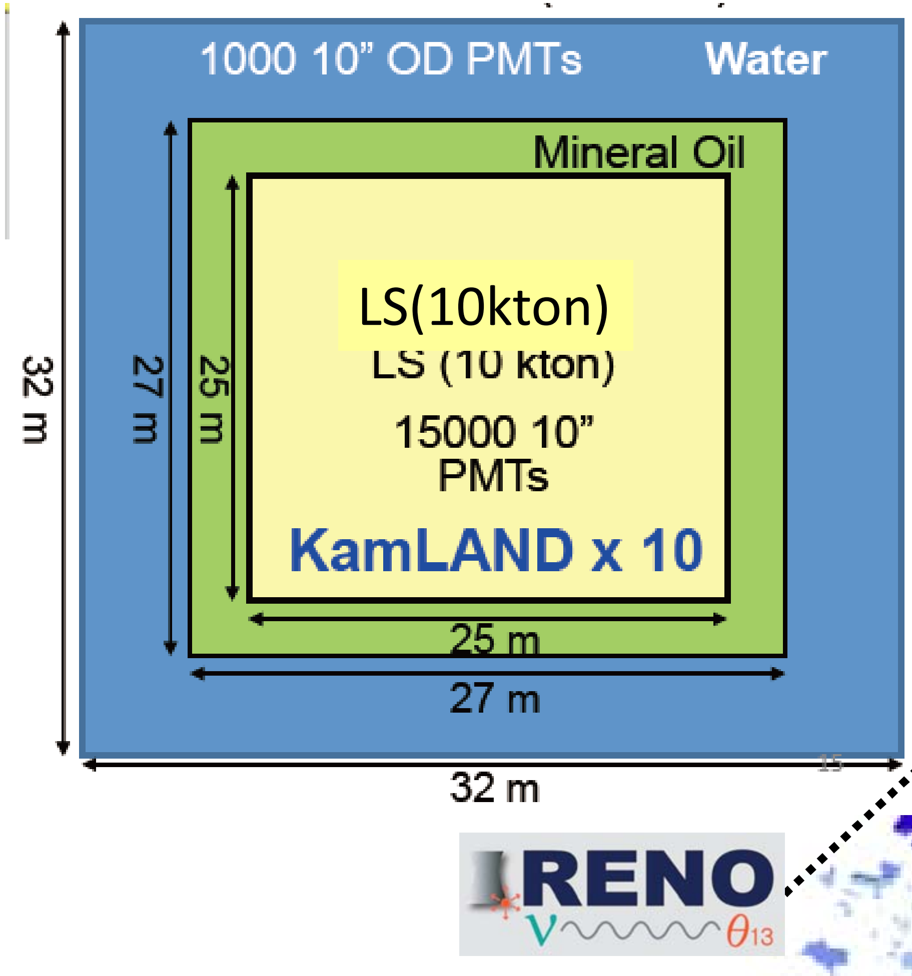


JUNO
(previous Daya Bay II)

