Neutrino oscillations, today and tomorrow

Ewa Rondio

National Centre for Nuclear Research

Warsaw, Poland

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understanding neutrinos ?

- From sources to detectors (and in between)

- Neutrino oscillation was a surprise in 1990,
- now it is well established phenomenon and
  a lot of efforts are made to determine its parameters
- In future it can be a tool for
  - beyond SM effects
  - CP violation mechanism
  - Understanding matter-antimatter asymmetry

Neutrino oscillations – picture as of today

FLAVOR **PMNS mixing matrix** **MASS**

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

„atmospheric”
SK, K2K, T2K, MINOS

$$\Delta m^2_{31} = \begin{cases} 2.53^{+0.08}_{-0.10} \\ -(2.40^{+0.10}_{-0.07}) \end{cases} \times 10^{-3}\,\mathrm{eV}^2$$

CHOOZ, DayaBay, Reno, DblChooz, T2K

$$\theta_{12} = 34° \pm 1°$$

$$\theta_{23} = 40° + 5° / - 2°$$

$$\theta_{13} = 9.1° \pm 0.6° !$$

Based on PDG 2012

„solar”
SNO, KamLand, SK, Borexino

$$\Delta m^2_{21} = (7.62 \pm 0.19) \times 10^{-5}\,\mathrm{eV}^2$$

last unknown parameter θ_{13} found to be non zero !!!

mixing angles, squared mass differences, CP violation phase - fundamental parameters of nature

* $\Delta m^2_{ji} = m_j^2 - m_i^2$
Two free parameters for the three Δm^2's.
($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

… and ways of measuring θ_{13}

- dissappearance -> **reactor experiments**

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

$$P_{\rm sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)\,,$$

Energy ~ a few MeV
Distance ~ a few km

- appearance -> **long-baseline experiments** with ν_μ beam

$$\nu_\mu \rightarrow \nu_e$$

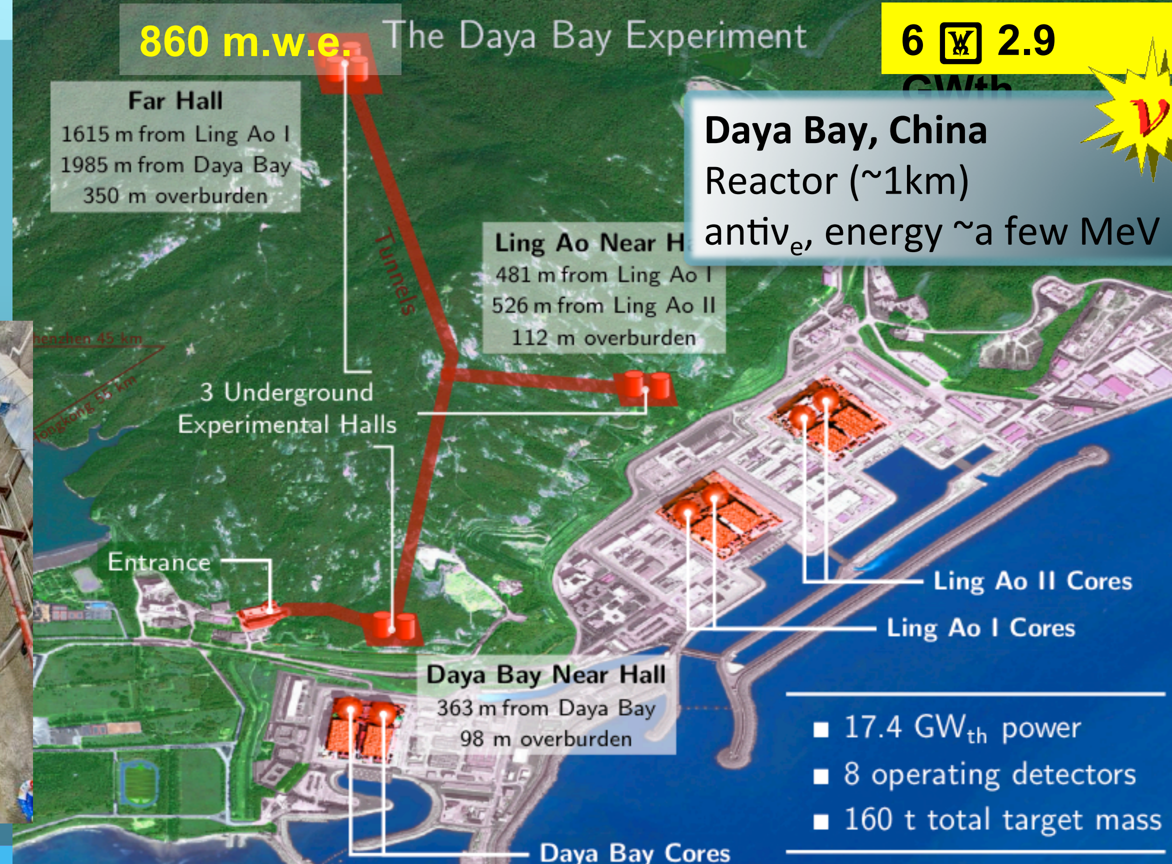
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27 \Delta m_{23}{}^2 L/E\right)$$

Leading terms!

Second order terms depend on δ and mass hierarchy

Energy ~ a few GeV
Distance ~ a few hundred km

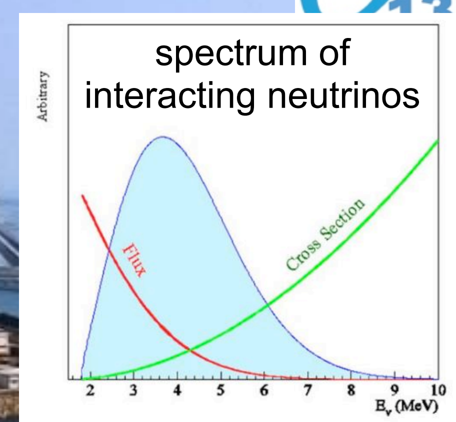
Daya Bay experiment



6 2.9 GWth

Daya Bay, China
Reactor (~1km)
antiν_e, energy ~a few MeV

Dàyà Bay (大亚湾) and Lǐng ào (岭澳) nuclear power plants

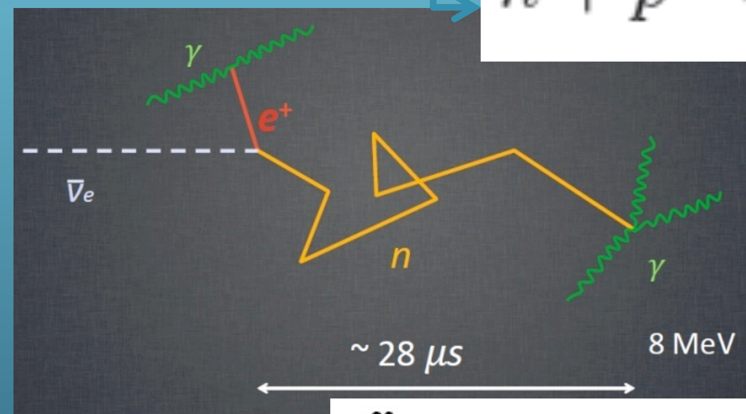


Daya Bay: detection mechanism

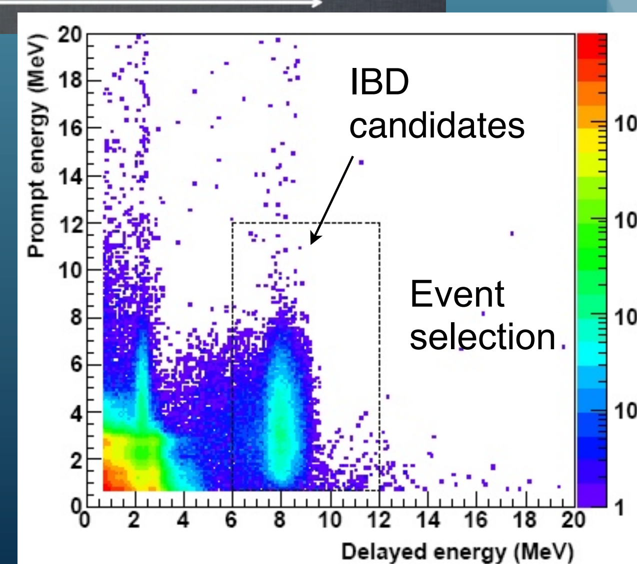
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

- Gadolinium-doped liquid scintillator (Gd-LS)
- Inverse beta decay
  - **prompt signal**: positron (its energy is correlated with neutrino energy)
  - **delayed signal**: neutron capture

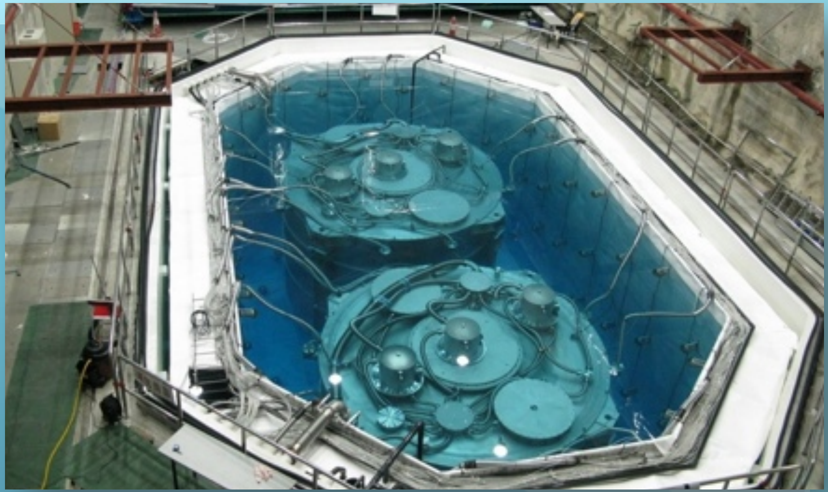


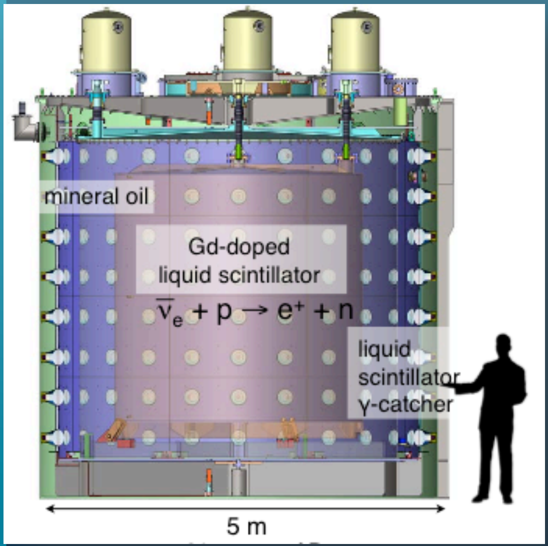
- Systematic error minimisation:
  - Identical far and near detectors
  - Identical detection modules
  - Good background rejection (3-zone modules, water system, RPCs)



Daya Bay: detection modules

- 3-zone detection modules immersed in water, shielded by RPC plane
  - target – 20t of Gd-LS (0.1% Gd)
  - gamma catcher – 21t of LS
  - radiation shield – 37t of mineral oil
  - 192 8inch photomultipliers on the walls (scintillation light detectors)
  - 3 calibration modules

