Нейтринные осцилляции: от измерений θ_{13} к иерархии масс и CP нарушению

Ю.Г. Куденко
ИЯИ РАН

Сессия секции ЯФ ОФН РАН,
ИФВЭ, Протвино, 5 ноября 2013

2013 год: 100-летие со дня рождения Б.М. Понтекорво

Mesonium and anti-mesonium
B. Pontecorvo
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551

Inverse beta processes and nonconservation of lepton charge
B. Pontecorvo (Dubna, JINR)
Sov.Phys.JETP 7 (1958) 172-173,
Zh.Eksp.Teor.Fiz. 34 (1957) 247

Neutrino Experiments and the Problem of Conservation of Leptonic Charge
B. Pontecorvo (Dubna, JINR)
Sov.Phys.JETP 26 (1968) 984-988,
Zh.Eksp.Teor.Fiz. 53 (1967) 1717-1725

Outline

- neutrino mixing
- measurements of θ_{13}
- observation of ν_e appearance
- near future: mixing parameters, MH and CP
- far future prospects
- summary

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

by June 2011

3 families $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ $U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$

atmospheric

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

link between atmospheric and solar

$\theta_{23} \sim 45^0$

$|\Delta m^2_{23}| \cong |\Delta m^2_{31}| =$

$|\Delta m^2_{atm}| \approx 2.4 \times 10^{-3} \text{eV}^2$

***U* parameterization:**

three mixing angles θ_{12} θ_{23} θ_{13}

CP violating phase δ

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

two independent Δm^2

$\theta_{12} = (34 \pm 1)^0$

$\Delta m^2_{12} = \Delta m^2_{sol} \approx 7.5 \times 10^{-5} \text{eV}^2$

$\sin^2 2\theta_{13} < 15^0$ at 90% CL

?? θ_{13} , mass hierarchy , δ ??

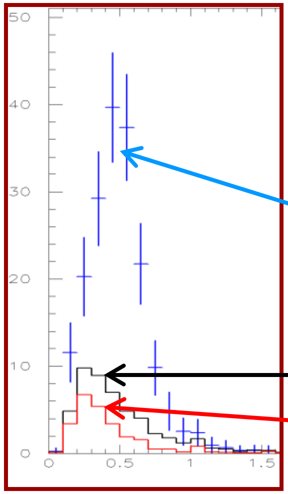
Hunt for θ_{13}

Two methods

Appearance:

$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$ + CPV term + matter term + …

Search for electron neutrinos in beam of muon neutrinos at L/E tuned to the maximum of "atm" oscillations



$\sin^2 2\theta_{13} = 0.1$

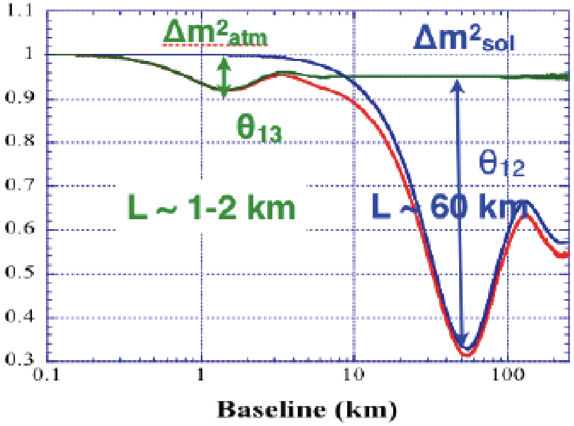
Signal: $(\nu_e + n \to e^- + p)$

Backgrounds:
beam ν_e
NC π^0

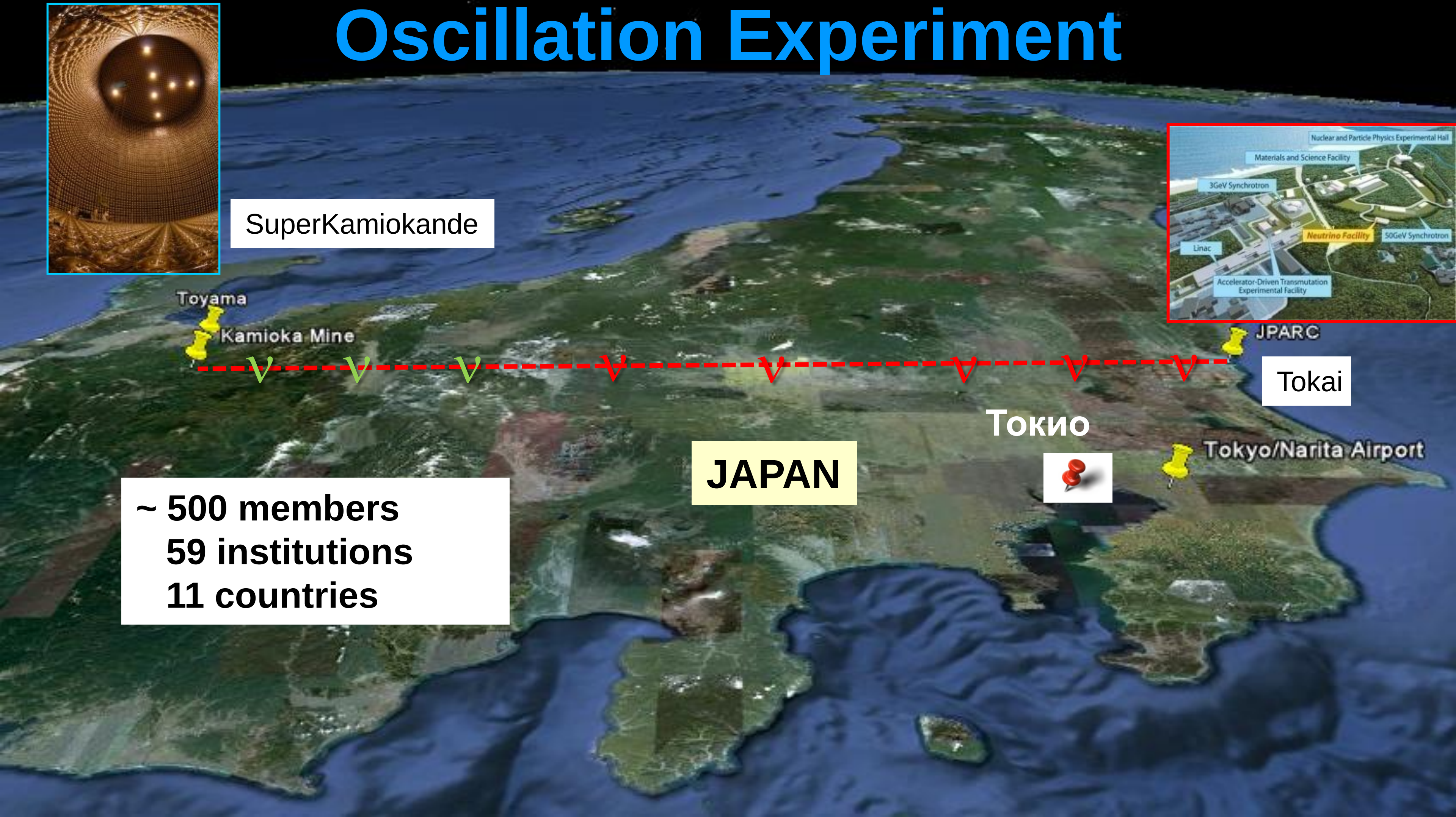
Disappearance:

$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} L/4E)$

Measurement of deficit of reactor antineutrinos at L ~ 1-2 km

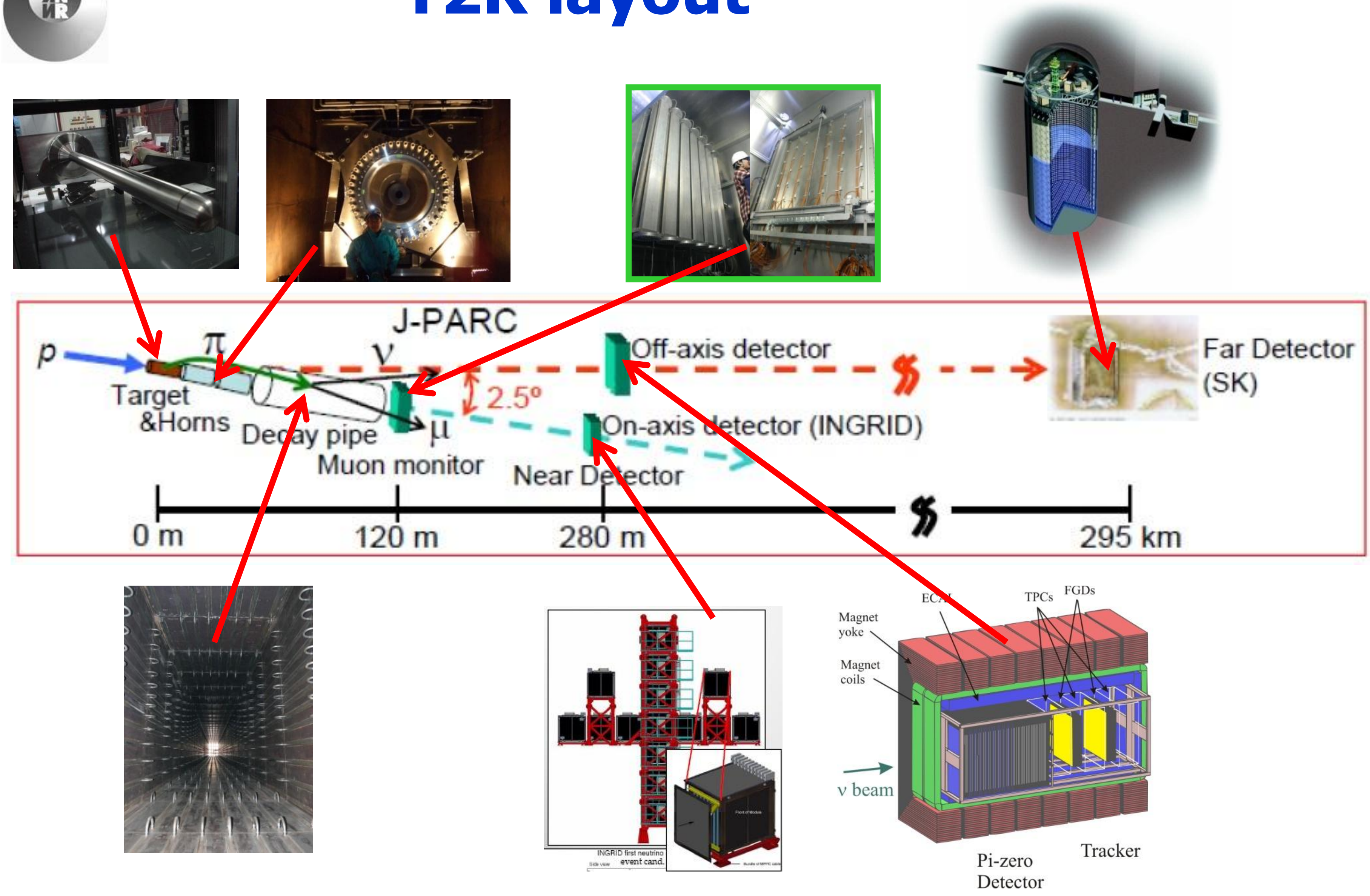


Long-Baseline Neutrino Oscillation Experiment



~ 500 members
59 institutions
11 countries

T2K layout

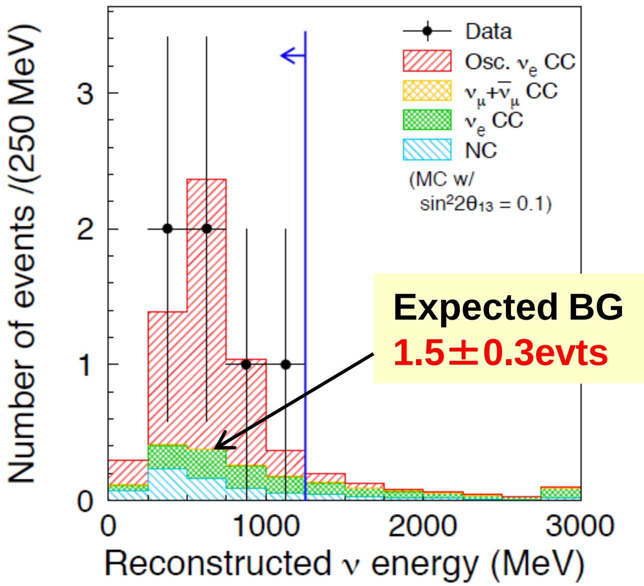

J-PARC
p
π
ν
μ
Target
&Horns
Decay pipe
Muon monitor
2.5°
Off-axis detector
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km
Magnet
yoke
Magnet
coils
ECAL
TPCs
FGDs
ν beam
Pi-zero
Detector
Tracker

First T2K result

6 ν_e events

changed neutrino physics landscape

1.43×10^{20} POT
January 2010 –
March 2011



In June 2011
T2K published first clear indication
of electron neutrino appearance ($\theta_{13} \neq 0$)

Then,
1 - Confirmation from MINOS
2 - Precise measurements by
Double Chooz
Daya Bay
RENO

Selected for a Viewpoint in *Physics*
PRL **107,** 041801 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

K. Abe,[49] N. Abgrall,[16] Y. Ajima,[18,†] H. Aihara,[48] J. B. Albert,[13] C. Andreopoulos,[47] B. Andrieu,[37] S. Aoki,[27] O. Araoka,[18,†] J. Argyriades,[16] A. Ariga,[3] T. Ariga,[3] S. Assylbekov,[11] D. Autiero,[32] A. Badertscher,[15] M. Barbi,[40] G. J. Barker,[56] G. Barr,[36] M. Bass,[11] F. Bay,[3] S. Bentham,[29] V. Berardi,[22] B. E. Berger,[11] I. Bertram,[29] M. Besnier,[14] J. Beucher,[8] D. Beznosko,[34] S. Bhadra,[59] F. d.M. M. Blaszczyk,[8] A. Blondel,[16] C. Bojechko,[53] J. Bouchez,[8,*] S. B. Boyd,[56] A. Bravar,[16] C. Bronner,[14] D. G. Brook-Roberge,[5] N. Buchanan,[11] H. Budd,[41] D. Calvet,[8] S. L. Cartwright,[44] A. Carver,[56] R. Castillo,[19] M. G. Catanesi,[22] A. Cazes,[32] A. Cervera,[20] C. Chavez,[30] S. Choi,[43] G. Christodoulou,[30] J. Coleman,[30]

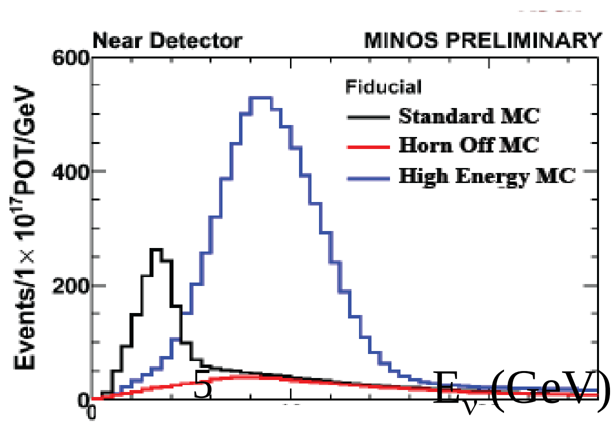
The T2K experiment observes indications of $\nu_\mu \to \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{13} = 0$, the expected number of such events is 1.5 ± 0.3(syst). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{CP} = 0$ and a normal (inverted) hierarchy.

