Neutrino oscillations: recent results and perspectives

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IHEP, Protvino, Russia, 27 June 2013

OUTLINE

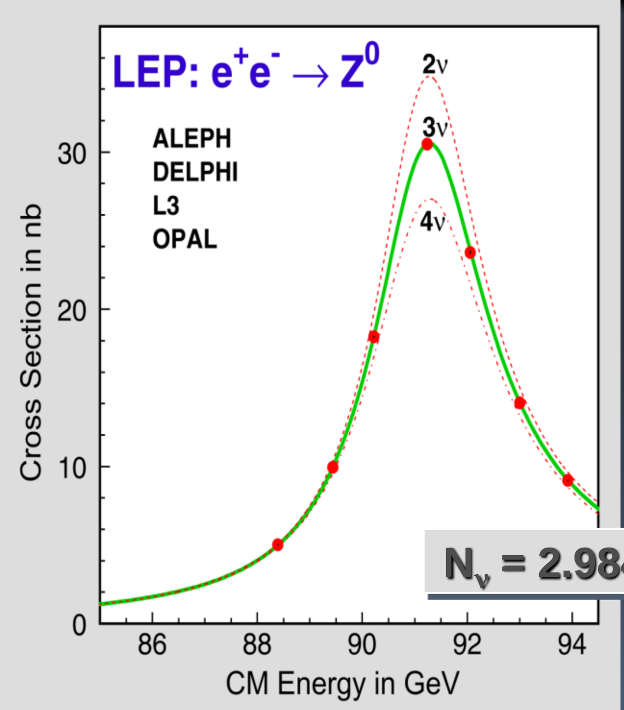
- neutrino oscillations
- long baseline accelerator experiments
- measurements of θ_{13}
  - accelerator experiments
  - reactor experiments
- near and far future perspectives

Standard Model

Three neutrino flavours: ν_e ν_μ ν_τ
Neutrino – partner of charged lepton: $W \to e\nu_e$ $W \to \mu\nu_\mu$ $W \to \tau\nu_\tau$
Neutrinos – massless particles
Lepton numbers L_e L_μ L_τ conservation
Neutrino oscillations forbidden
CP = 1 in lepton sector

LEP experiments:
from the width of Z

Three active neutrinos

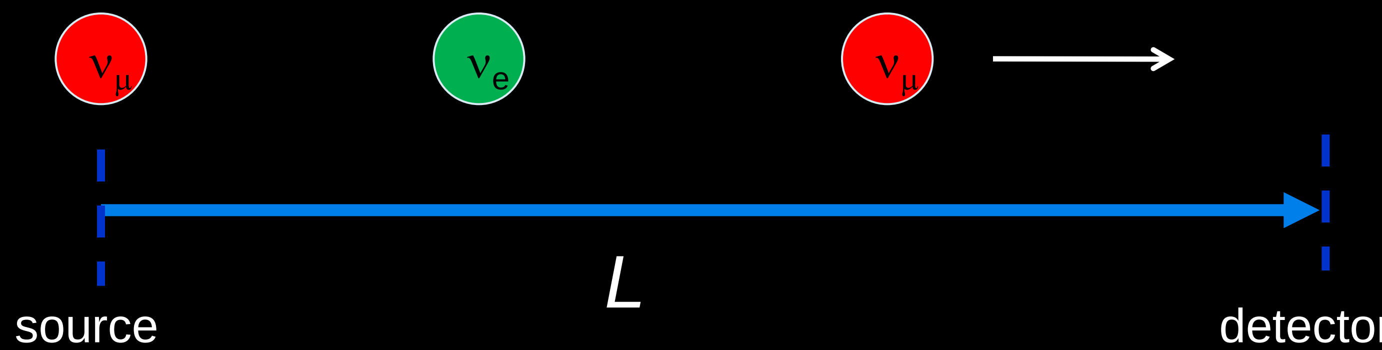


$N_\nu = 2.984 \pm 0.008$

Neutrino oscillation hypothesis

B. Pontecorvo: the idea of massive neutrino and oscillations – 1957

- neutrino – antineutrino transitions
- non-zero mass and mixture of neutrinos
- oscillation probability depends of neutrino **mass**, neutrino energy E_ν and path length L



Weak interaction eigenstates

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

m_1, m_2, m_3 — Mass eigenstates

Weak (active) eigenstates are not equal to mass eigenstates

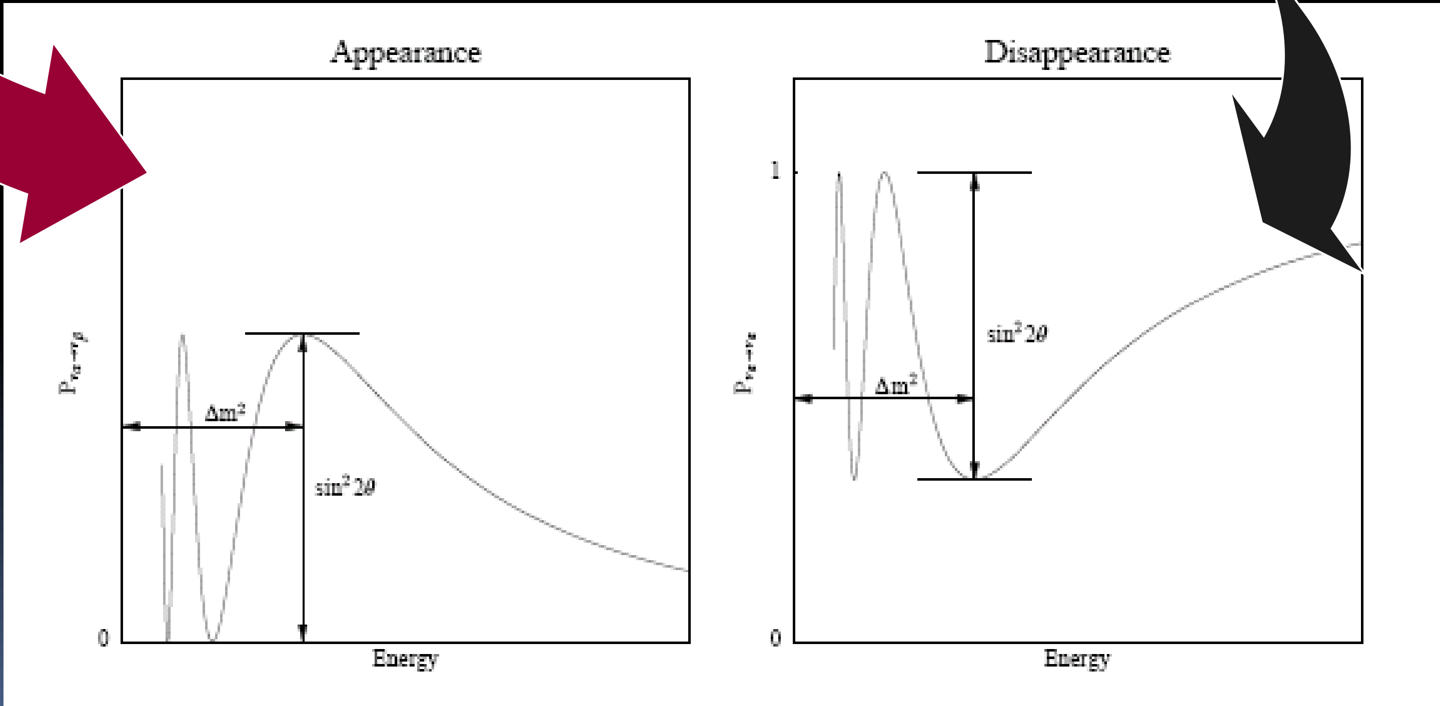
2 types of oscillation experiments

Oscillation experiments:
Appearance and Disappearance

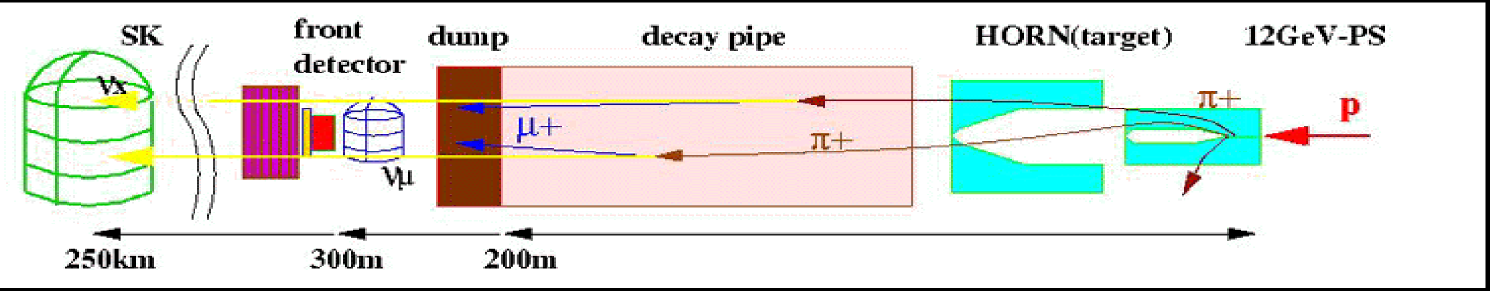
Baseline, L — **fixed**
Neutrino energy, Eν — **measured**

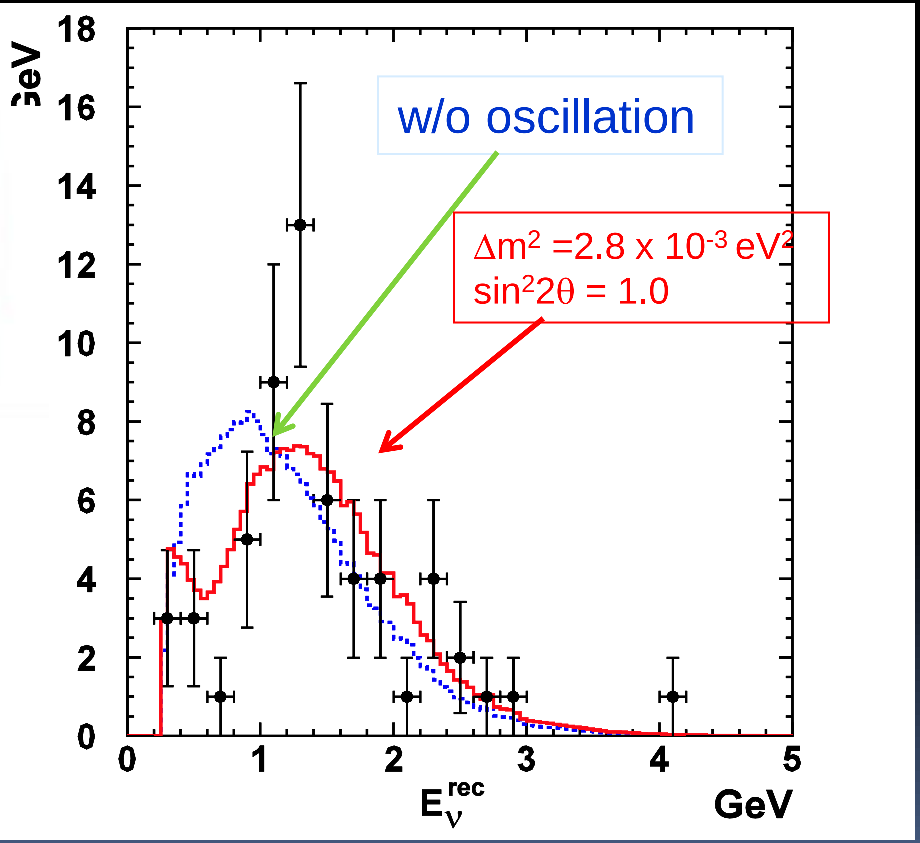
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



K2K: first LBL experiment

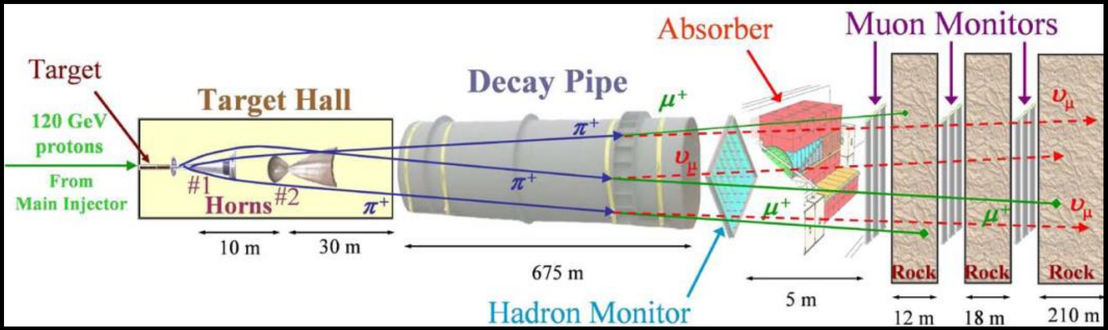


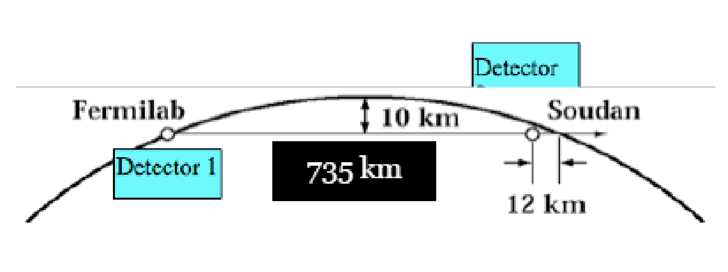


K2K confirmed SK result:
oscillations of atmospheric neutrinos

Null oscillation probability = 0.0050%(4.1σ)

MINOS





Proton beam: 120 GeV protons

ν- beam: ν_μ- 92.9%, anti-ν_μ- 5.8%, (ν_e + anti-ν_e)- 1.3%, peak energy ~(3-9) GeV