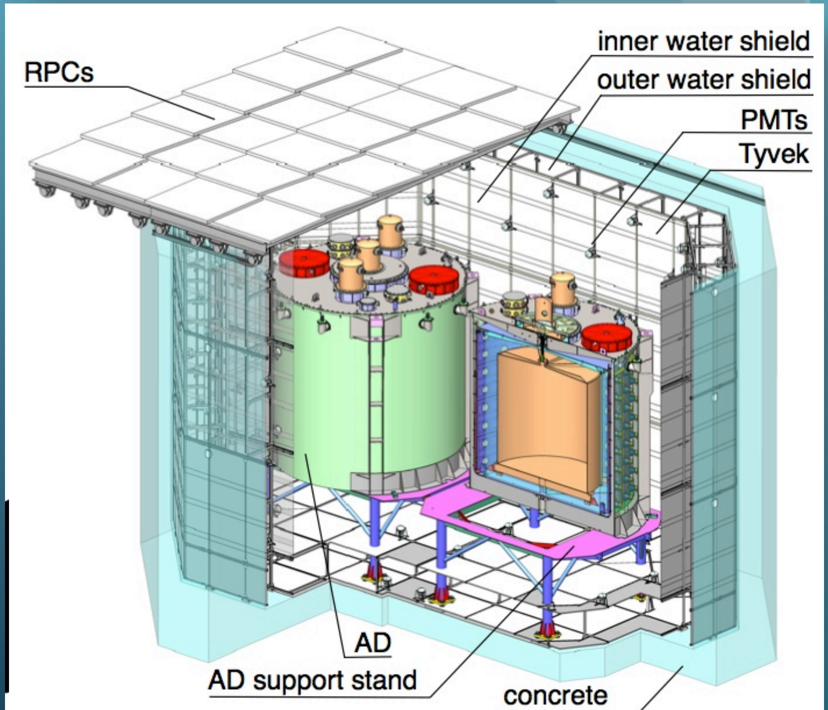




Muon water system

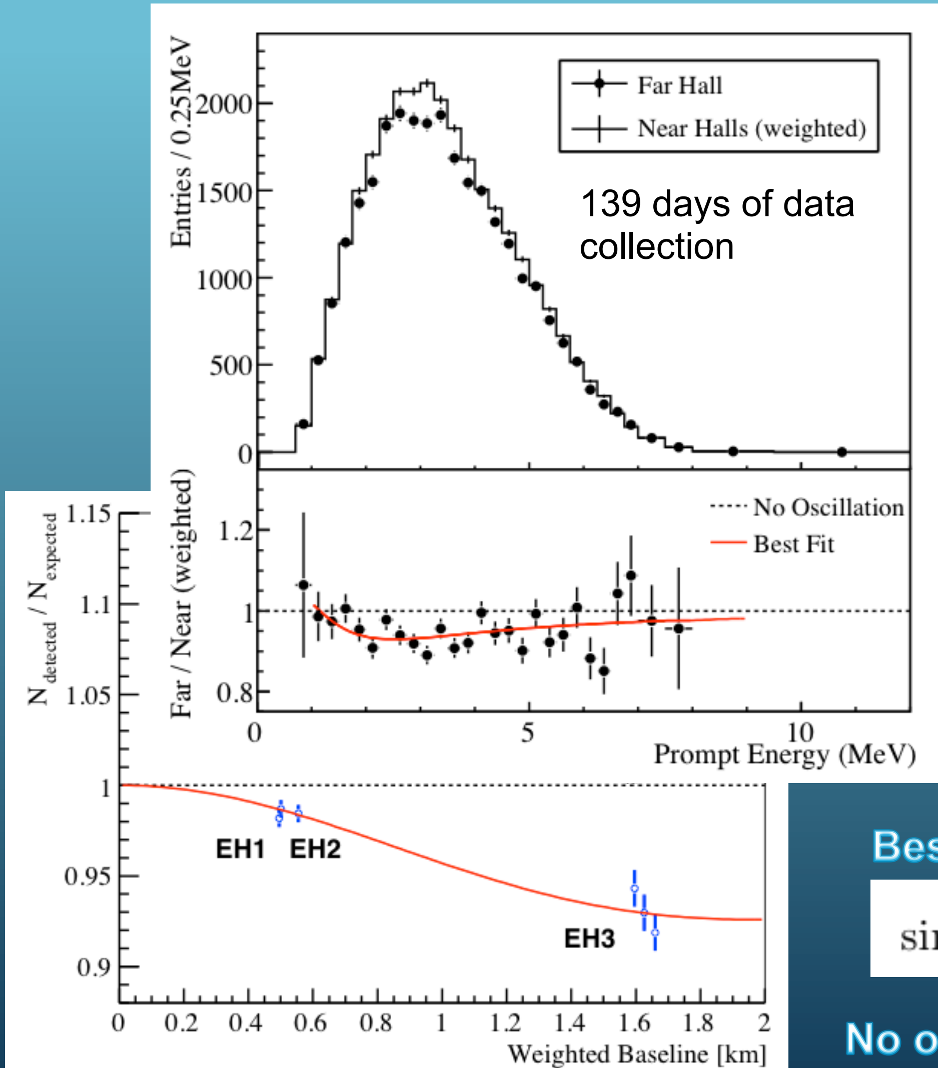
- Cherenkov water shield – at least 2.5m in every direction, 1200/1950t of water in two separated vessels, each equipped with photomultipliers

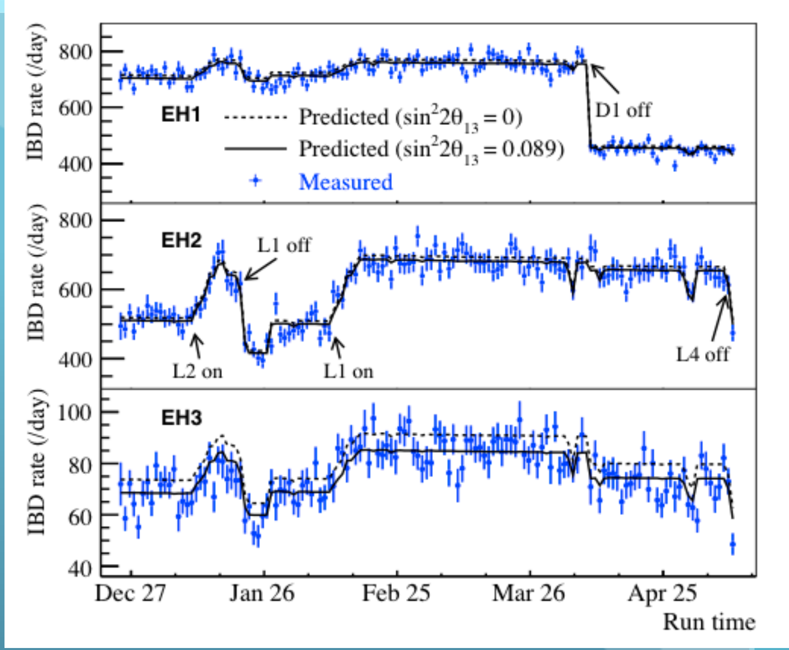
Detects muons that can produce spallation neutrons, attenuates gamma rays from surroundings, moderates neutrons



Two-zone ultrapure water Cherenkov detector

Results: rate only





Time variations: flux prediction + detector MC vs data in the three stations

Far to near ratio:

$$R = 0.944 \pm 0.007(\text{stat.}) \pm 0.003(\text{syst.}),$$

Best fit, assuming $\Delta m^2_{31} = 2.32 \times 10^{-3}\text{eV}^2$

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

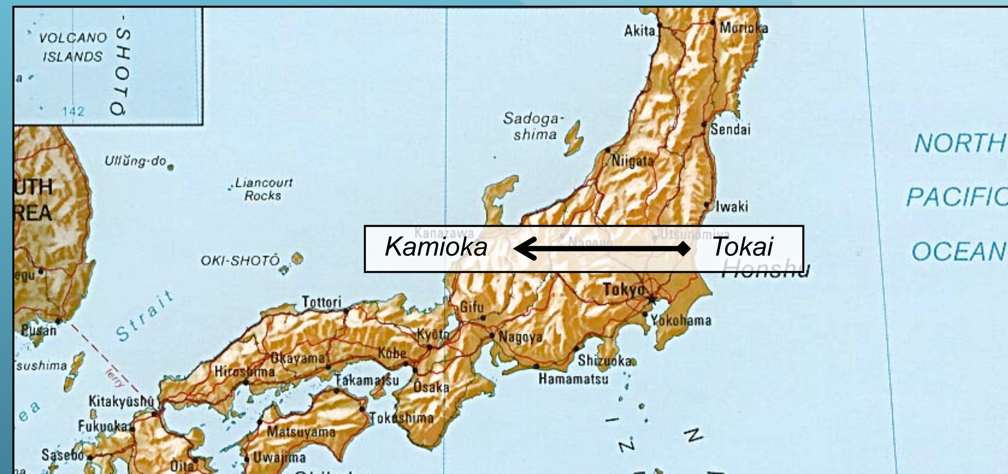
No oscillations excluded at the level of 7.7σ

Results: Chinese Physics **C37**:011001 (2013), new shape analysis: see Soeren Jetter's slides, NuFact 2013

Accelerator experiments: T2K

Tokai2Kamioka, Japan
Long Baseline (~300km)
ν_μ beam, energy ~1GeV

- **Tokai2Kamioka**: long baseline experiment with narrow-band beam
- Neutrinos produced in J-PARC laboratory in **Tokai** (30GeV proton beam hits a graphite target)
- **Near detector** 280m from the production point measures non-oscillated beam
- **Far detector** – Super-Kamiokande, large water Cherenkov detector in Kamioka mine studies effects of oscillations



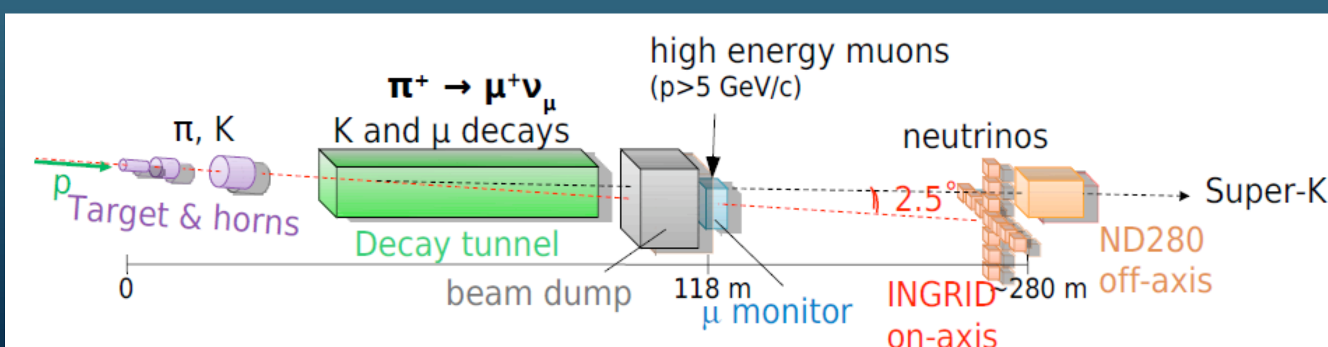
Main goal: neutrino **oscillation studies**

- muon neutrino dissapearance
- **electron neutrino appearance**

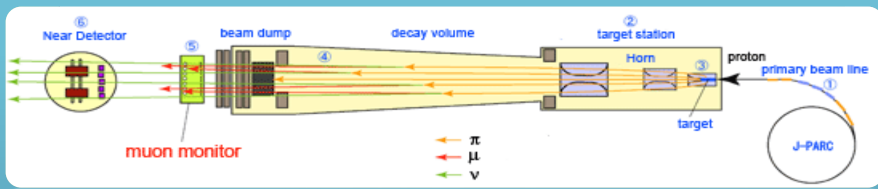
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2\left(1.27\Delta m_{23}^2 L / E\right) - P(\nu_\mu \to \nu_e)$$

