Recent measurements of θ_{13} mixing angle in neutrino oscillation experiments

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Layout of the presentation

- Neutrino oscillations
- How to measure θ_{13} mixing angle
- Results from reactor experiments
  - Daya Bay
  - Reno
  - Double Chooz
- Results from long baseline experiments
  - T2K
  - Minos

Neutrino oscillations

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

CHOOZ, DayaBay, Reno, DblChooz, T2K

„solar”
SNO, KamLand, SK, Borexino

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

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

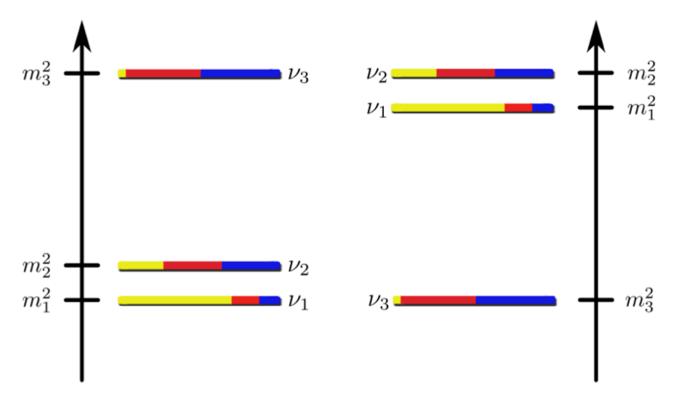
mixing angles, squared mass differences, CP violation phase - fundamental parameters of nature

What's so interesting about θ_{13}?

- The last unknown mixing angle
  - difficult measurement – to get θ_{13} one has to measure small effects (deficit or excess of interactions of neutrinos of certain flavor)
- If it is non-zero we have the possibility to study CP violation in neutrino sector, also matter effects (mass hierarchy!)