DOI: 10.1103/PhysRevLett.107.041801 PACS numbers: 14.60.Pq, 13.15.+g, 25.30.Pt, 95.55.Vj

MINOS

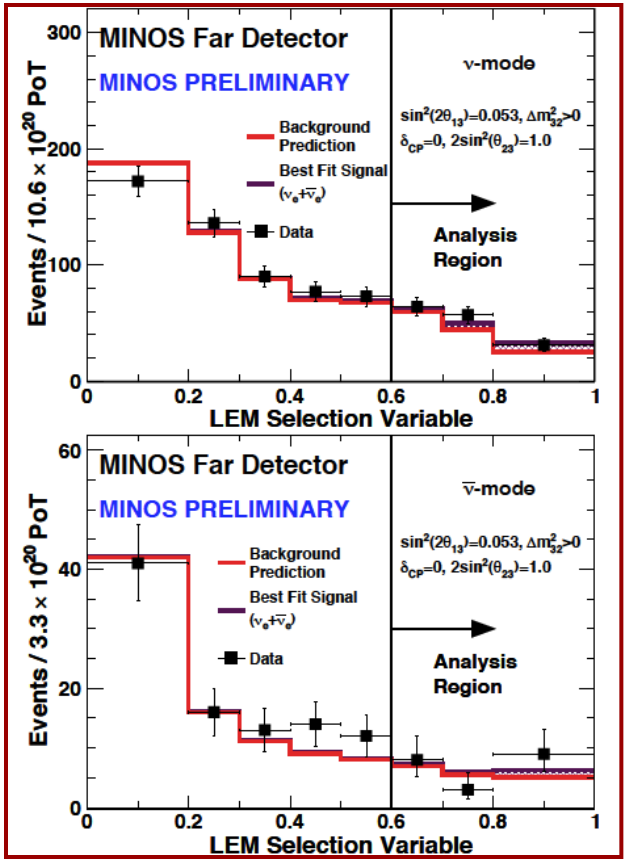
Far detector

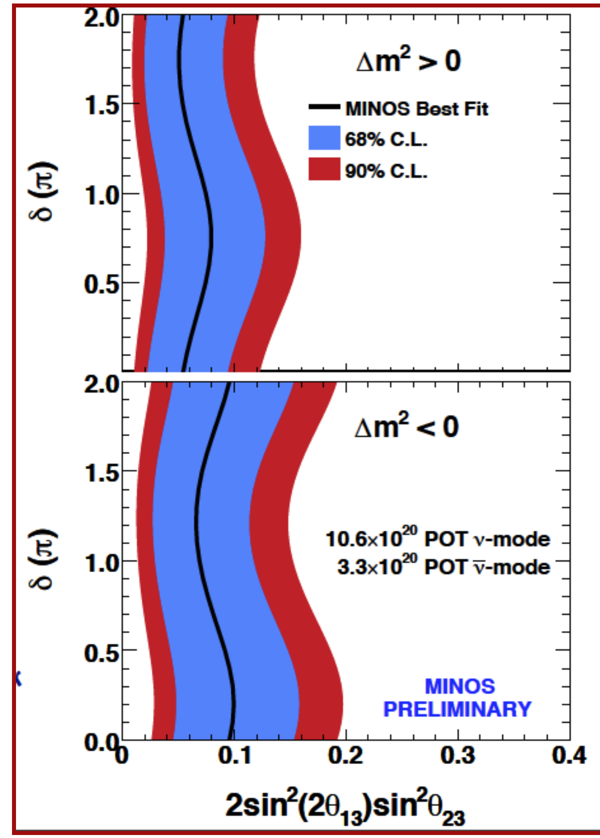
- ~3GeV ν_μ beam from FNAL 120GeV MI
  - ~350kW operation achieved
- (magnetized)Iron-scintillator tracker at 735km (5.4kt) and near (980t)
- Main physics goals
  - (anti-)ν_μ disappearance
  - ν_e appearance
- **Integral luminosity**
  - 10.7×10^{20} POT for ν_μ
  - 3.4×10^{20} POT for anti-ν_μ



MINOS: θ_{13}

- Neutrino beam
    - Expect: 128.6(+32.5) events
    - Observe: 152 Events
- Antineutrino beam
    - Expect 17.5(+3.7) events
    - Observe 20 events

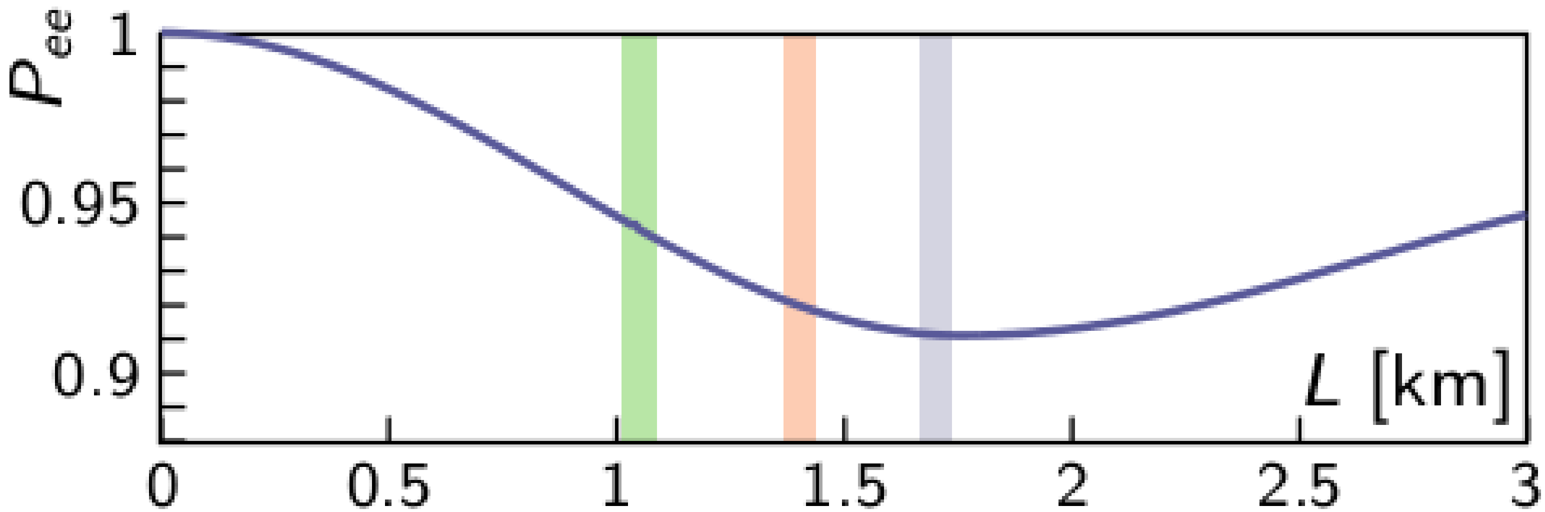




disfavour θ_{13}=0 at 96% CL
For normal mass hierarchy and δ=0

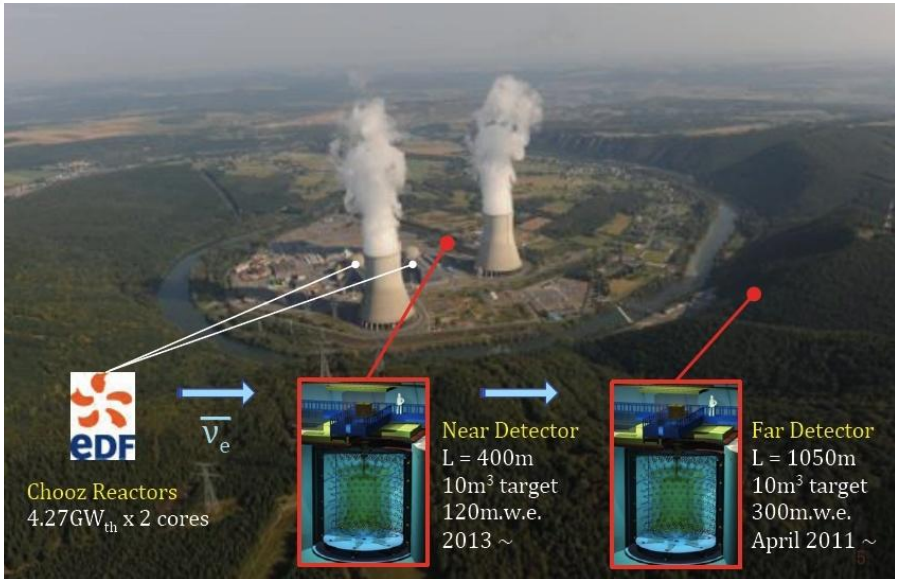
θ_{13} from reactor experiments

3 reactor experiments: Double Chooz, Daya Bay, RENO



	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

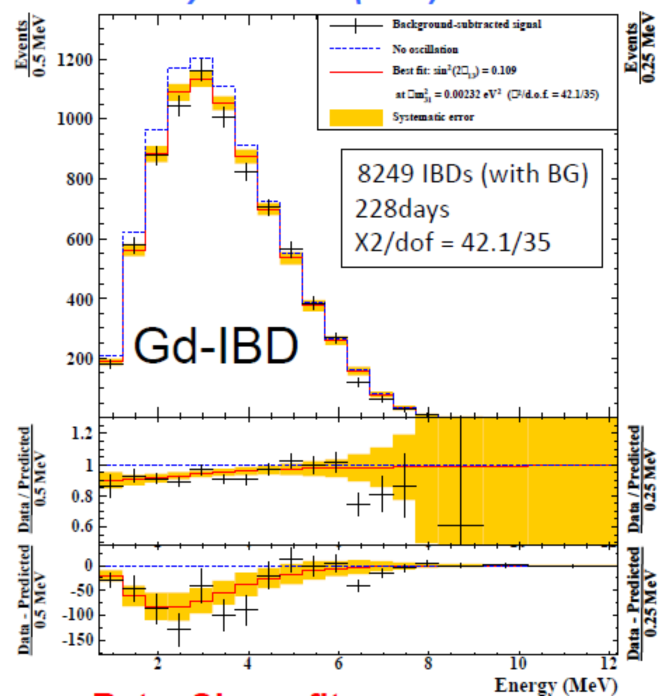
Double Chooz



„Standard“ Gd analysis:

- high cross section for capture of thermal neutrons
- capture time $\tau \approx 30$ μs
- delayed energy: 8 MeV

Phys. Rev. D86 (2012) 052008

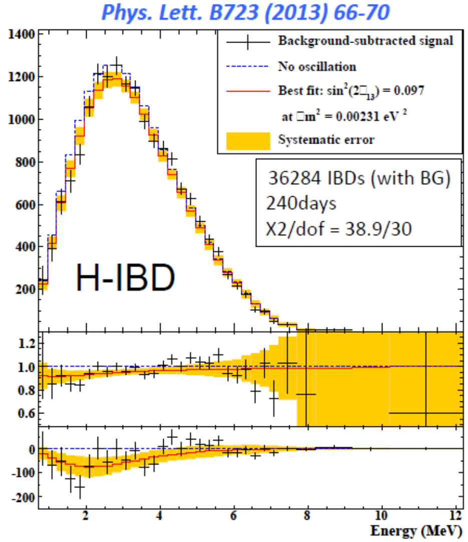


Rate+Shape fit:
$\sin^2 2\theta_{13} = 0.109 \pm 0.039$

H analysis: n+p →d + **γ** (2.2 MeV)

- Target + Gamma Catcher
  => 3 x more volume (2 x statistics)
- capture time: $\tau \approx 180$ μs
- delayed energy: 2.2 MeV
  ⇒ background!
- different systematics

Phys. Lett. B723 (2013) 66-70



$\sin^2 2\theta_{13} = 0.097 \pm 0.048$

Combined:
$\sin^2 2\theta_{13} = 0.109 \pm 0.035$

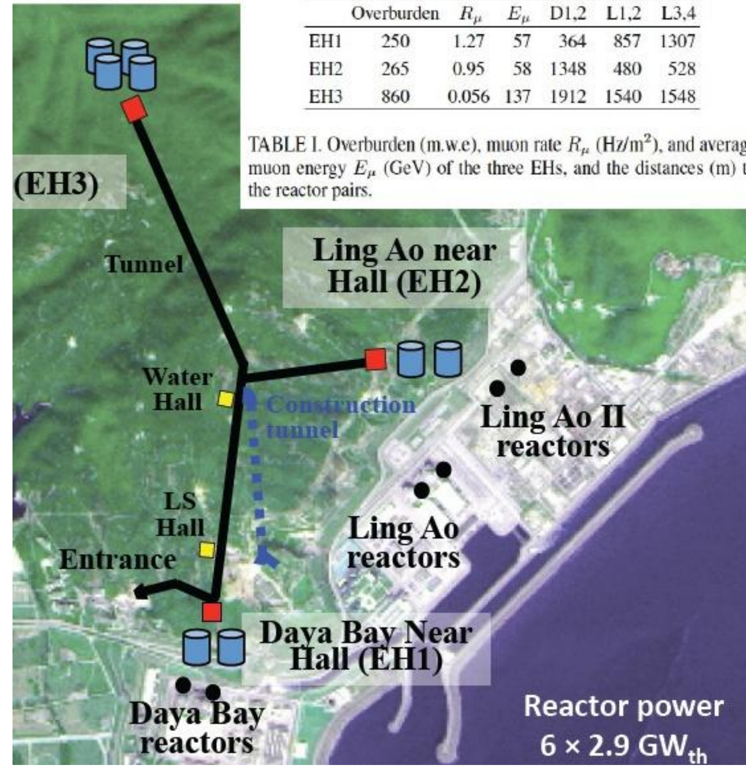
Daya Bay

Reactor experiment in China

- 17.4 GW$_{th}$ power
- 8 operating detectors
- 160 t total target mass

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

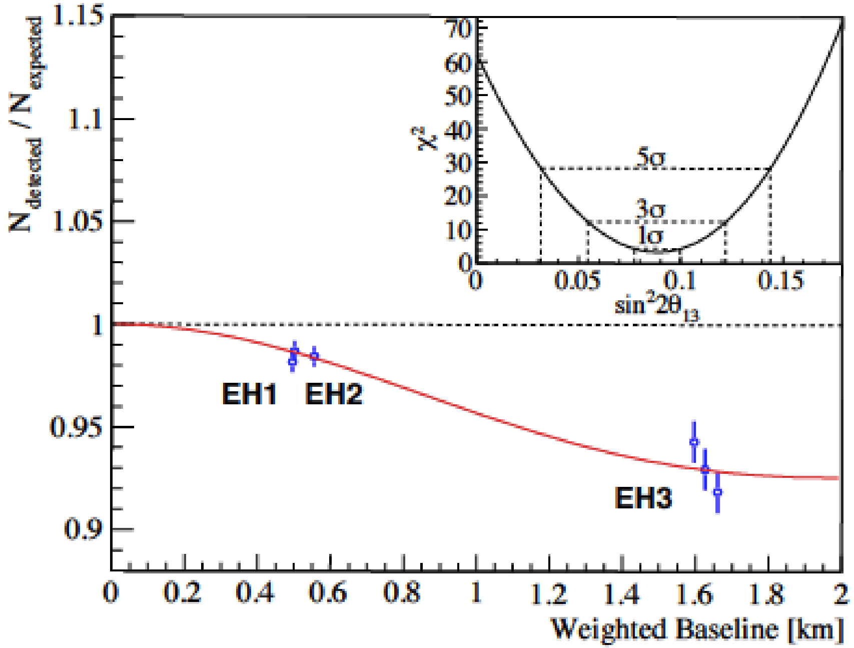
TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

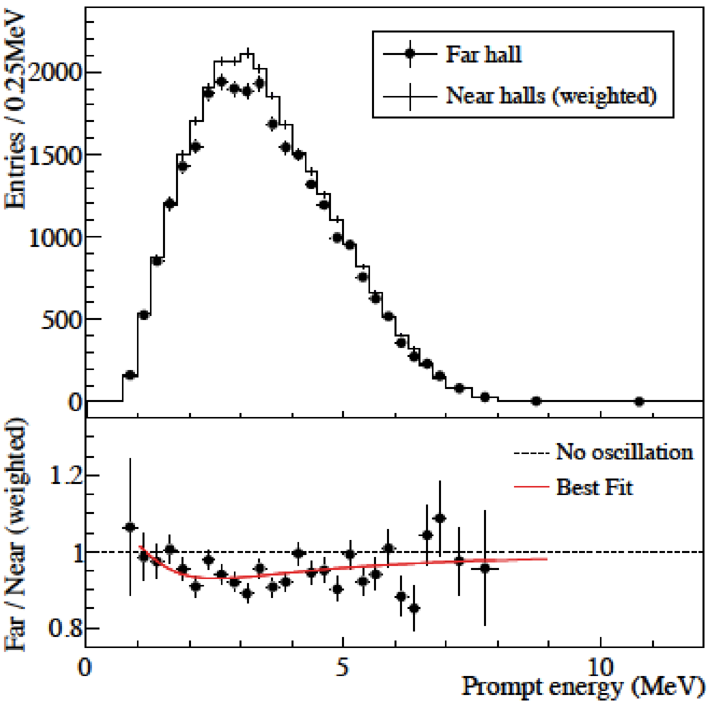


3.5×10^{21} neutrinos per second

Daya Bay result (I)