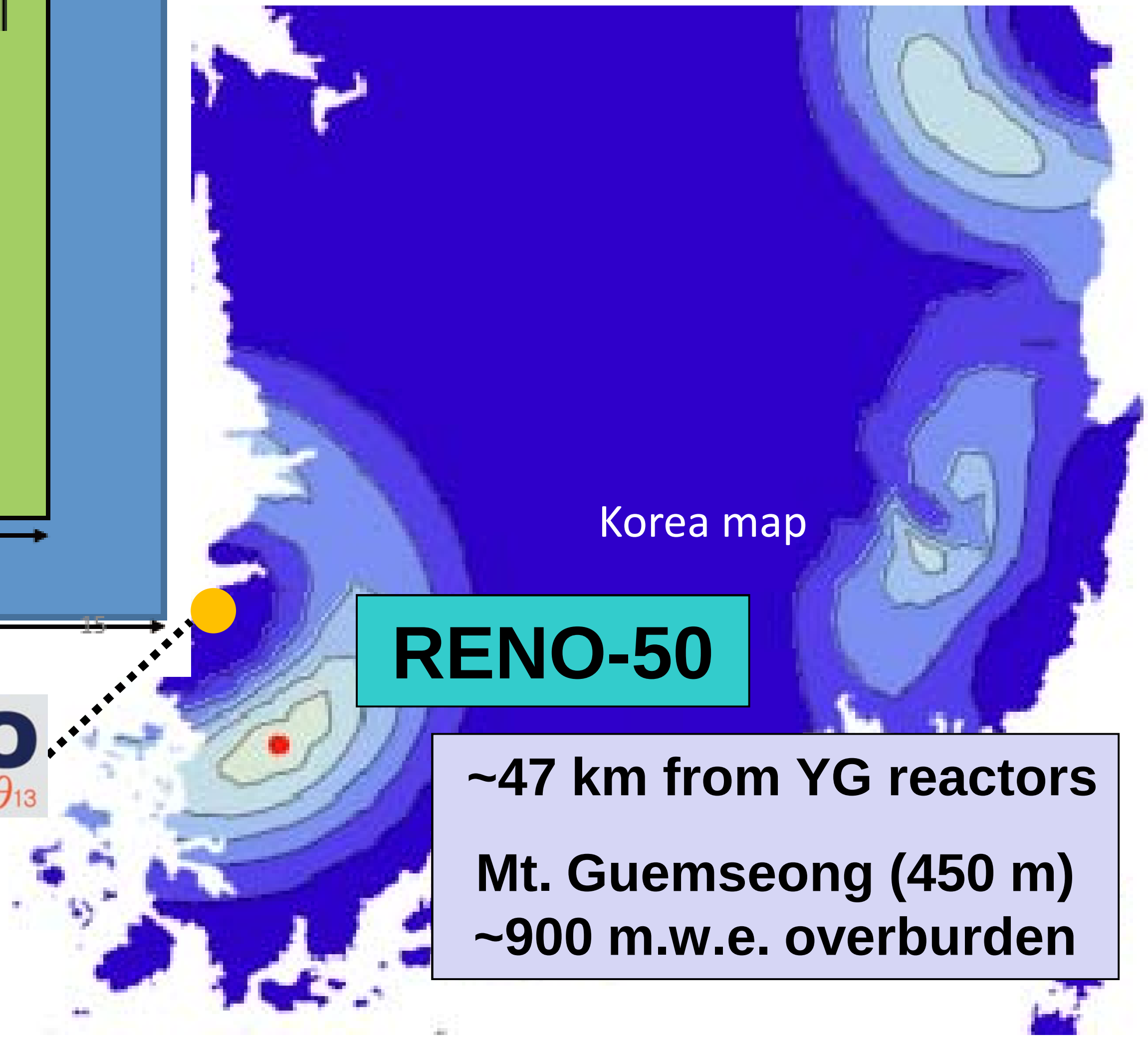


Reactor experiments for MH

Refs: RENO-50 workshop June 2013



RENO-50



~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

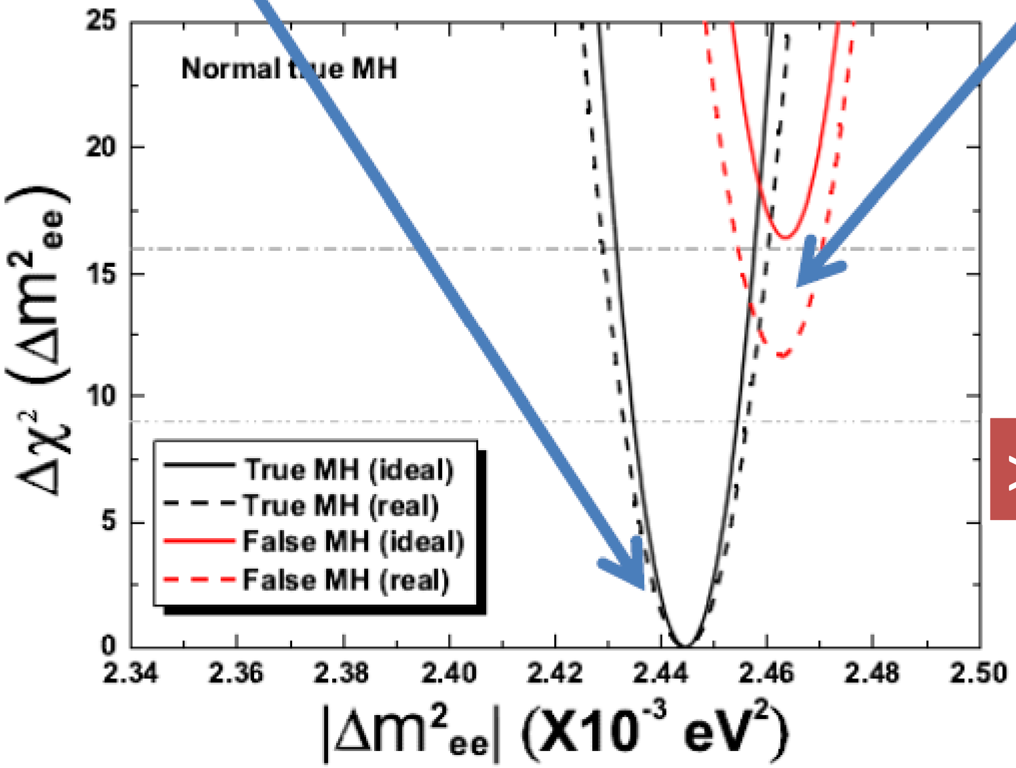
Sensitivity

JUNO

L. Zhan, RENO-50 WK June 2013

NH spectrum fits to NH

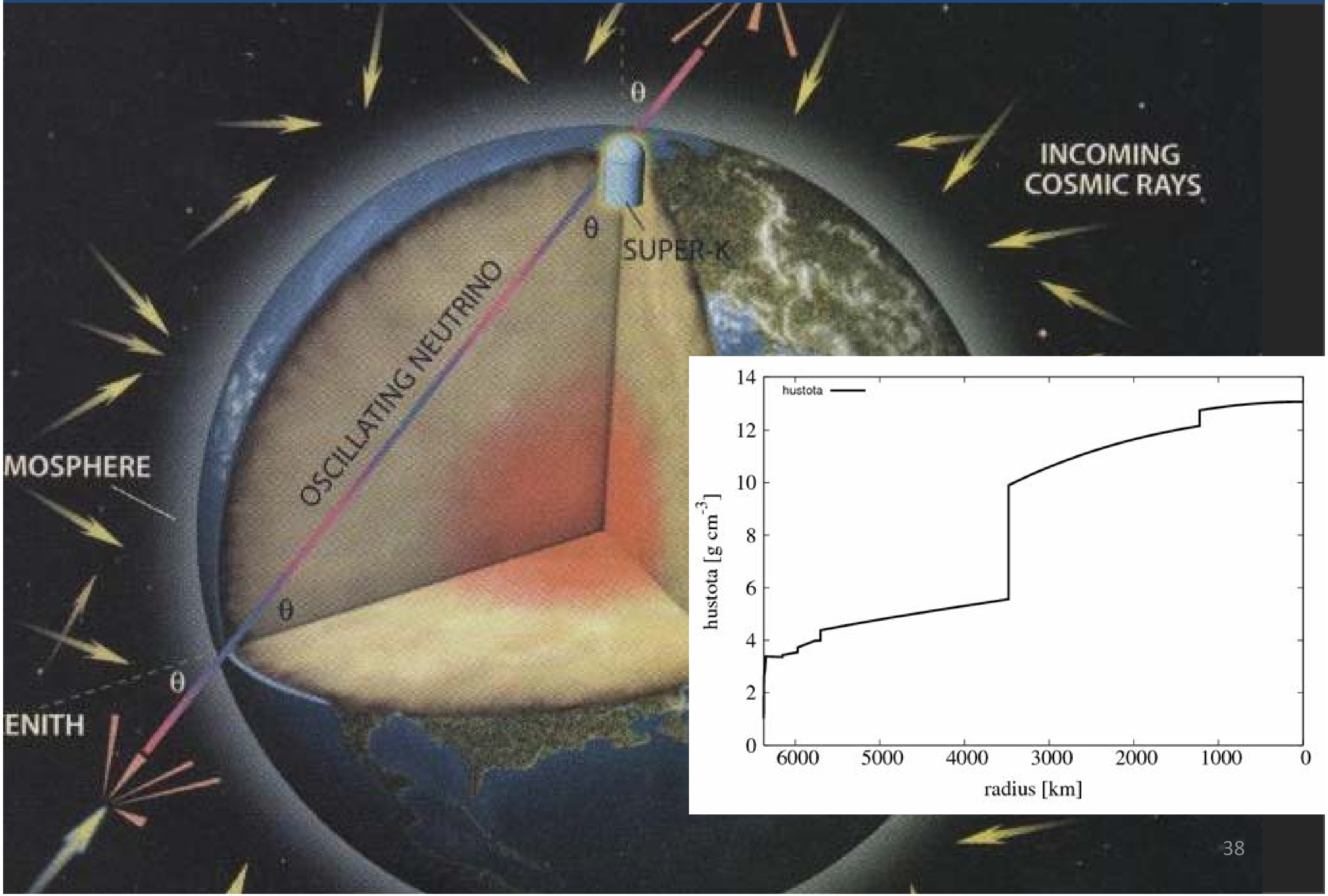
IH spectrum fits to NH



> 3 σ

Other physics: precise measurements of θ_{12}, Δm_{12}^2, Δm_{13}^2, supernova neutrinos, …

Atmospheric ν experiments for MH

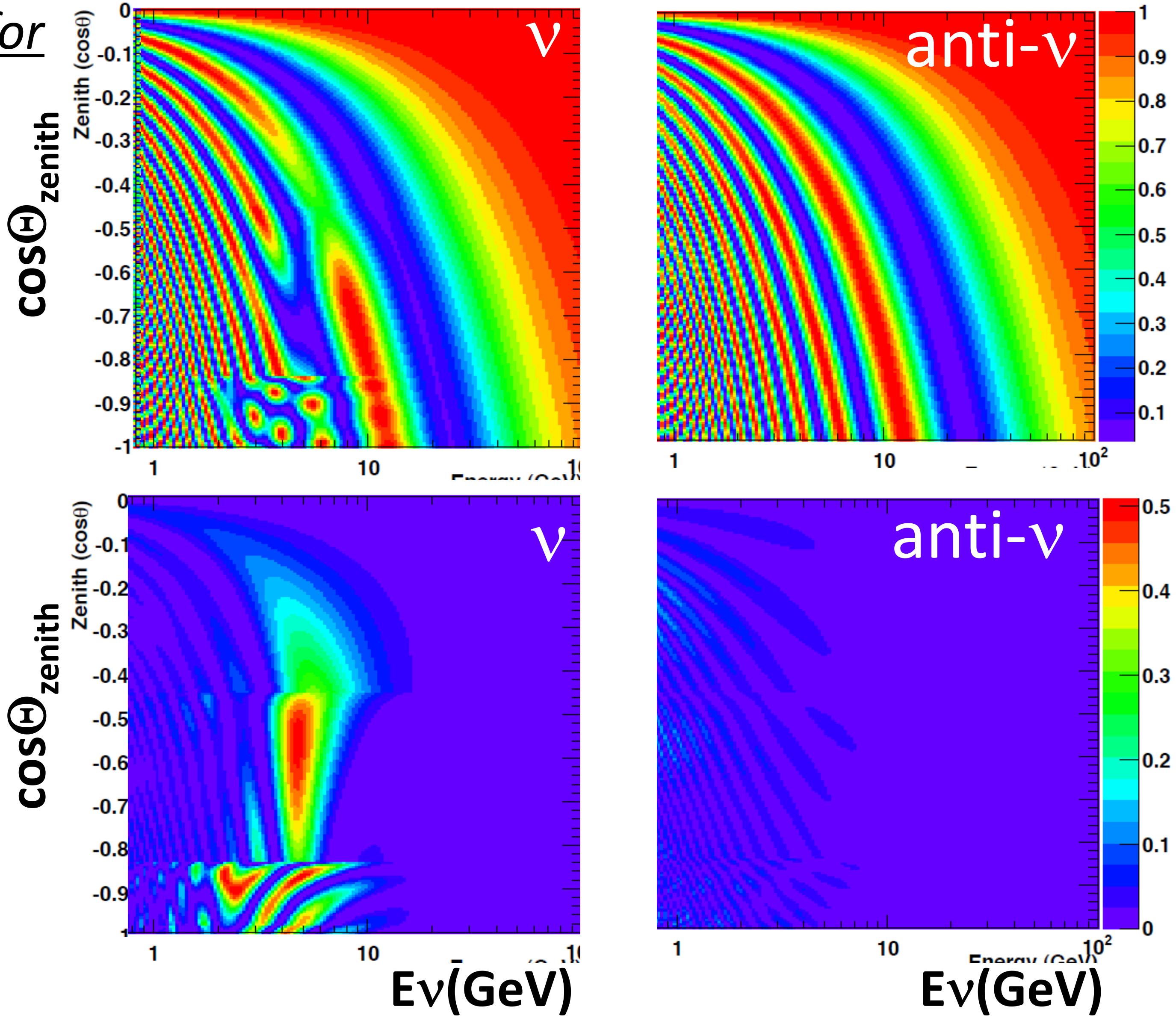


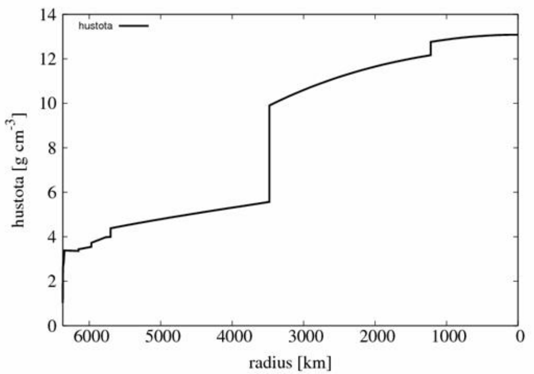
Oscillation probabilities

Osci. Probabilities for Normal Hierarchy

$P(\nu_\mu \rightarrow \nu_\mu)$

$P(\nu_\mu \rightarrow \nu_e)$

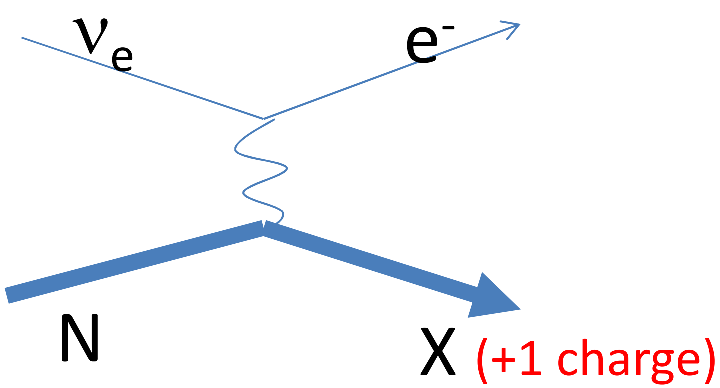


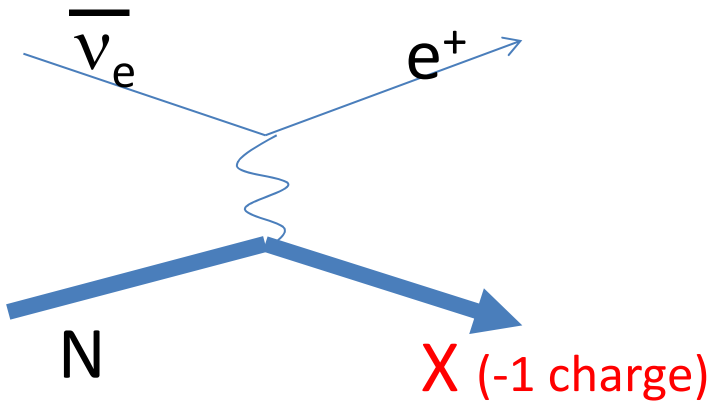


Super-K 3 flavor analysis for mass hierarchy

Super-K has carried out a 3 flavor neutrino oscillation analysis with “ν_e” and “anti-ν_e” enriched multi-GeV events.