~1 kT Near Detector

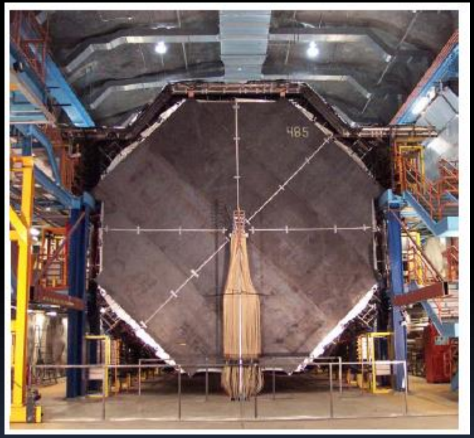
Far Detector

5.4 kton magnetized Fe/Sci Tracker/Calorimeter

Near Detector

980 ton at L ≈ 1 km

the same technology in both detectors



5.4 kT Far Detector

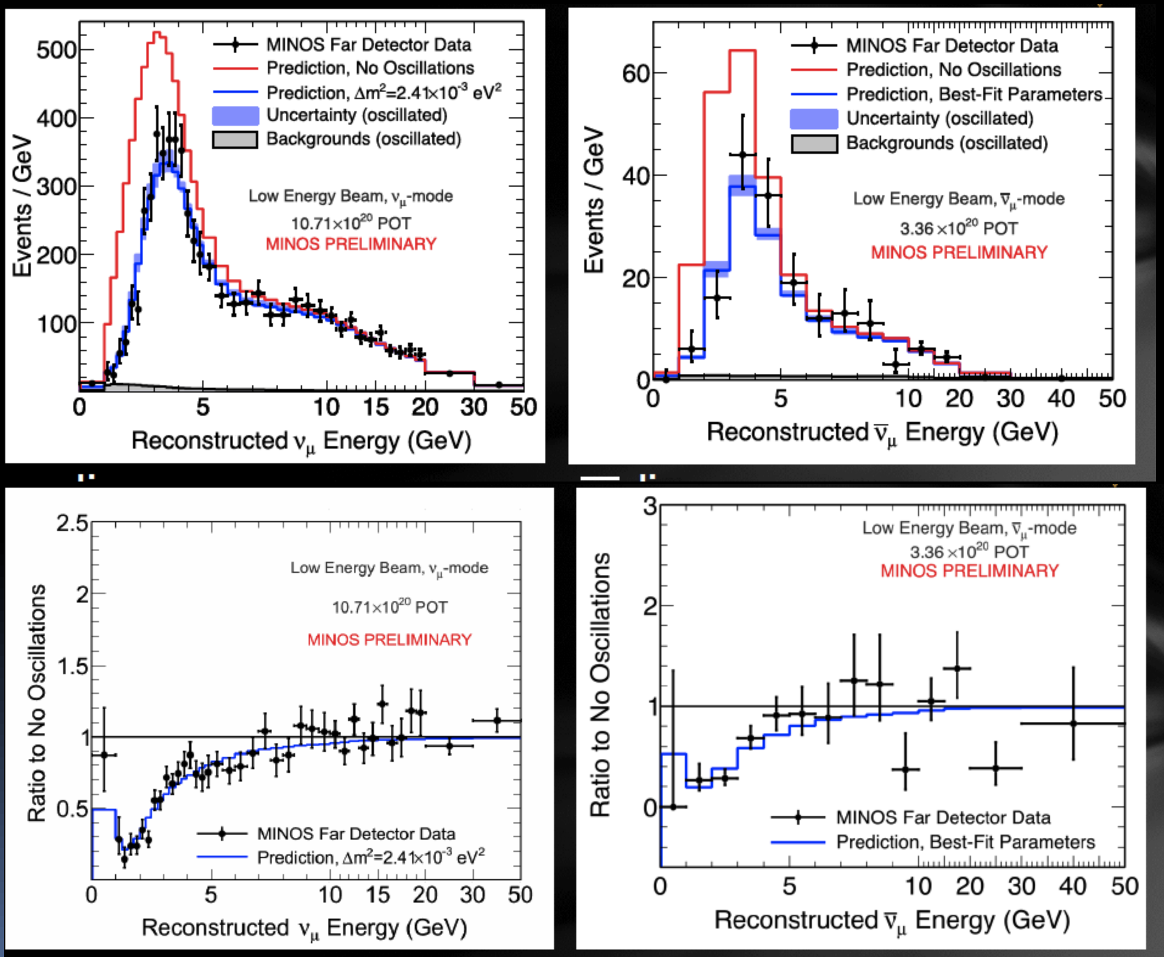
MINOS

J.de Jong, NOW2012

almost final result

ν → 2894 events detected in MINOS Far Detector
3564 event expected in the absence of oscillations

anti-ν → 226 events detected in MINOS Far Detector
312 events expected in the absence of oscillations



ν
$|\Delta m|^2=(2.35+0.11-0.08)\times10^{-3}$
$\sin^2(2\theta)>0.91$ (90% CL)

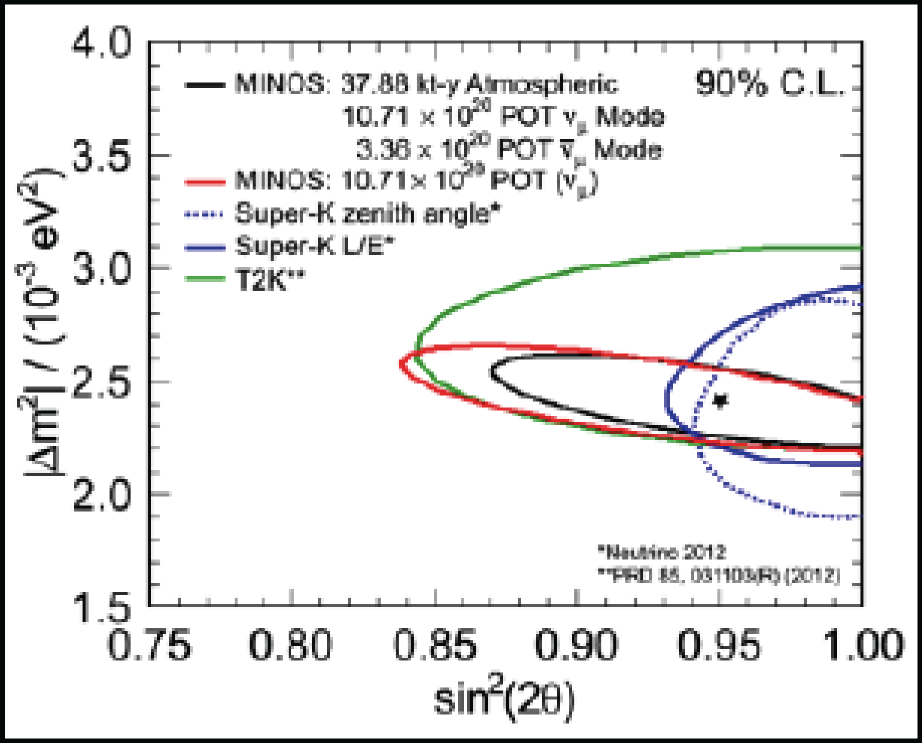
anti-ν
$\Delta m^2=(2.64+0.28-0.27)\times10^{-3}$
$\sin^2(2\theta)>0.78$ (90% CL

no tension between neutrinos and antineutrinos

MINOS: combined ν + anti-ν

All data sets (neutrino, anti-neutrino, atmospheric) combined for final measurement of ν_μ disappearance parameters

arXiv:1304.6335



Combined analysis

$$\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$$

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

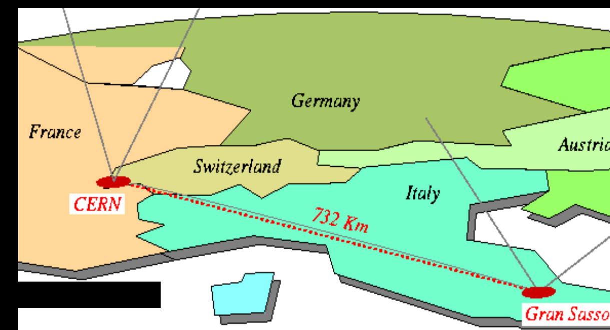
a hint on non-maximal mixing angle θ_{23}

OPERA

$\nu_\mu \rightarrow \nu_\tau$ direct search

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2\theta_{23}\sin^2[1.27\Delta m^2_{23}L(km)/E(GeV)]$$

High energy, long baseline ν beam
($E \approx 17$ GeV $L \sim 730$ km)

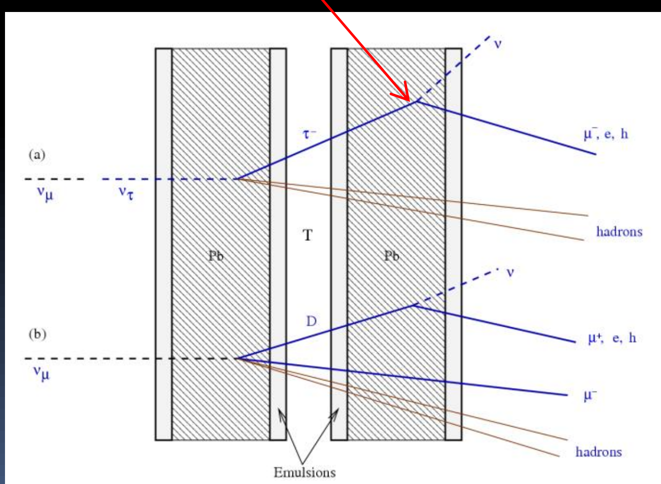


kink

Target mass ~1300t

$E/L \sim 2.3\times10^{-2} \sim 10\Delta m^2_{23}$ (atm)

pure beam: 2% anti ν_μ ; <1% ν_e

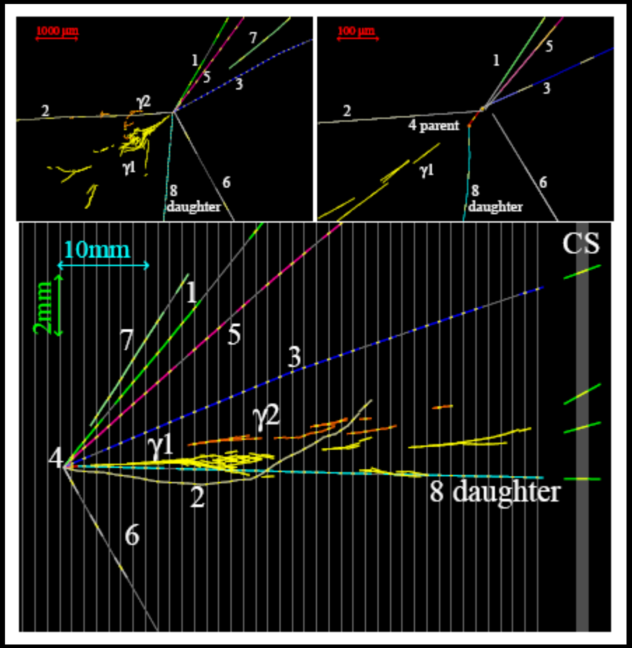


Main background

Expectation after 5 years data taking:
~22000 ν interactions
~120 ν_τ interactions
~10 ν_τ reconstructed
<1 background event

OPERA

1st event



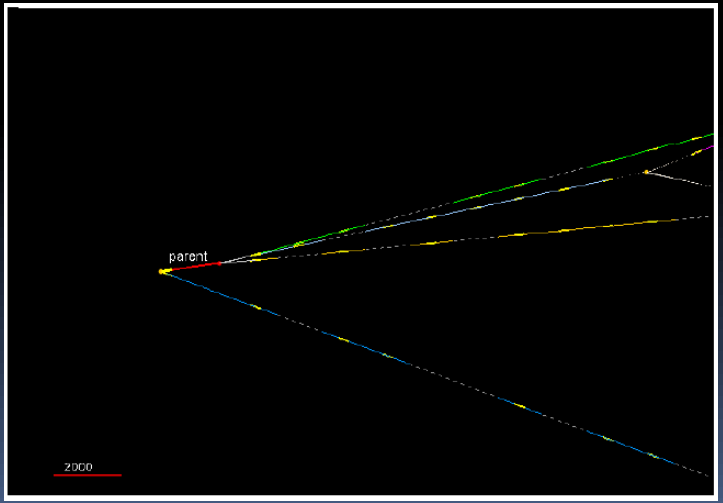
For $|\Delta m|^2 = 2.5 \times 10^{-3}\ eV^2$
18.9×10^{19} POT

2.7 tau events expected

0.3 events background

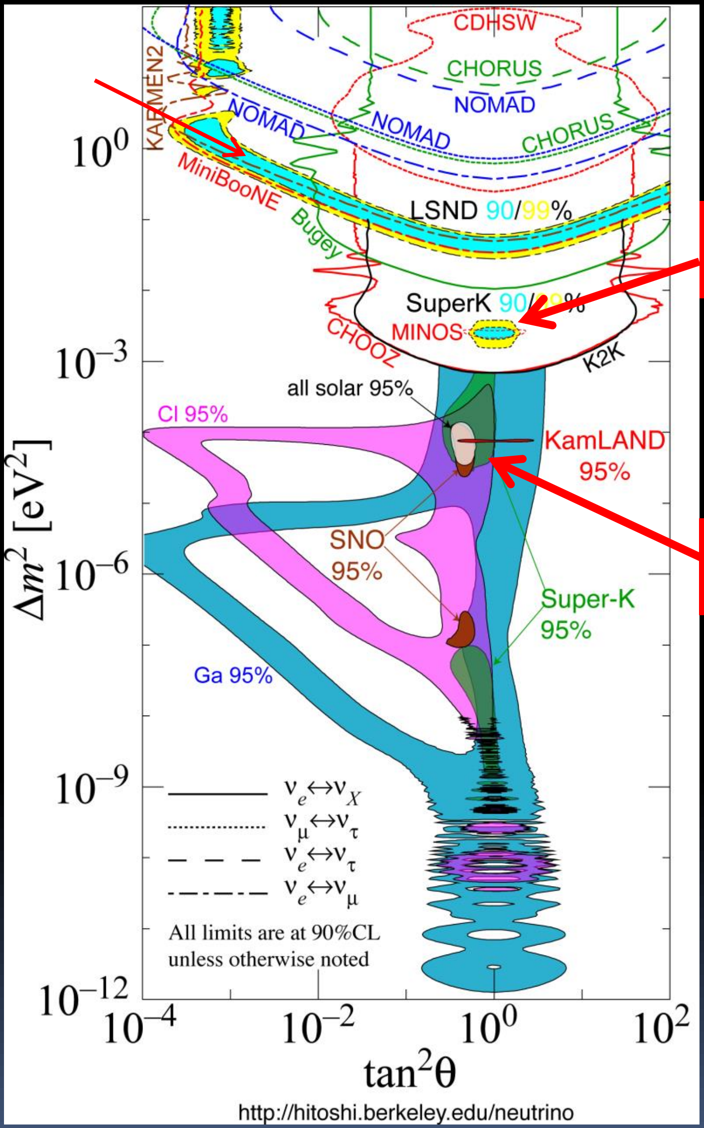
3 candidates observed

2nd event



Oscillation results

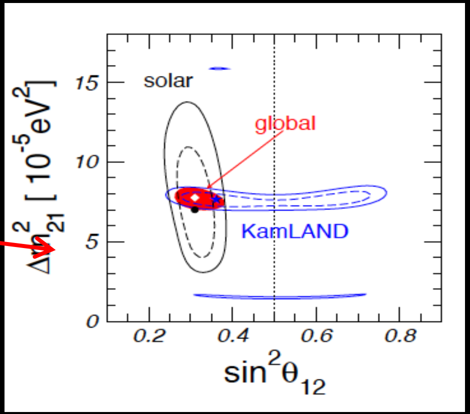
By June 2011



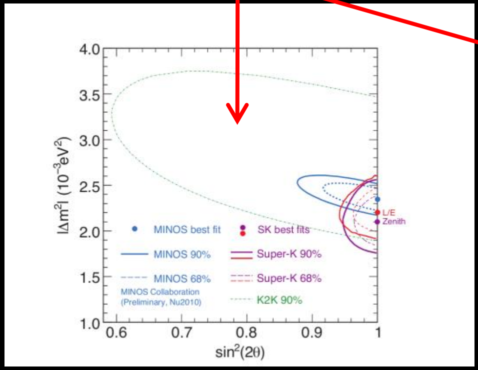
atm

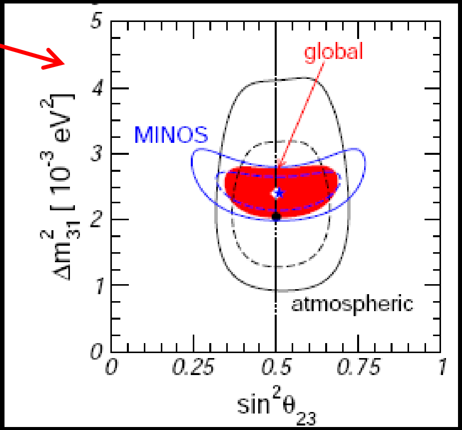
sol

Solar + KamLAND

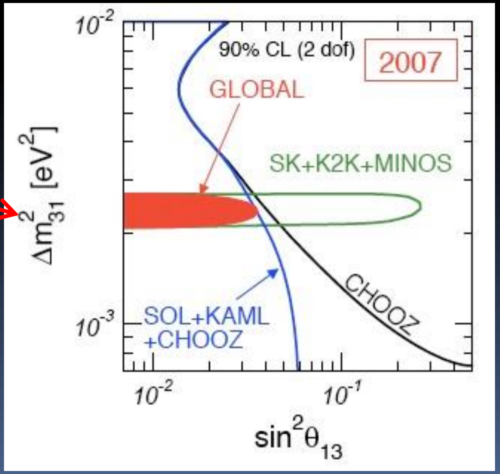


SK + K2K + MINOS





CHOOZ +atm + LBL
$\sin^2(2\theta_{13})<0.11$ (90%CL)



ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

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

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

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

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

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

$\theta_{12} \sim 34^0$

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

two independent Δm^2

by June 2011

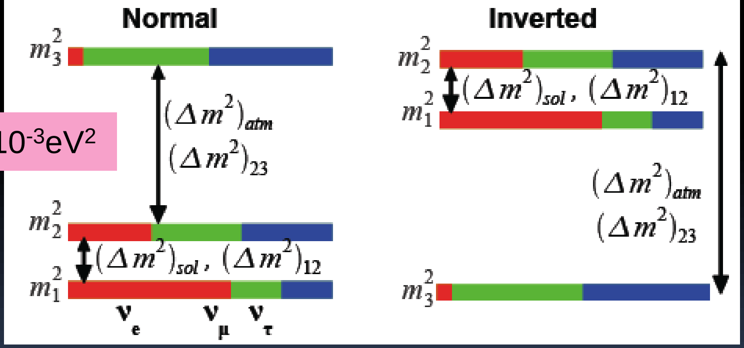
$\sin^2 2\theta_{13} < 0.15$ at 90% CL

Before Summer 2011

T.Schwetz, M.Tortola,J.Valle, hep-ph:1103.0734v2

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

~2.5x10^{-3}eV^2



- ✓ only upper limit on θ_{13}
- ✓ θ_{23} maximal?
- ✓ mass hierarchy (sign of Δm_{31}^2)
- ✓ no hint on CP violation

?? θ_{13} , mass hierarchy , δ ??

Importance of θ_{13}

- Zero value of θ_{13} would be a hint on a new symmetry (tri-bi-maximal)

- Zero value of θ_{13} would eliminate a possibility for the CKM mechanism in neutrino mixing

- A non-zero value of θ_{13} opens a door for searching of leptonic CP violation

- A non-zero (and not small) value of θ_{13} gives good chances for measurement of mass hierarchy and CP violation in neutrino oscillations using present neutrino beams and detectors

The size of θ_{13} $\rightarrow$ Future Program of neutrino physics

T2K

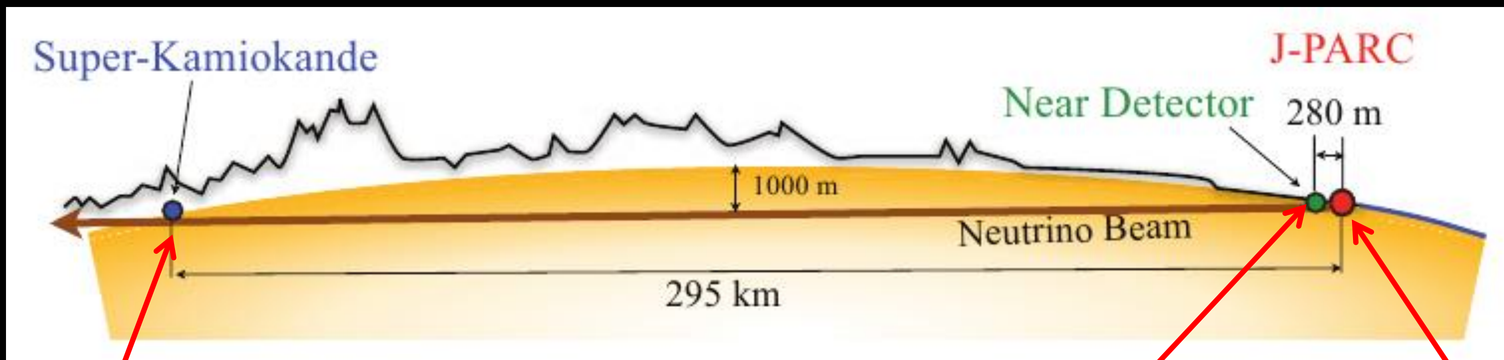
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

- 12 countries
- 59 institutes
- ≃ 500 collaborators

Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA.

T2K: - search for $\nu_\mu \rightarrow \nu_e$
- measurement of θ_{13}
- CP - violation

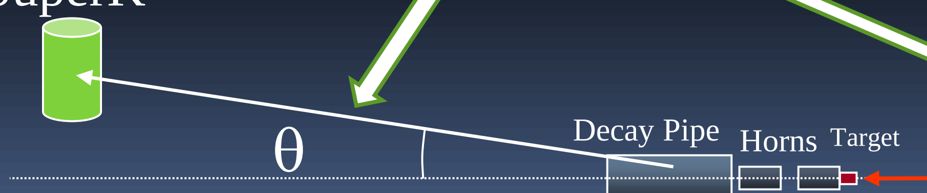
- >500 members from 12 countries
- Russia: INR RAS

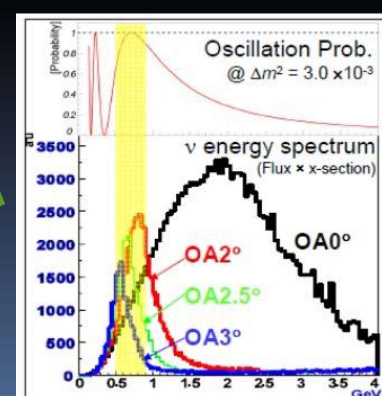


Off-axis beam conception: neutrino detectors are placed at a small angle θ with respect to the proton beam

ND280

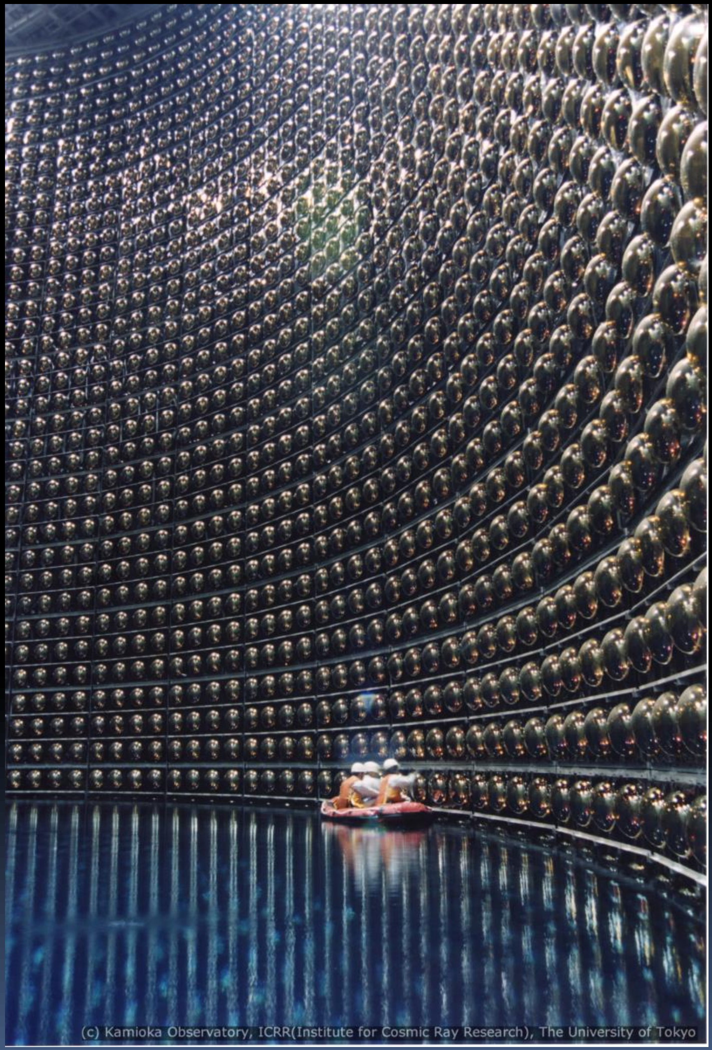
J-PARC

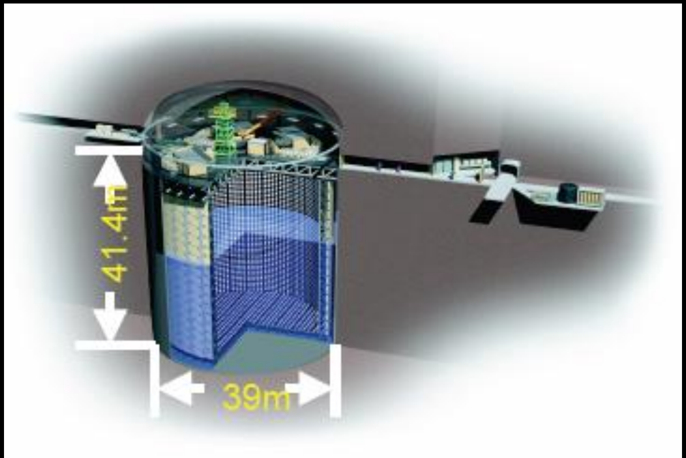




With 2.5 degree off-axis angle the neutrino energy is tuned to the oscillation maximum

SuperKamiokande –
T2K Far Detector

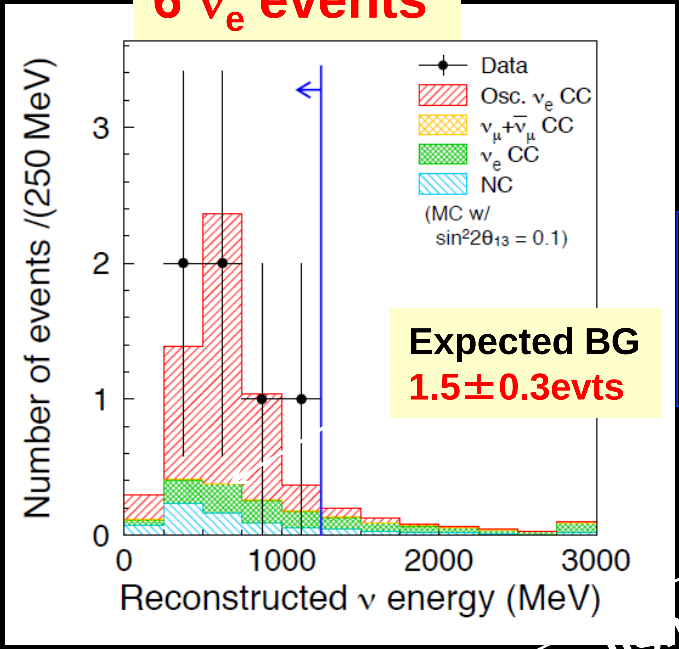




50 kt of pure water;
Fiducial Volume: 22.5 kt
Inner Detector: >11000 PMTs (20")
Outer Detector: ~2000 PMTs (8")
(see talk by M. Smy)

First T2K result

6 ν_e events



published in June 2011

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

About two years ago, T2K published FIRST clear indication of electron neutrino appearance ($\theta_{13} \neq 0$)

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

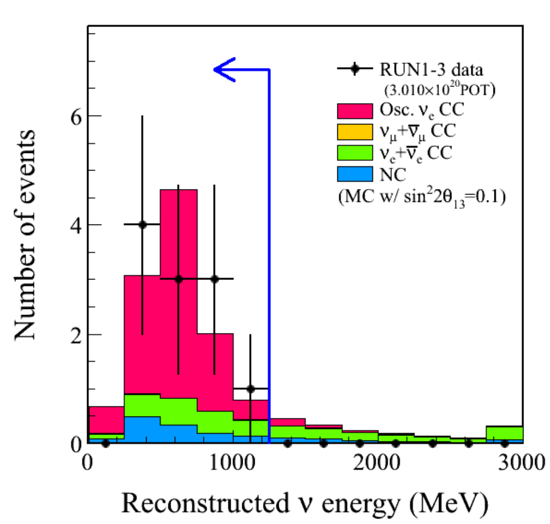
Then,

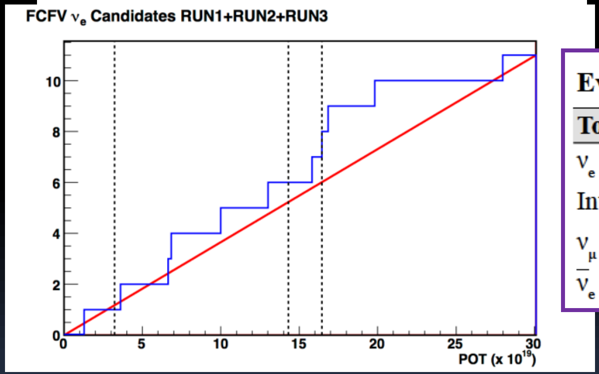
1 - Confirmation from MINOS

2 - Precise measurements by
 Double Chooz
 Daya Bay
 RENO

ν_e events

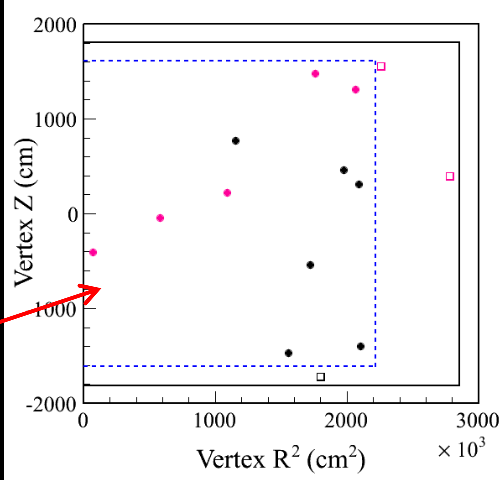
Energy spectra of ν_e events



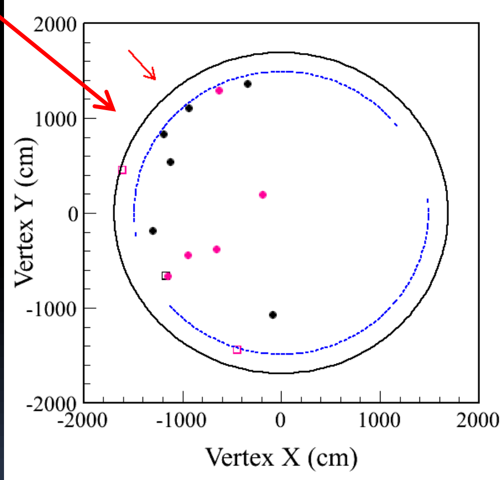


3.01x10^{20} POT
Statistics accumulated from January 2010 to July 2012

Run1 + Run2 + Run3



p-value = 6%



Event Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Total	**3.22 ± 0.43**	**10.71 ± 1.10**
ν_e Signal	0.18	7.79
Intrinsic ν_e Background	1.67	1.56
ν_μ Background (mostly π^0)	1.12	1.12
$\bar{\nu}_e + \bar{\nu}_\mu$ Background	0.16	0.16