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

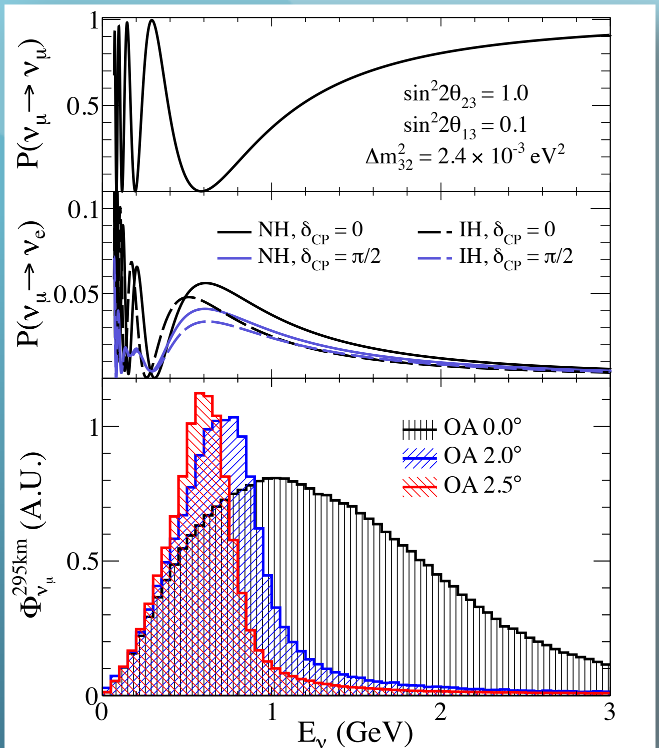
Leading terms only



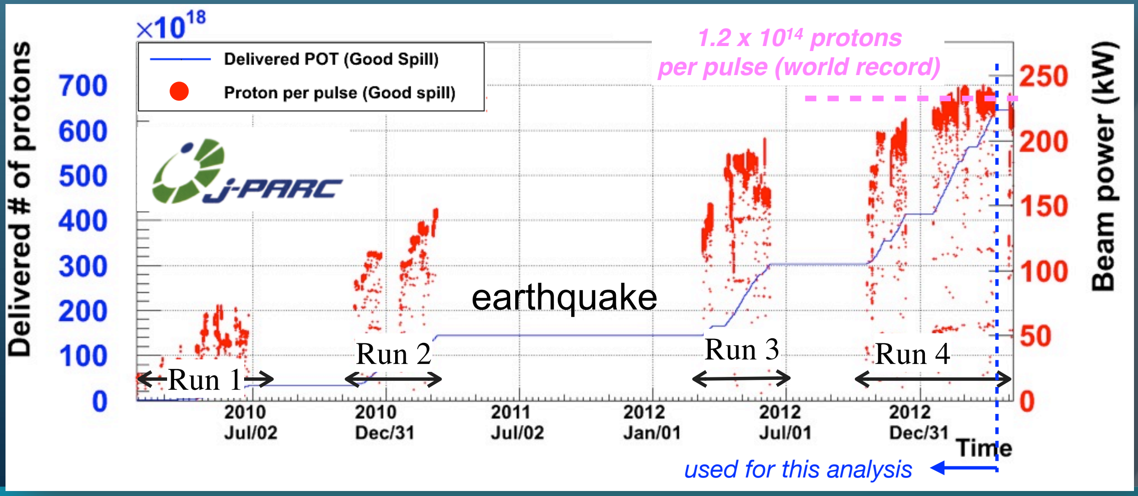
T2K: beam



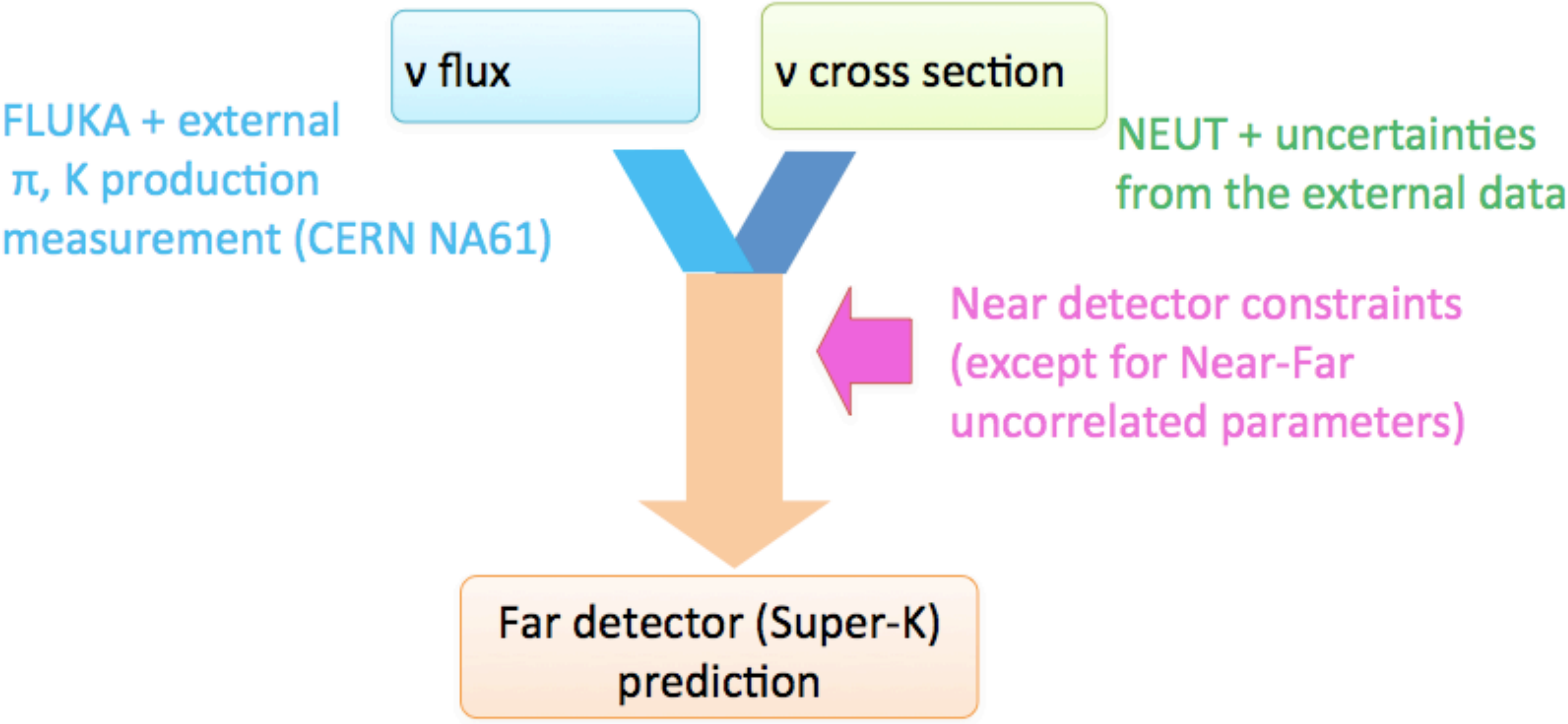
- Proton beam hits the target, produces hadrons, mainly pions
- **The pions decay:** $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- **Beam contamination:** $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$, $K^+ \rightarrow \pi^0 e^+ \nu_e$
- Detectors positioned off-axis to get favorable spectrum shape
- Hadron production measured with target replica in NA61 experiment for better predictions of neutrino flux



Off-axis angle chosen: 2.5 degrees



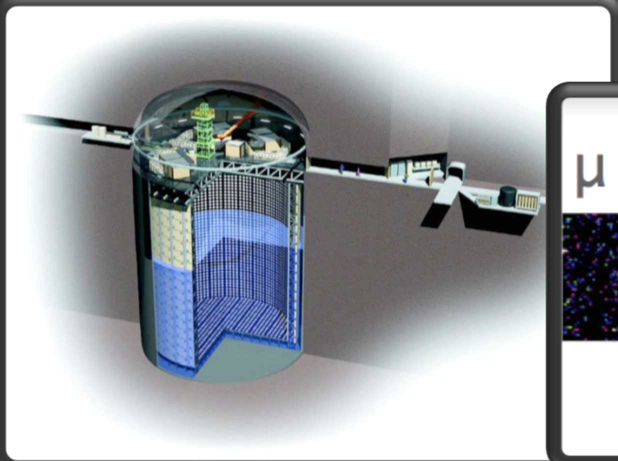
Oscillation analysis constraints

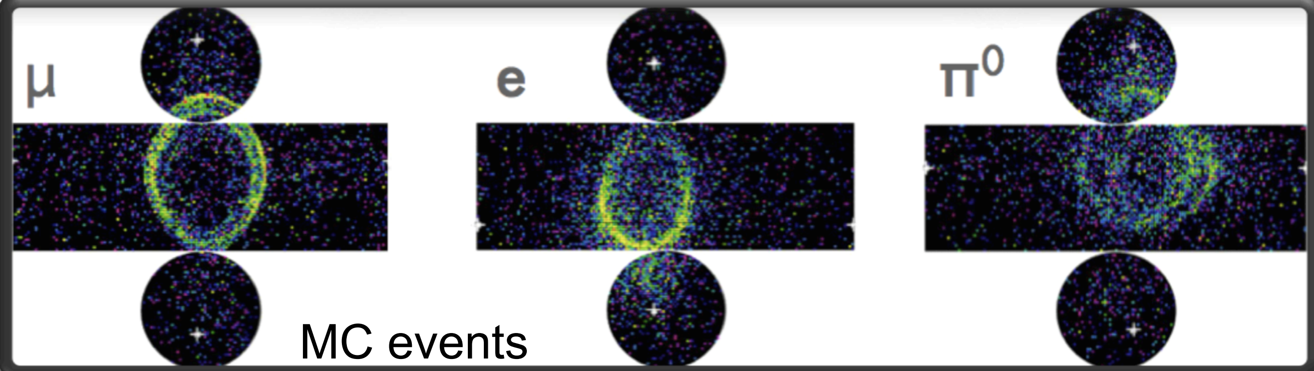


Improvements for 2013 results:

- Measurements from NA61 and implementation in beam MC
- From T2K near detector constraints for QE, 1π and other (multi π)
- Improvements on cross section uncertainties (other experiments)

T2K: Super-Kamiokande





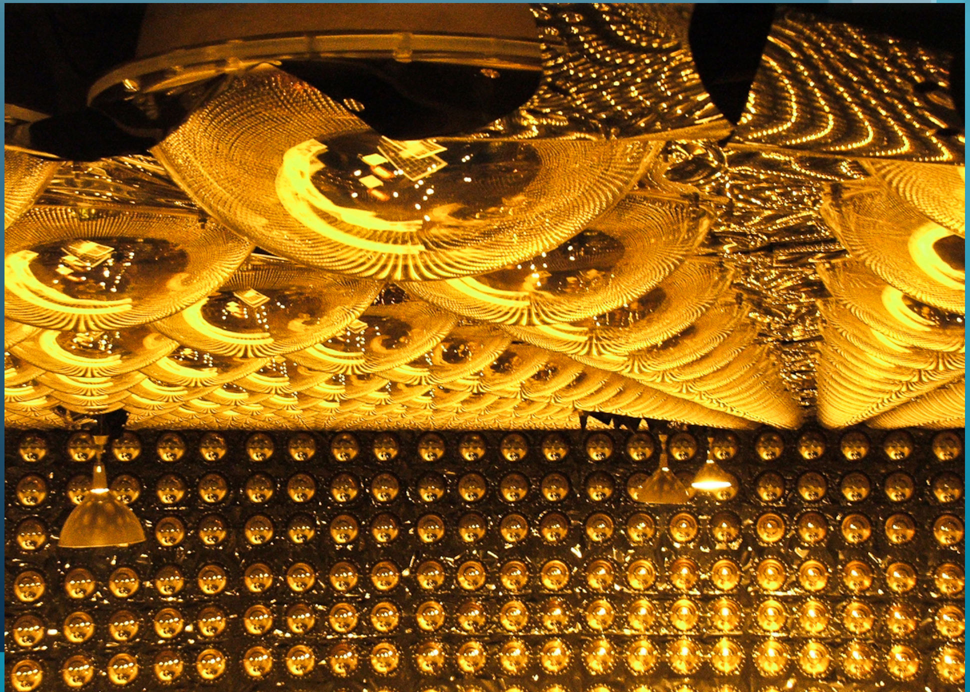
Good muon/electron separation

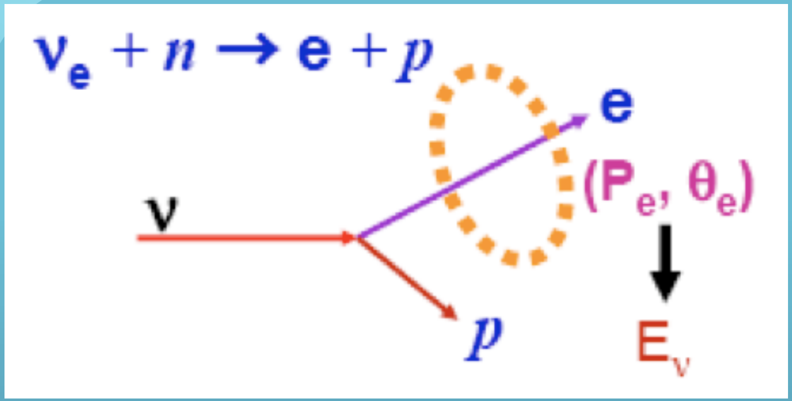
Large water Cherenkov detector

50 kton of water, 22.5 kton fiducial volume, >11,000 photomultipliers on the walls observe Cherenkov light

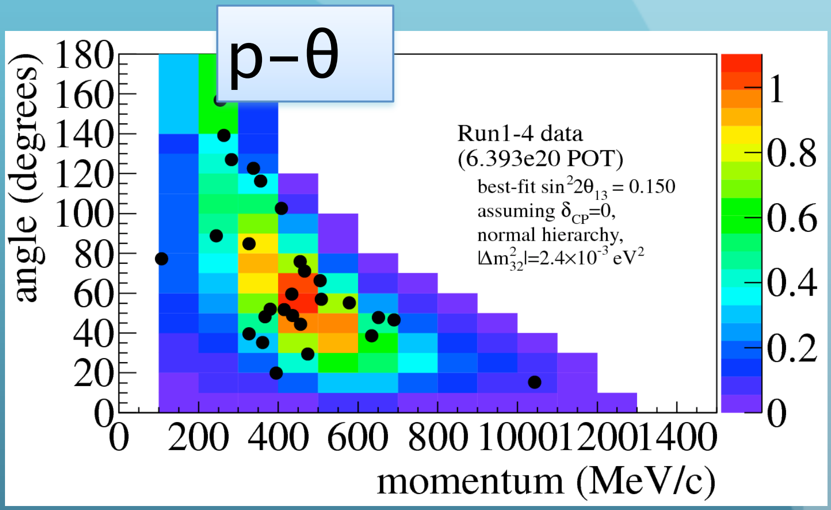
Many years of experience, very well known detection technique, systematic errors known and understood

Studies also atmospheric, solar neutrinos

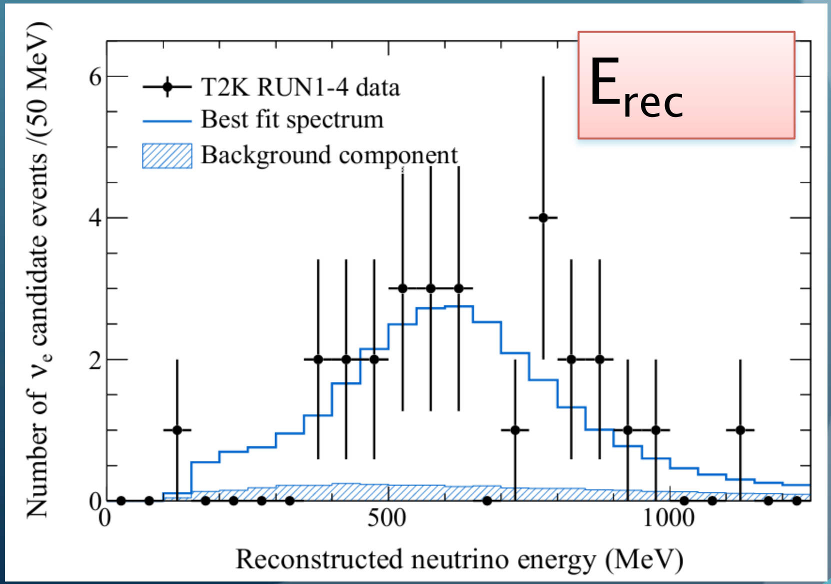




T2K, 2013 results



- Neutrino oscillation parameters extracted in two ways:
  - using reconstructed neutrino energy distribution
  - using observed electron momentum and angle
- **28 events observed**
  - for $\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, $\delta=0$ we would see 20.4±1.8 events
  - expected background 4.64±0.53