March 2012, after 55 days of data taking



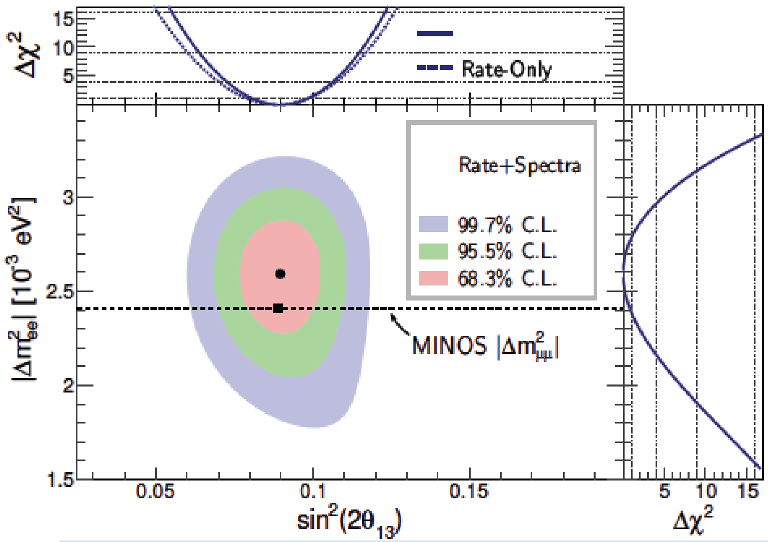


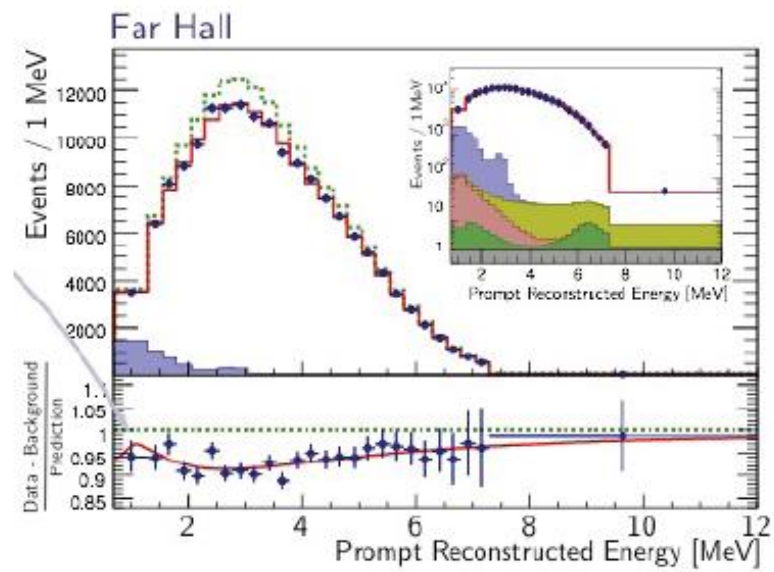
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

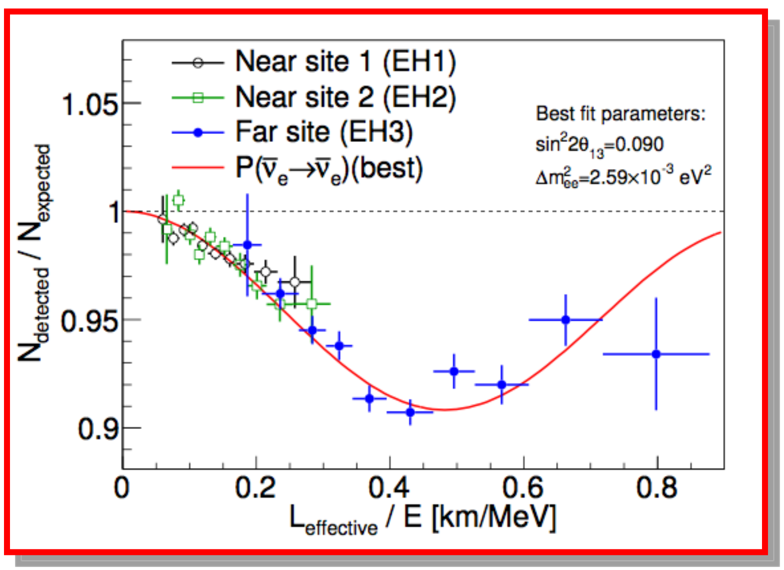
Daya Bay result (II)

Rate and spectral analysis

217 days of data taking







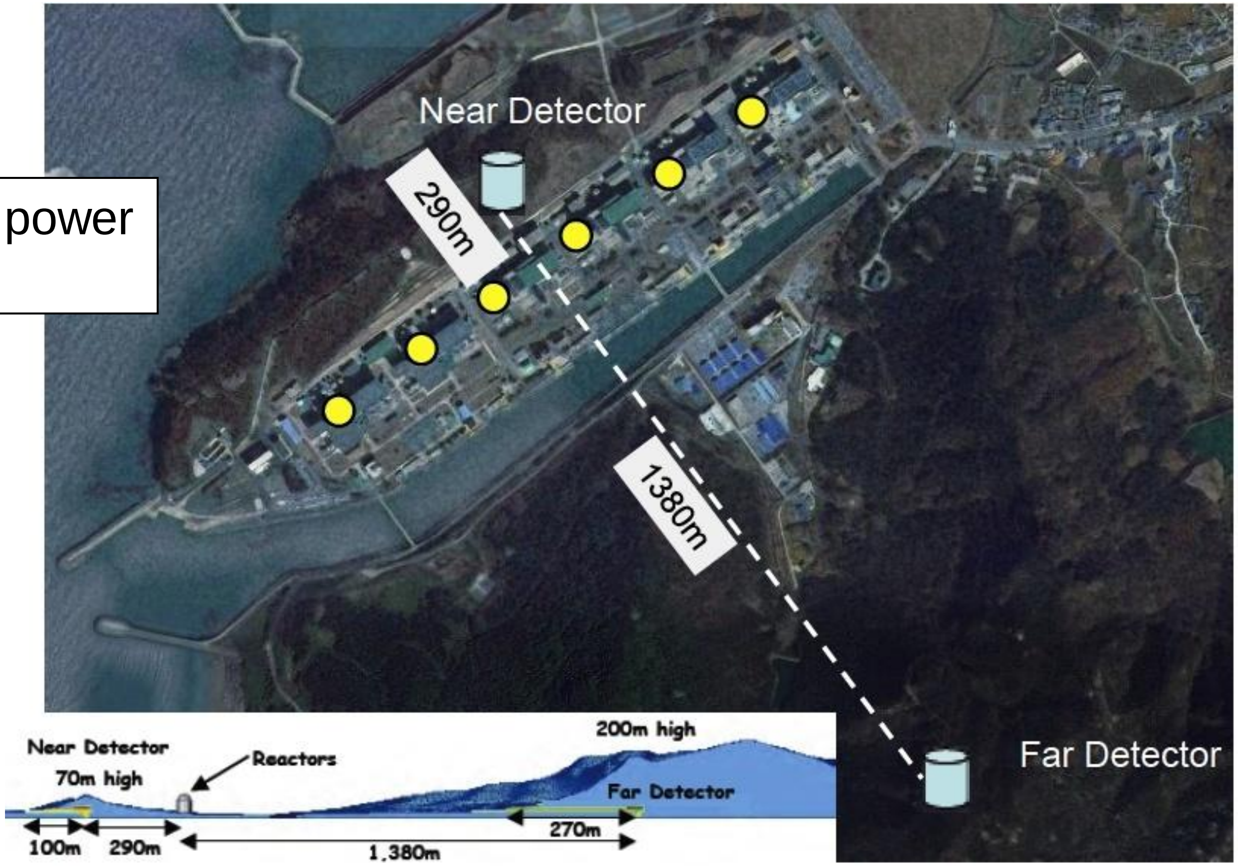
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\,\text{eV}^2$$

RENO

Reactor experiment in Korea

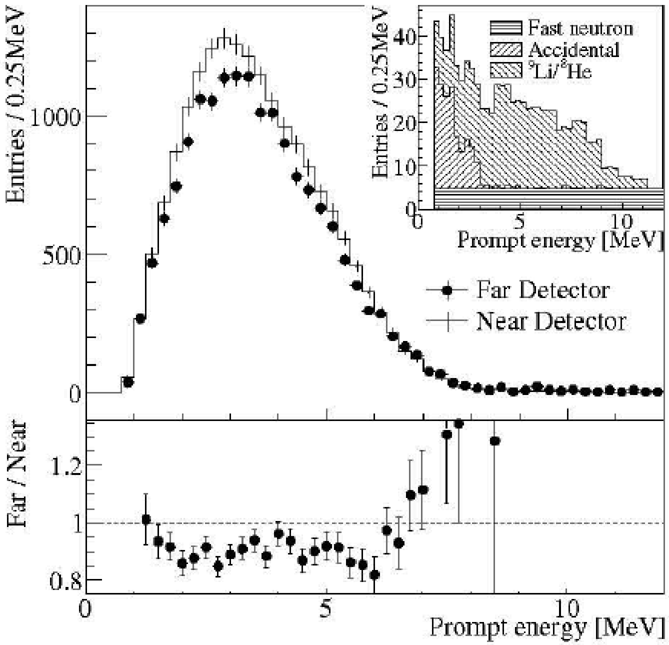
Reactor power
2.8 GW



- 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

Data taking since 1st August 2011
First result published in May 2012

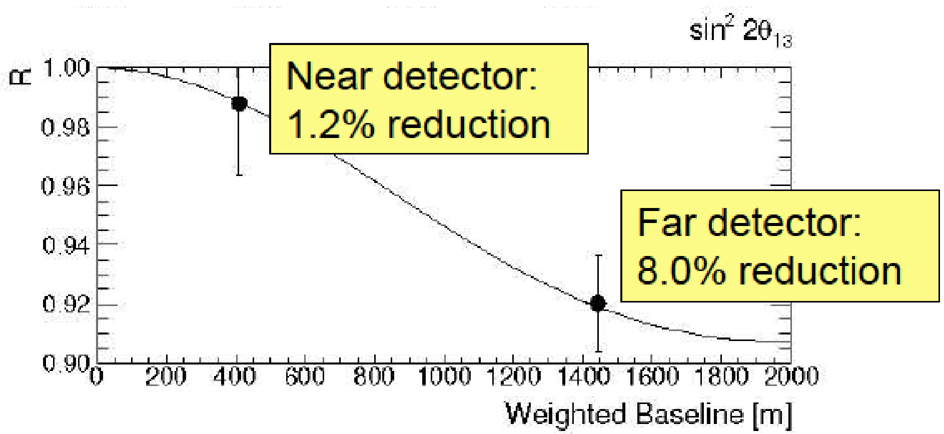
RENO result (I)



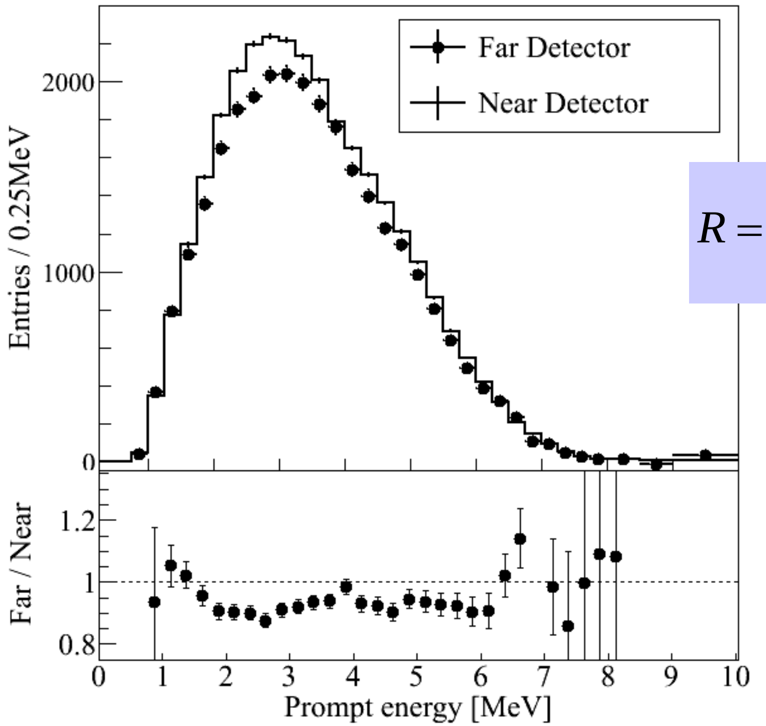
$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.920 \pm 0.009(stat) \pm 0.014(syst)$$

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

significance 4.9σ



RENO result (II)



S.-B.Kim
Erice/Sicily, Sep. 2013

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat) \pm 0.007(syst)$$

- A clear deficit in rate (~ 7 % reduction)
- Consistent with neutrino oscillation in the spectral distortion

- a new result on mixing angle θ_{13}.

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.012(syst)$$

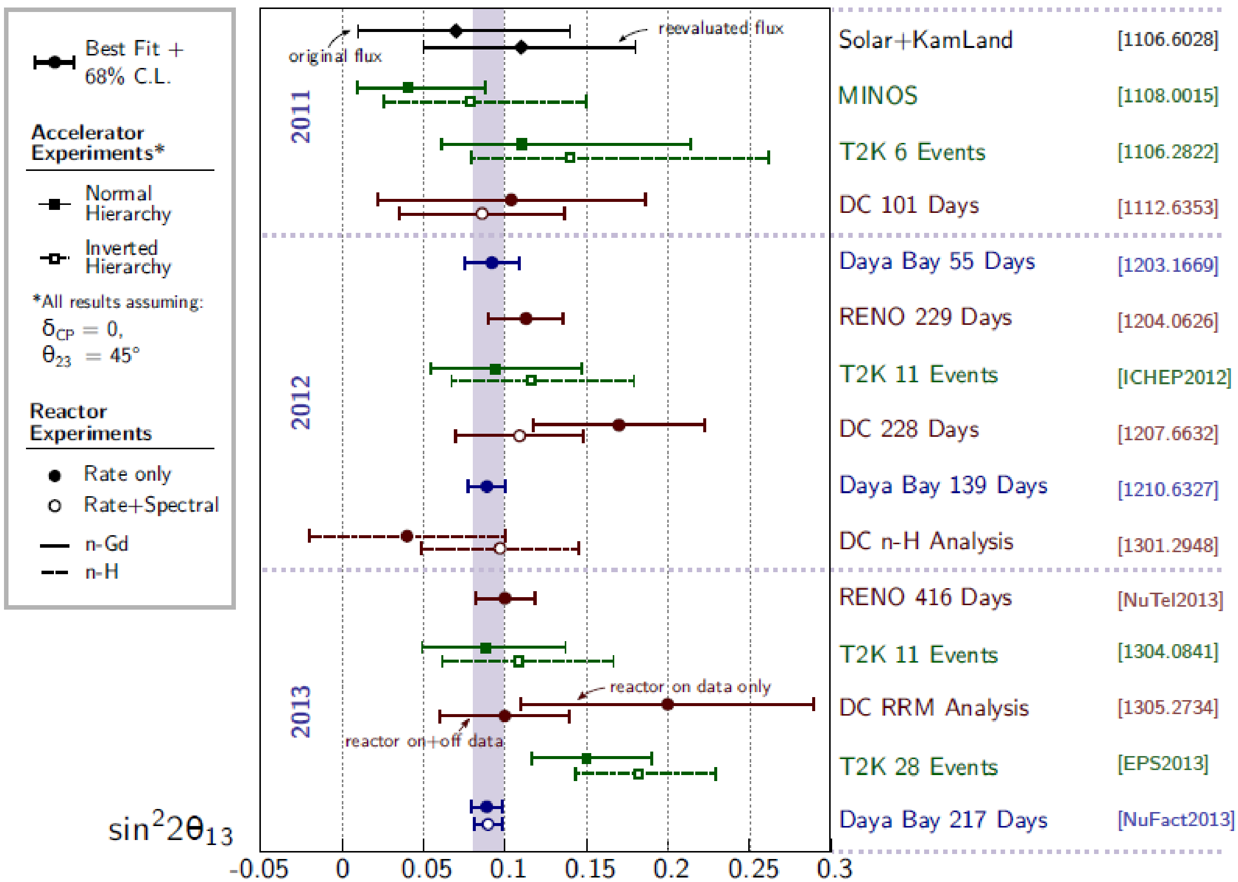
(402 days data taking)

(systematic error will be further reduced)

History of θ_{13} measurements

Only 2 years of measurements!