Idea





$$y = \frac{E_\nu - E_l}{E_\nu}$$

・・・larger (CC ν_e) ・・・smaller (CC anti-ν_e)

	CC ν_e	CC anti-ν_e
MER (Most Energetic Ring) momentum fraction	Smaller	Larger
Number of identified Cherenkov rings	More	Less
Decay-electron	More	Less

Maximum likelihood (for multi-ring events)

Super-K 3 flavor analysis for mass hierarchy

Super-K has carried out a 3 flavor neutrino oscillation analysis with "ν_e" and "anti-ν_e" enriched multi-GeV events.

Monte Carlo

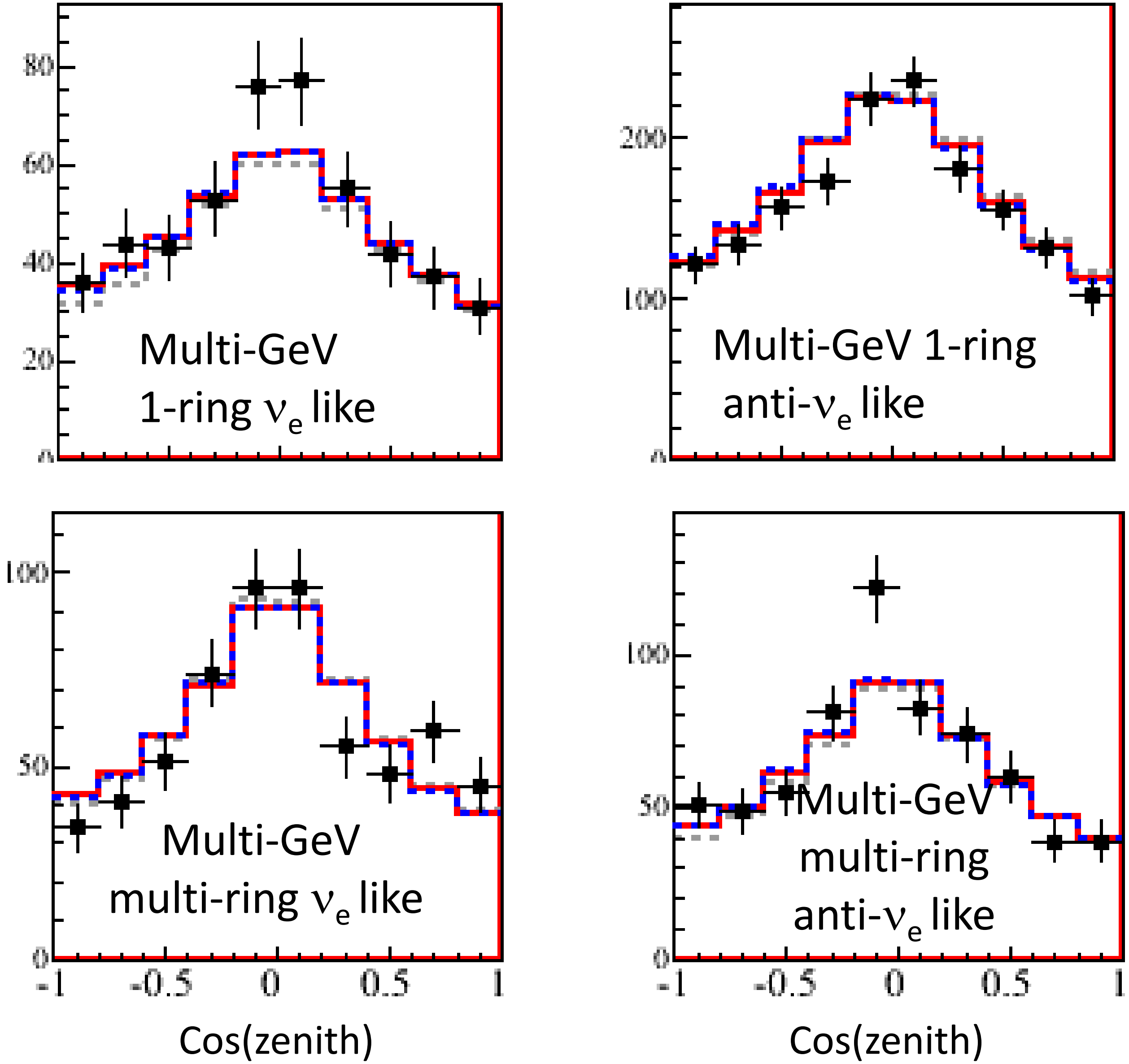
Multi-GeV 1ring e-like events:

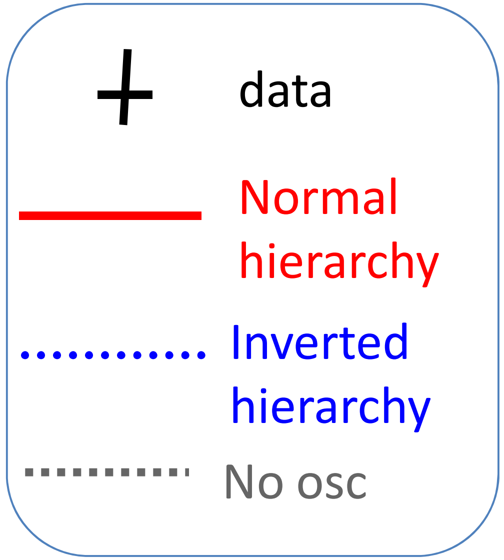
	Before separation	ν_e-like	Anti-ν_e-like
CCν_e	57.6%	62.8%	55.9%
CC anti-ν_e	30.6%	10.8%	36.7%
NC+ CCν_μ	12.0%	26.3%	14.7%
Nuber of events	568.7	135.9	432.8

Multi-GeV multi-ring e-like events:

	Before separation	ν_e-like	Anti-ν_e-like
CCν_e	56.1%	59.4%	53.1%
CC anti-ν_e	19.5%	17.9%	21.0%
NC+ CCν_μ	24.5%	22.7%	25.9%
Nuber of events	341	161.9	168.1

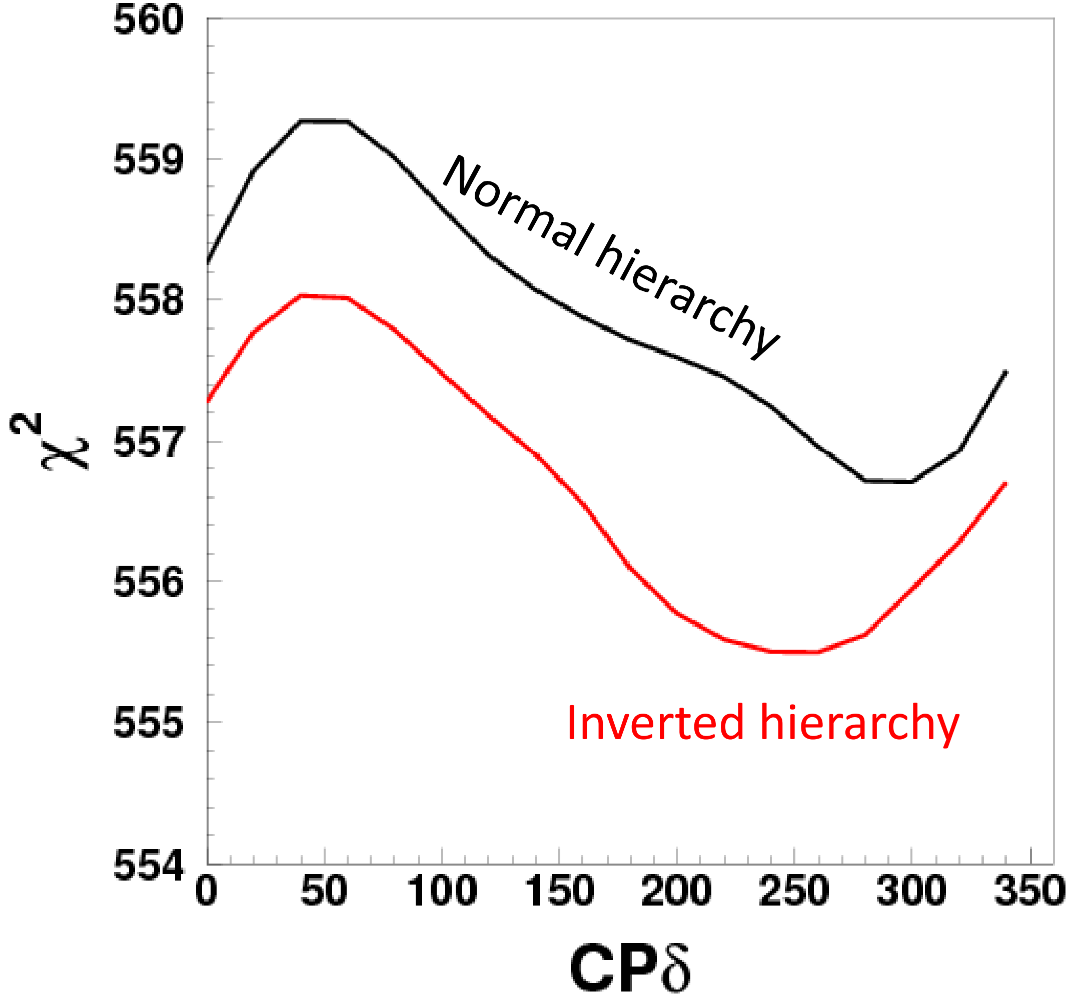
Super-K multi-GeV e-like data





No clear excess seen in the up-going directions.