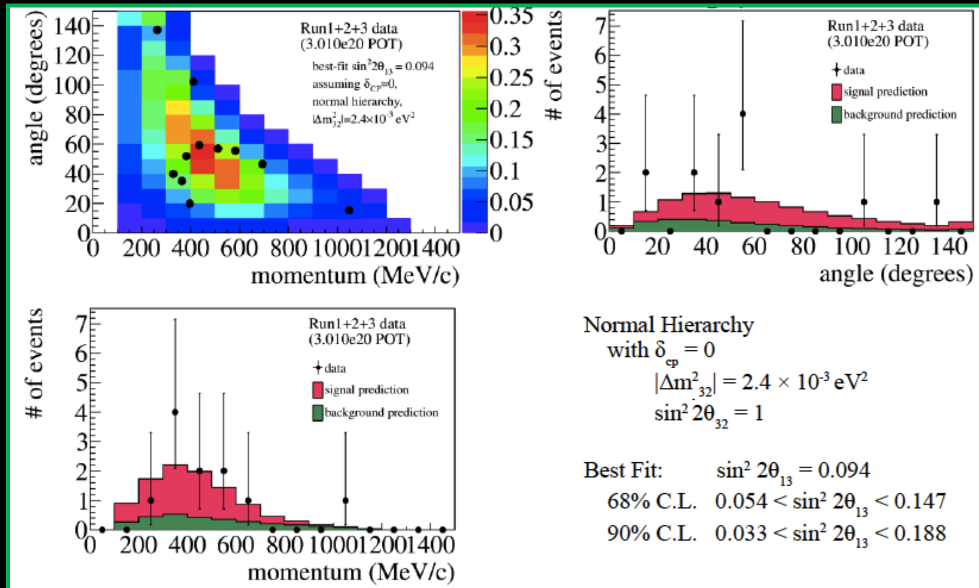
Detected 11 evens
Expected 3.3 ±0.4(syst) events
for θ_{13}=0, NH and δ = 0

3.1σ observation of $\nu_\mu \rightarrow \nu_e$

T2K Collaboration, arXiv:1304.0841

T2K: ν_e events

July 2012



Probability (p-value) to observe 11 events for $\theta_{13} = 0$ $\rightarrow$ 0.08%

Event Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
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ν_e Signal	0.18	7.79
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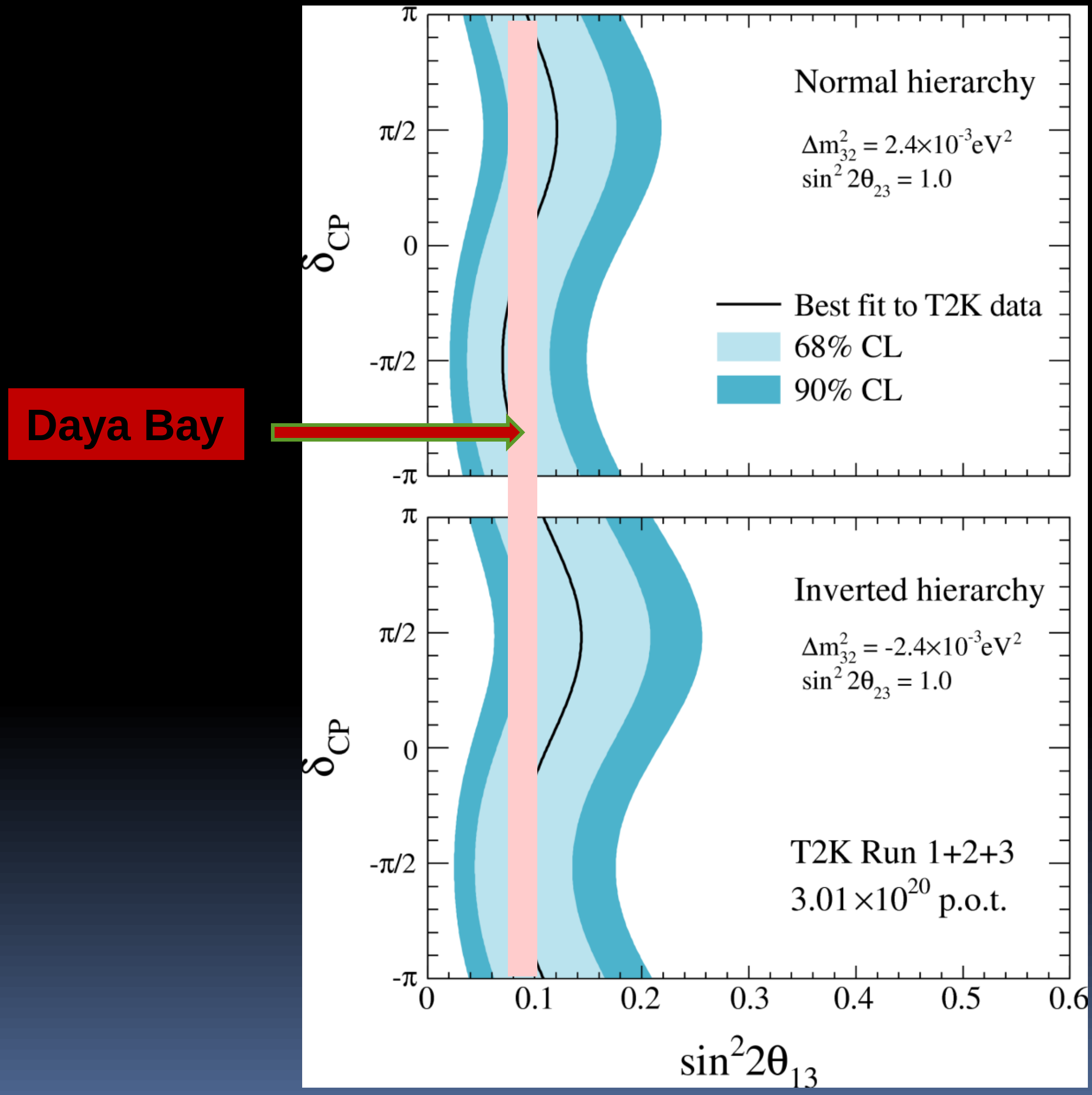
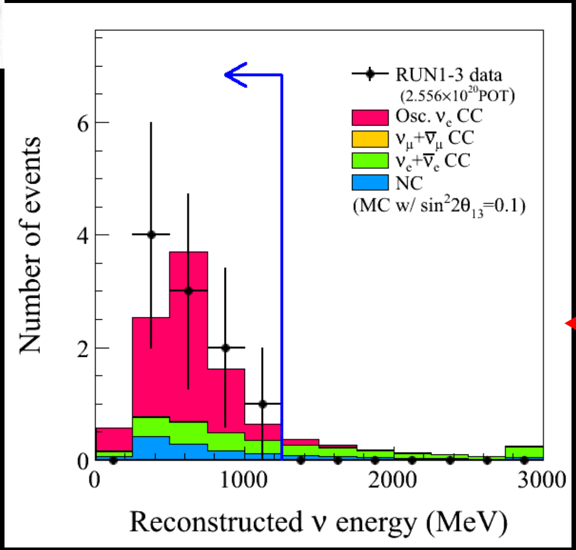
θ_{13} and δ

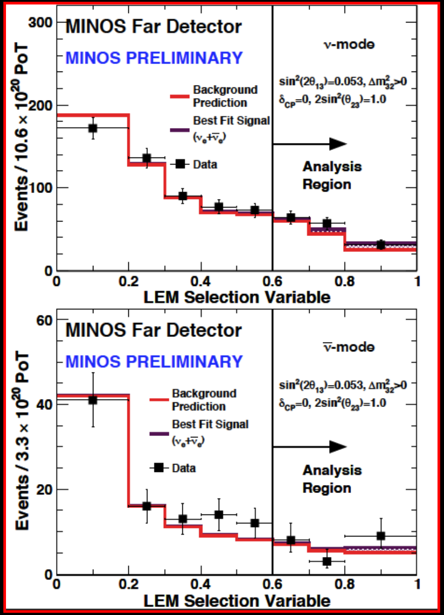


$\theta_{13} \neq 0$

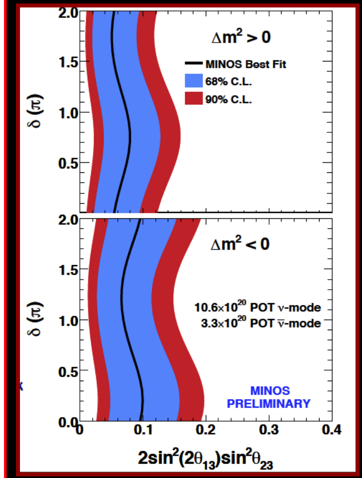
T2K



Accelerator experiments

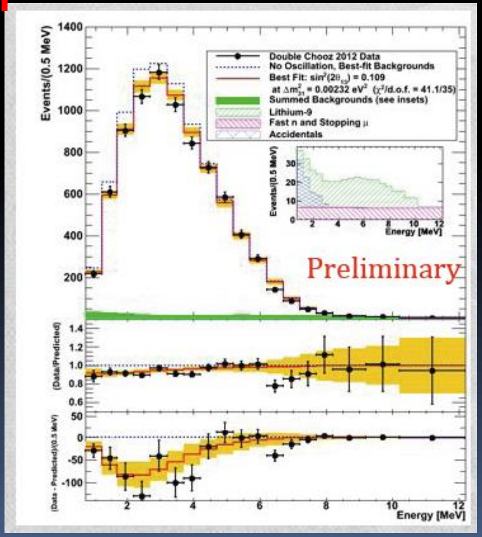


MINOS

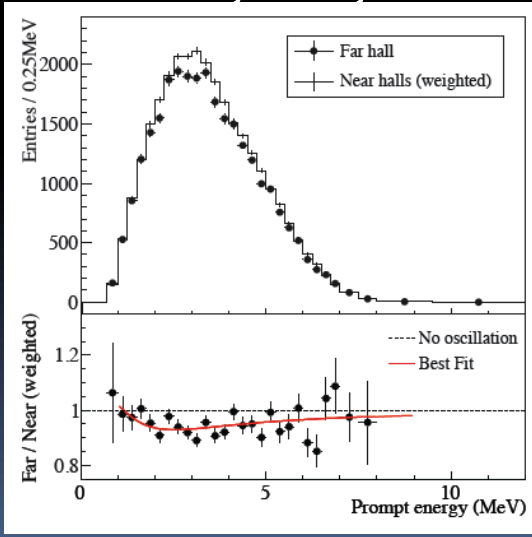


Reactor experiments

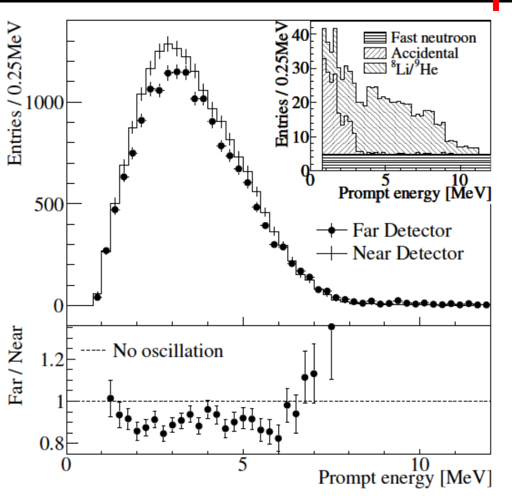
DChooz



Daya Bay



Reno

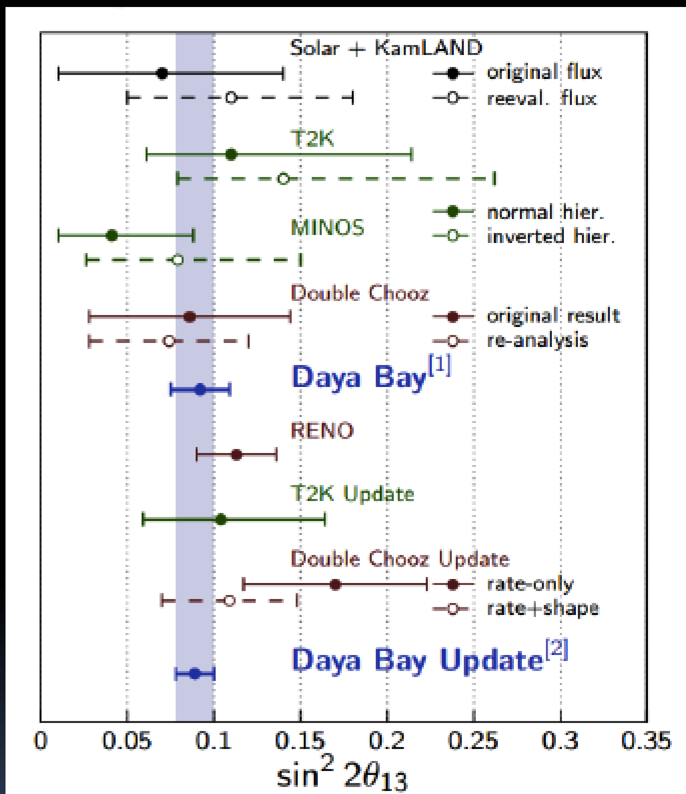


θ_{13}: one year story

from upper limit to precise measurement !