S. Jetter, Nufact2013

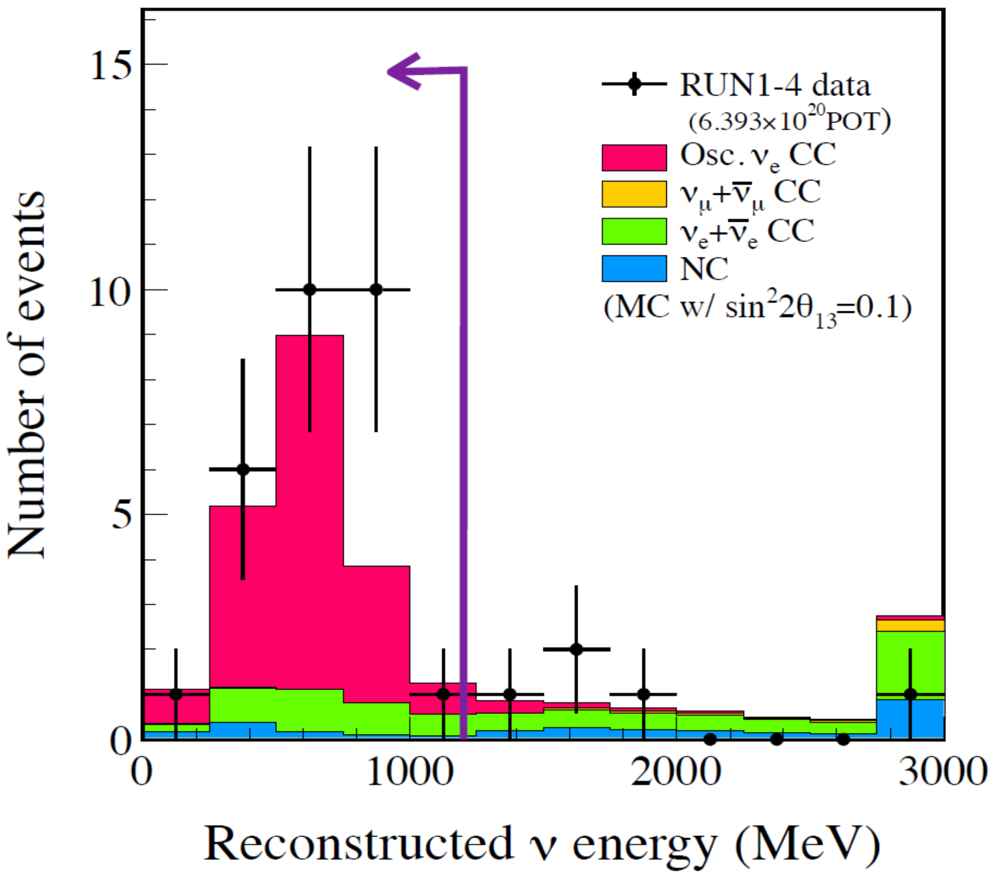


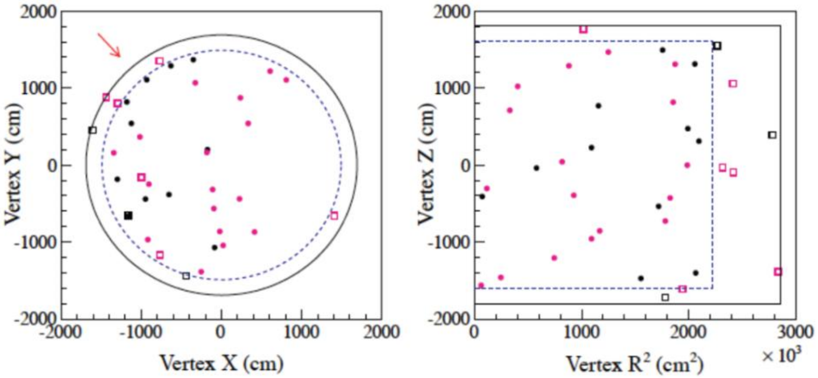
$\theta_{13} \approx 9^o$

T2K: observation of ν_e appearance

Summer 2013: integral luminosity 6.39×10^{20} pot

28 ν_e candidates

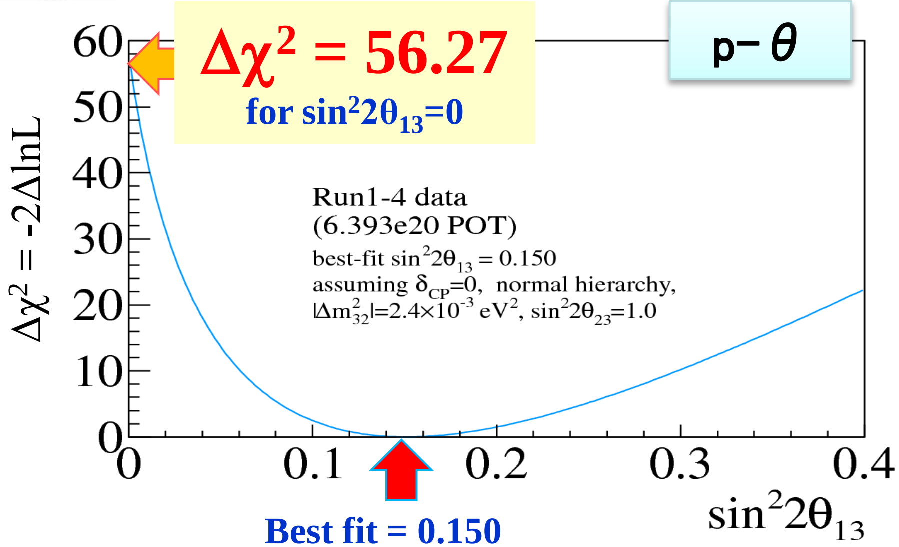


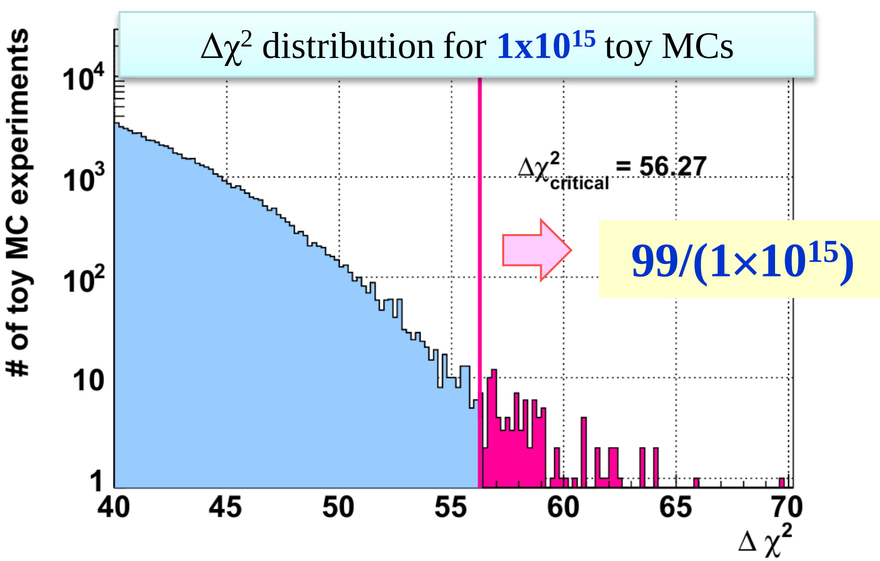


Expected background
($\sin^2 2\theta_{13}$=0.0)
4.64 ± 0.52 events

Significance

significance is calculated as $\sqrt{\Delta\chi^2}$





28 ν_e events detected
expected background
4.64 ± 0.52 events

$\sqrt{-2\Delta\ln L}=\sqrt{56.27}$
$= 7.5\sigma$

p-value is calculated as follows:

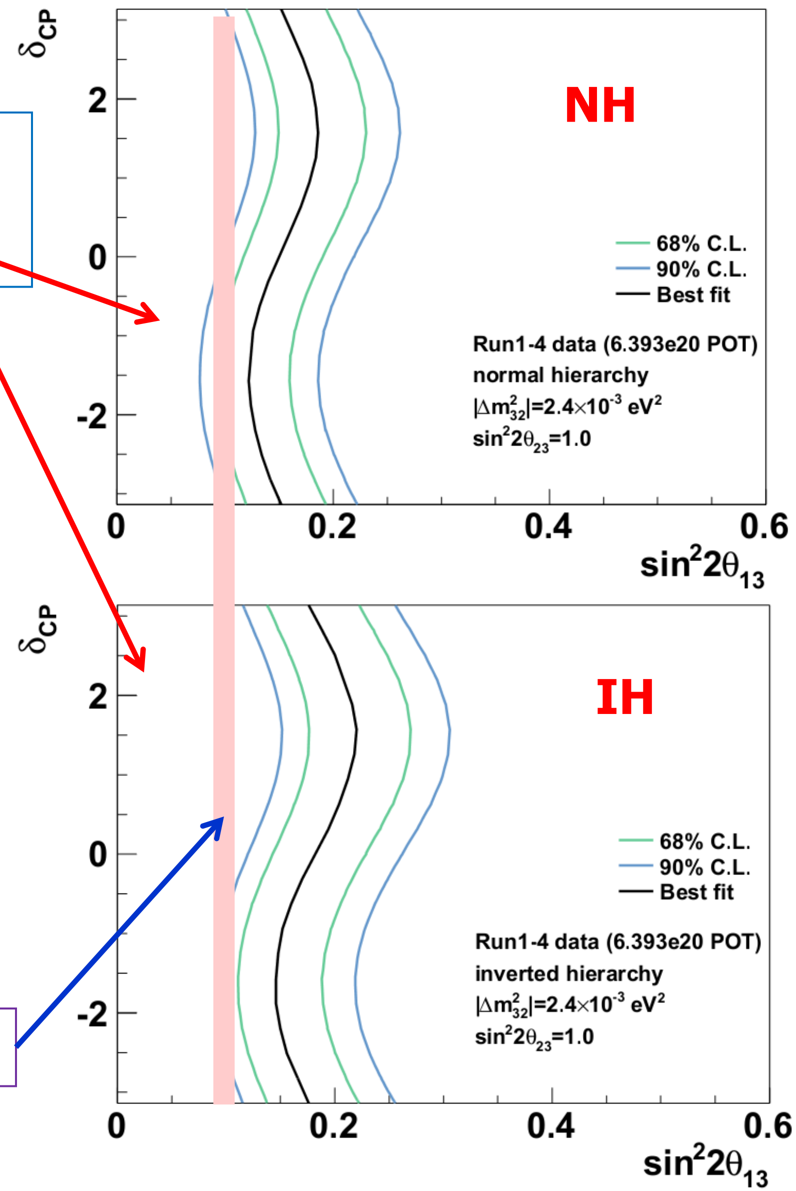
1. Generate 1e15 toy experiments with $\sin^2 2\theta_{13}=0.0$.
2. Fit each toy experiment extract $-2\Delta\ln L$ ($=\Delta\chi^2$).
3. p-value is the fraction of toy experiments above $\Delta\chi^2_{data}$

p-value = 9.9×10^{-14}

Discovery of ν_e appearance

Result: θ_{13} vs δ

allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



Best fit for $\delta_{CP}=0$

NH

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

IH

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

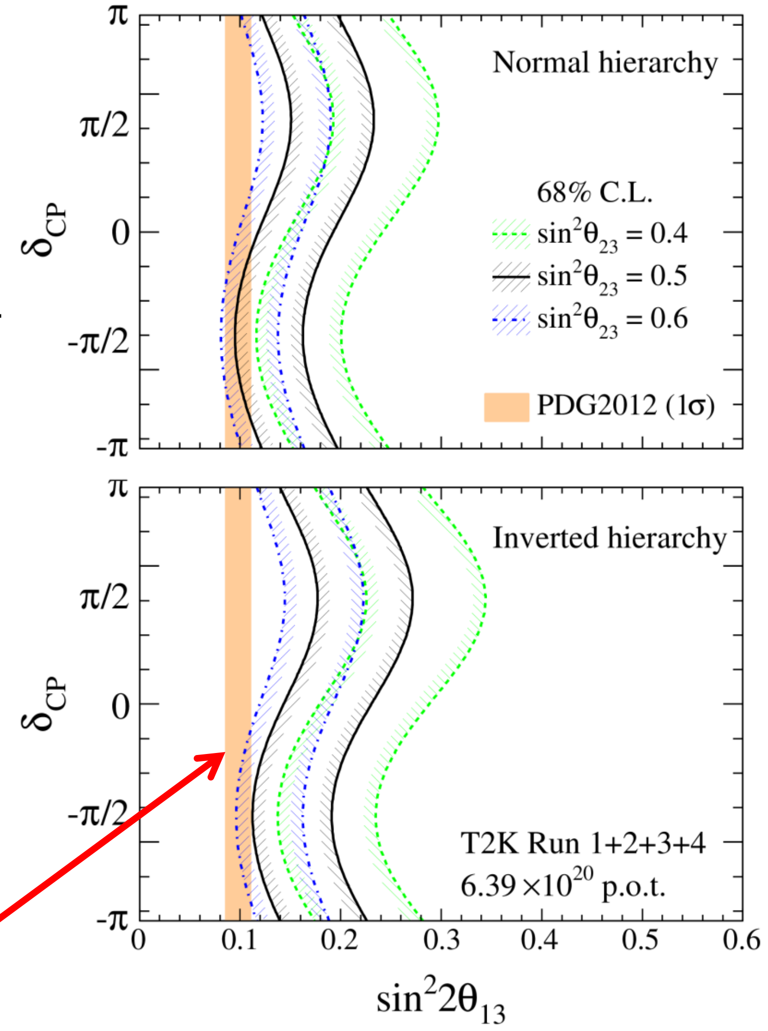
PDG(2012): $\sin^2 2\theta_{13}$: 0.098±0.013

θ_{23} issue

θ_{23} uncertainties dominate in δ - $\sin^2 2\theta_{13}$ plot

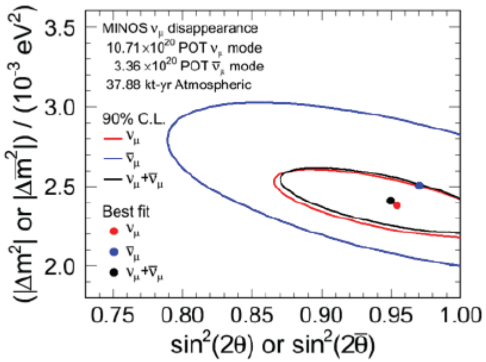
$$P_{\nu_\mu \to \nu_e} \approx \boxed{\sin^2\theta_{23}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

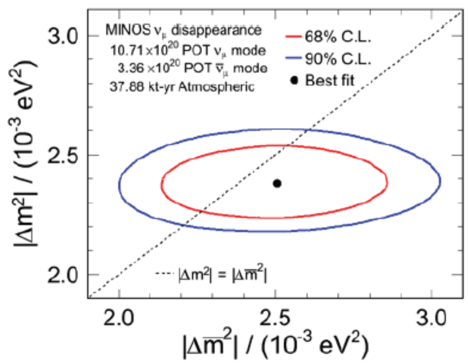
- **Oscillation probability is dependent on $\sin^2\theta_{23}$ (octant)**
  - **PDG2012: $\sin^2(2\theta_{23}) > 0.95$**
    - **$\sin^2\theta_{23} = 0.50 \pm 0.11$**
    - **$\theta_{23} = 45 \pm 6.5°$**
  - **Reduction of $\sin^2\theta_{23}$ error is critical for further improvements**