Mass hierarchy

Normal Inverted



… and ways of measuring it

- we need to look at oscillations involving electron neutrinos or antineutrinos

- we can look at dissappearance -> **reactor experiments**

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

Energy ~ a few MeV
Distance ~ a few km

$\overline{\nu}_e \rightarrow \overline{\nu}_e$

- we can look at appearance -> **long-baseline experiments** with ν_μ beam

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

Energy ~ a few GeV
Distance ~ a few hundred km

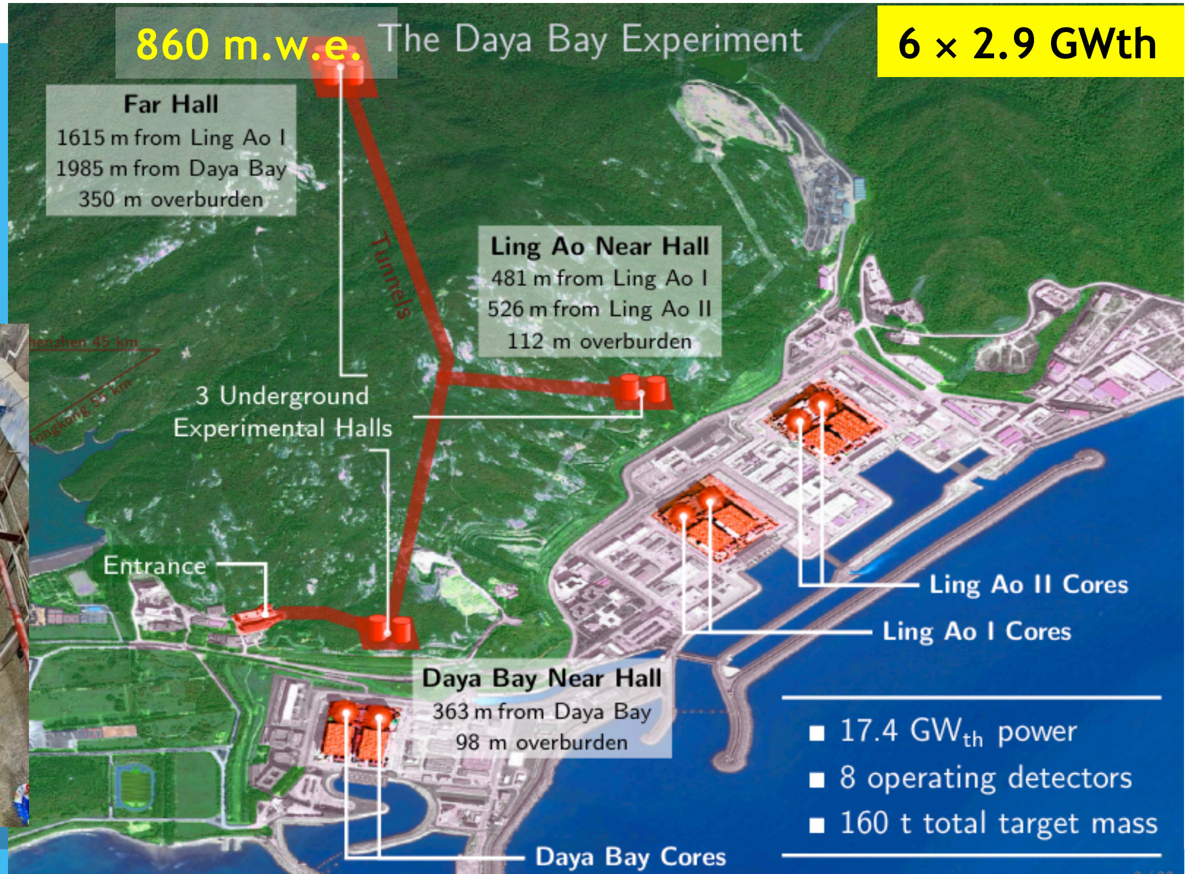
$\nu_\mu \rightarrow \nu_e$

Leading terms!

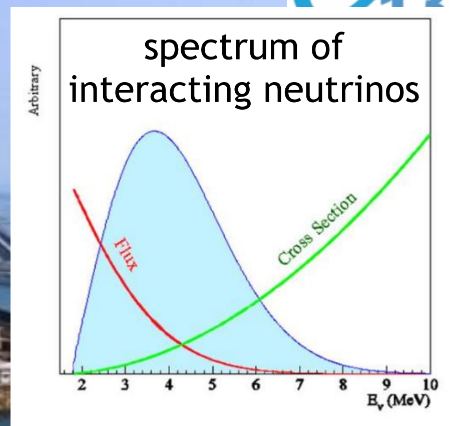
Second order terms depend on δ and mass hierarchy