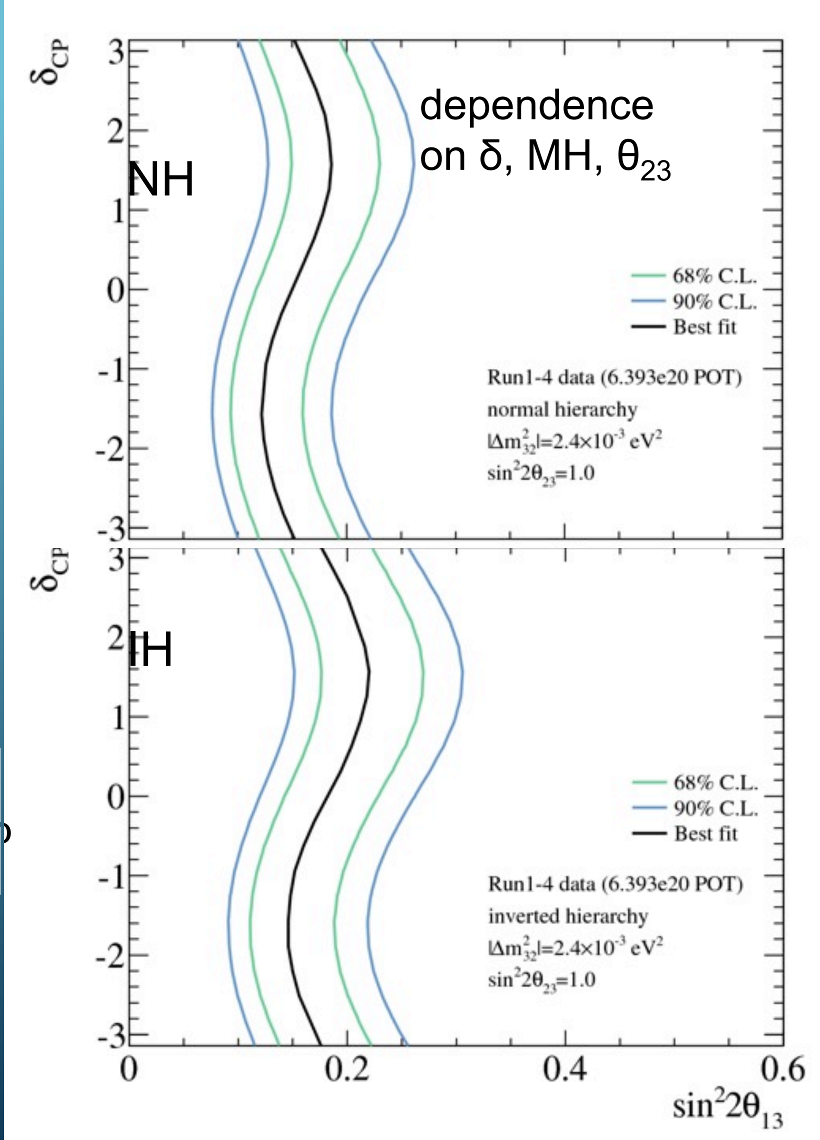
T2K: 2013 results

- Electron neutrino appearance result – 2012 update
  - new data (run 4)
  - new SK reconstruction algorithm (fiTQun), better π^0 background rejection
  - near detector CC inclusive measurement improved by using new event categories

- Best fit results for δ=0 (68% C.L. error)
  - normal hierarchy $\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$
  - inverted hierarchy $\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$

- **7.5σ significance** for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel!



NOTE: These are 1D contours for various value of δ_{cp}, not 2D contours

T2K: θ_{23} uncertainty and reactor results

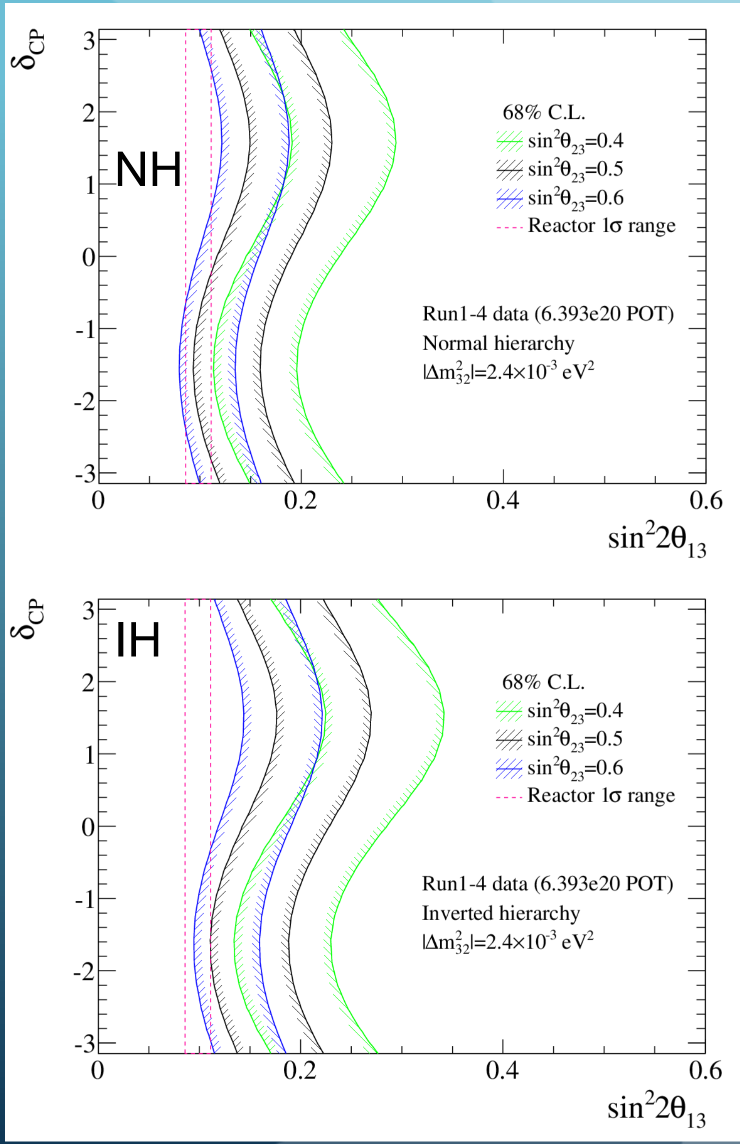
- ν_e appearance contours depend on the value of θ_{23}
- This needs to be determined more precisely by studying ν_μ dissapearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27\Delta m^2_{23} L / E\right)$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2\left(1.27\Delta m^2_{23} L / E\right)$$

Leading terms

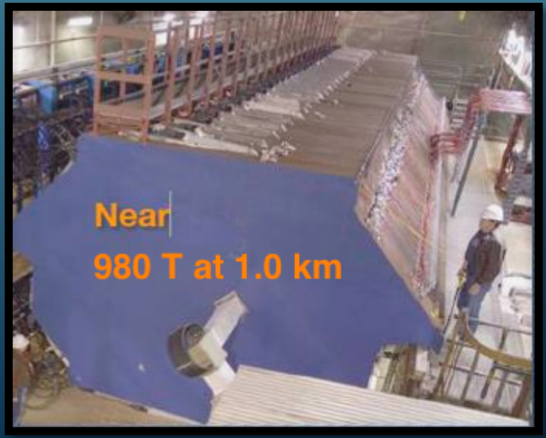
Comparison with reactor results (PDG2012):
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$



NOTE: These are 1D contours for various value of δ_{cp}, not 2D contours

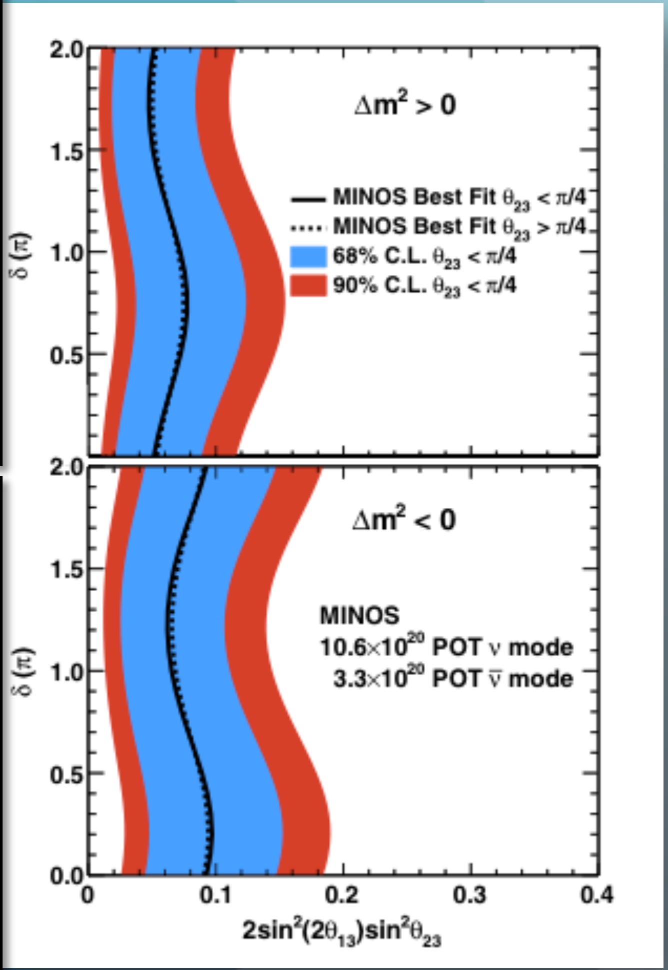
Accelerator exps: MINOS

- LB (735km) experiment in USA, started in 2005
- NuMI beam from FermiLab - mainly muon (anti)neutrinos
- Near detector in FermiLab, far detector in Soudan mine (3.8kT fiducial) – magnetized tracking calorimeters
- Neutrino ($10.6 * 10^{20}$ POT) and antineutrino ($3.3 * 10^{20}$ POT) beam data collected



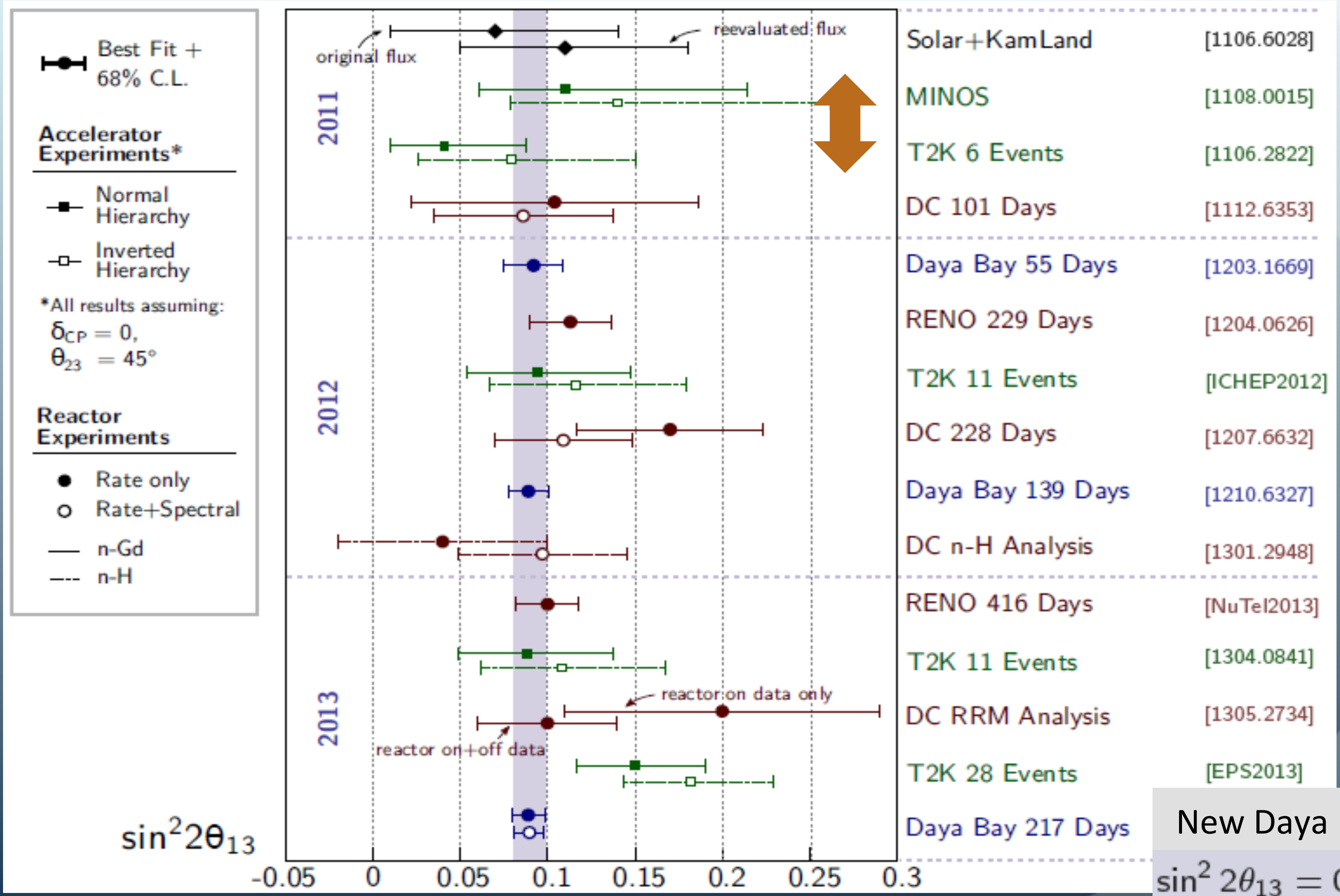
θ_{13} measurement:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$



Global summary of θ_{13} measurements

Compilation from Soeren Jetter (HEP), NuFact 2013

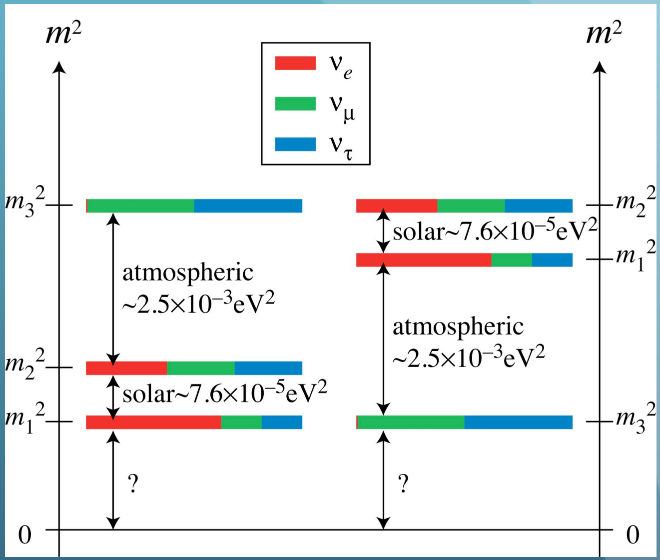


New Daya Bay Result

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

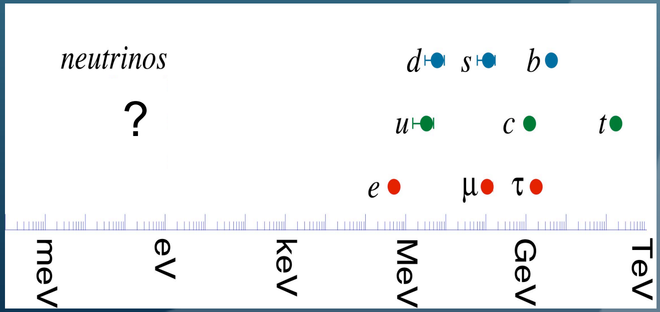
questions we'd like to ask

- What is the neutrino mass ordering (hierarchy)
- Is there a CP violation in neutrino sector?
- Are there only three neutrino types?
- What are the exact values of neutrino mixing parameters?