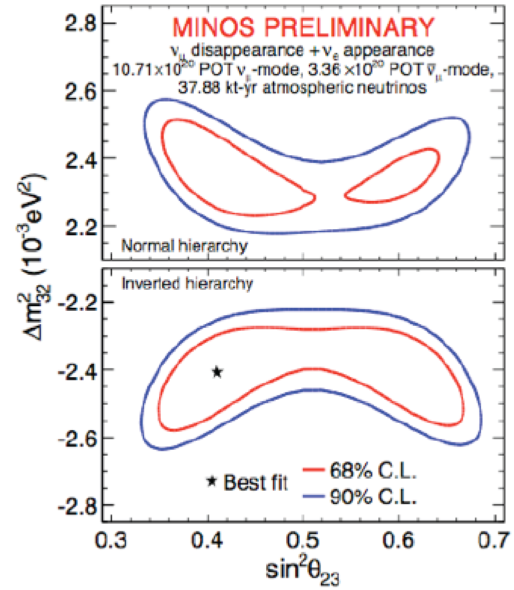


PDG(2012)

MINOS







$\bar{\nu}$ oscillation parameters

$$\sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08}$$

$$\Delta\overline{m}^2 = 2.50^{+0.23}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \ (90\% C.L.)$$

ν oscillation parameters

$$\sin^2(2\theta) = 0.95^{+0.035}_{-0.036}$$

$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

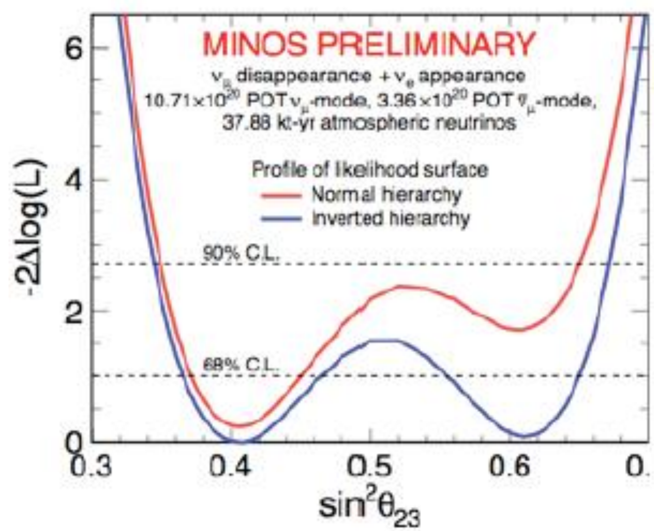
$$\sin^2(2\theta) > 0.89 \ (90\% C.L.)$$

MINOS Preferences:

Low octant, $\theta_{23} < 45^o$

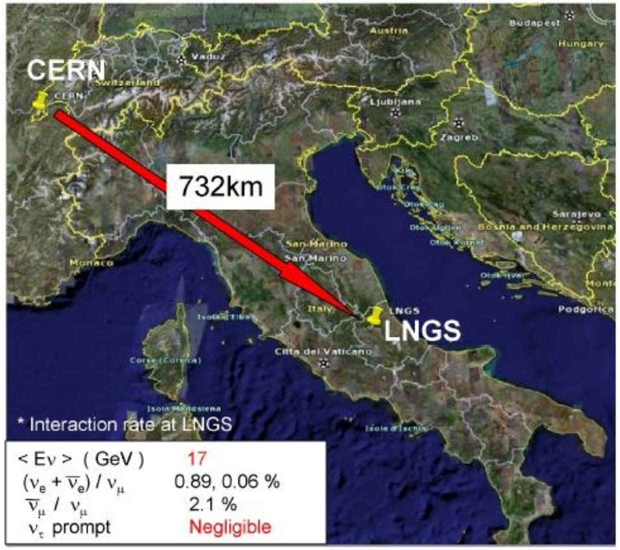
Non-max mixing

Inverted Mass hierarchy

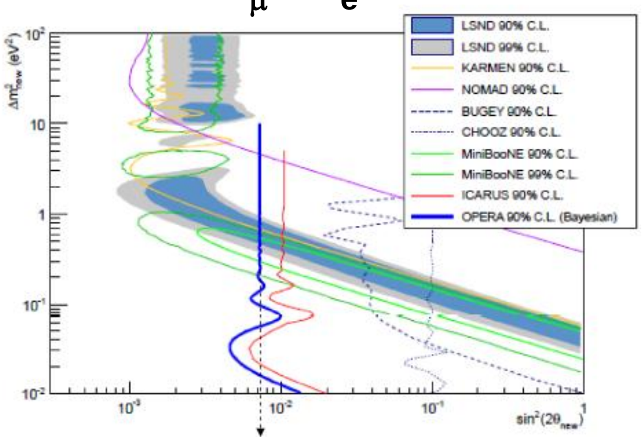


OPERA

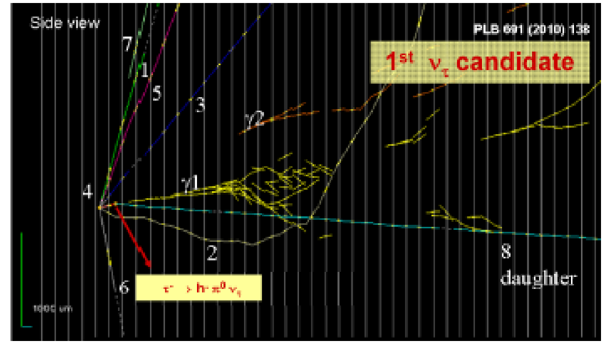
Neutrino beam from CERN to Gran Sasso

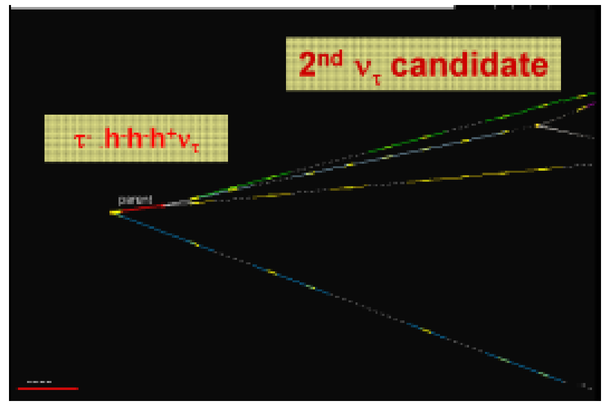


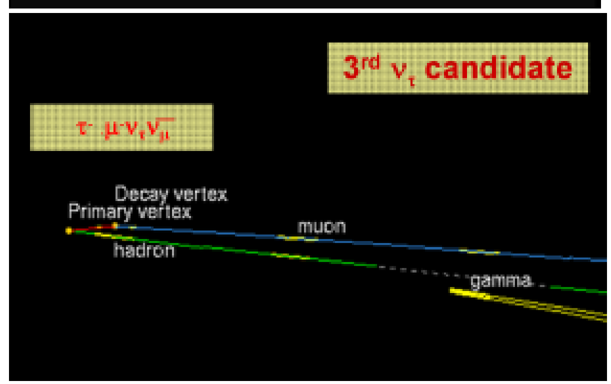
$\nu_\mu \to \nu_e$



$\nu_\mu \to \nu_\tau$







Data 2008-2009

Expected bkg 0.226 ν_τ events

3 ν_τ events: significance **3.2σ**

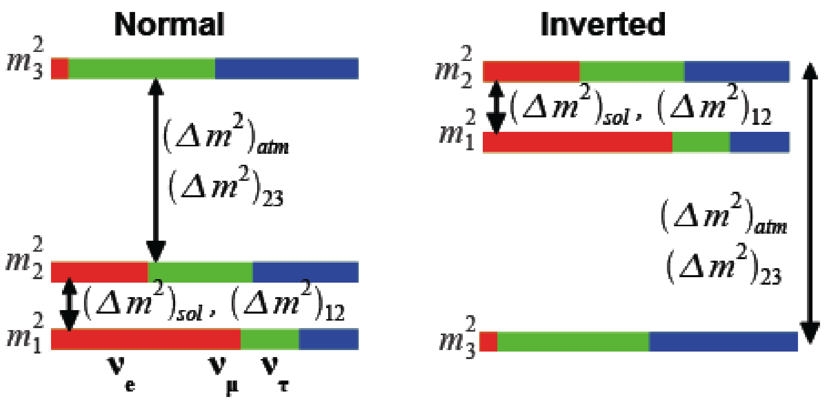
p-value of background **7.3×10^{-3}**

Next targets ?

2011-2013
Great milestones

- $\theta_{13} = (9 \pm 0.6)^0$
- ν_e appearance observed at 7.5σ

Mass Hierarchy



+

precision measurement of oscillation parameters

θ_{23}: $\geq 45^o$ or $\leq 45^o$

CP violation

$J_{CP} = Im(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = Im(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2})$
$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta$

all mixing angles $\neq 0 \rightarrow$ $J_{CP} \neq 0$ if $\delta \neq 0$

CKM

$$\begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

PMNS

$$\begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quark sector $J_{CP} \approx 3\times10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta$

$\nu_\mu \to \nu_e$ in matter

Physics reach oscillation mode for accelerator LBL experiments is $\nu_\mu \to \nu_e$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] && \rightarrow \theta_{13} \\
&+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{CP-even} \\
&- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{CP-odd} \\
&+ 4s_{12}^2 c_{13}^2(c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu} && \rightarrow \text{Solar} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2), \quad (30) && \rightarrow \text{Matter}
\end{aligned}
$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij} \qquad a[eV^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[g/cm^3\right]E_\nu[GeV]$$

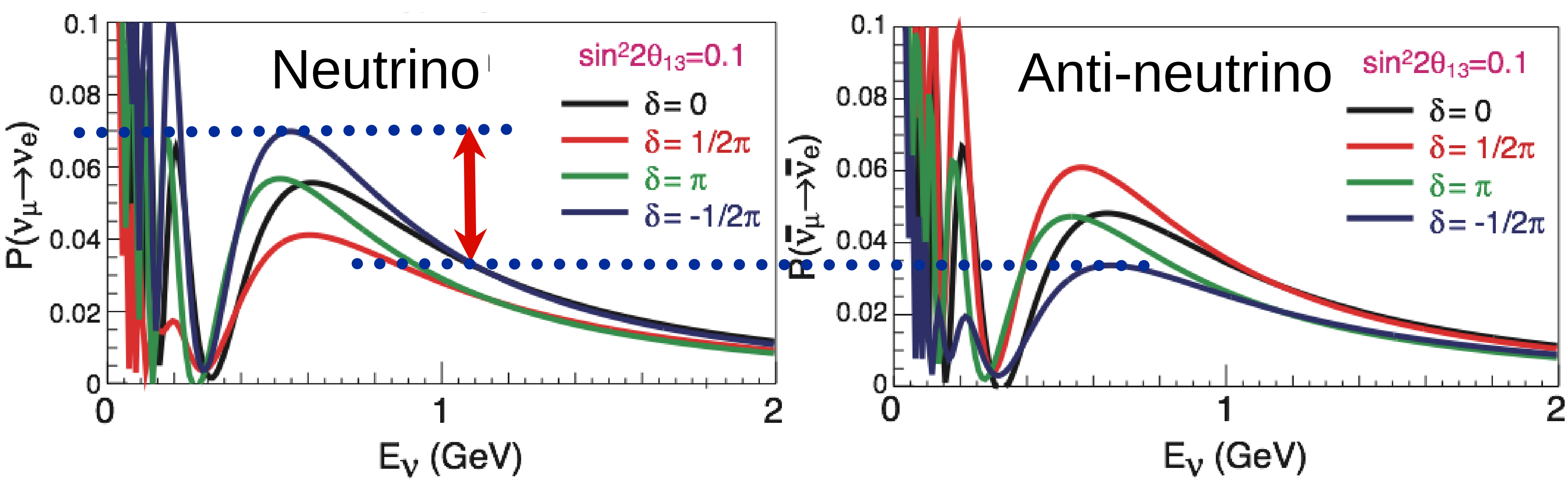
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow a \to -a \qquad \delta \to -\delta$$

change sign for NH → IH

CP measurements

for 295km baseline, normal hierarchy

$P(\nu_\mu \rightarrow \nu_e)$: ν_e appearance probability



- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_e)$
  Max. ~±25% (L=295 km) change from δ=0 case
- Measure 1st and 2nd oscillation maxima in **$P(\nu_\mu \rightarrow \nu_e)$**
- Comparison of accelerator **$P(\nu_\mu \rightarrow \nu_e)$** and reactor **P(anti-$\nu_e$ → anti-ν_e)**

Matter effect → fake CP violation, BUT sensitive instrument to determine mass hierachy

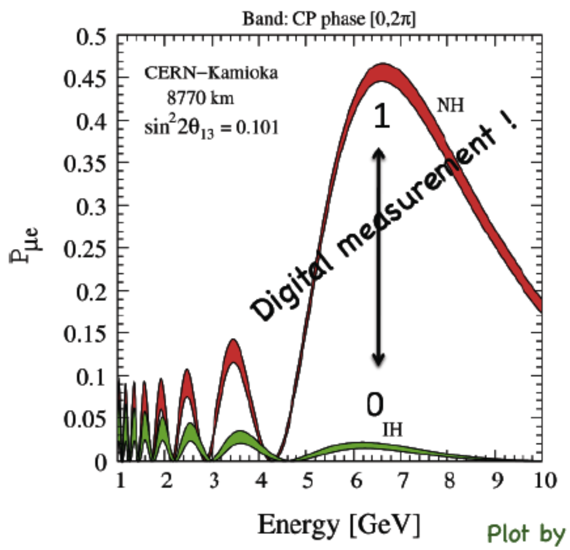
Measurement of MH

Matter effect: appearance – accelerator experiments NOvA, LBNE, LBNO
disappearance – PINGU,ORCA, INO, HyperK

Interference effect between
solar and atmospheric oscillations: reactor experiments JUNO, RENO50

accelerator experiments

MSW effect at ~6.5 GeV
only neutrino beam



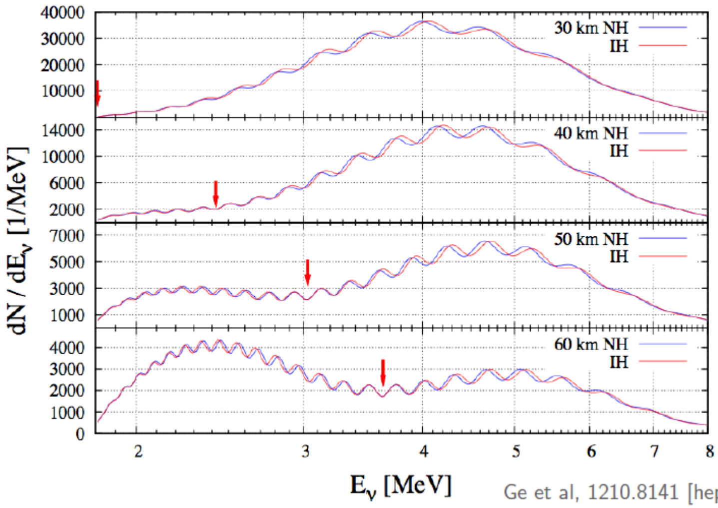
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e},$$

$$n_e(L)L|_{L_{\rm max}} = \frac{\pi}{\sqrt{2}G_F \tan 2\theta_{13}}$$

Plot by S. Agarwalla

reactor experiments

$$\begin{aligned} P_{ee} \; = \; & 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ & - \sin^2 2\theta_{13}\sin^2\Delta_{31} \\ & - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{21}\cos 2\Delta_{31} \\ & \pm\frac{1}{2}\sin^2\theta_{12}\sin^2 2\theta_{13}\sin 2\Delta_{21}\sin 2\Delta_{31} \end{aligned}$$