Super-K result: Mass hierarchy

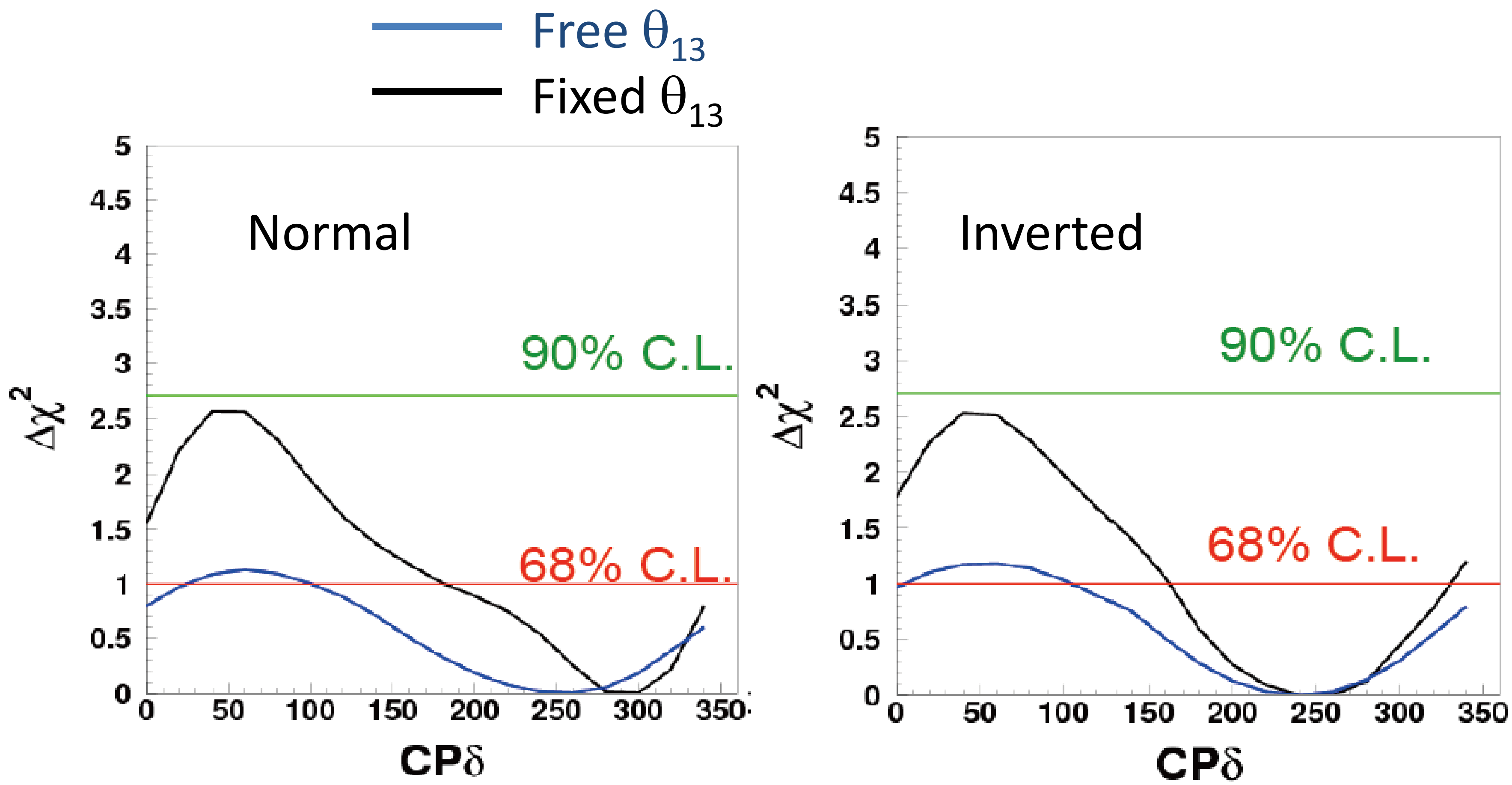


$$\chi^2_{\min}(NH) - \chi^2_{\min}(IH) = 1.2$$

Inverted hierarchy gives very slightly better fit.

Sensitivity:
$\chi^2(NH)$- $\chi^2(IH)$ = 0.463
for $\sin^2\theta_{23}$ =0.425
(if a larger $\sin^2\theta_{23}$ is assumed the sensitivity is larger, since $P \propto \sin^2\theta_{23} \cdot \sin^2\theta_{13}$.)

More results from Super-K 3f analysis: δ_{CP}

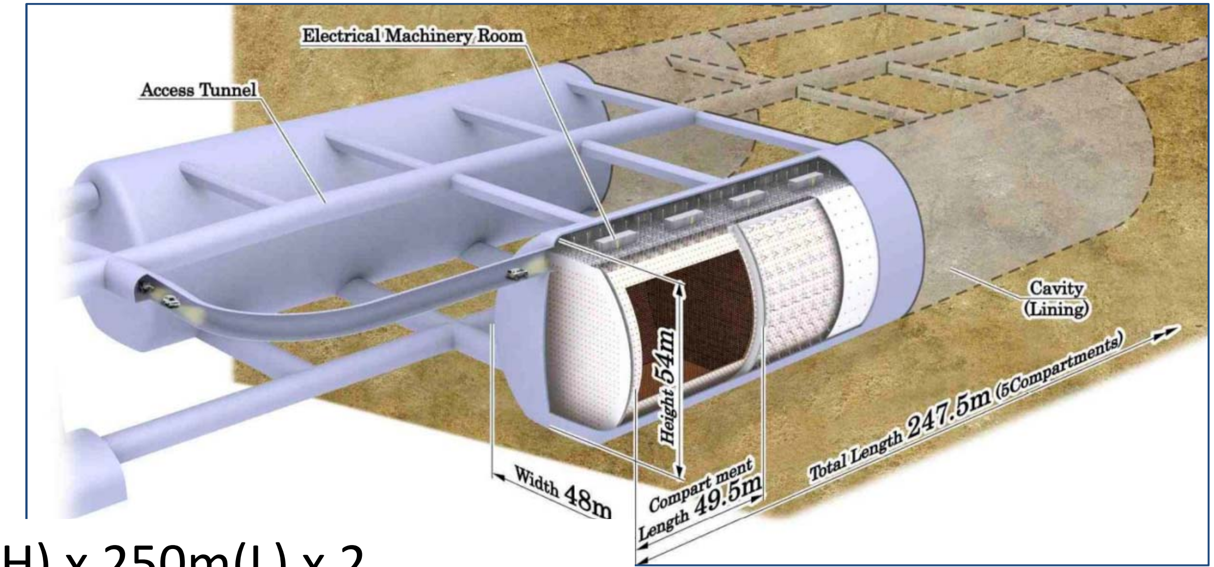


- At 90% C.L., there is no constraint on δ_{CP}.
- Knowing θ_{13} is important to estimate the allowed region of other parameters (δ_{CP} in this case).

Future atmospheric neutrino experiments (MH)