- in both cases near detectors are useful to minimize systematic errors

Reactor experiments: Daya Bay



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

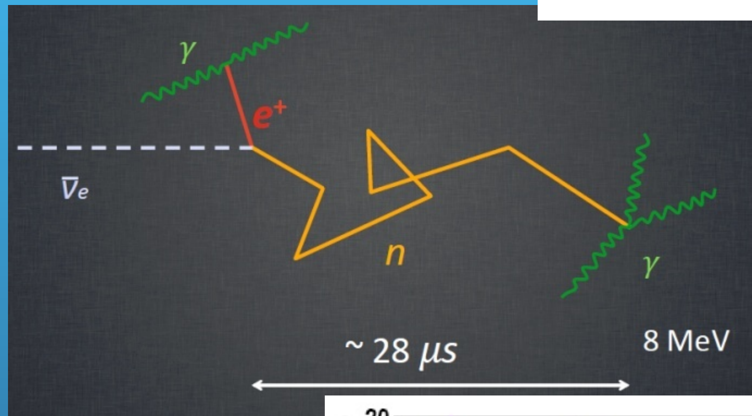


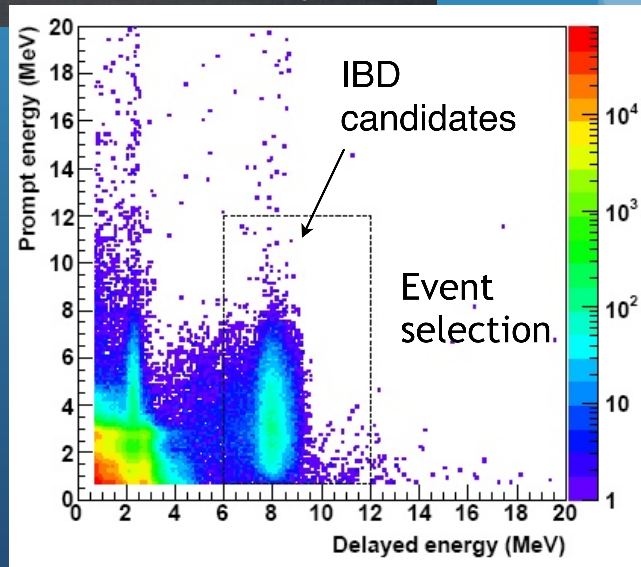
Daya Bay: detection mechanism

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

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

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

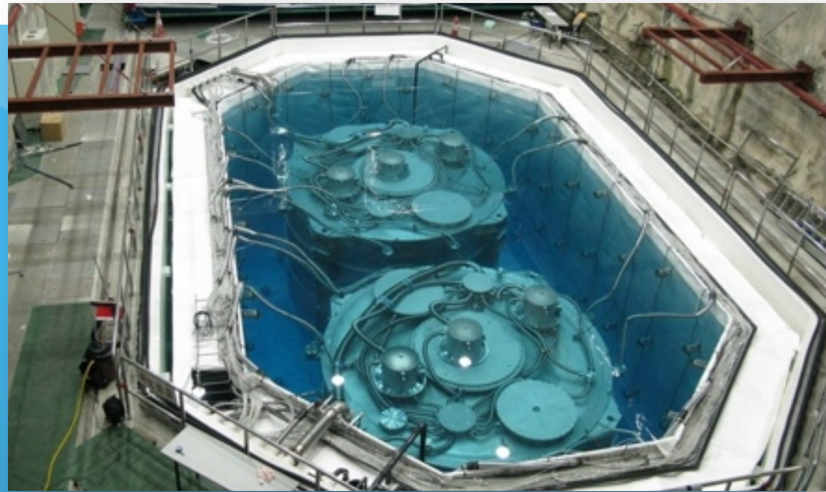


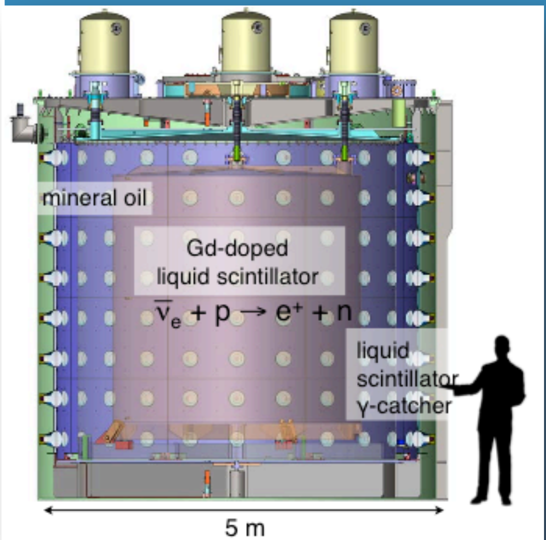


- Systematic error minimisation:
  - Identical far and near detectors
  - Identical detection modules
  - Good background rejection (3-zone modules, water system, RPCs)