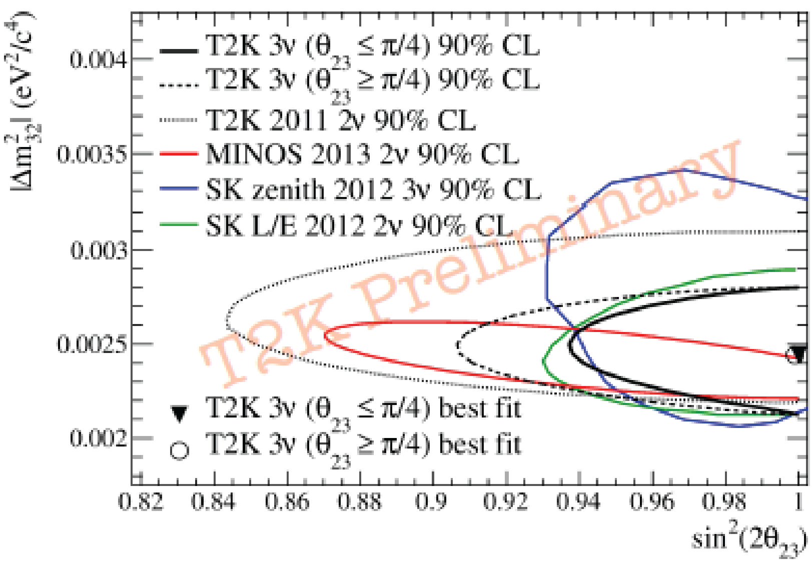
Ge et al, 1210.8141 [hep-ph]

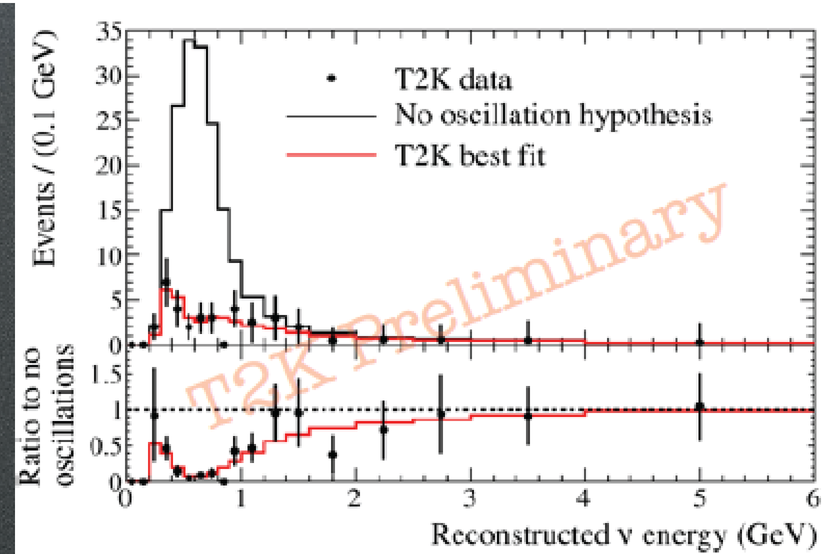
θ_{23} measurement

ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

Leading — Next-to-leading

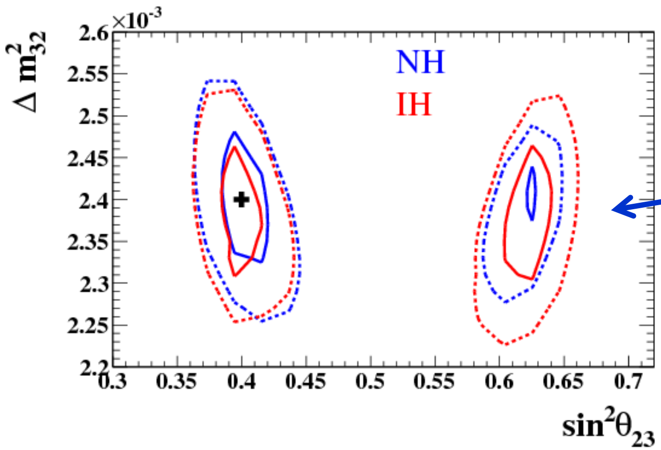




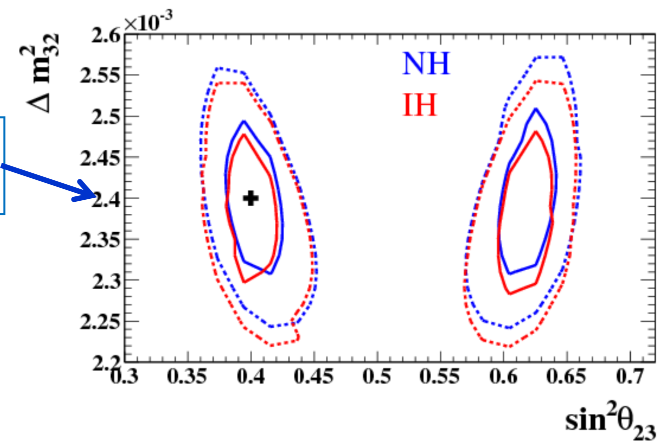
Perspectives: θ_{23}

T2K

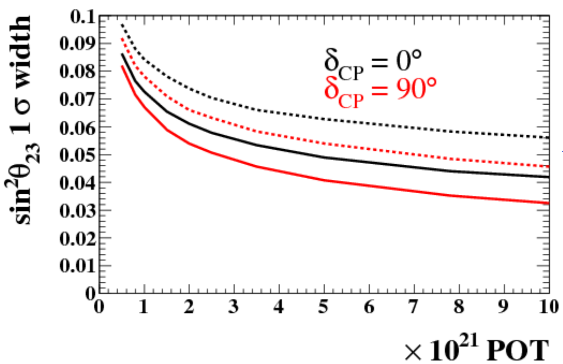
7.8×10^{21} pot
100% ν running 90% CL
$\sin^2 2\theta_{13} = 0.1$ + reactor data
solid: stat only; dashed: stat +current sys



7.8×10^{21} pot
50% ν - 50% anti-ν running 90% CL
$\sin^2 2\theta_{13} = 0.1$ + reactor data
solid: stat only; dashed: stat +current sys

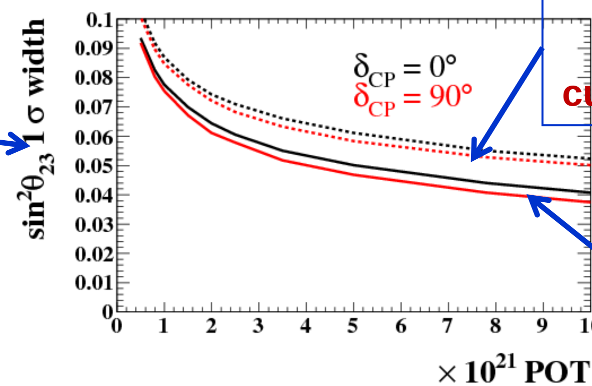


Octant



θ_{23}

estimation
$\sigma(\theta_{23}) \sim 2$ deg

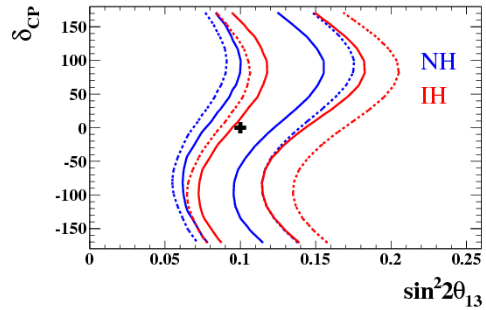


stat + current syst

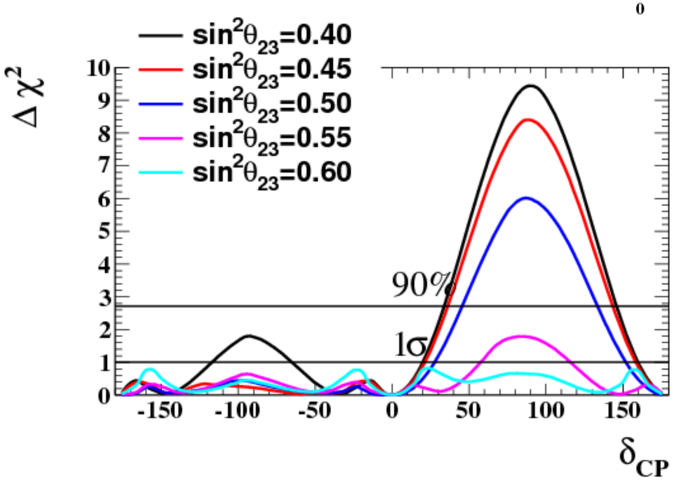
stat only

T2K: sensitivity to CP

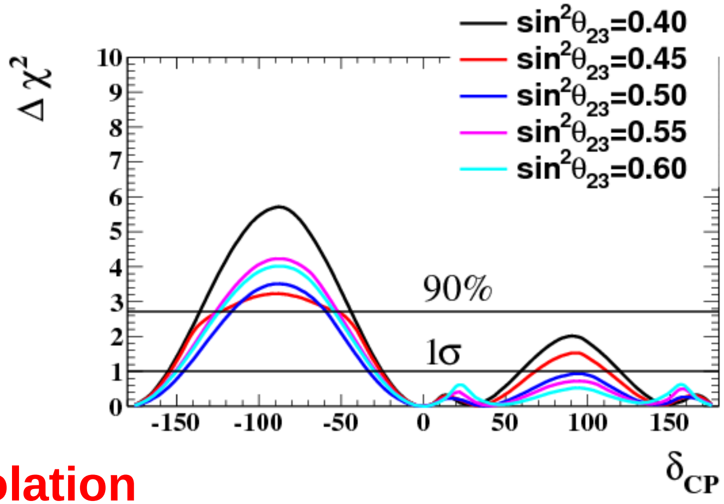
IH 7.8×10[21] pot
100% ν running
$\sin^2 2\theta_{13} = 0.1$
+ reactor data



NH 7.8×10[21] pot
50% ν - 50% anti-ν running
$\sin^2 2\theta_{13} = 0.1$ + reactor data

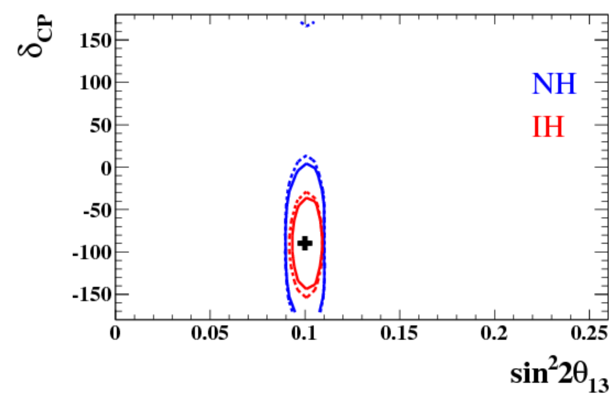


T2K



Chance to find an indication for CP violation if δ is about π/2 or -π/2

7.8×10[21] pot
50% ν - 50% anti-nu running
$\sin^2 2\theta_{13} = 0.1$ + reactor data
$\sin^2 2\theta_{23} = 0.5$
δ = - 90 deg



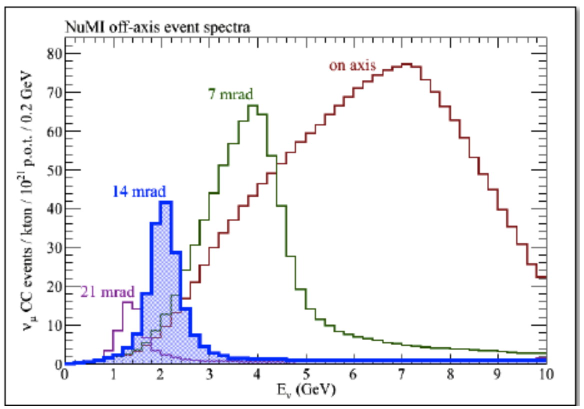
Nova

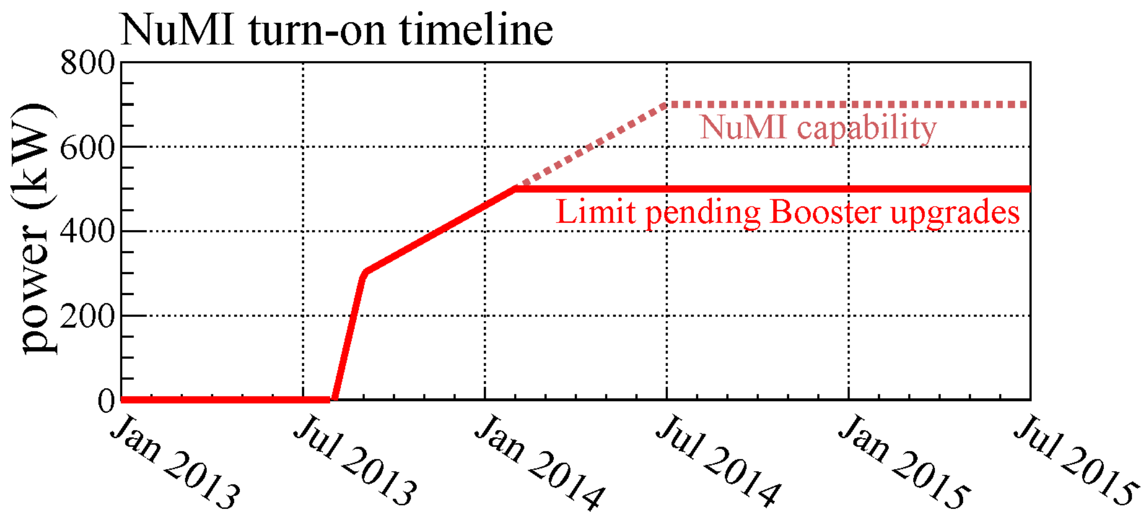
LBL experiment using neutrino off-axis narrow-band beam from FNAL

- 810 km long baseline.
- 700 kW NuMI beam.
- 2 GeV peak energy.
- Far detector in Ash River, MN.
- Near detector 1 km from target.
- 14 mrad off-axis beam.

Beam schedule

NOvA: first run in September 2013 with beam operating at ~300 kW



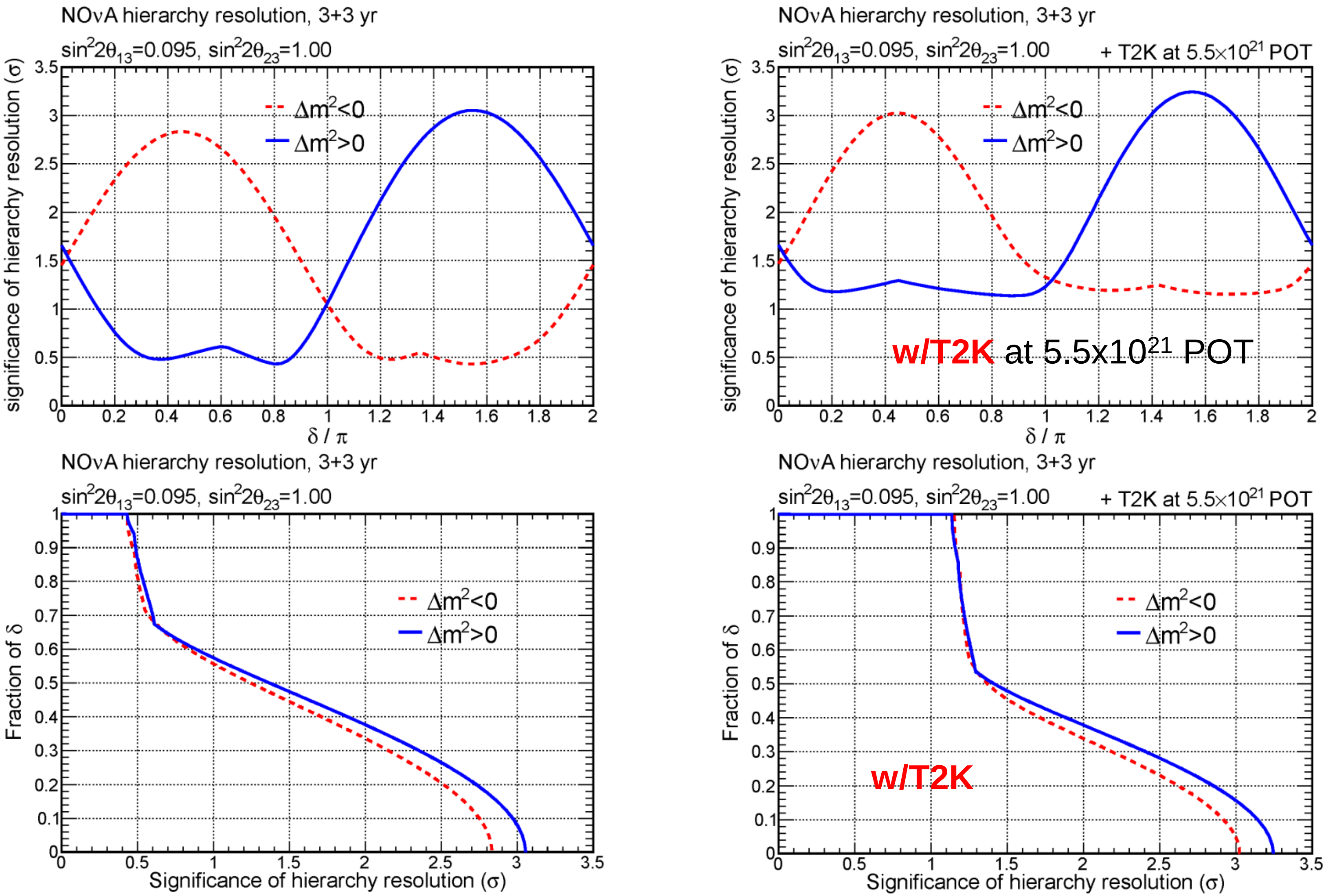


Beam intensity will be increased up to 500 kW next year and to 700 kW in 2 years.