Future atm. ν exp:(1) Hyper-Kamiokande

arXiv:1109.3262

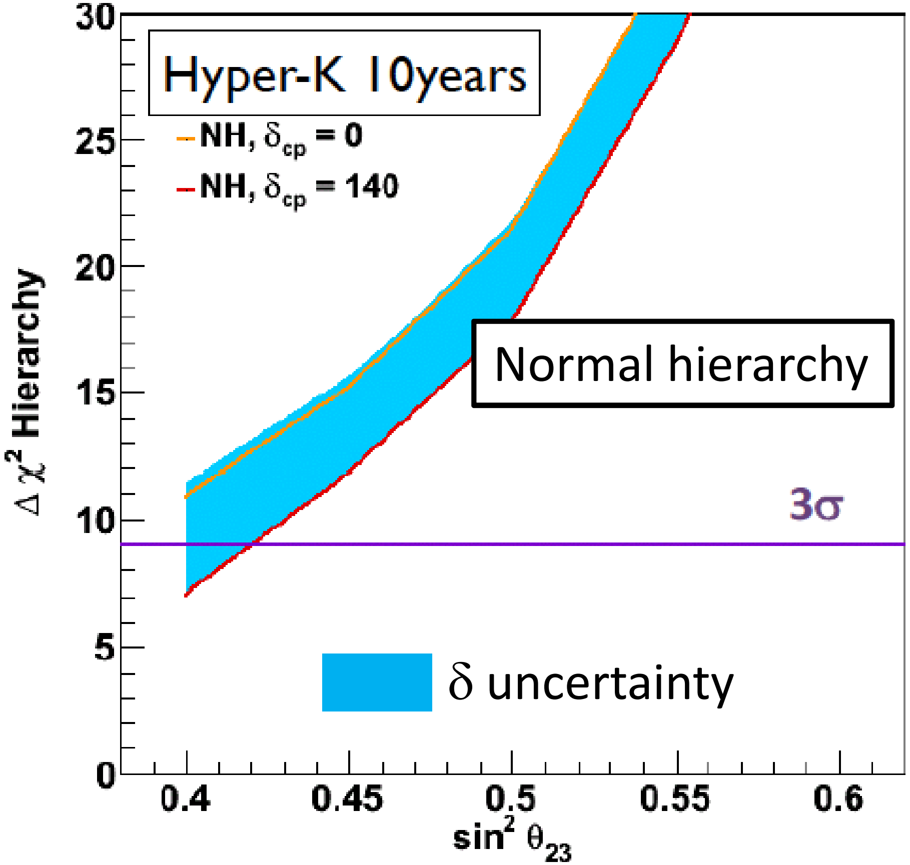


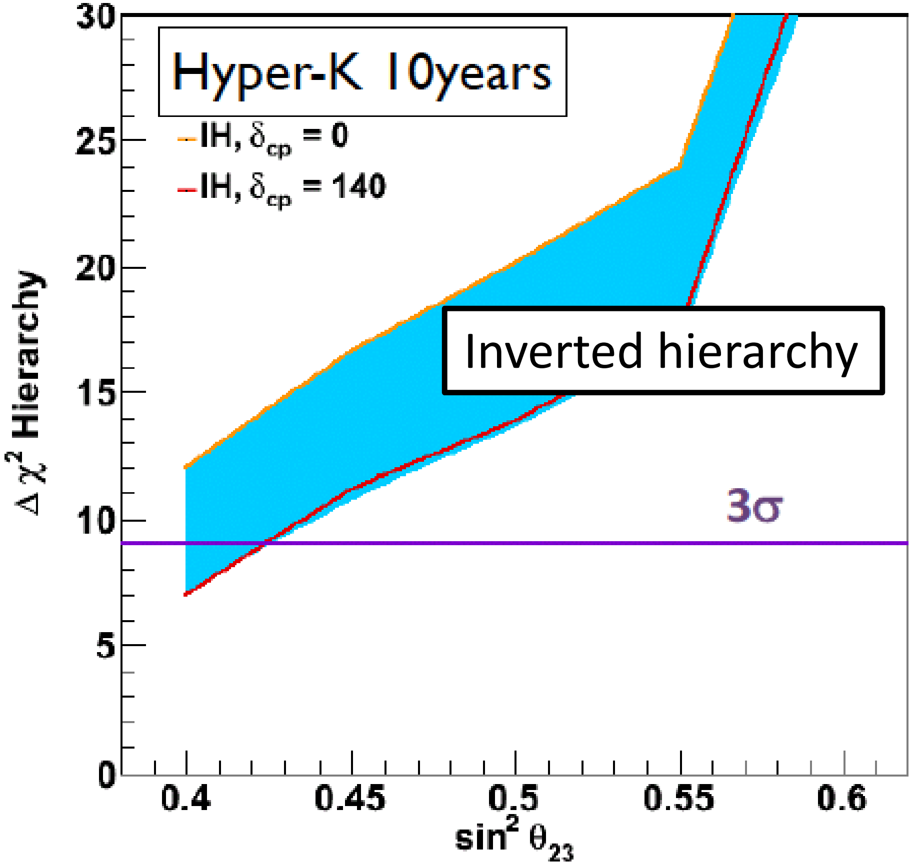
- Cavity : 48m(W) x 54m(H) x 250m(L) x 2
- Water volume :
  - Total : 0.496x2 = 0.99 Mton
  - Fiducial volume = 0.56 Mton (25x SK)
  - Depth of tank water : 48m
- Photo-detectors :
  - ID : ~99,000 20” PMTs, 20% photo-coverage
  - OD : ~25,000 8” PMTs, same coverage as SK

(LBL experiments with J-PARC as well.)

Mass hierarchy measurement

Atmospheric neutrinos only

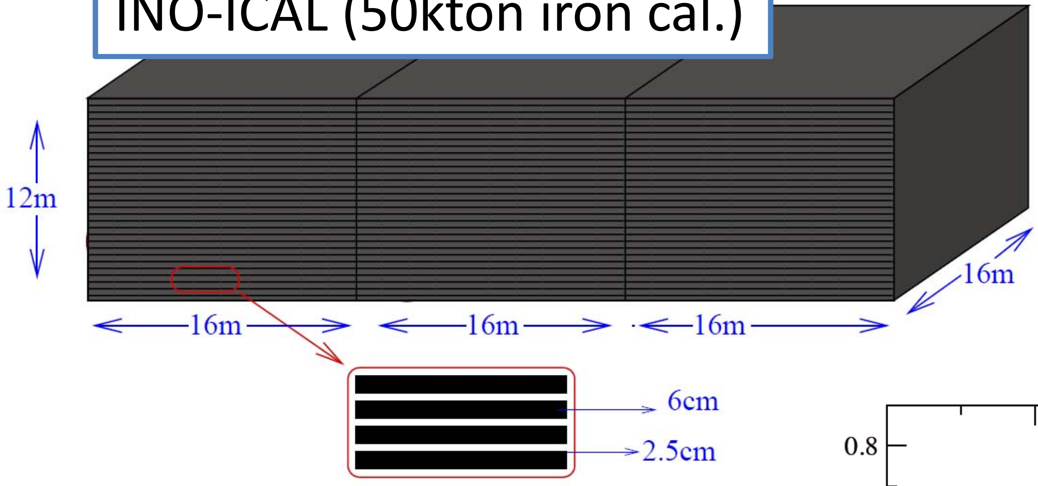




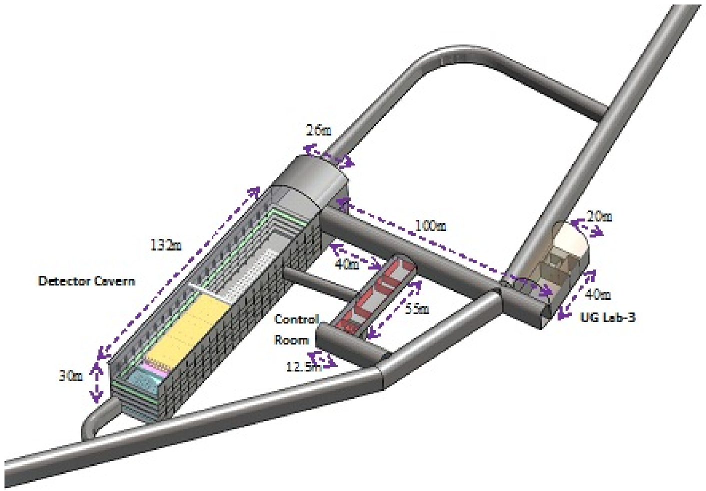
- 10 years HK atmospheric ν data can determine the MH at >~3σ
- Sensitivity depends on θ_{23} , and slightly on CP-δ and the MH itself.
- Cross check by beam and atmospheric.

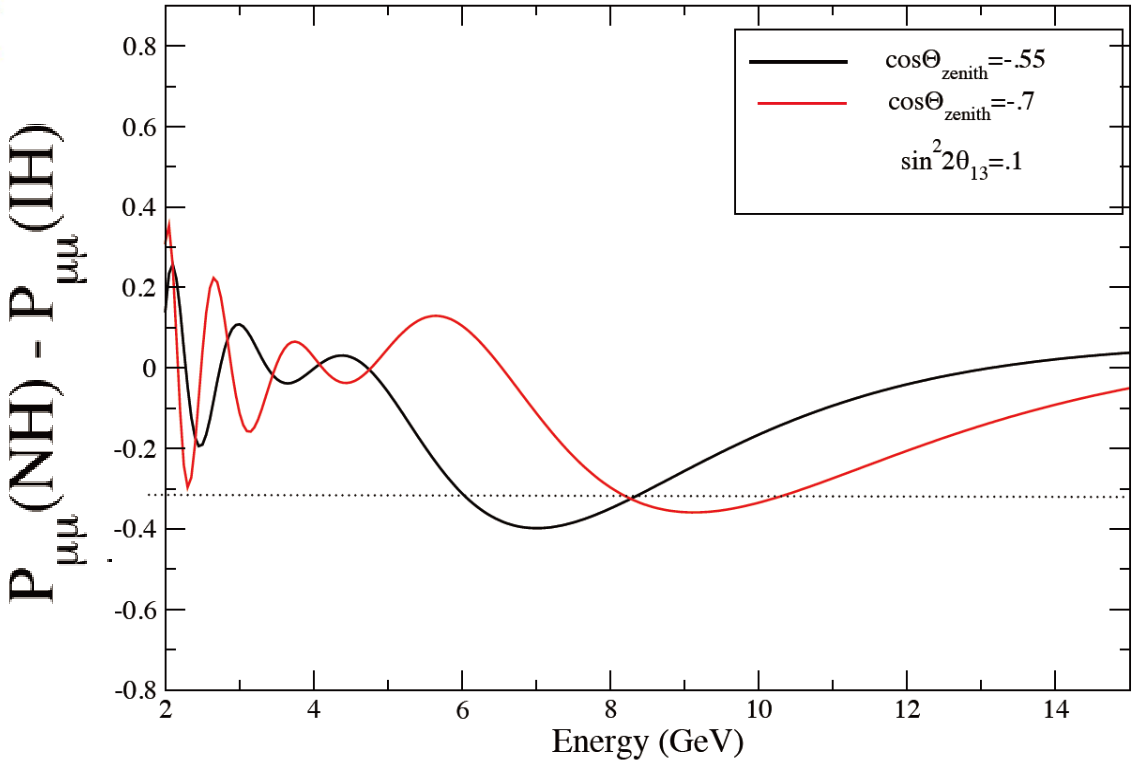
Future atm. ν exp: (2) INO-ICAL

INO-ICAL (50kton iron cal.)