- θ_{13} has been well measured by 5 experiments

R.Barbiery ICHEP2012



$\theta_{13} \approx 9 \pm 1$ deg

T2K $\nu_\mu \to \nu_e$

first indication of $\theta_{13} \neq 0$ 3.1σ significance

MINOS $\nu_\mu \to \nu_e$

$\theta_{13} = 0$ *disfavored at 1.7 σ*

Double Chooz $\bar{\nu}_e \to \bar{\nu}_e$

$\theta_{13} \neq 0$ *at 3.1σ*

Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$

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

~ 8σ significance

RENO $\bar{\nu}_e \to \bar{\nu}_e$

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

4.9σ significance

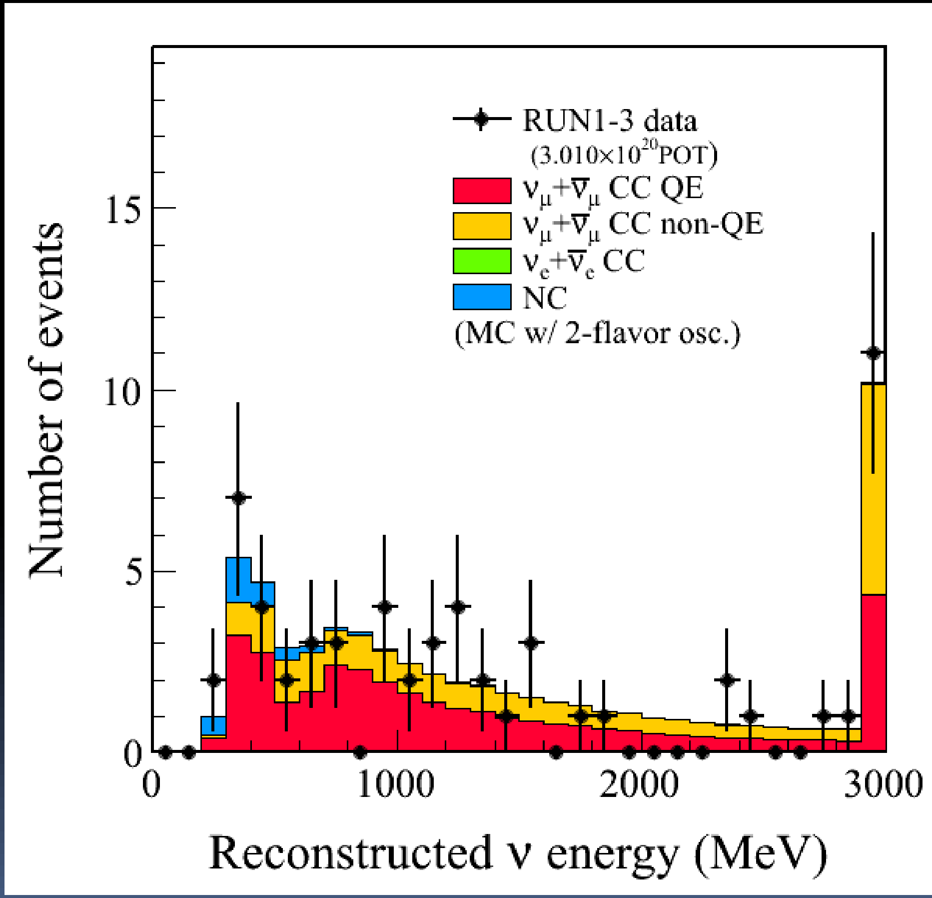
T2K: ν_μ disappearance

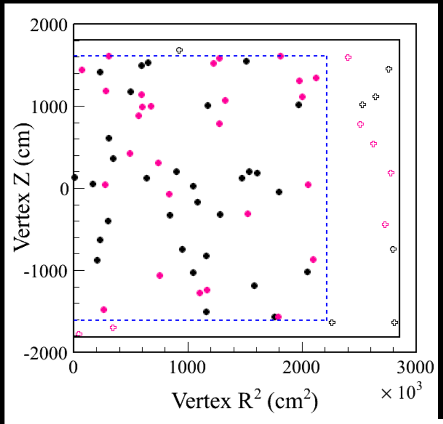
3.1×10^{20} POT

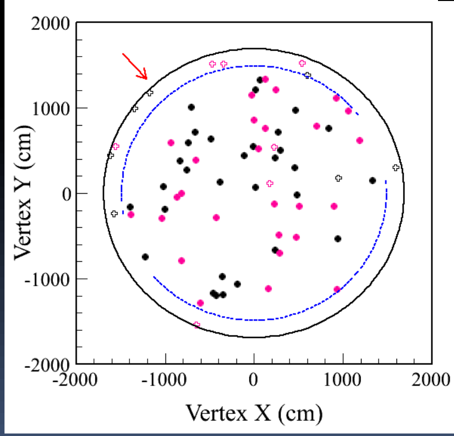
Measurement: 58 events observed

Monte Carlo: 196.2 events no oscillations

Monte Carlo: 57.8 events with oscillations





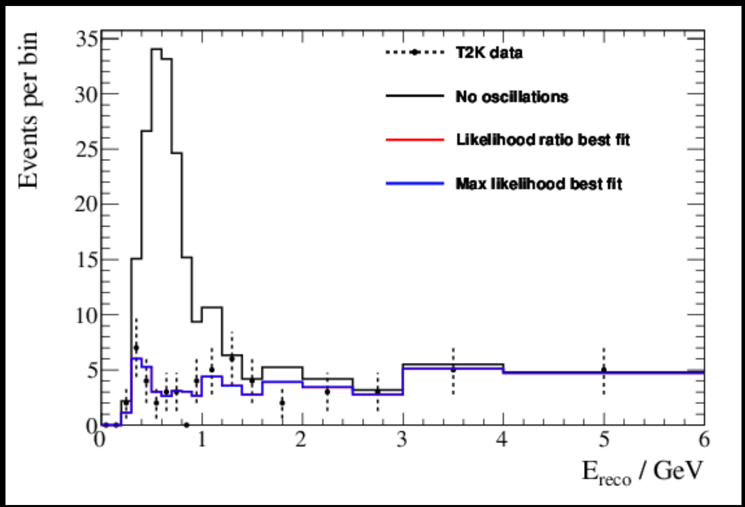


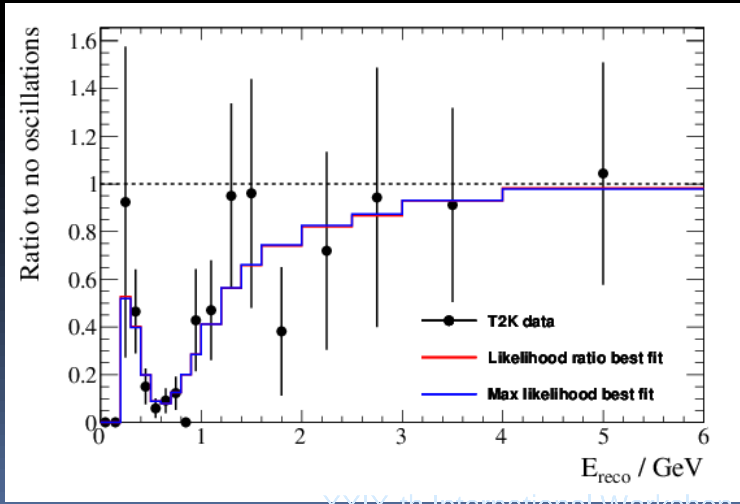
- Run 1+Run 2
- Run 3

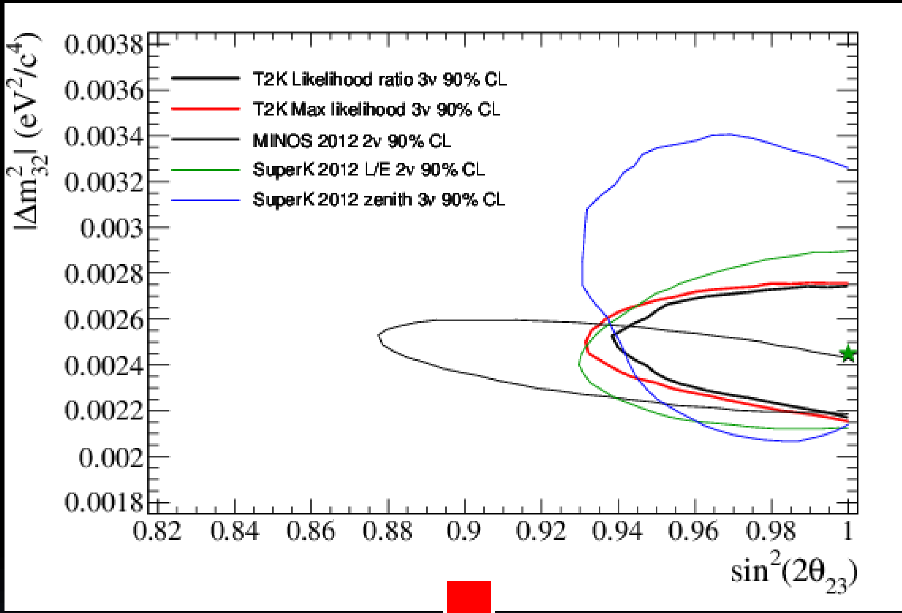
T2K: $\nu_\mu \rightarrow \nu_\mu$

Maximum Likelihood fit

Best fit results: $\sin^2 2\theta_{23} = 1.00$ $\Delta m^2_{32} = 2.45 \times 10^{-3} \mathrm{eV}^2$





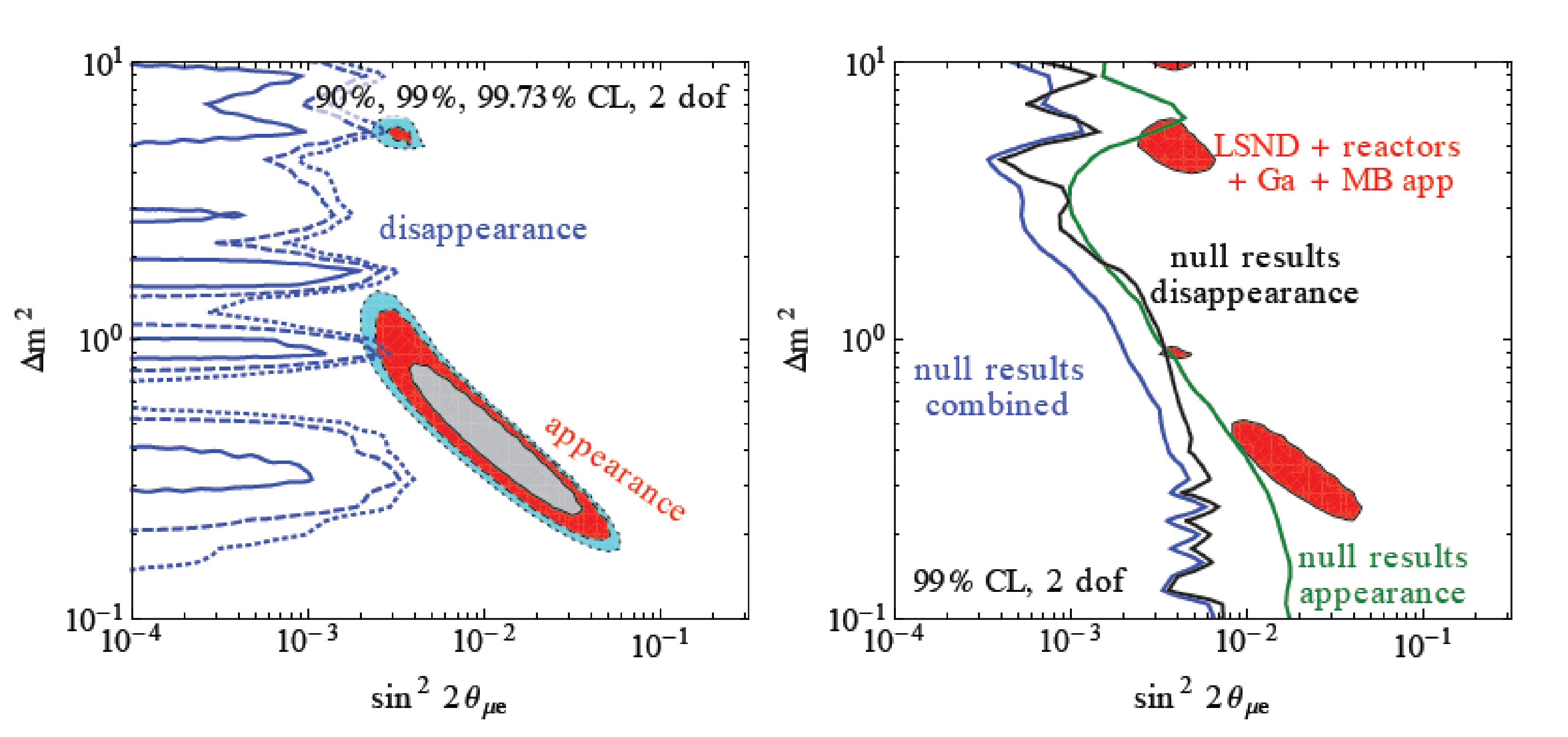


T2K obtained best sensitivity to mixing angle θ_{23}

Sterile neutrinos

MiniBooNe/LSND, reactor, Ga anomalies

Kopp, Machado, Maltoni, Schwetz, 1303.3011



strong tension between appearance and disappearance data

tension between signals and negative results

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

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right]$$ → θ_{13}

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → CP-even

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → CP-odd

$$+ 4s_{12}^2 c_{13}^2 (c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu}$$ → Solar

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1 - 2s_{13}^2), \quad (30)$$ → Matter

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

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

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

change sign for NH → IH

J_{CP}

$\theta_{13} \neq 0$

The strength of CP violation in neutrino oscillations

Jarlskog invariant J_{CP}

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = \mathrm{Im}(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2}) =$$

$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta$$

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

Quark sector $J_{CP} \approx 3\times 10^{-5}$

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

neutrinos	quarks
$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$	$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$

Real chance to test CP violation in neutrino oscillations

CP measurements

If $\theta_{13} \neq 0$ and not too small → measurement of δ in LBL accelerator experiments

(1) ν and anti-ν narrow beams tuned to 1st oscillation maximum

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

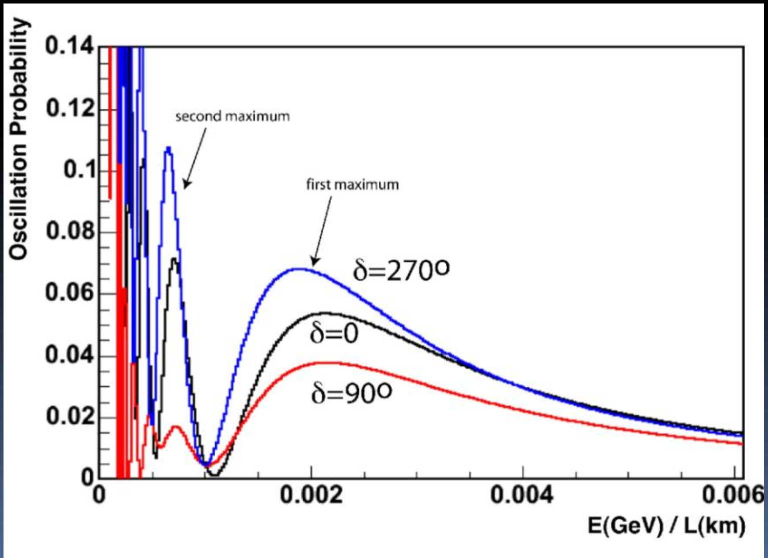
$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{13}$$

- neutrino and antineutrino beams
- massive far detector

(2) wide ν (anti-ν) beam to cover 1st and 2nd oscillation maxima

- wide energy muon neutrino beam
- measurements of two oscillation maxima

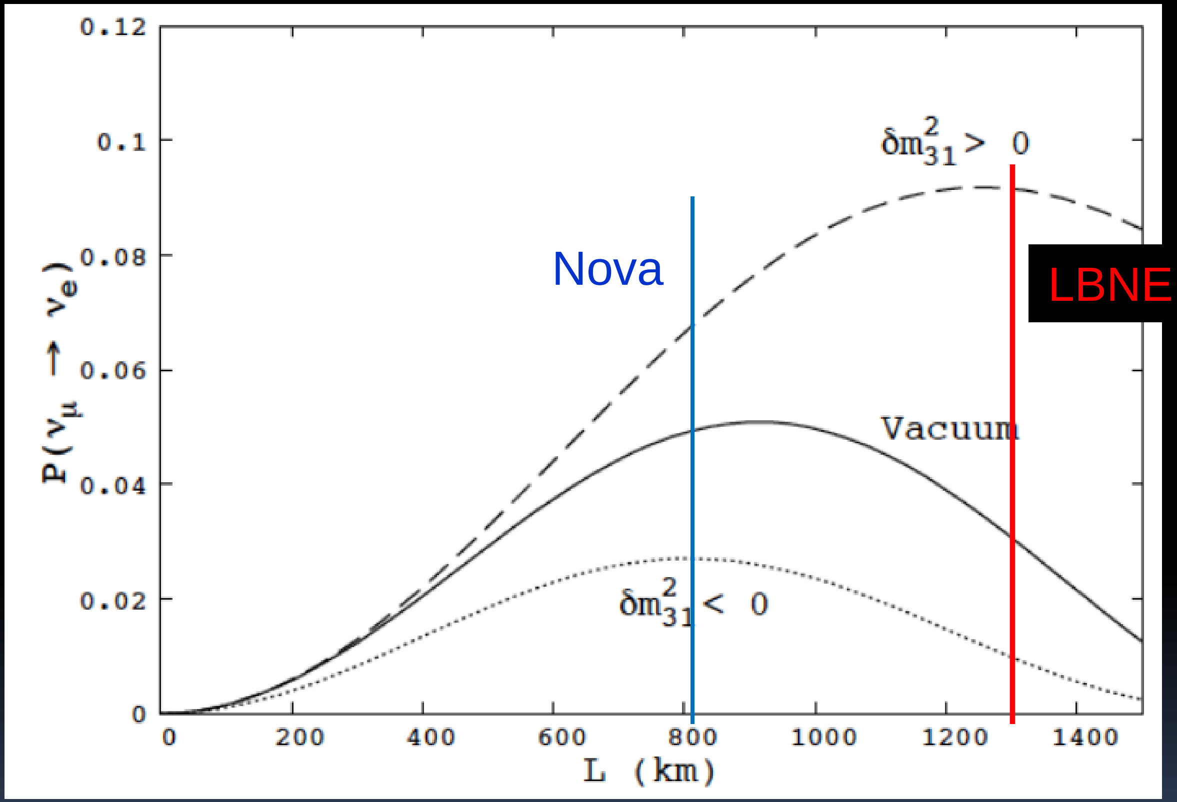
$P(\nu_\mu \to \nu_e)$ for $\sin^2 2\theta_{13}$=0.1