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

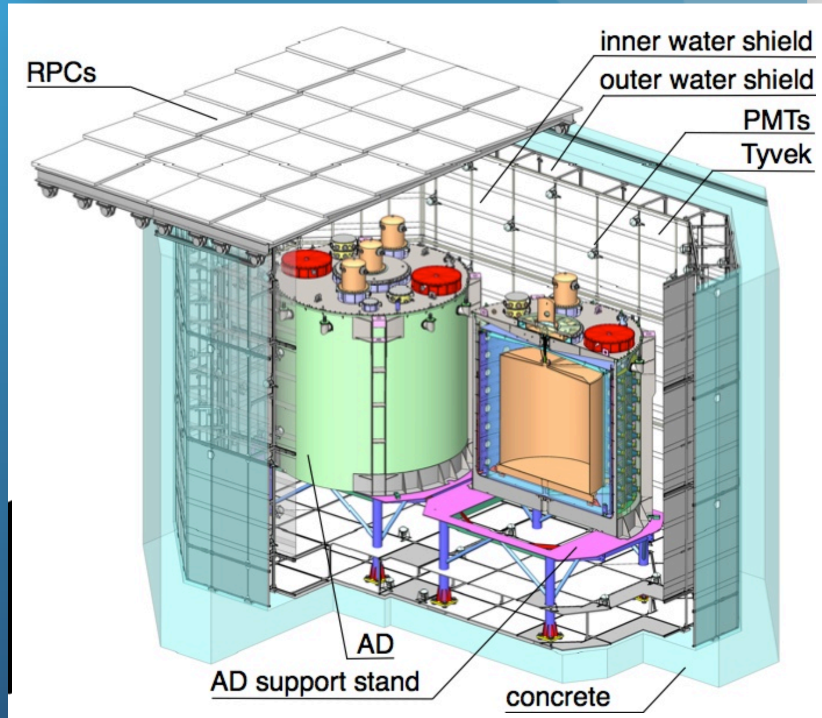




Muon water system

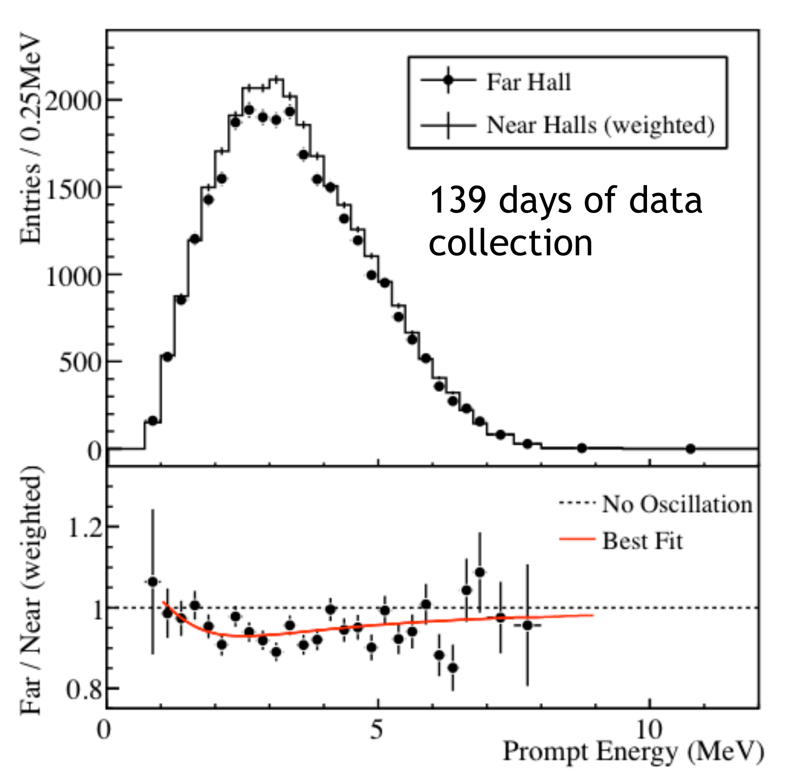
- Cherenkov water shield – at least 2.5m in every direction, 1200/1950t of water in two separated vessels, each equipped with photomultipliers

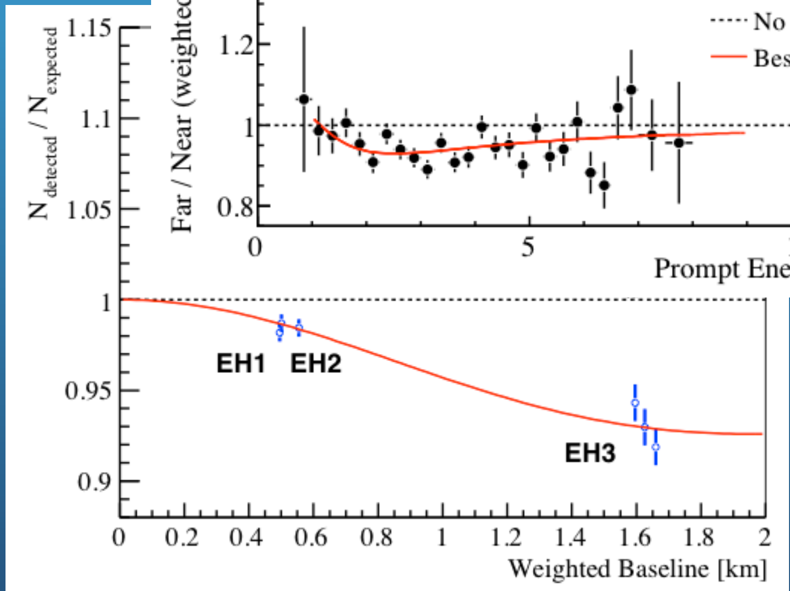
Detects muons that can produce spallation neutrons, attenuates gamma rays from surroundings, moderates neutrons