- 50 kton magnetized (1.4T) detector
- Will be located 115 km west of Madurai



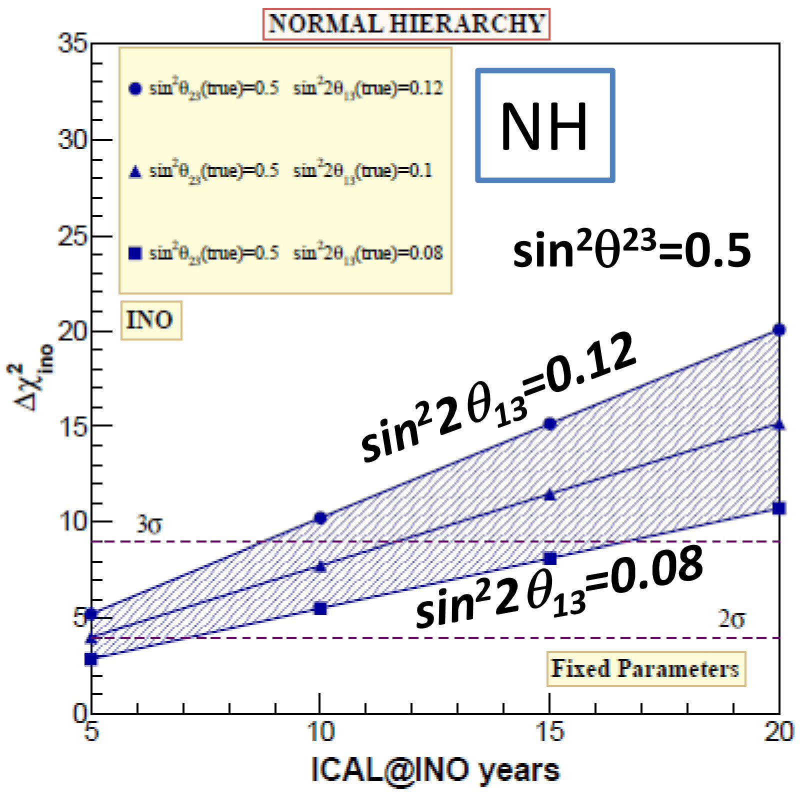


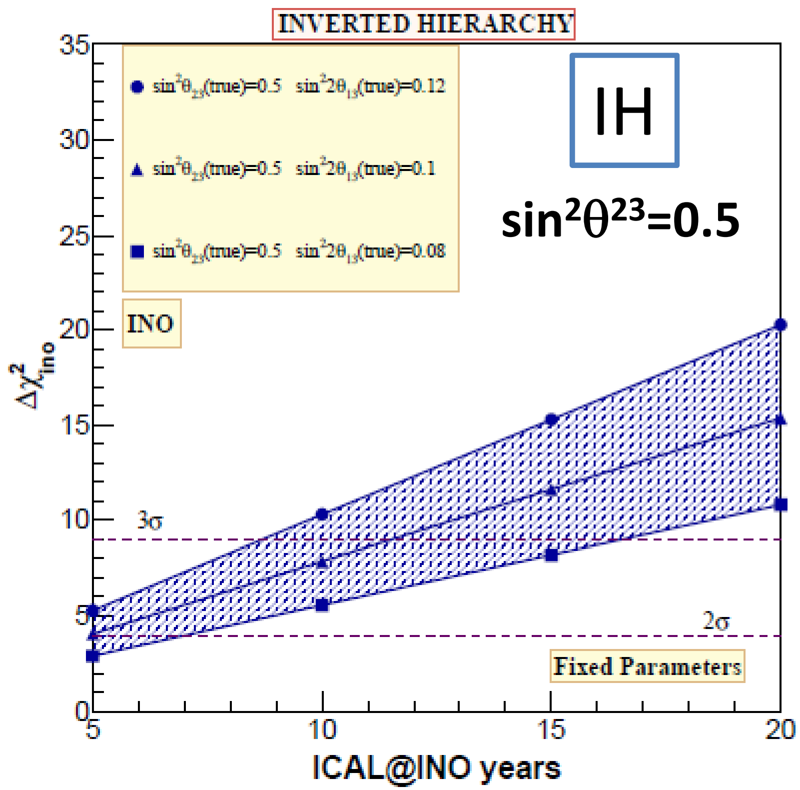
INO-ICAL

INO-ICAL

A. Ghosh, T. Thakore, S. Choubey, arXiv: 1212.1305
N.Mondal, Int. Sym. On Opp. in Und. Grand Phys. May, 2013

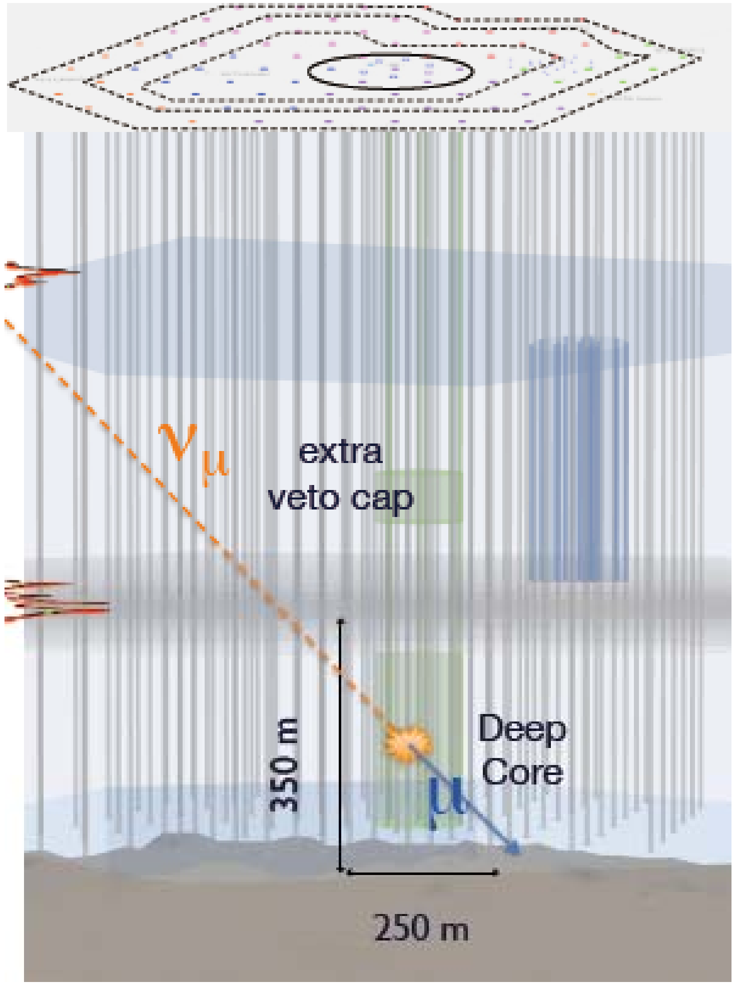
> 3σ in ~12 years

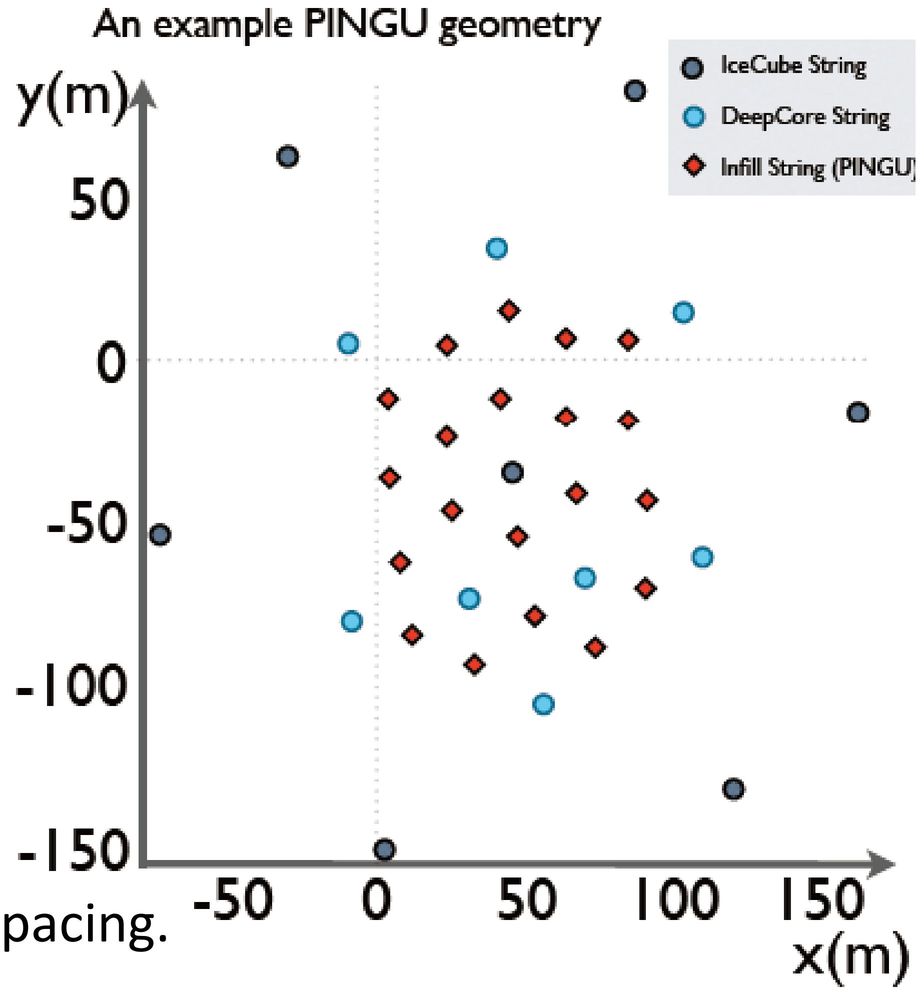




Future atm. ν exp: (3) PINGU

Aartsen et al., arXiv: 1306.5846
C. Rott RENO50 workshop
J. Adams lecture (INSS2013)