LBL experiments: near and far future

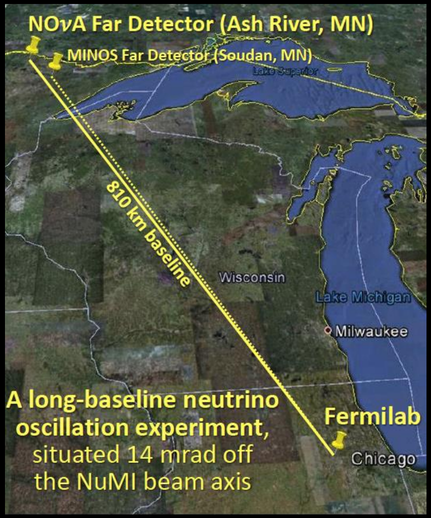
Matter effect in LBL experiments

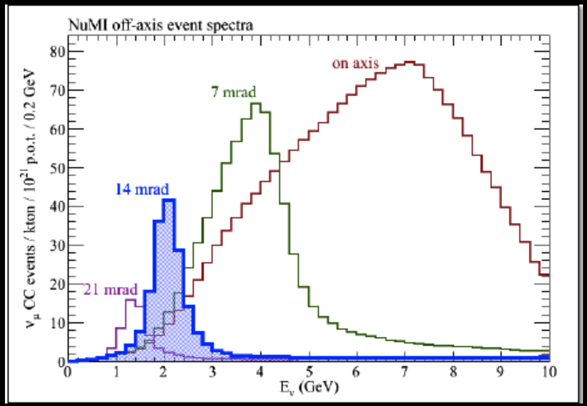
$E\nu \sim 2$ GeV



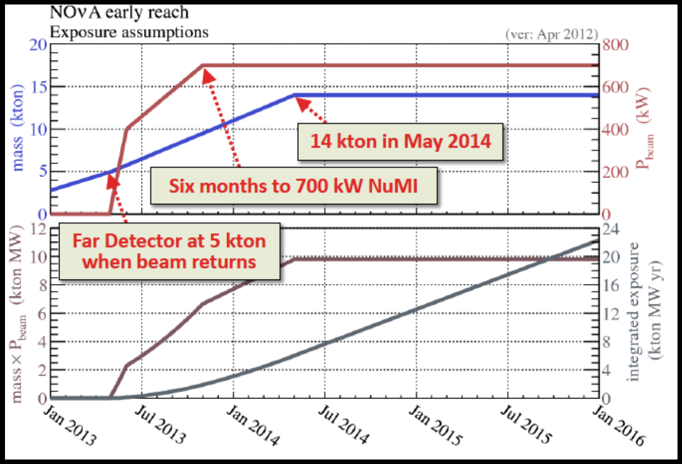
Nova

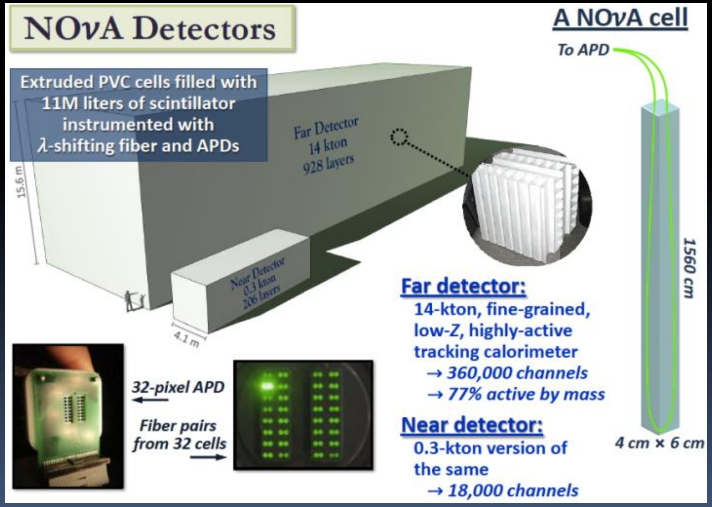
Neutrino off-axis narrow-band beam from FNAL
L = 810 km, E~2GeV, 700 kW beam power





R.Patterson, Neutrino 2012

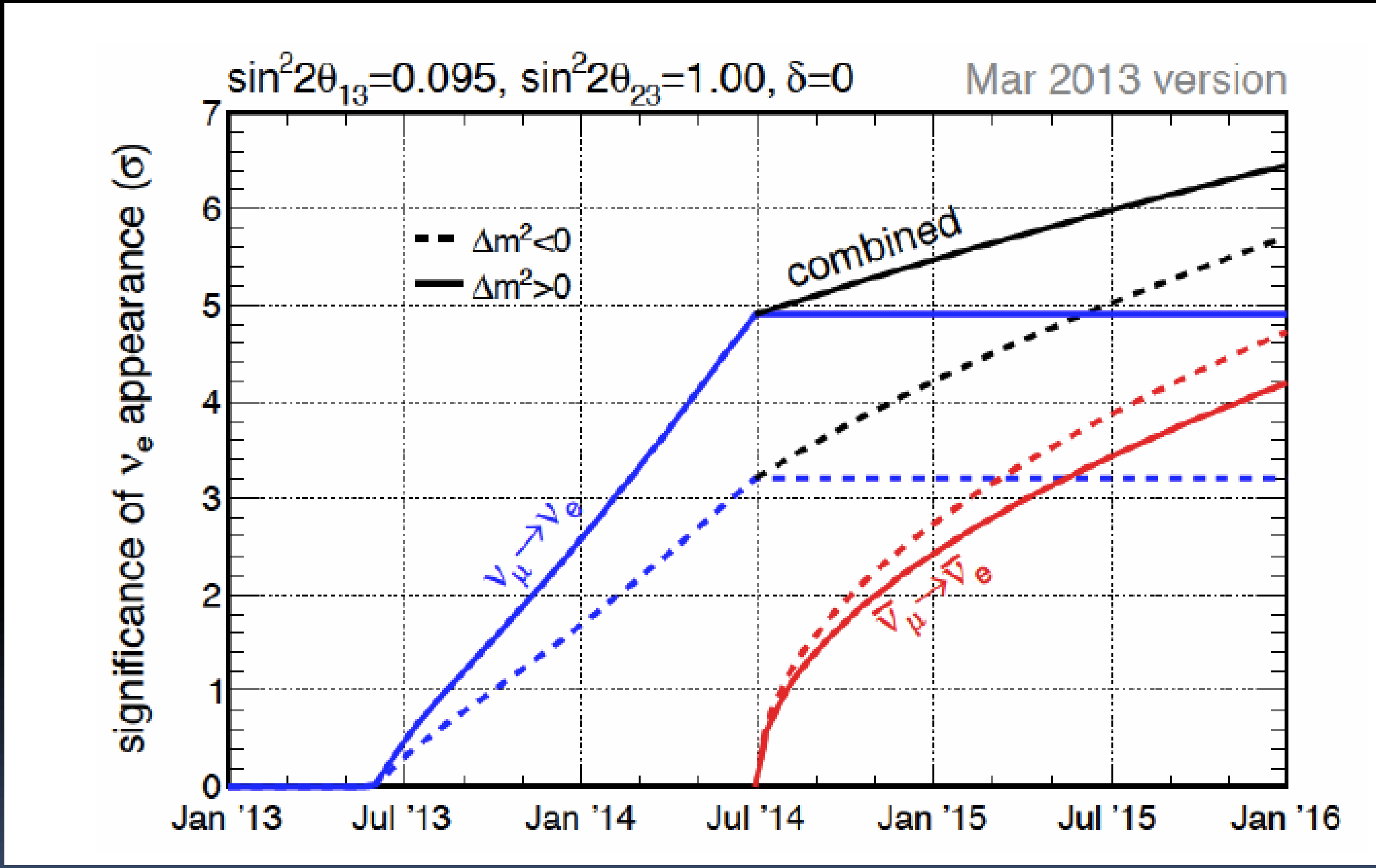




Experiment
will start data taking
in late 2013

Nova: early sensitivity

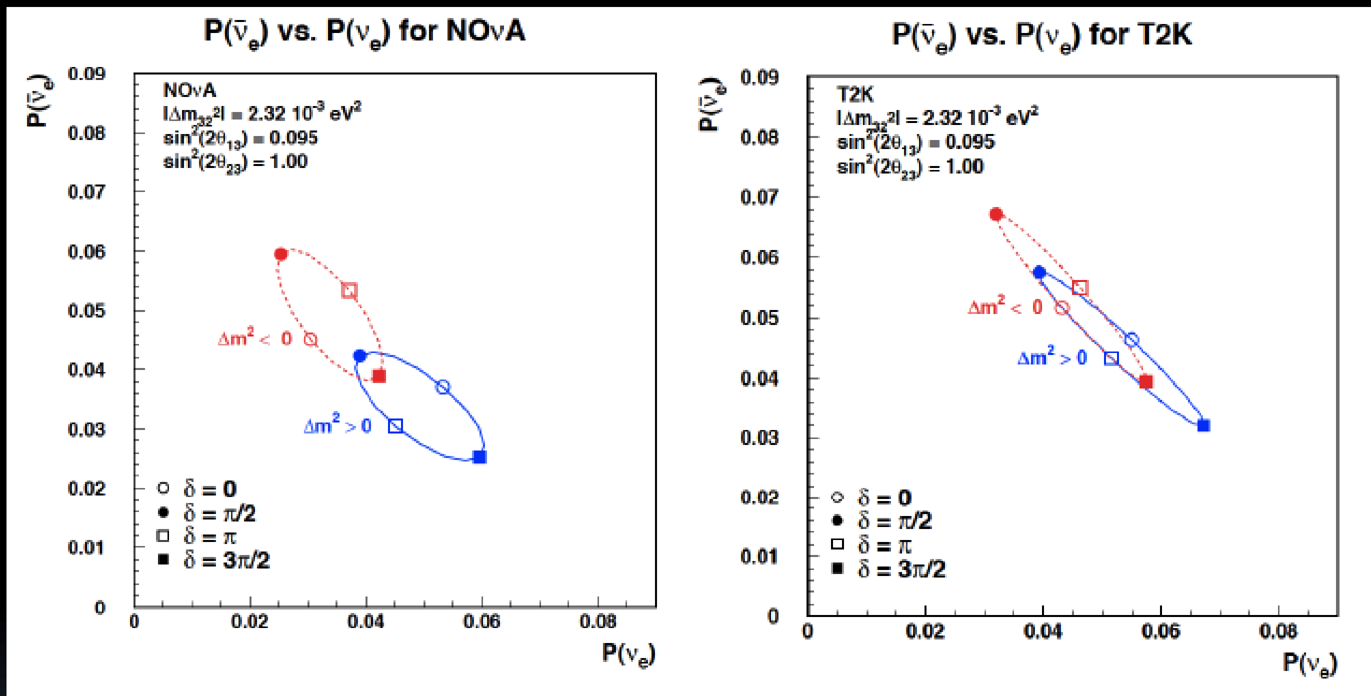
M.Messier talk Prague CP violation Colloquium, May 2013



T2K and Nova

C.Backhouse, NNN Workshop, 4-6 October 2012

Possible measurement of mass hierarchy and CP violation



For $\sin^2 2\theta_{13}=0.1$, approximately (at 90%C.L.):

- MH: ≈50% coverage
- CPV: ≈30-40% coverage

LBNE

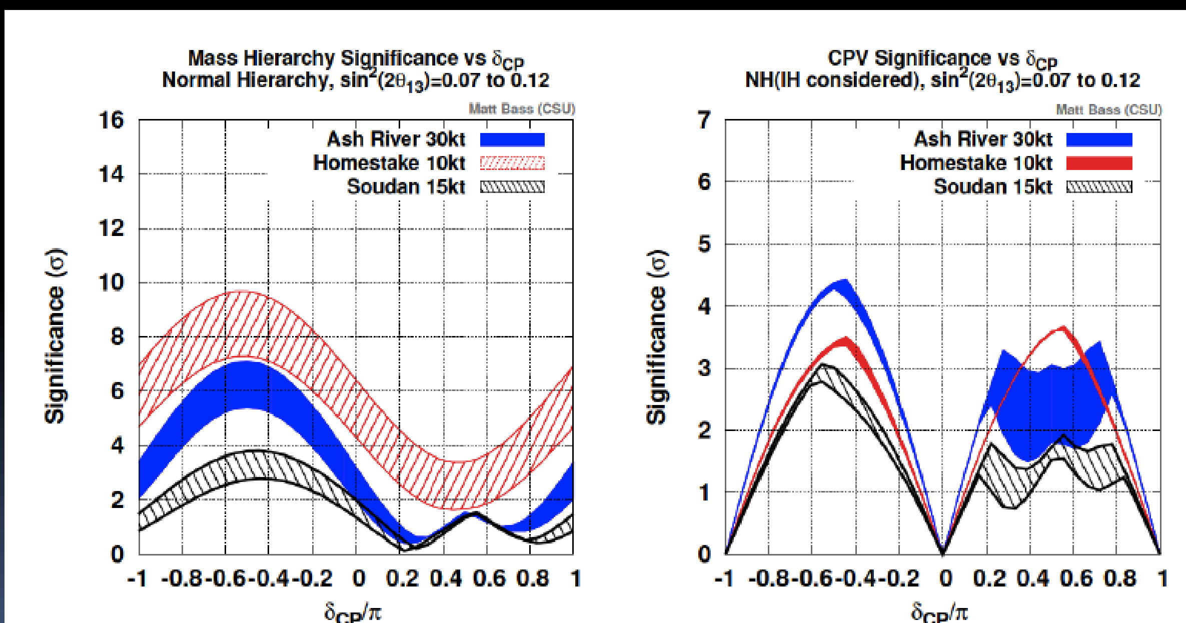
$\nu_\mu \rightarrow \nu_e$

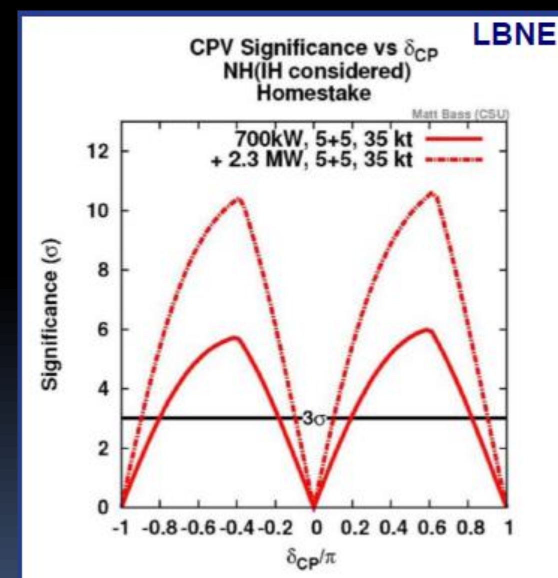
The US based LBL project

Neutrino beam from FNAL to Homestake
L = 1300 km, Ep=120 GeV, 700 kW NuMI beam,
E_ν = 0.5 – 5 GeV