... and for non-oscillation experiments:

- Are neutrinos Majorana or Dirac?
- What is the absolute scale of masses?



What's next?

Unknown	
CPV	$\delta \neq 0, \pi?$
MH	$m_3 \gtrless m_2?$
	$\theta_{23} \gtreqless 45°?$

Differences in neutrino vs antineutrino oscillation probabilities

Changes the contribution from matter effects
(important for neutrinos travelling through dense matter e.g through Earth)

Additional source of degeneracies

An unknown hierarchy usually leads to a reduced ability to observe CP violation

Measurement strategies (for LBL):

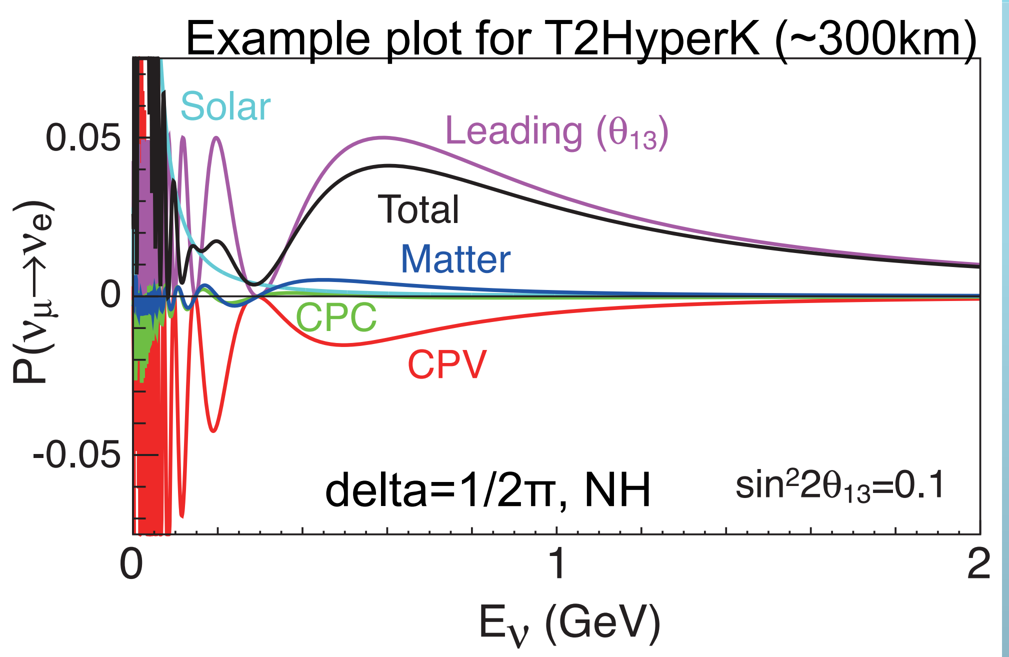
- Looking for appearance

$$P(\nu_\mu \to \nu_e) \quad vs. \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

- The longer the baseline the better (matter effects!)
- Study more than one oscillation maximum to disentangle the effects

CPV and MH

- In long baseline neutrino experiments



$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

leading term

CP conserving

CP violating

solar term

matter effects

$C_{ij},\ S_{ij},\ \Delta_{ij}$

$\cos\theta_{ij},\ \sin\theta_{ij},\ \Delta m_{ij}^2\, L/4E_\nu$

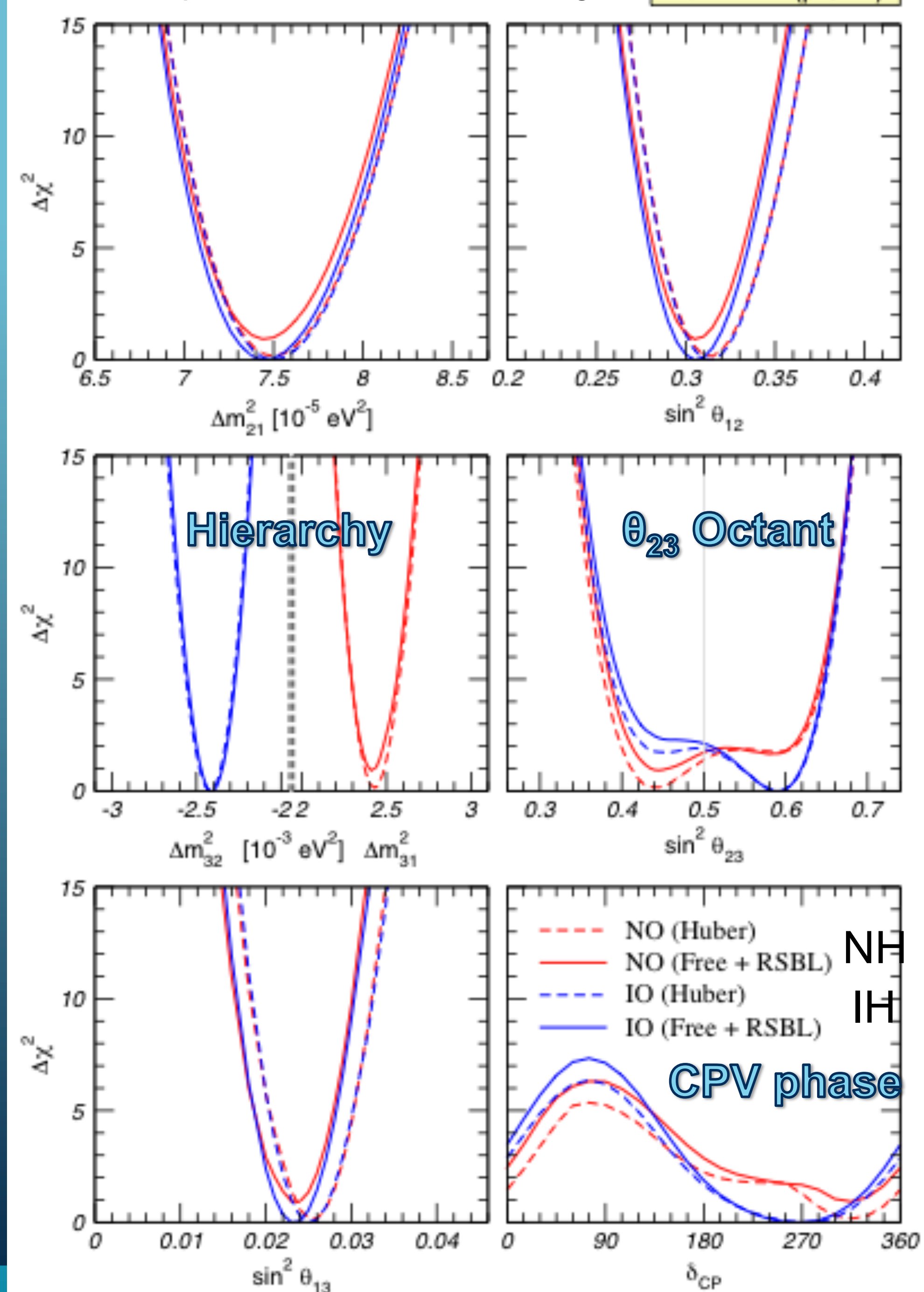
for $\overline{\nu}_\mu \to \overline{\nu}_e$ $\delta \to -\delta$ $a \to -a.$

$\alpha \sim \rho^* E_\nu$

Gonzalez-Garcia et al.,arXiv:1209.3023 with updates, see www.nu-fit.org

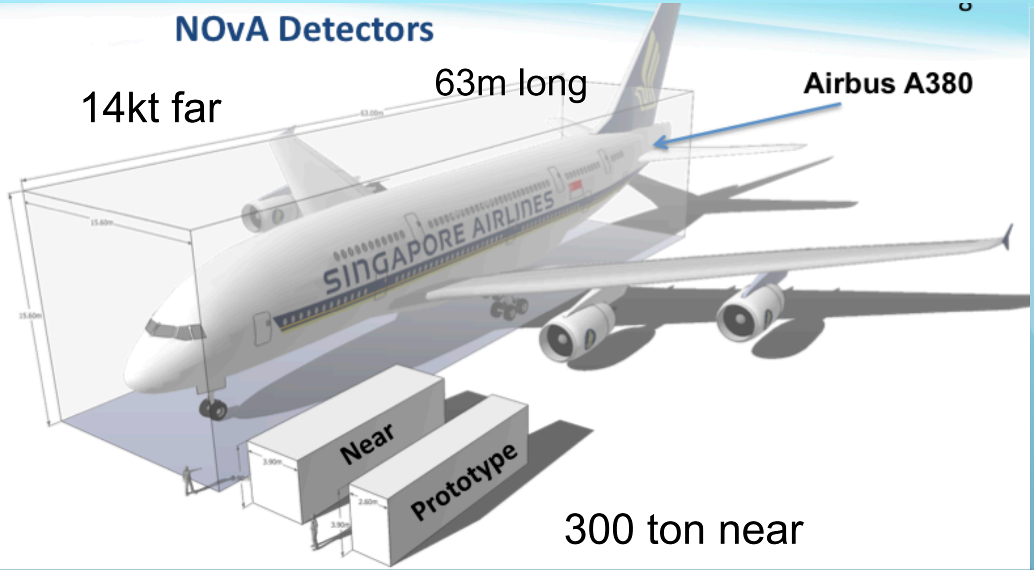
Hints from current results

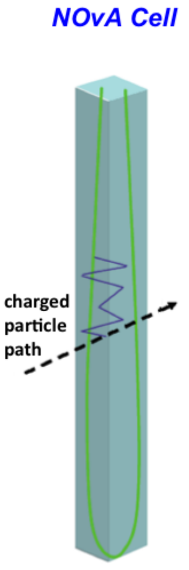
- We definitely need new experiments



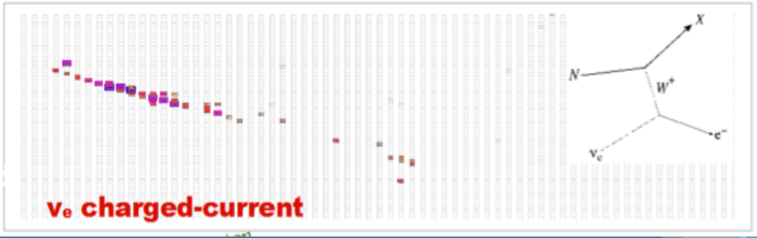
New player: NOvA

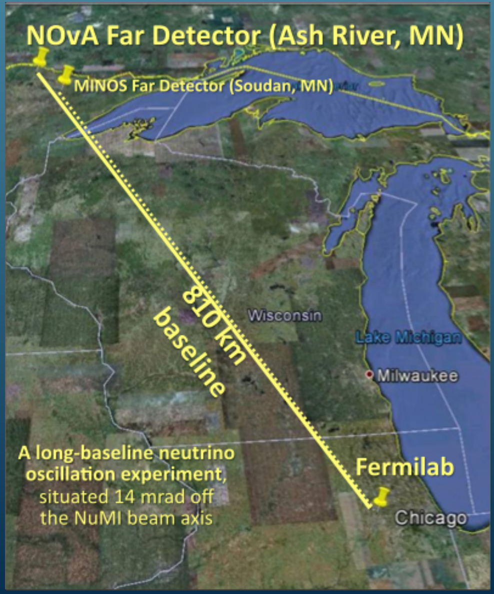
- Neutrinos from NuMI beam, 810 km long baseline
- An off-axis detector layout (14 mrad), beam max energy ~2GeV
- Will measure $\nu_\mu \to \nu_{e}$, nu as well as antinu runs
- Hopes to determine MH and octant, constrain δ_{cp}