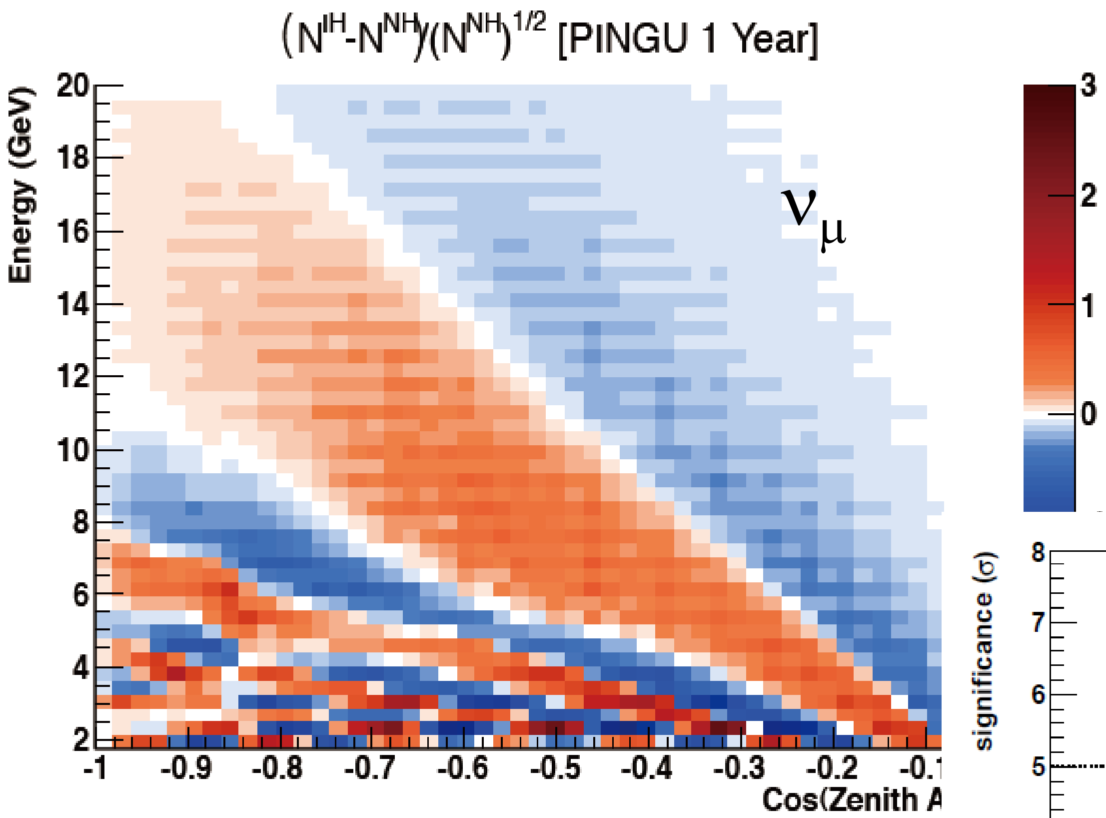




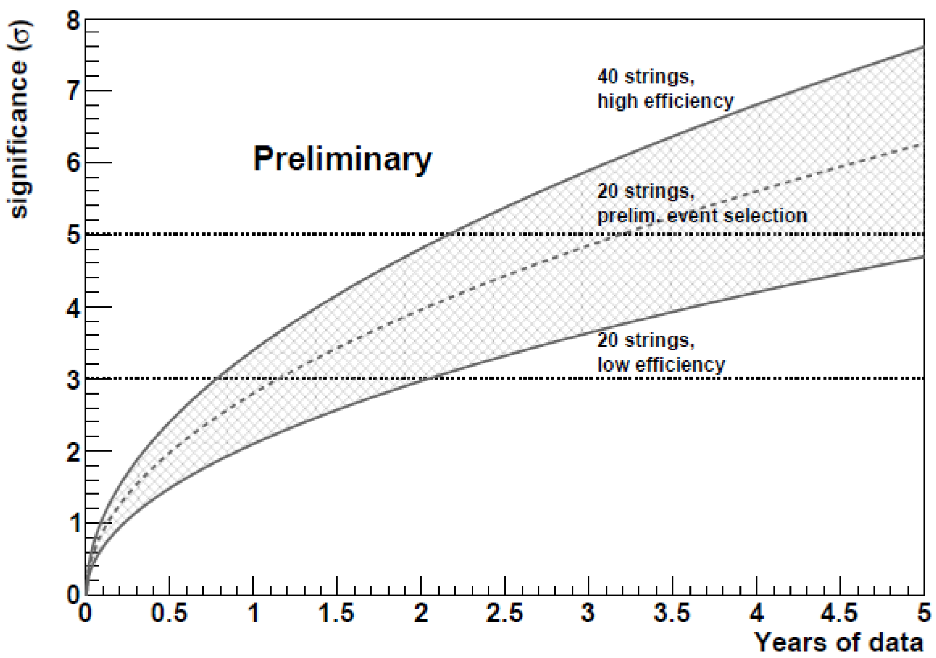
20 additional strings with 26m string spacing.
60 high QE PMTs per string.
Several Mtons for 10GeV neutrinos

PINGU sensitivity to mass hierarchy

Aartsen et al., arXiv: 1306.5846
C. Rott RENO50 worksho



>3σ within a few years
(syst. Included)



- Idealized case w/ perfect event ID, 100% event selection efficiency, no quality cuts and no background

Future atmospheric neutrino experiments (θ_{23} and CP): Hyper-Kamiokande

Oscillation probability

Peres & Smirnov NPB 680 (2004) 479

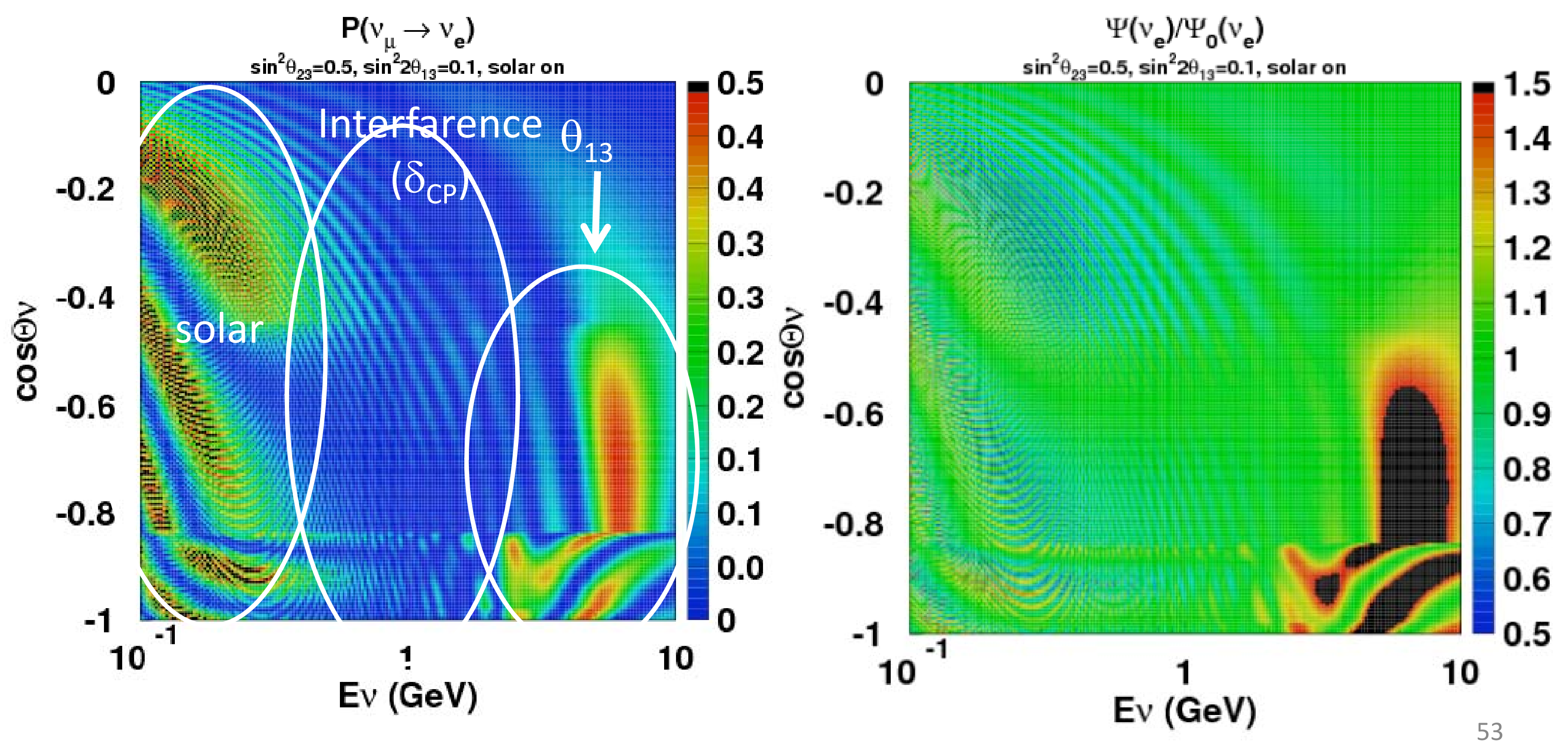
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$ Solar term

r : νμ/νe flux ratio (~2 at low energy)

P_2 : νe→νx transition prob. in matter

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ Interference term

$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1)$$ θ_{13} resonance term (Matter term)

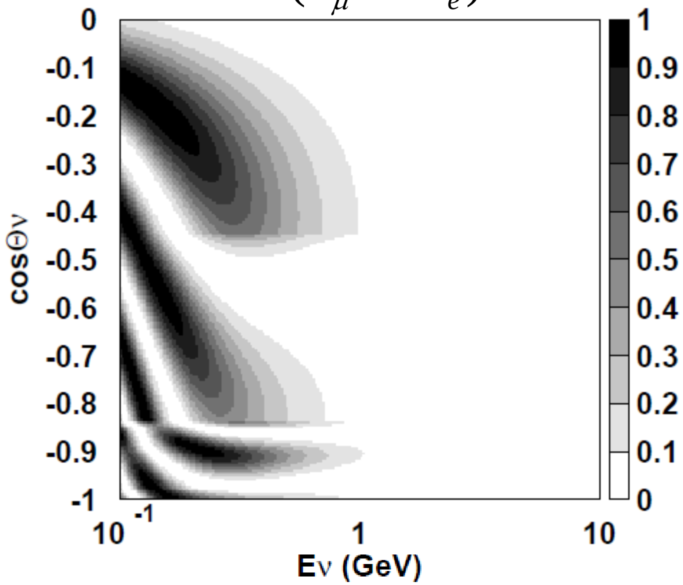


Expected oscillation with solar terms (Q on Aug.13)

Peres & Smirnov NPB 680 (2004) 479

Because of the LMA solution, atmospheric neutrinos should also oscillate by (θ_{12}, Δm_{12}^2).