Far detector 10 kt LAr TPC, on surface
No near detector

Sensitivity to MH and CP phase

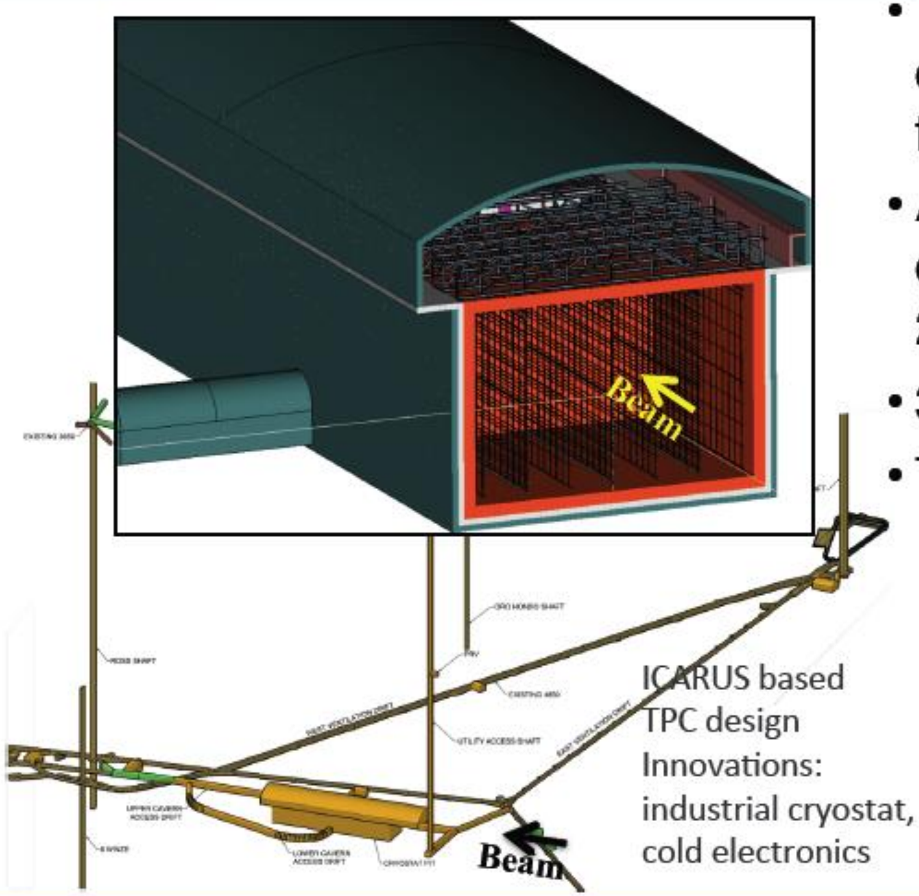




LBNE: Far Detector concept

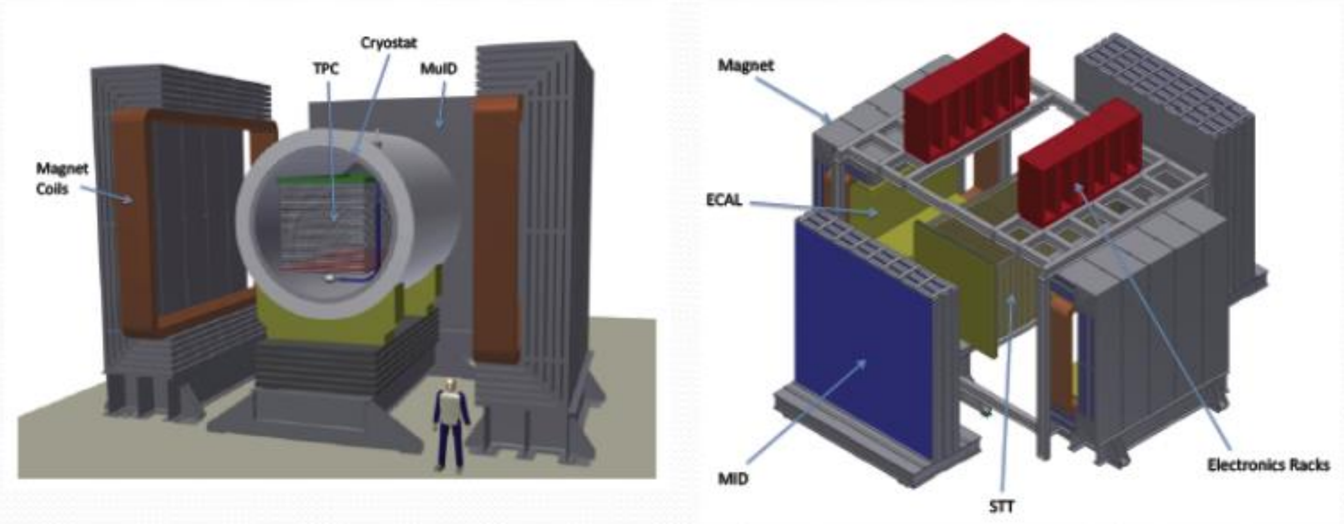
M.Diwan, talk at ISOUP13

Later phase: 34 kt LAr TPC underground



- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector:
  22.4 x 14 x 45.6 m^3
- 34 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views
  - 2X108 anode chambers
  - 2 X 275k channels
  - S/N ~ 10

LBNE: Near Detector options



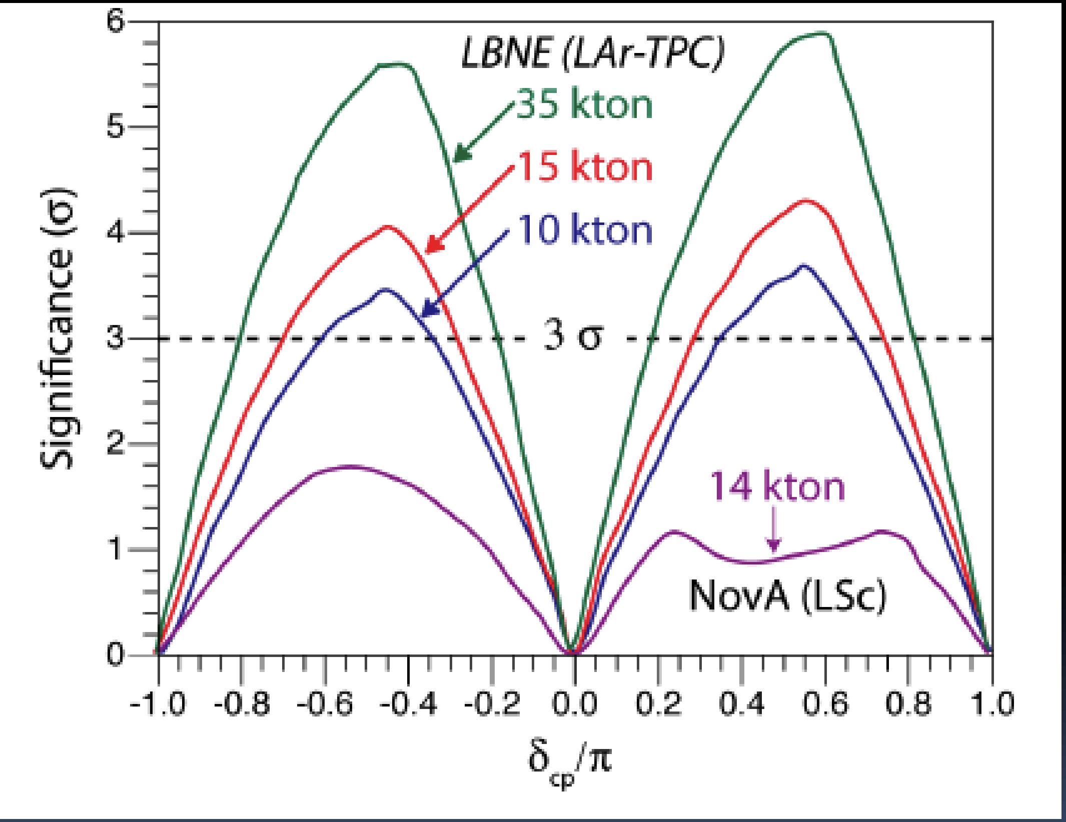
Liquid Argon TPC Tracker
(~18 ton LAr)

Fine-Grained Tracker
(~0.14 ton Ar@140atm)

LBNE: sensitivity to δ

arXiv:1110.6249

Several options for LBNE far detector



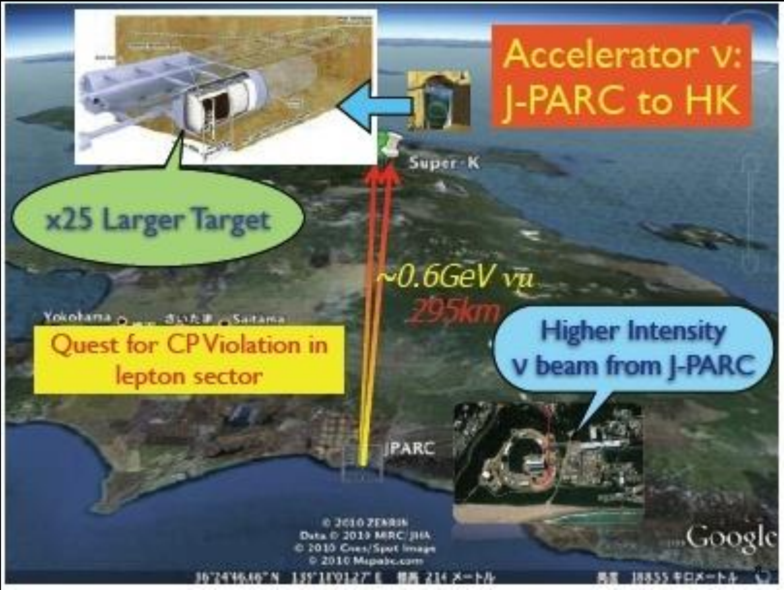
T2HK

$\nu_\mu \rightarrow \nu_e$

arXiv:1109.3262 [hep-ex]

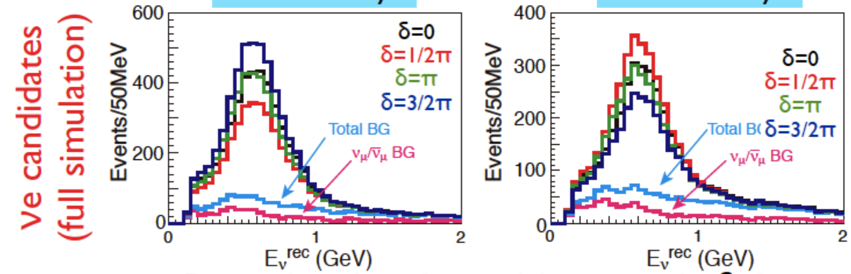
The LBL project in Japan

T.Nakaya, NNN2012



Example: case of Hyper-K

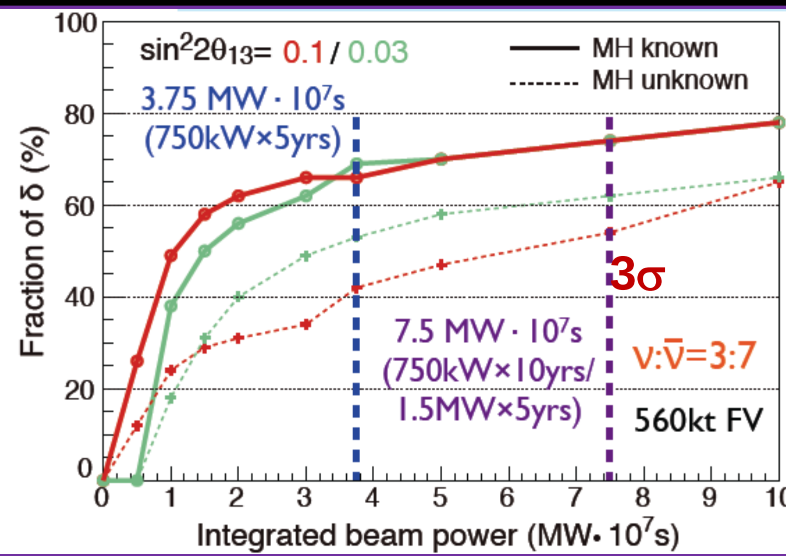
$\sin^2 2\theta_{13}=0.1$



Expected number of ν_e candidate events for $\delta=0$

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

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

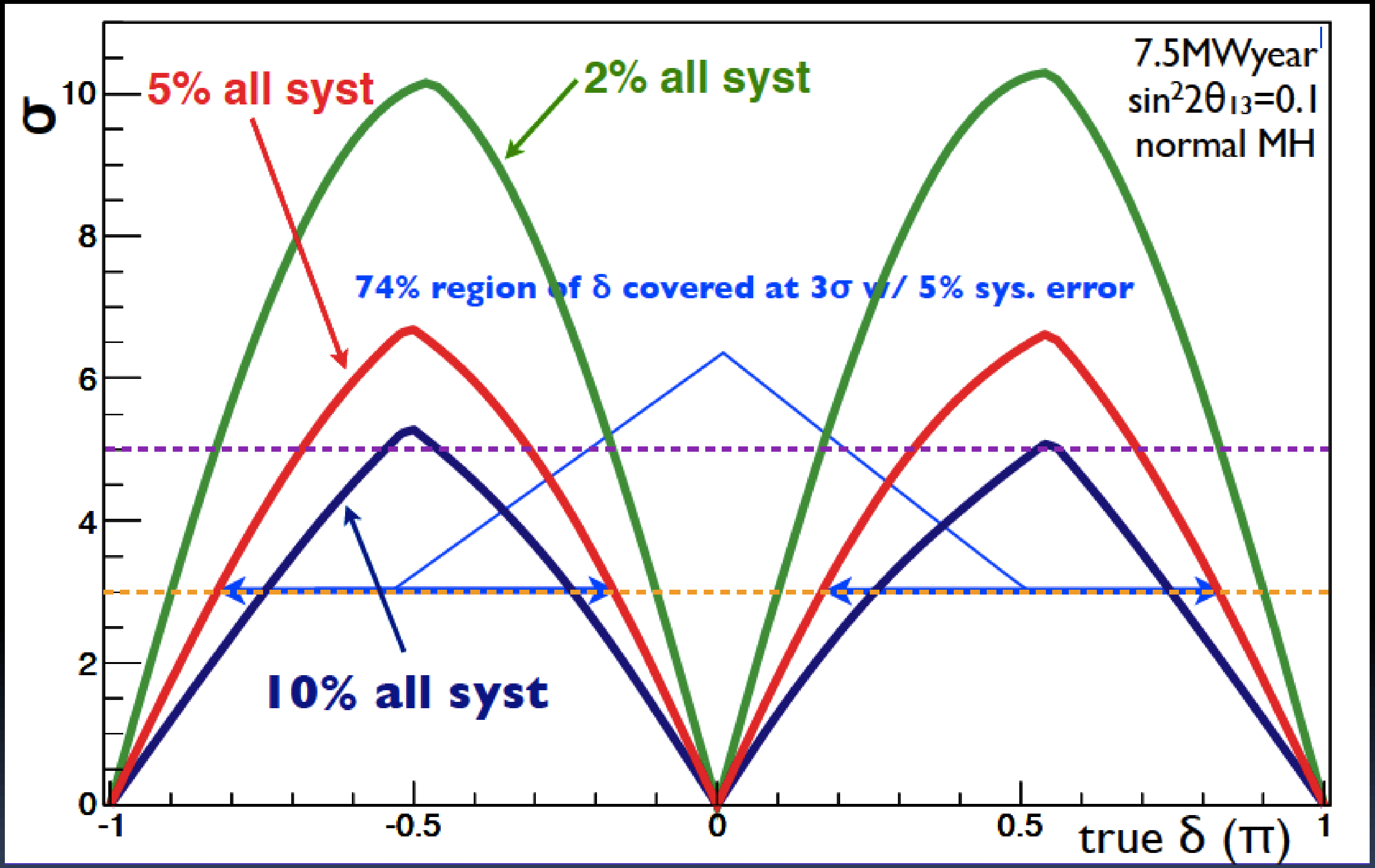


For $\sin^2 2\theta_{13}=0.1$

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 !