Far Detector mass will be added at a rate of about 1 kton/3 weeks.
Full installation of NOvA detectors will be completed in 2014.

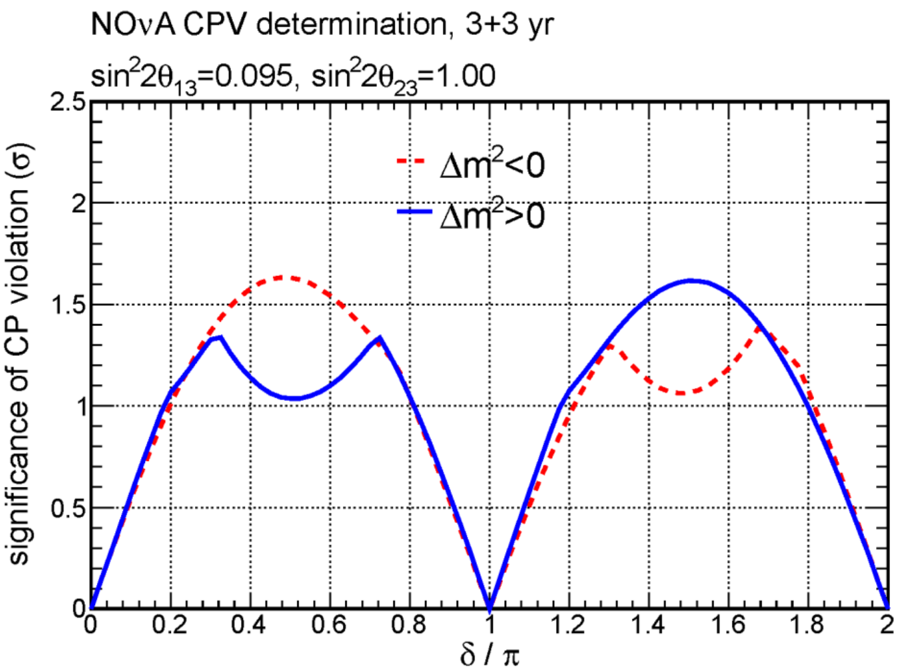
Mass Hierarchy

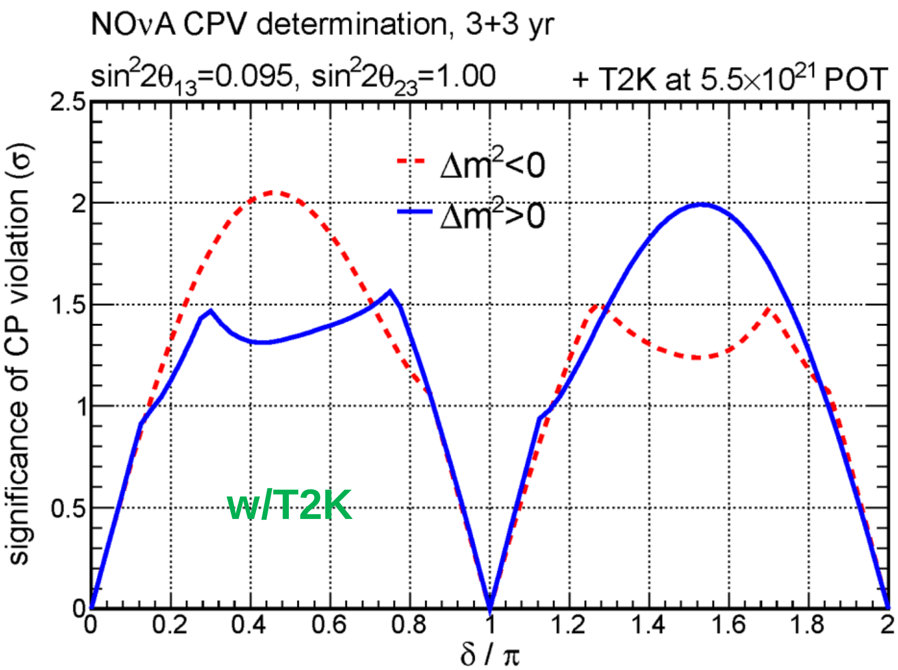
Significance of the MH determination



CP violation

Significance with which NOvA (+T2K) can establish CP violation.



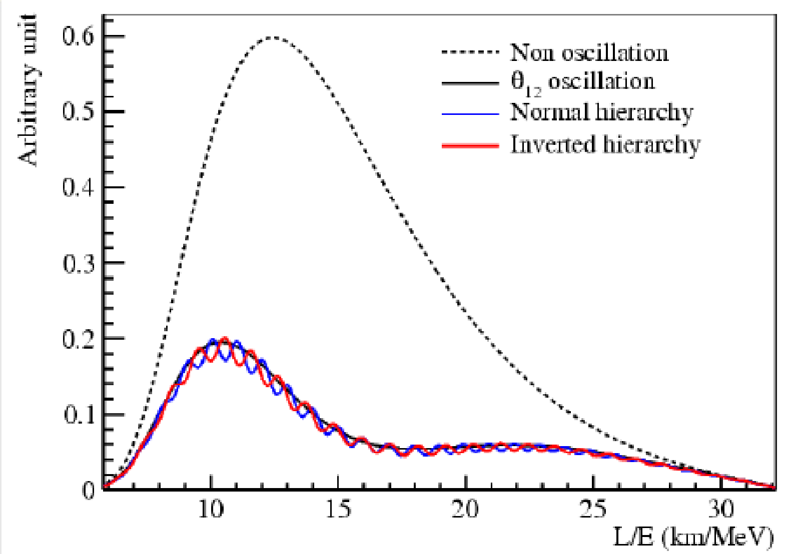


The significance goes to zero at $\delta = 0$ and $\delta = \pi$ since there is no CP violation at those points. The dips in the peaks occur because the mass ordering has not been resolved.

Best case: CP violation at 1.6σ (Nova only) and 2.0σ (Nova + T2K)

Far Future Prospects

JUNO and RENO50



Two reactor experiments with L~ 50 km proposed in China and Korea

RENO50

10 Kton liquid scintillator

L~47 km (very close to optimal)

RENO used as near detector

Data taking expected to start in 2019

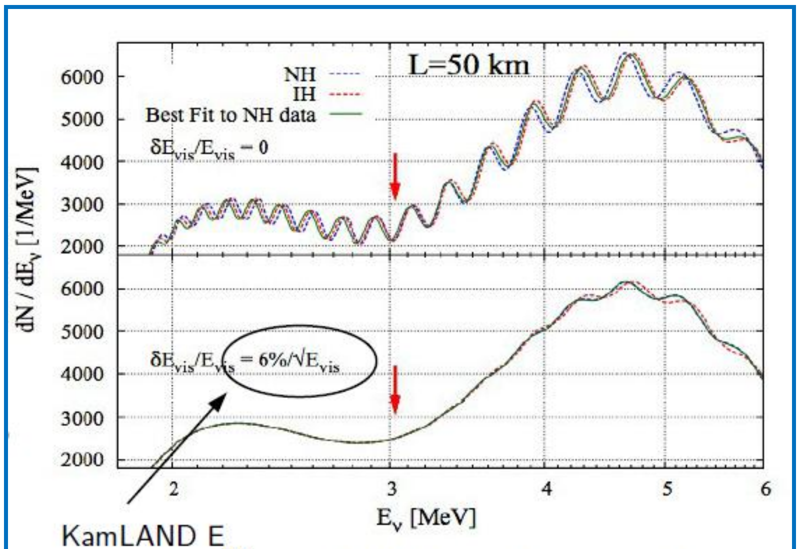
JUNO

20 Kton liquid scintillator

L=53 km (very close to optimal)

2 reactors, each of them with P~18 GW

Data taking expected to start in 2020



JUNO can determine the mass hierarchy with a confidence level of $\Delta\chi2 \sim 19$ (4.4 σ) after 6 years of data taking

LBNE

$\nu_\mu \to \nu_e$

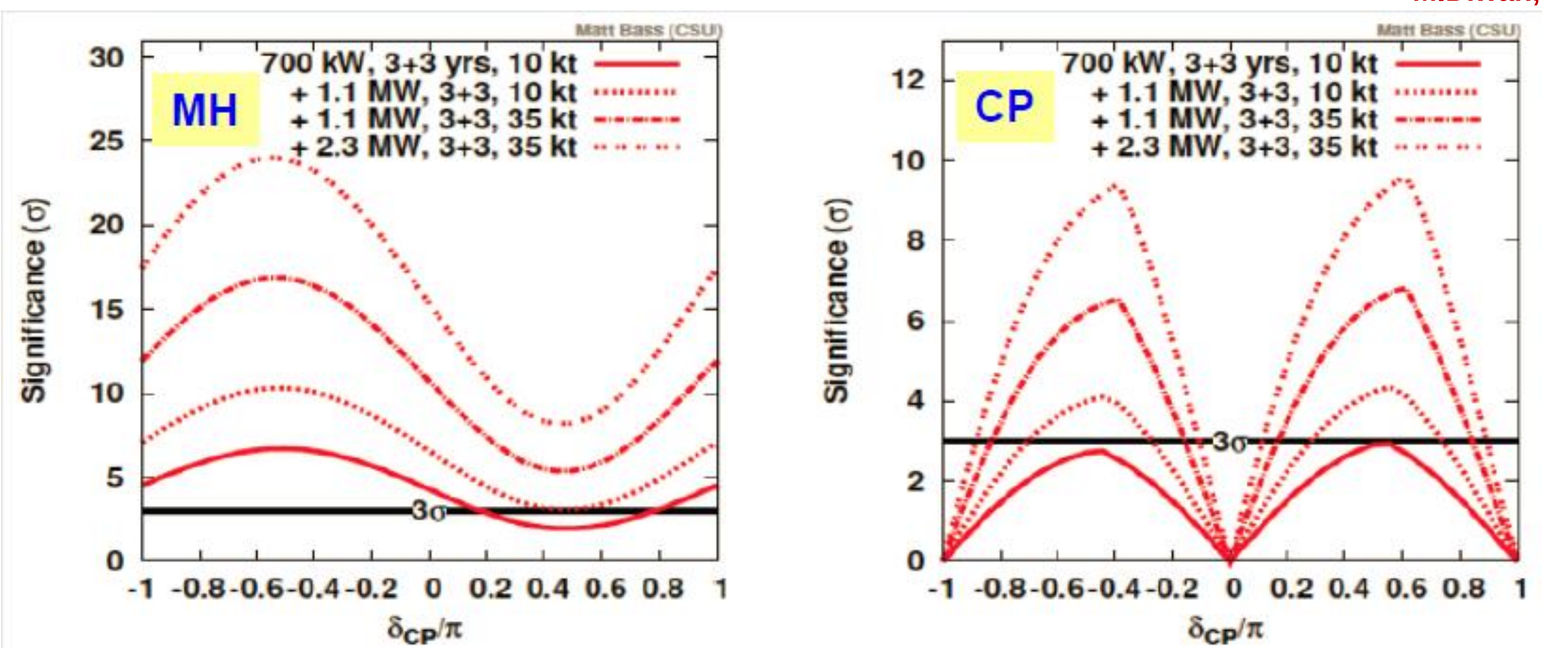
The US based LBL project

Neutrino beam from FNAL to Homestake
L = 1300 km, Ep= 80-120 GeV, 0.7-2.3 kW NuMI
E_ν = 0.5 – 5 GeV

1st stage: far detector 10 kt LAr TPC, on surface
2nd stage: far detector 34 kt Lar TPC, underground

Sensitivity to MH and CP phase

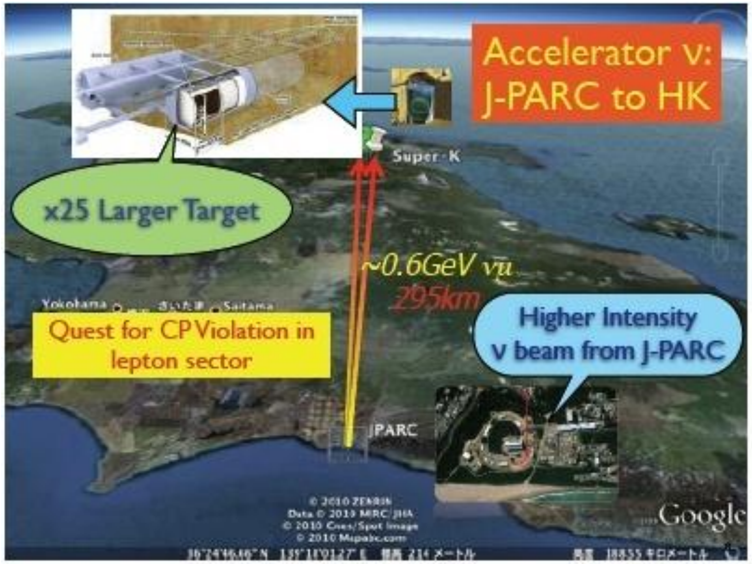
M.Diwan, NeuTel 2013



T2HK

$\nu_\mu \rightarrow \nu_e$

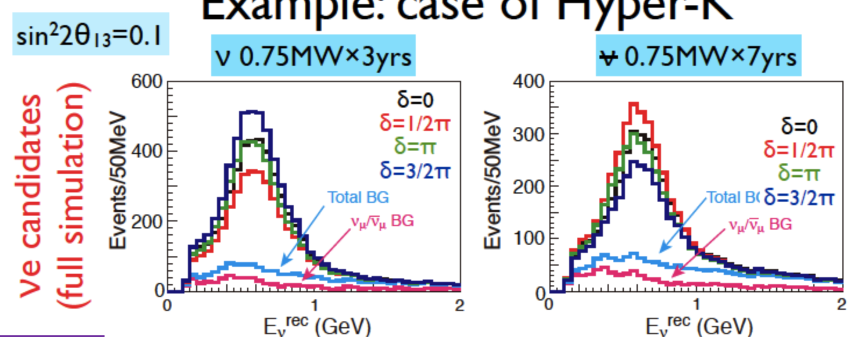
The LBL project in Japan



- **JPARC 1.66MW**
- **off-axis ν beam**
- **L = 296 km**
- **far detector HyperKamiokande total mass 1 Mt**