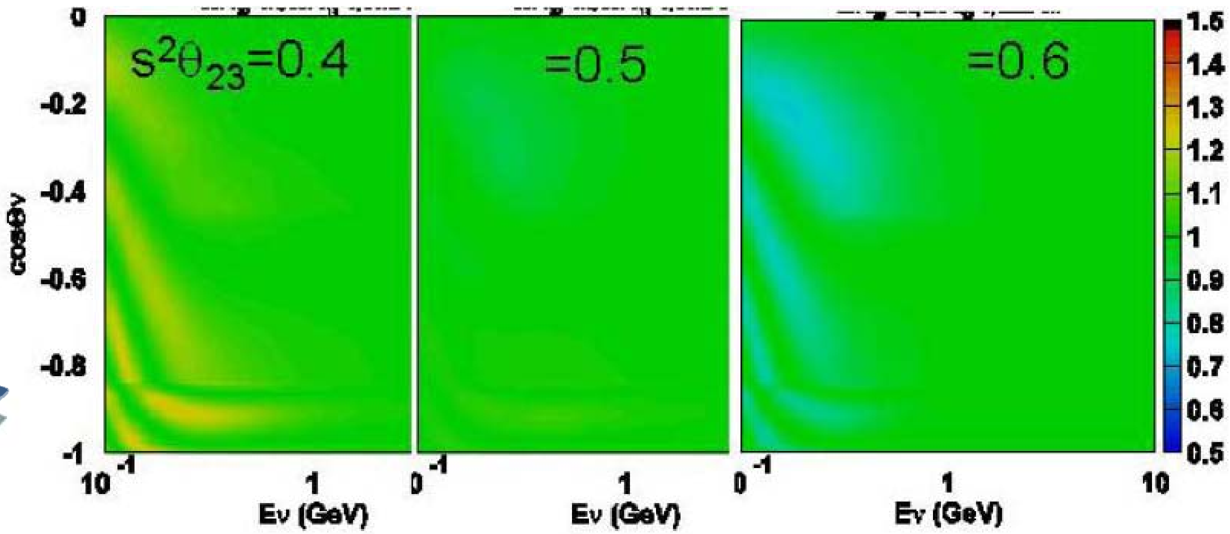
$$P(\nu_\mu \rightarrow \nu_e)$$



$s^2\theta_{12}=0.31$
$\Delta m^2_{12}=7.9\times10^{-5}$
$\sin^2\theta_{13}=0$

However, due to the cancellation between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$, the change in the ν_e flux is small.

$$\frac{\nu_e \;\; flux(osc)}{\nu_e \;\; flux(no\ osc)}$$



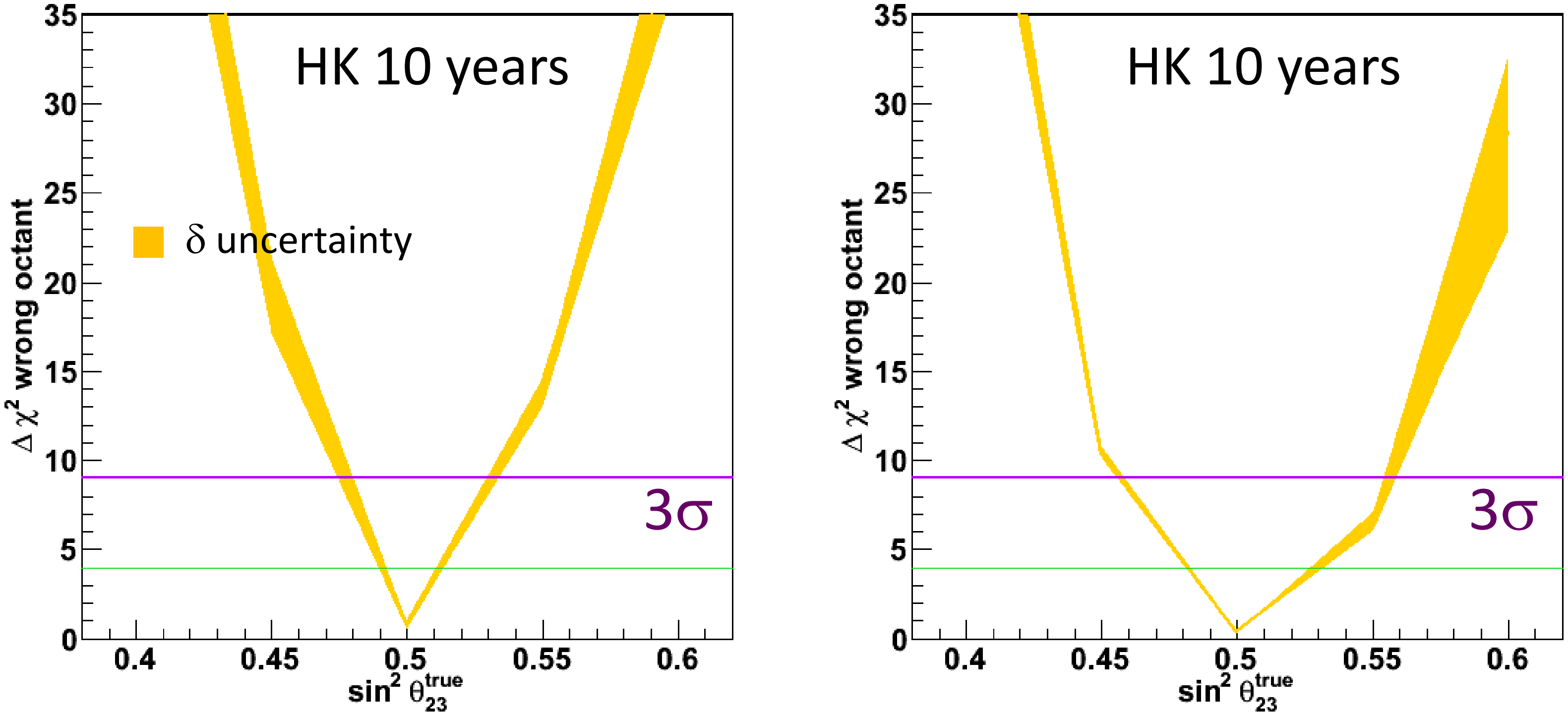
Oscillation probability is different between $s^2\theta_{23}$=0.4 and 0.6
discrimination between θ_{23} >π/4 and <π/4 might be possible.

Determining the octant of θ_{23}

Hyper-K 10 years (solar term + θ_{13} term)

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.1$

Normal Hierarchy (unknown) Inverted Hierarchy (unknown)

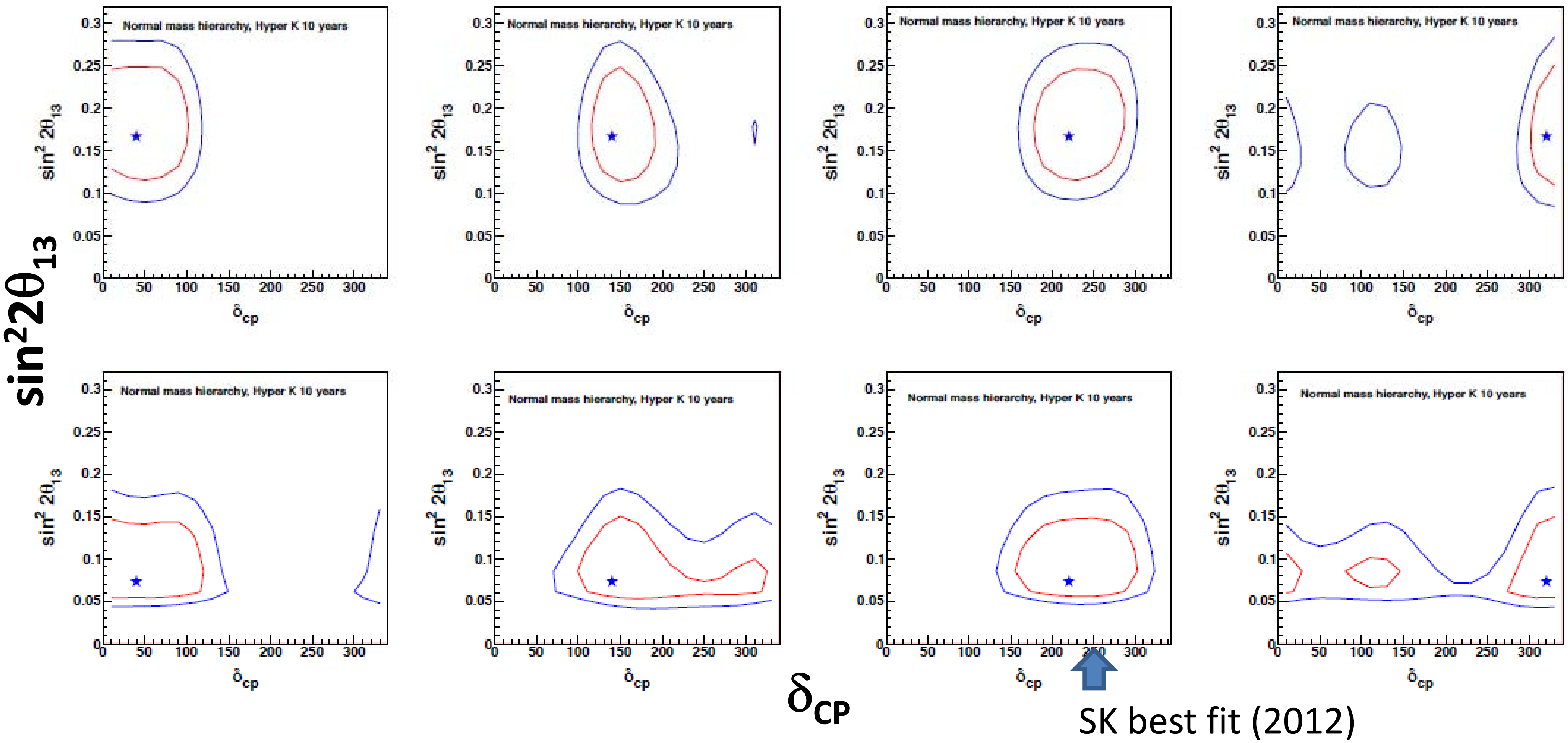


✓ If $\sin^2 2\theta_{23}$<0.99 ($\sin^2\theta_{23}$<0.45 or >0.55), θ_{23} octant can be determined at >3σ using 10 years of HK atmospheric ν data.

Measurement of the CP phase

Hyper-K 10 years

arXiv: 1109.3262



◆There is some sensitivity on δ_{CP}. However, the sensitivity is not high compared with the planed accelerator LBL experiments.

Summary of Lecture-3

- In 2011-2012, θ_{13} has been measured. Daya Bay, RENO and Double-Chooz reactor experiments played a central role to this measurement. The accuracy of the measurements already reached to almost the 10% level.
- The subsequent big goals in neutrino oscillation experiments are CP violation and mass hierarchy. Planned reactor and atmospheric neutrino experiments have good sensitivities for the mass hierarchy determination.

Summary

- Search for proton decay
  ➔ Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation, large mixing (and SN neutrino burst, not discussed in my lectures)
- Study of energy generation in the Sun
  ➔ Discovery of $\nu_e \rightarrow \nu_{(\mu, \tau)}$ oscillation, LMA
- θ_{13} was measured by carefully planed experiments.
- Trying to measure CP violation, mass hierarchy, …
  ➔ ? ? ?
- Neutrino physics seems to be related to “big questions” in nature.

Let’s enjoy neutrino physics!