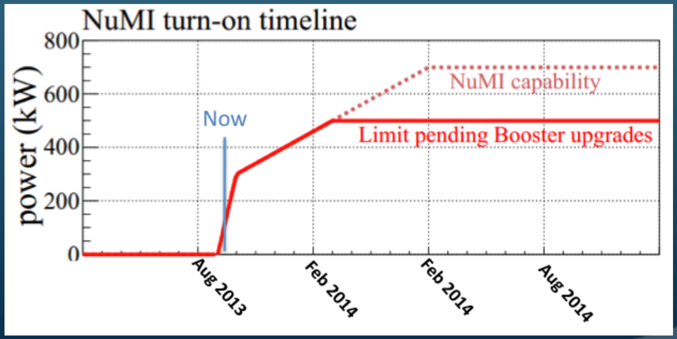


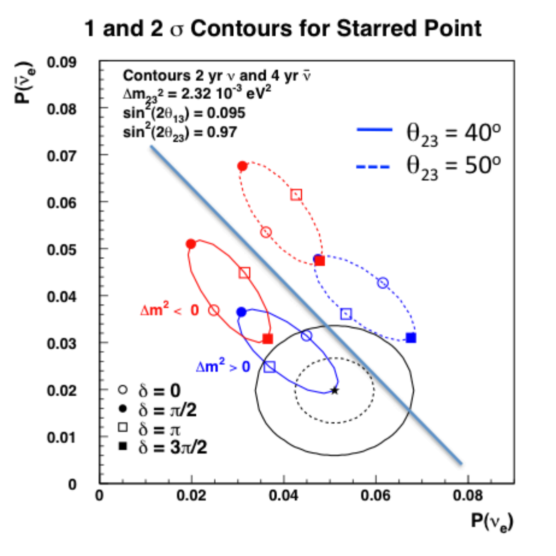


- Fine grained and highly active tracking calorimeters
- Plastic extrusions filled with liquid scintillator
- Light captured by a fiber and read by an APD
- First kiloton intrumented by the end of May 2013, completion expected by May 2014
- The beam has just started operation

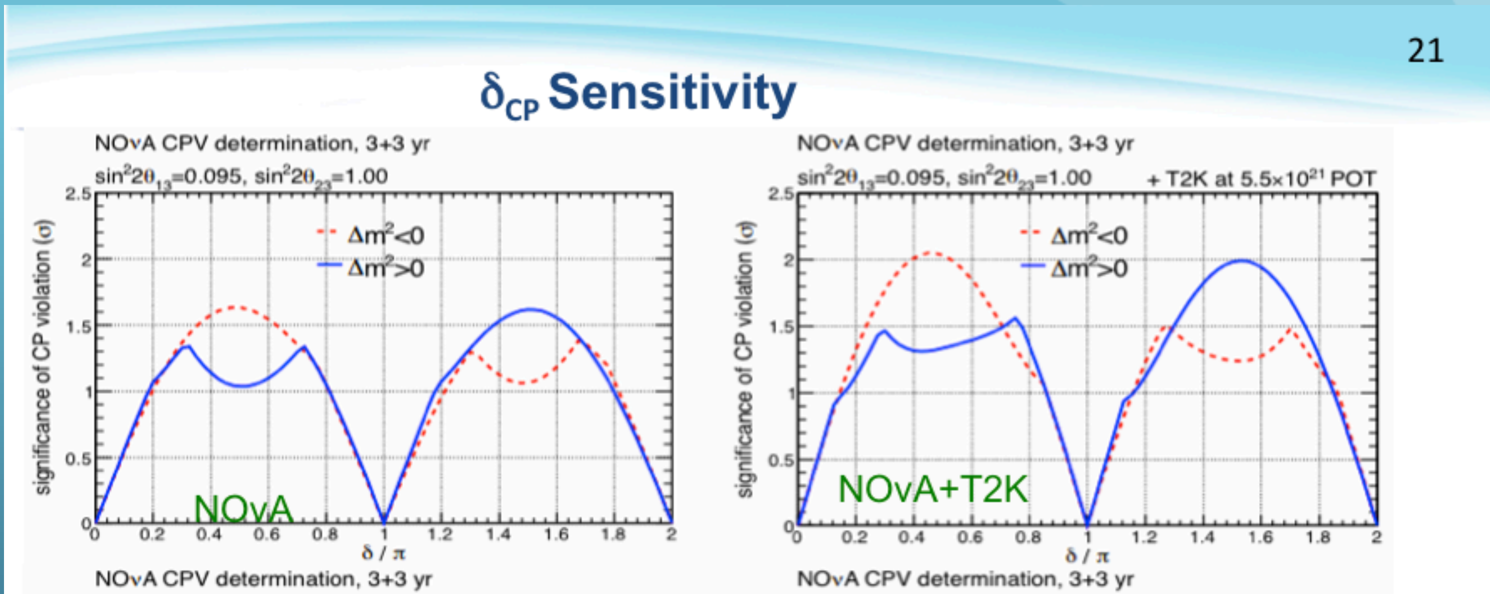


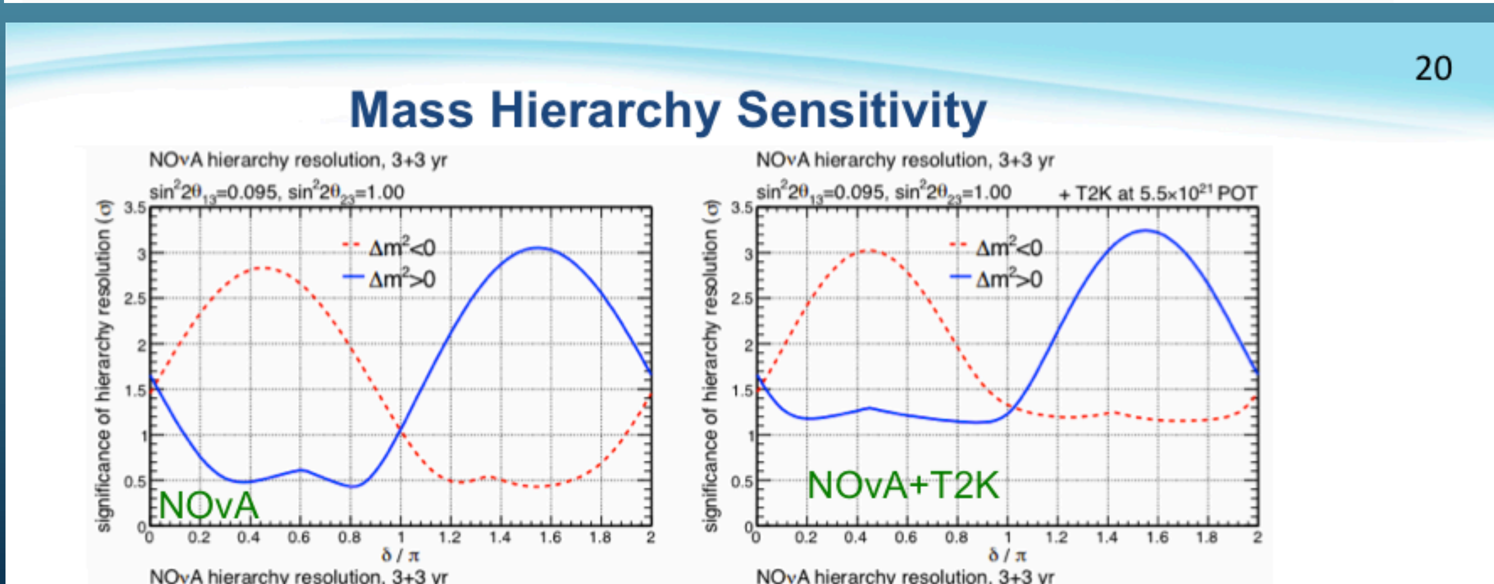




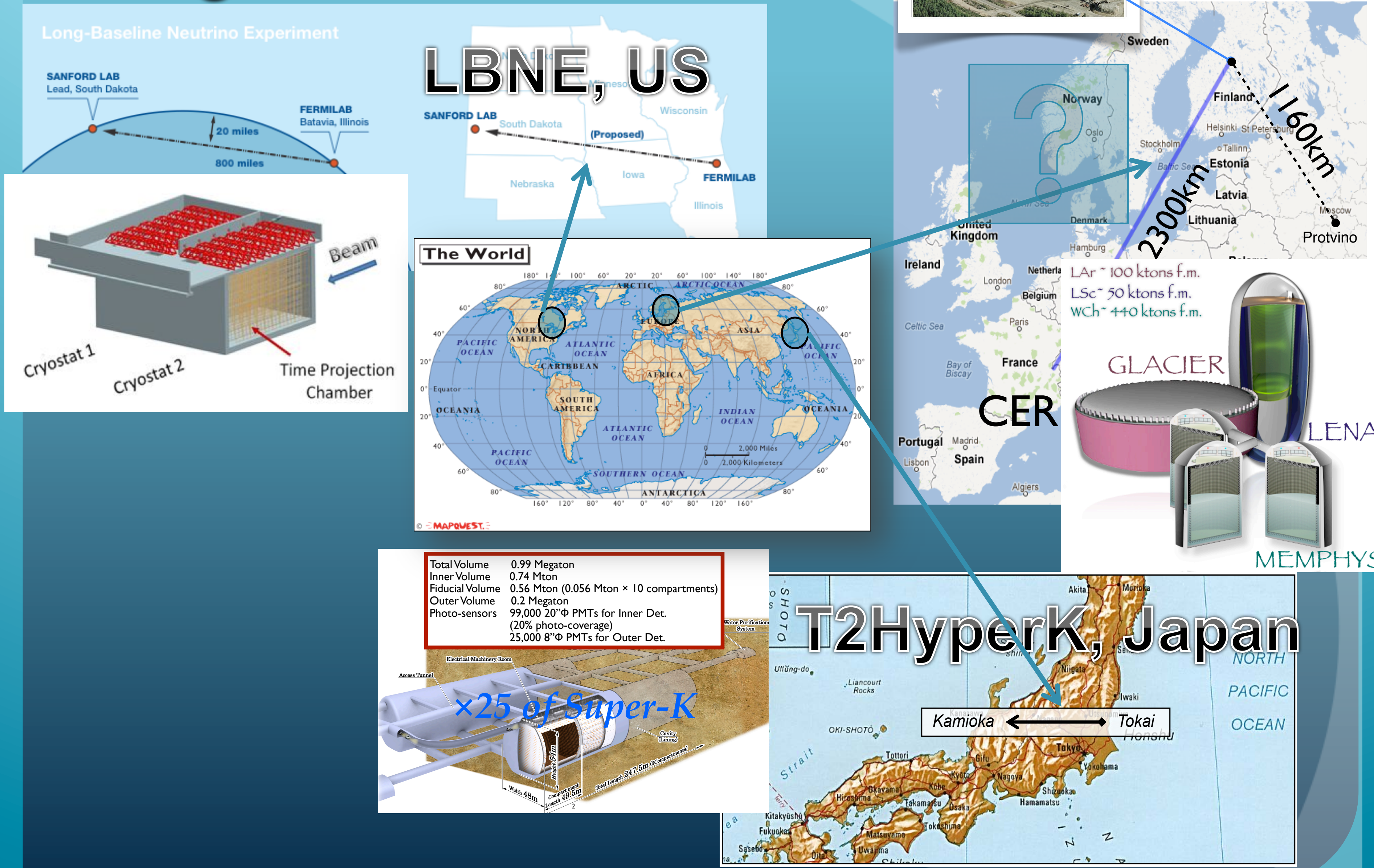


Expected sensitivity



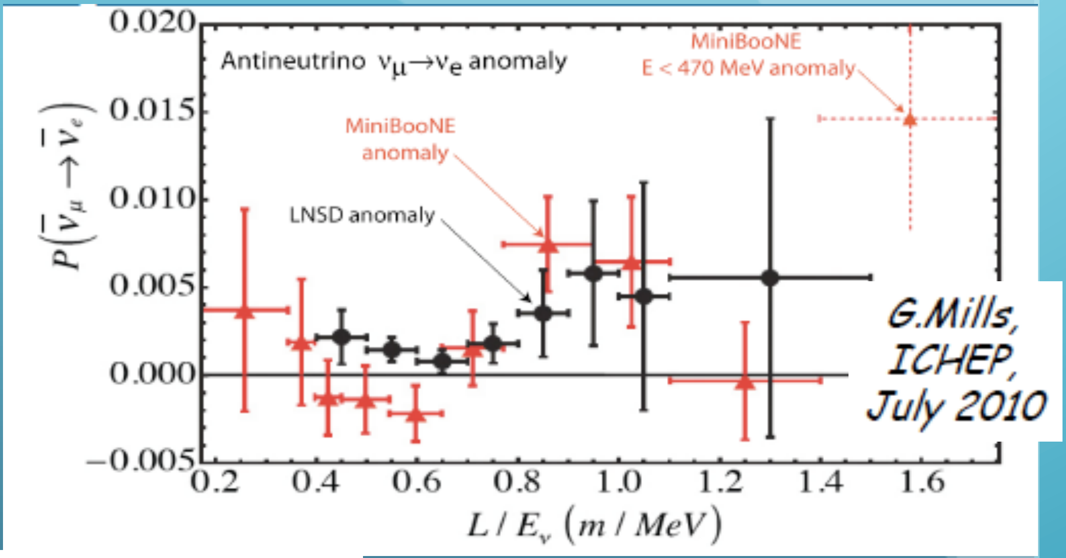


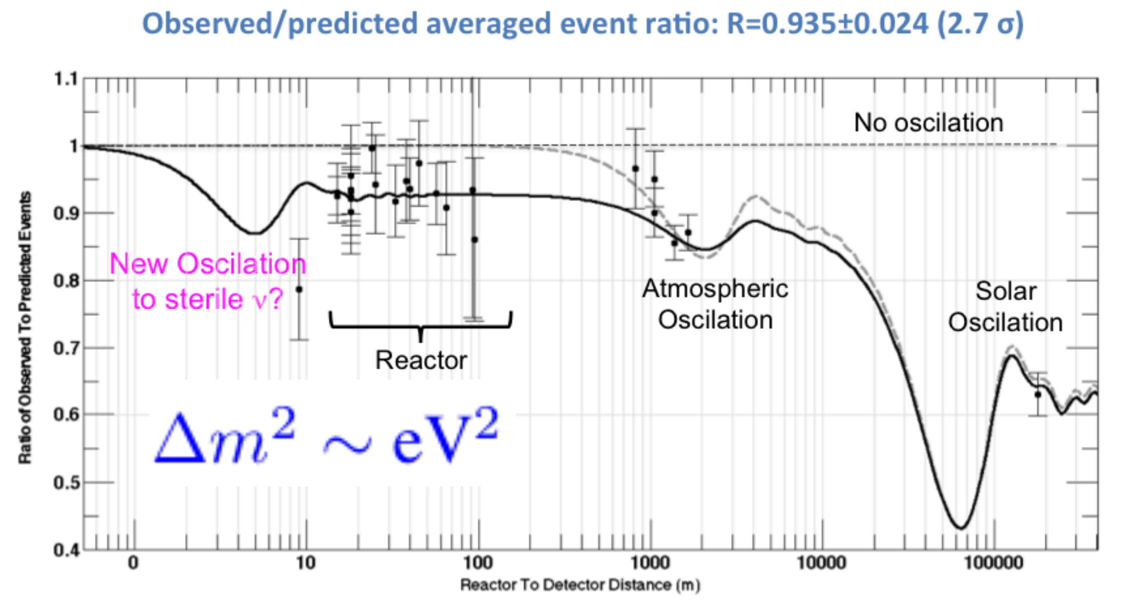
Long Baseline Future



Sterile neutrinos were hypothesized in a paper by Pontecorvo in 1957

- Maybe we need at least one additional neutrino type to explain some anomalous results from experiments?
  - Short baseline experiments (LSND, MiniBoone)
  - Reactor neutrino anomaly