Example: case of Hyper-K

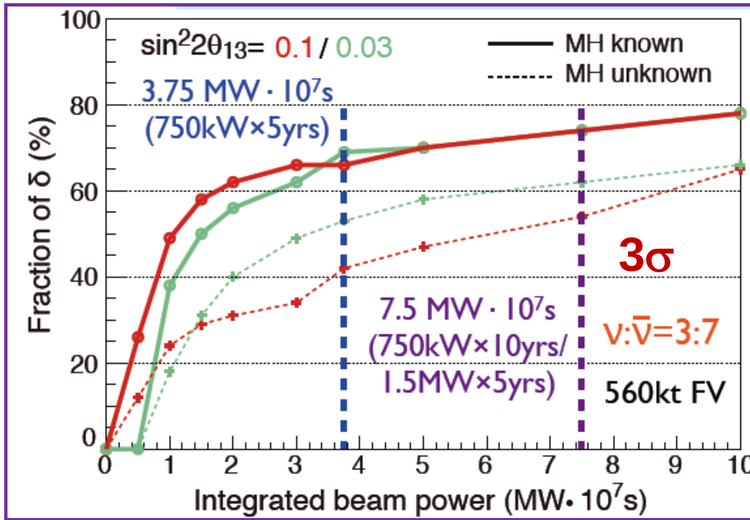
$\sin^2 2\theta_{13}=0.1$



Expected number of ν_e candidate events for δ=0

$\nu_\mu \rightarrow \nu_e$ CC	3606
$\nu_\mu + \bar{\nu}_\mu$ CC	35
$\nu_e + \bar{\nu}_e$ CC	880
NC	649

$\nu_\mu \rightarrow \nu_e$ CC	2339
$\nu_\mu + \bar{\nu}_\mu$ CC	23
$\nu_e + \bar{\nu}_e$ CC	878
NC	678

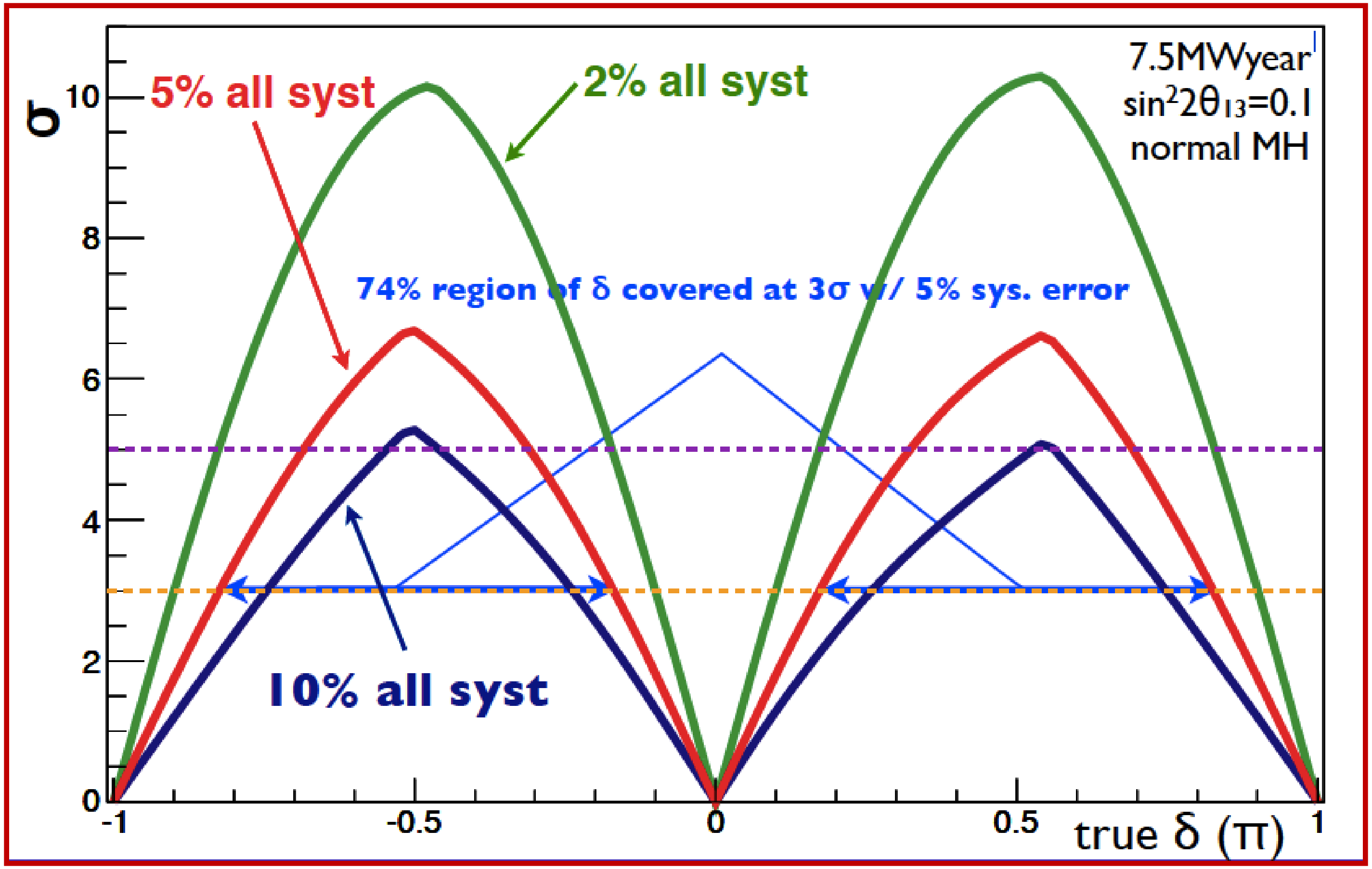


For $\sin^2 2\theta_{13}=0.1$

Integ. power ($MW\times 10^7 s$)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

T2HK: CPV discovery potential

MH is known !

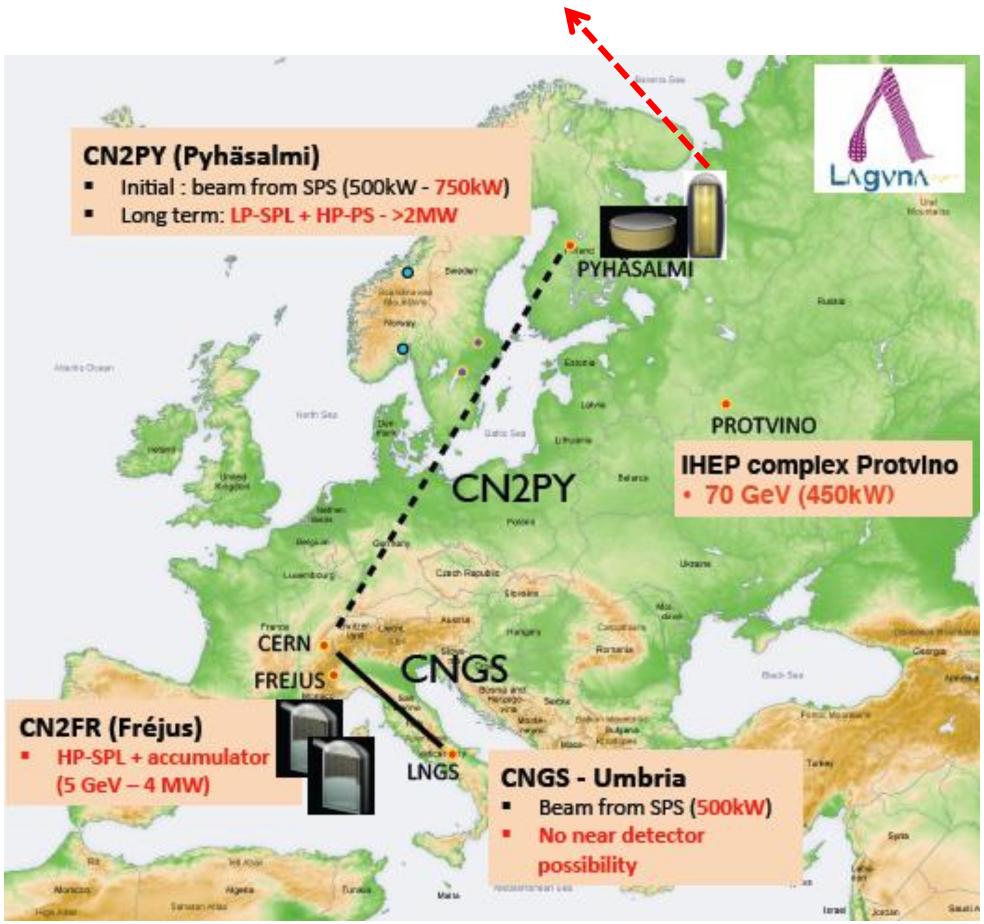


High sensitivity to CP phase for systematics < 5%

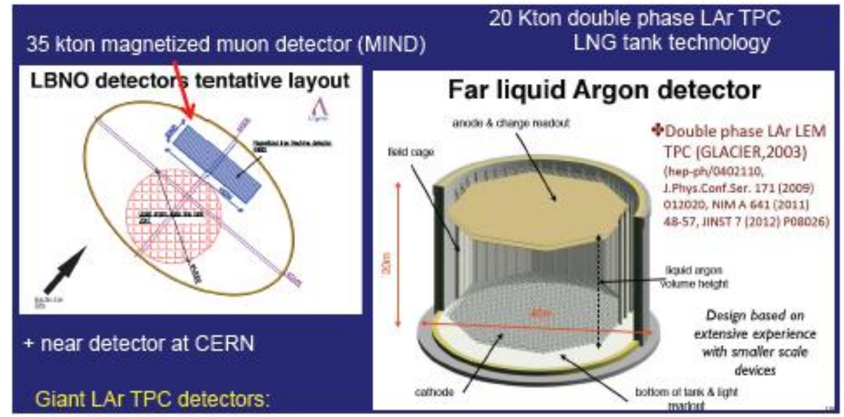
LAGUNA/LBNO

European LBL project

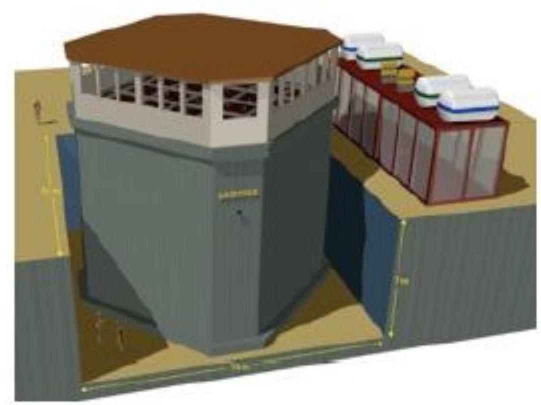
Wide band neutrino beam
from CERN to Pyhasalmi (Finland)
L = 2300 km



Far detector



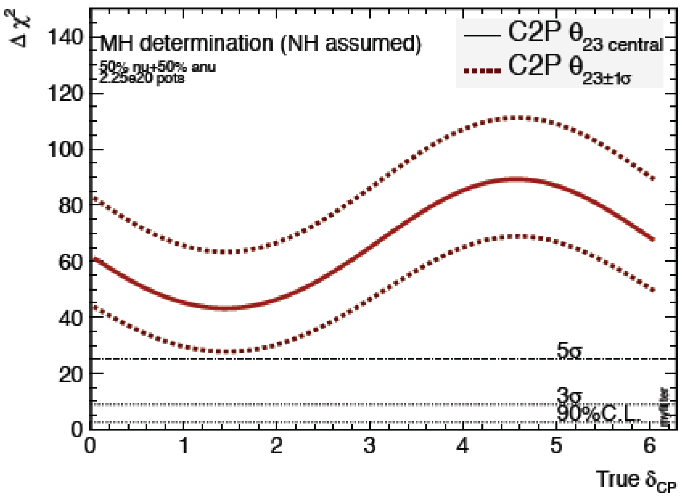
R&D: LAr demonstrator at CERN

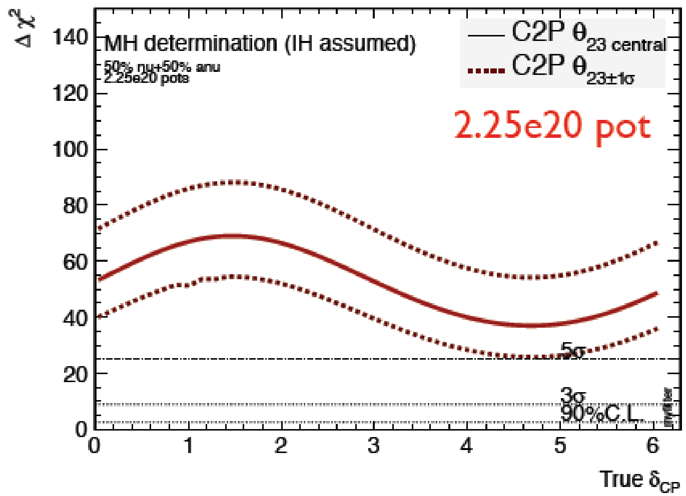


LAGUNA/LBNO sensitivity

More than 5σ determination of MH for all δ values

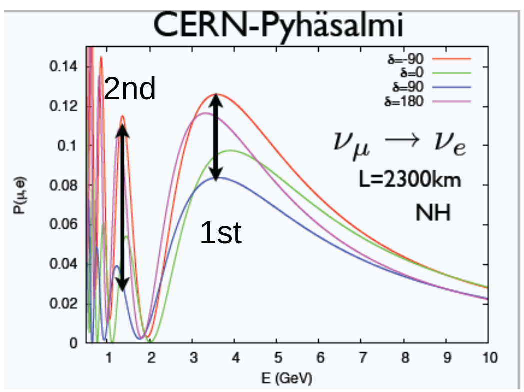
**A.Rubbia,
talk at Lomonosov
Conference 2013**

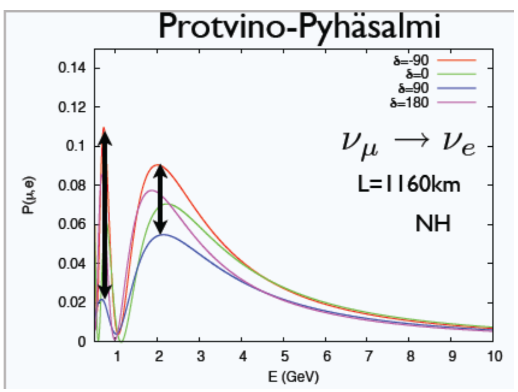


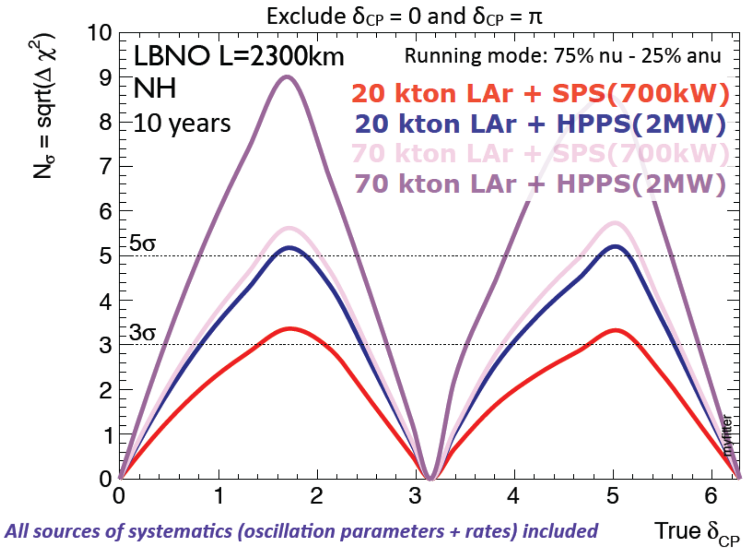


Sensitivity to δ

Measurement in 1st and 2nd oscillation maxima







Conclusion

- **2011-2013**
  - **θ_{13} is measured and large**
    Open very exiting perspectives in neutrino oscillations
  - **Observation of $\nu_\mu \rightarrow \nu_e$ appearance at 7.5 σ significance**
    A new type of transformation among neutrinos has firmly established

- **Near future:**
  - **precision measurements of neutrino mixing parameters**
  - **an initial search for CP violation in lepton sector**

- **Far future:**
  - **measurement of CP violation in lepton sector**
  - **determination of neutrino mass hierarchy**