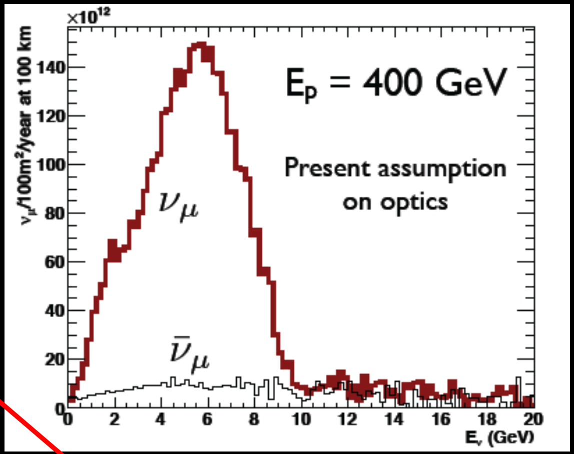


High sensitivity to CP phase for systematics < 5%

LAGUNA-LBNO

$\nu_\mu \rightarrow \nu_e$

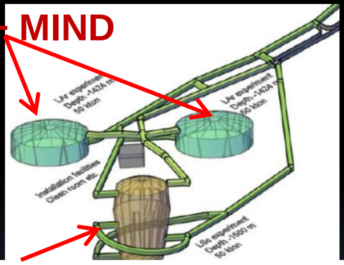
Wide-band neutrino beam from CERN to Pyhasalmi (Finland)



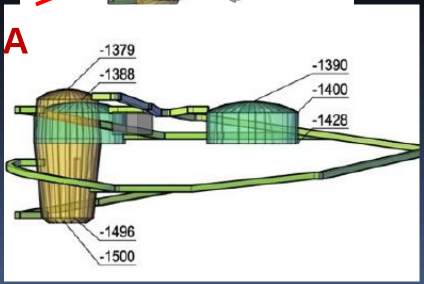
14 countries,
47 institutions
300 members
Russia:
INR
PNPI

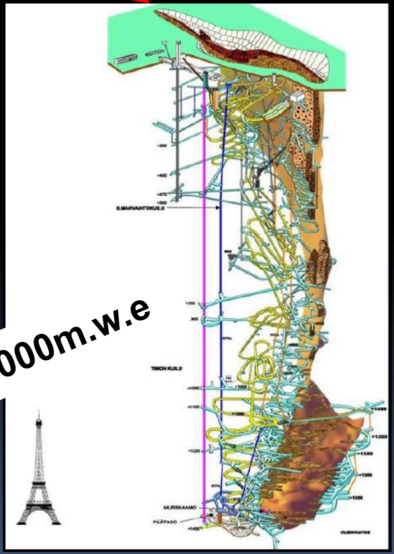
Far neutrino detectors

LAr + MIND



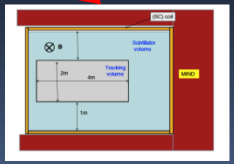
LENA





Depth 1400 m ≈ 4000m.w.e

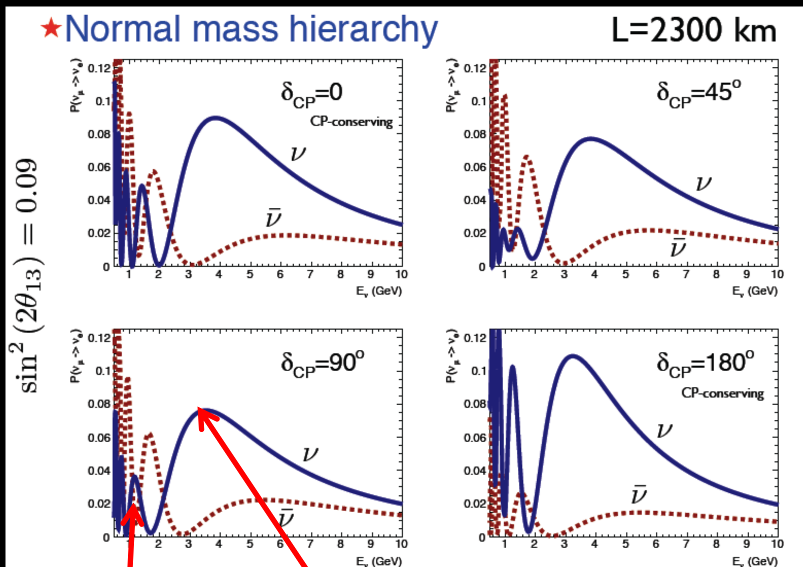
Near detector

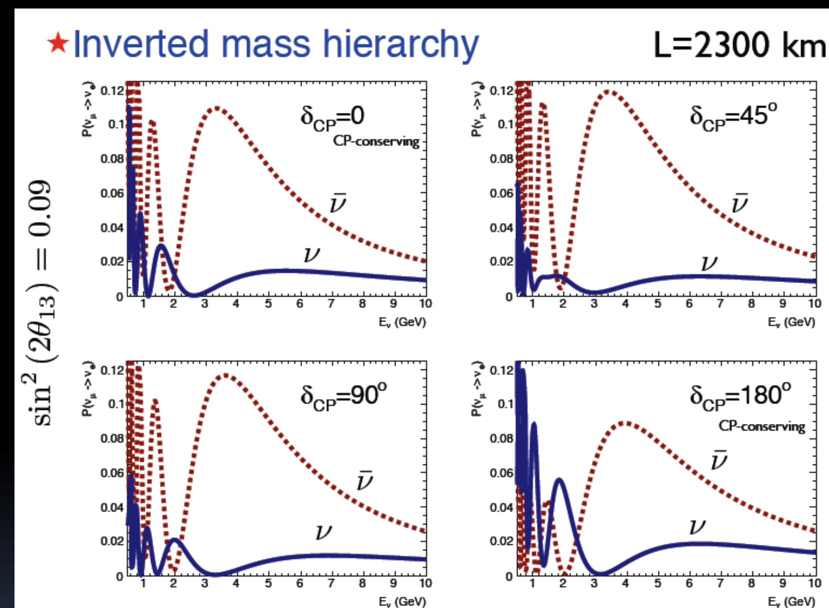


P ($\nu_\mu \rightarrow \nu_e$)

LAGUNA-LBNO

matter effect
- easy to measure MH
- more difficult CP violation





2^{nd} maximum

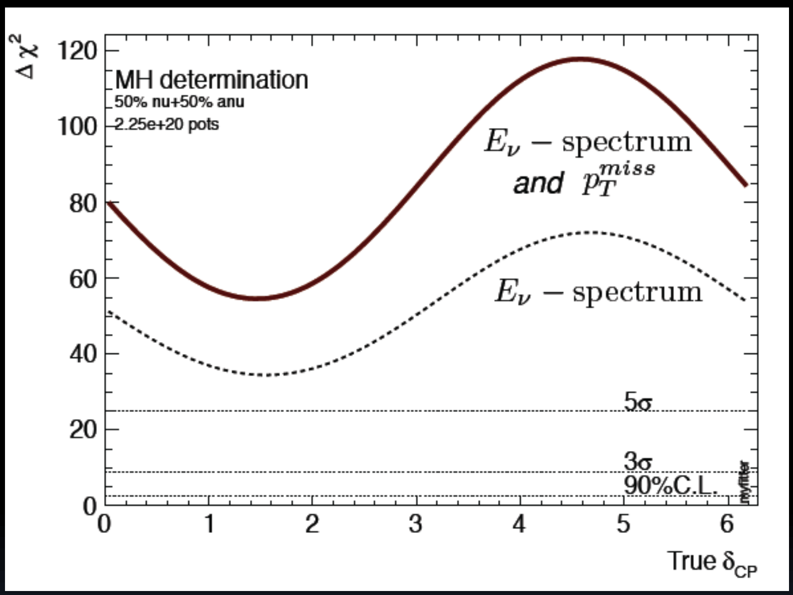
1^{st} maximum

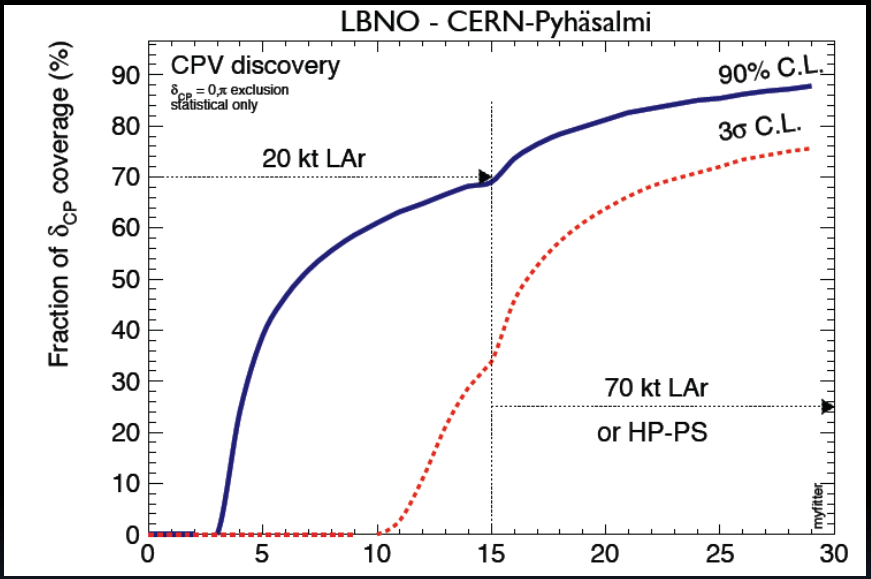
Sensitivity

LAGUNA-LBNO

MH: 100% at >5σ

CPV: ~60% at 3σ



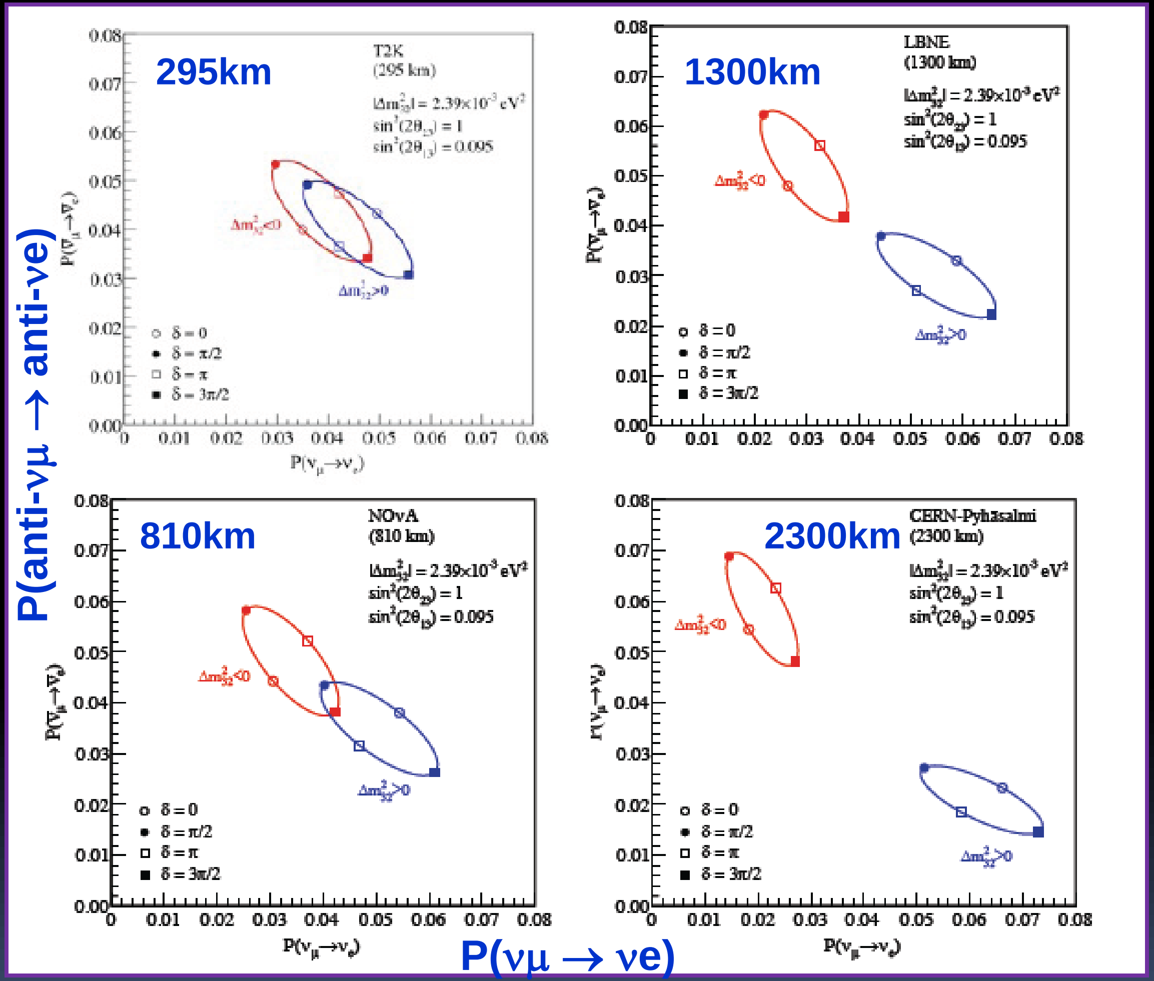


CERN SPS 400 GeV POT(x 10^{20})

δ and MH

LBL experiments

S.Wojcicki, NNN2012



Conclusion

- 3 neutrino mixing angles are measured and **non-zero**

- Large θ_{13} opens door for searching of CP-violation in lepton sector

- Time to start **MH** and δ measurements