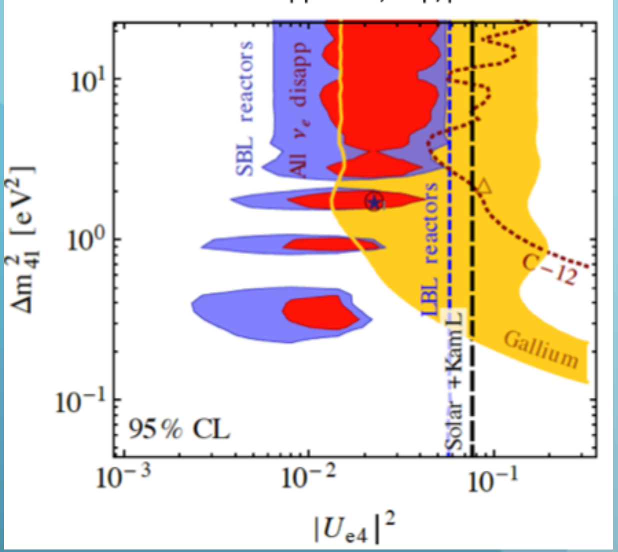
Hints
for more that 3 neutrinos
also from astrophysics

Sterile neutrinos?

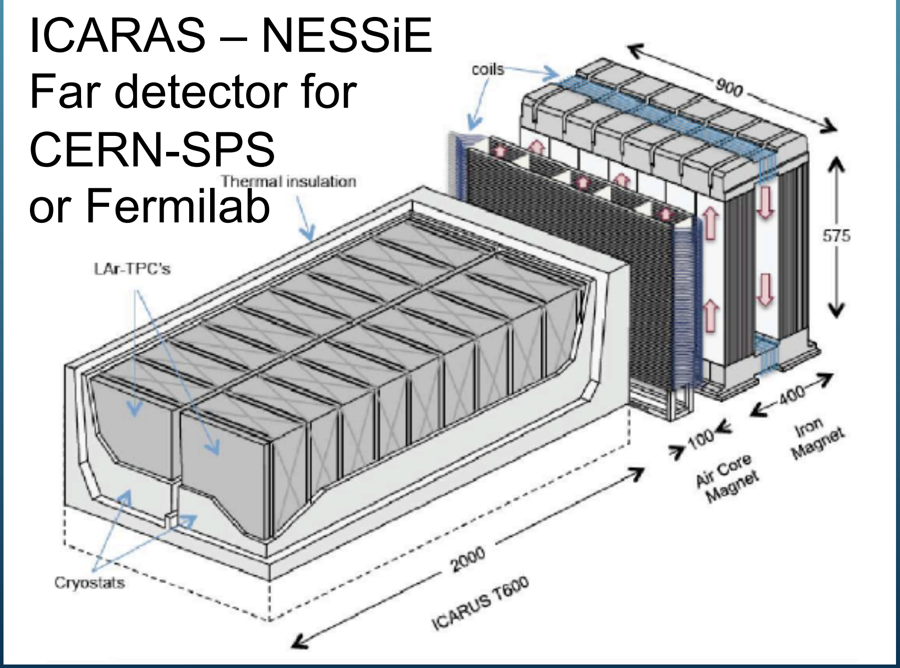
Several proposal to search for them

- Short baseline experiment on ~GeV beam with LAr detector
- Very short base line with radioactive sources (even with source inside detector)

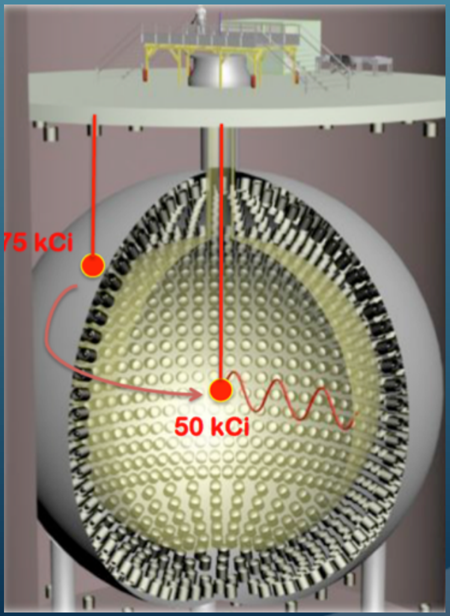
J. Kopp et al., hep/ph:1303.3011



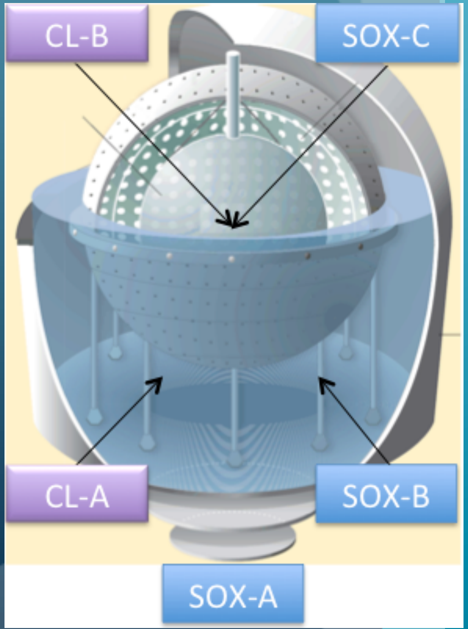
ICARAS – NESSiE
Far detector for CERN-SPS
or Fermilab



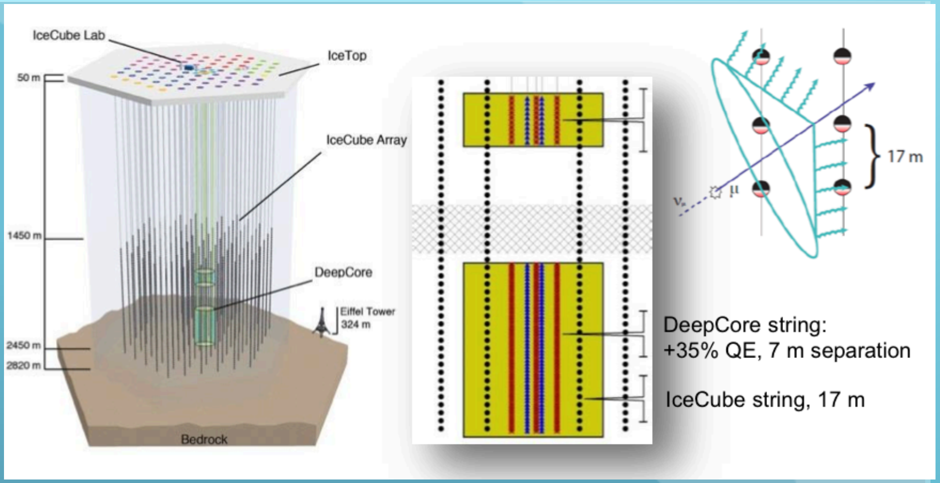
CeLAND (KamLAND)



SOX (Borexino)

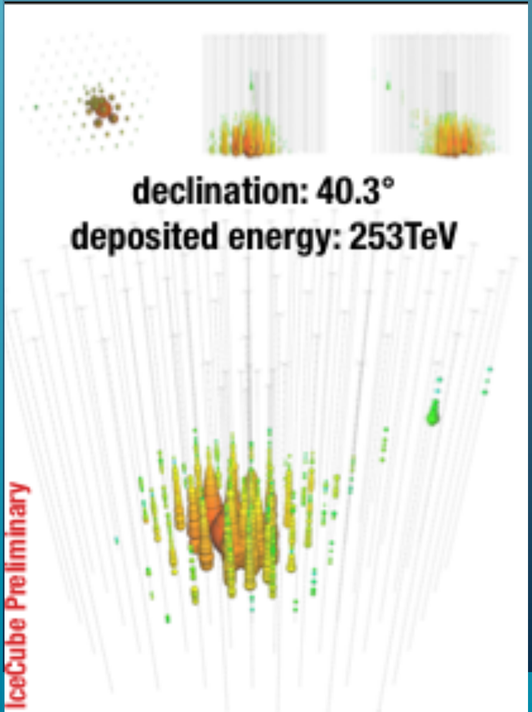


Connection with astroparticle physics → IceCube

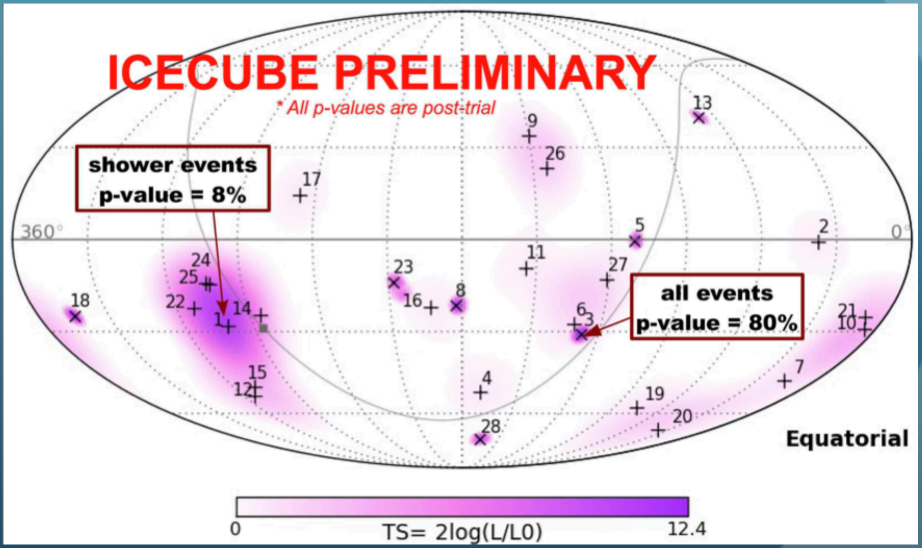


- IceCube
  - 1km^3 of instrumented ice
  - DeepCore - a dense core of IceCube in the deepest, clearest ice
  - energies > 10GeV
  - IceCube as a muon veto

→ a Cherenkov detector – which can reconstruct direction of neutrinos



What was found?



- 28 events with energies above 5-TeV (2010-2011 data)
- a clearly seen excess over the expected atmospheric background in the PeV range (4.1σ inconsistency with standard bg assumptions)

Summary

- It is a first time that we have all the oscillation parameters measured!

$$\Delta m^2_{21} = 7.44 \times 10^{-5}\,\mathrm{eV}^2\ (2.3\%) \qquad \begin{matrix} \Delta m^2_{31} = 2.45 \times 10^{-3}\,\mathrm{eV}^2 & \mathrm{NO} \\ |\Delta m^2_{32}| = 2.43 \times 10^{-3}\,\mathrm{eV}^2 & \mathrm{IO} \end{matrix}\ (2.6\%)$$

$$\sin^2\theta_{12} = 0.3\ (4\%) \qquad \sin^2\theta_{23} = \begin{matrix} 0.59 & \mathrm{IO} \\ 0.44 & \mathrm{NO} \end{matrix}\ (8.2\%) \qquad \sin^2\theta_{13} = 0.023\ (9.6\%)$$

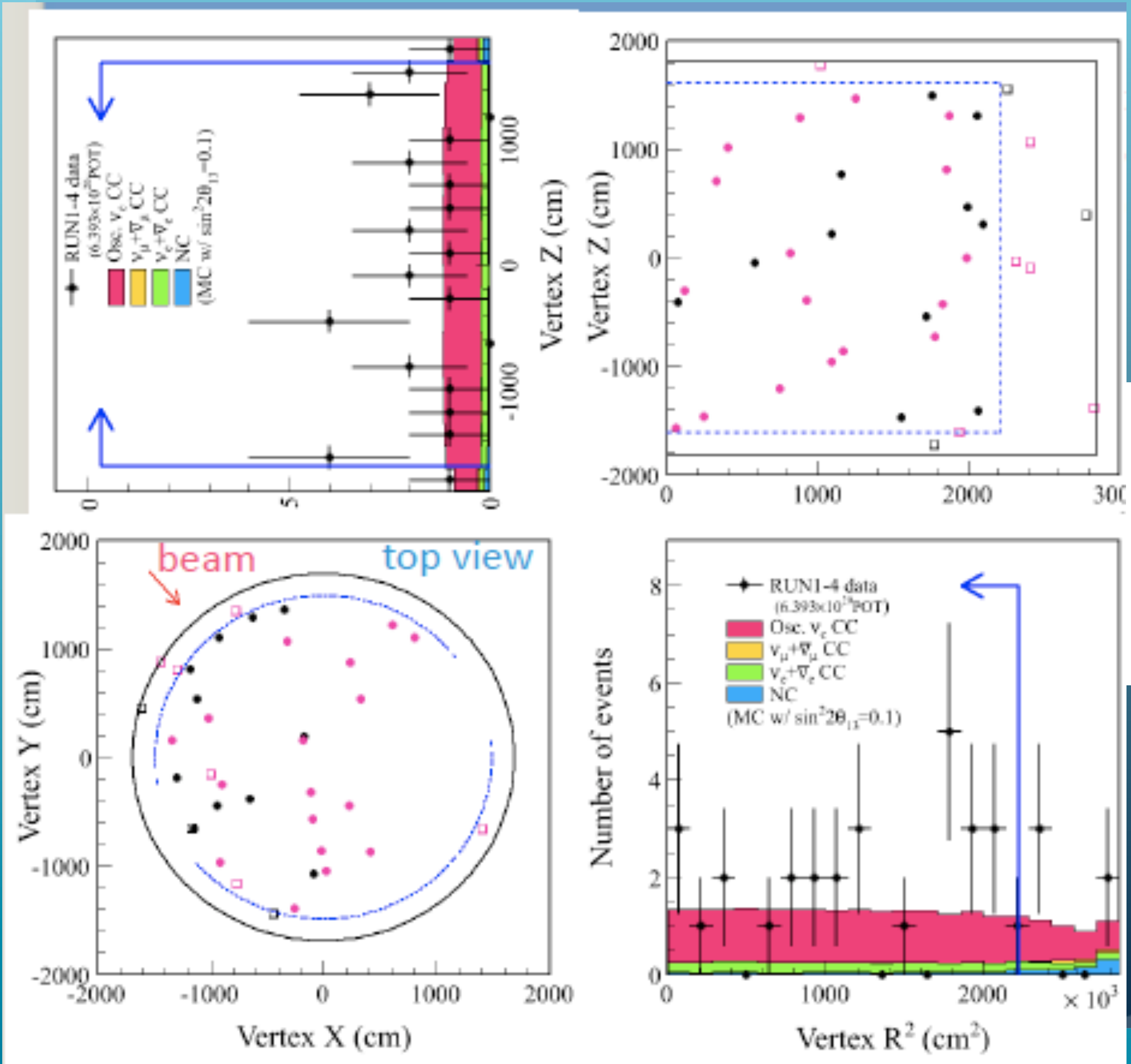
- There are lot of things going on in neutrino experimental physics ......

PLEASE CONTINUE TO ENJOY ^ NEUTRINO OSCILLATIONS

precision measurements of

BACK UP SLIDES

Neutrino interaction vertex distributions - expected uniform in FV



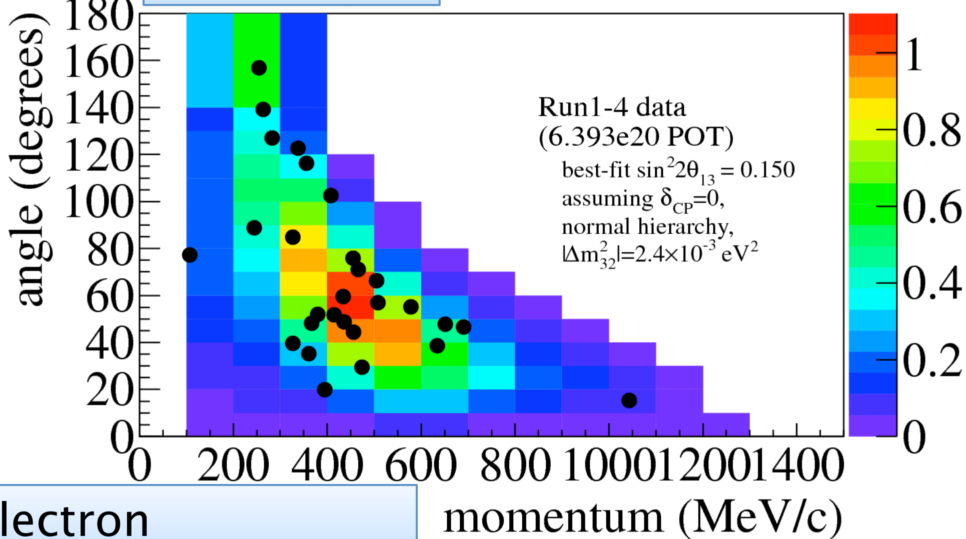
Probability for uniform distributions

→ Runs 1-3, 4 and all

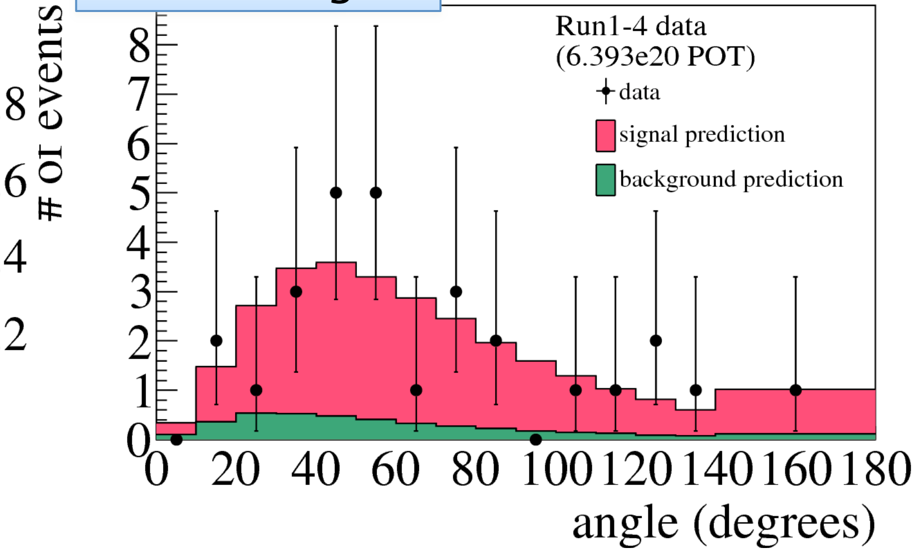
	Dwall	Fromwall (‖ beam)	R^2+Z
Run 1-3	34.4%	6.04%	32.4%
Run 4	54.7%	85.6%	98.1%
Run 1-4	20.9%	8.93%	64.5%

Results

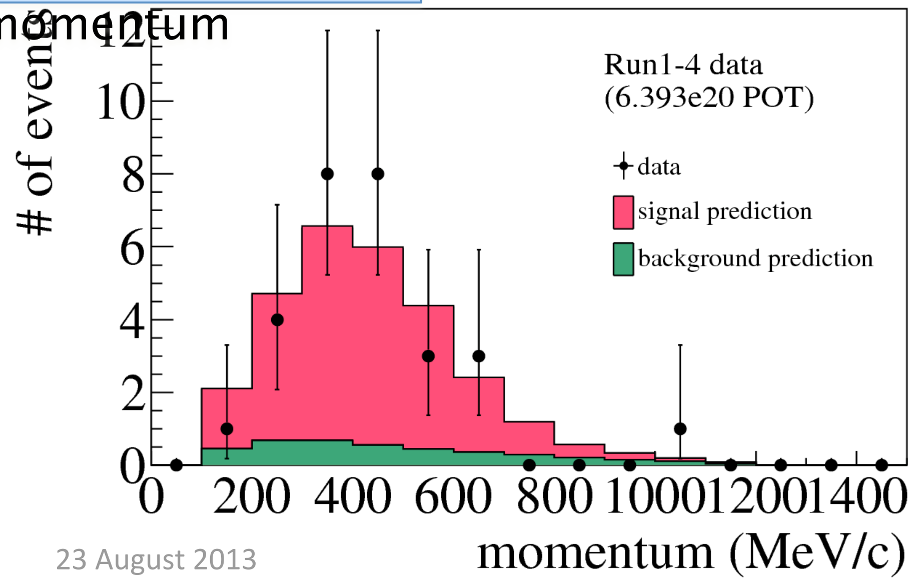
Electron p–θ



Electron angle



Electron momentum



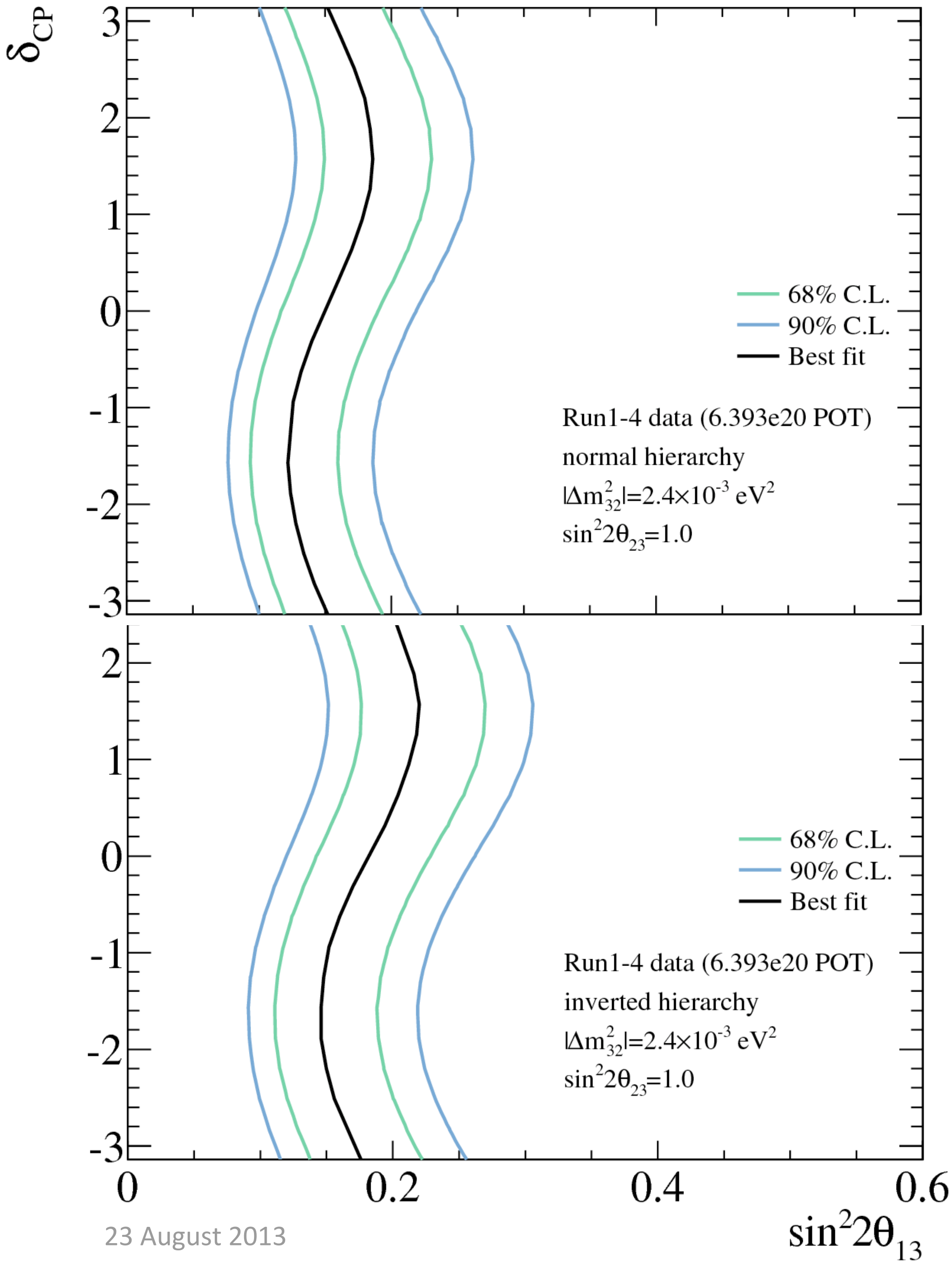
Assuming δ_{CP}=0, normal hierarchy, $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

Best fit w/ 68% C.L. error:

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

90% allowed region:

$$0.097 < \sin^2 2\theta_{13} < 0.218$$



Results

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

Best fit w/ 68% C.L. error @ δ_{CP}=0

normal hierarchy:

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

inverted hierarchy:

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

$\sqrt{}(2\Delta \ln L)$ significance of non-zero θ_{13} yields 7.5σ

NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

High energy neutrinos in IceCube

- What we are looking for?
  - Point-source searches looking for clustering in the sky
  - Diffuse fluxes above the atmospheric neutrino background
  - Gamma-ray bursts searches
  - Ultra-high energy “GZK” neutrinos from proton interactions on the CMB
- What have we found?
  - 28 events with energies above 5-TeV found (2010-2011 data)
  - a clearly seen excess over the expected atmospheric background in the PeV range (4.1σ inconsistency with standard bg assumptions)
  - merges well into the bg for lower energies
  - compatible with isotropic flux (events from Northern Hemisphere absorbed in Earth)
  - No significant clustering observed
  - Nature of these neutrinos not yet known (more data coming soon!)