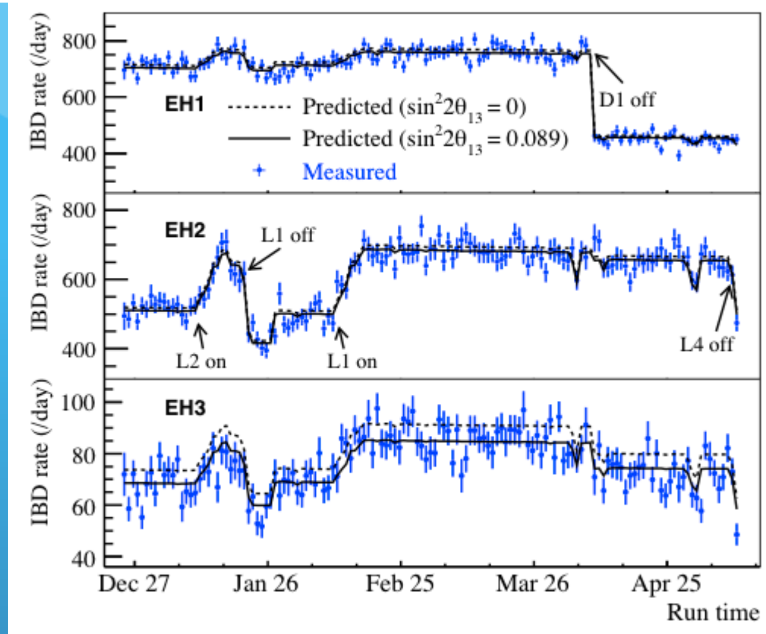


Two-zone ultrapure water Cherenkov detector

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

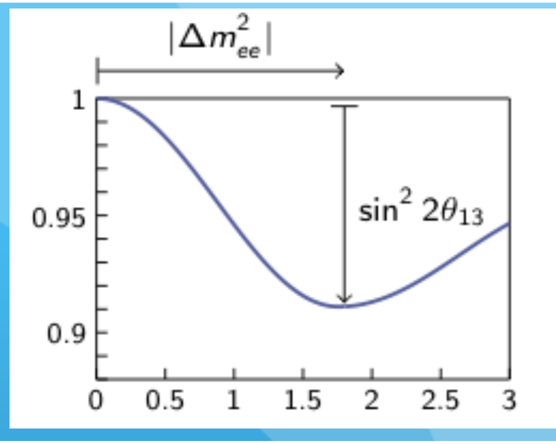
$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$$

No oscillations excluded at the level of 7.7σ

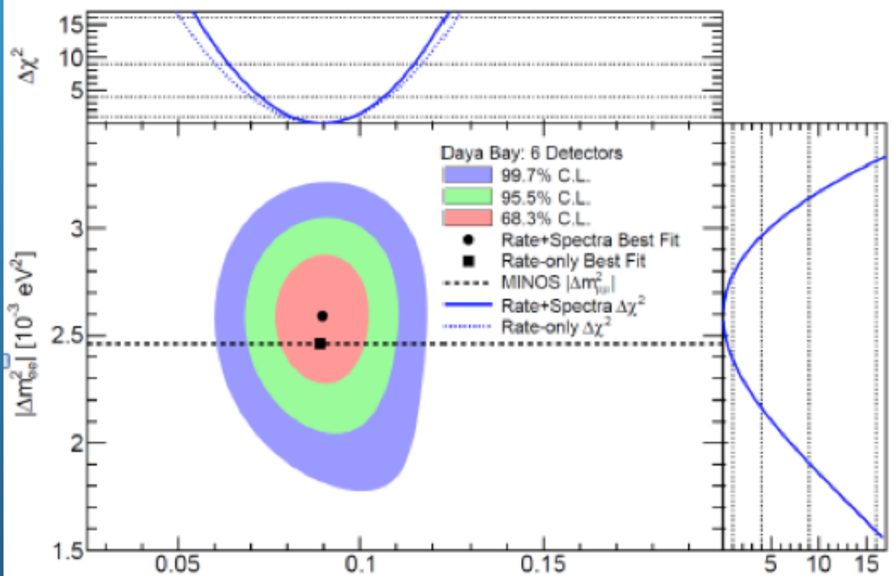
Results: Chinese Physics **C37**:011001 (2013), new shape analysis: Soeren Jetter's slides, NuFact 2013

Results: rate+shape

- New analysis, made public just a week ago (no paper yet)
- We can take advantage of measuring energy spectra and fit energy dependence (obtaining θ_{13} as well as the relevant Δm^2)



$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$



217 days of data collection

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

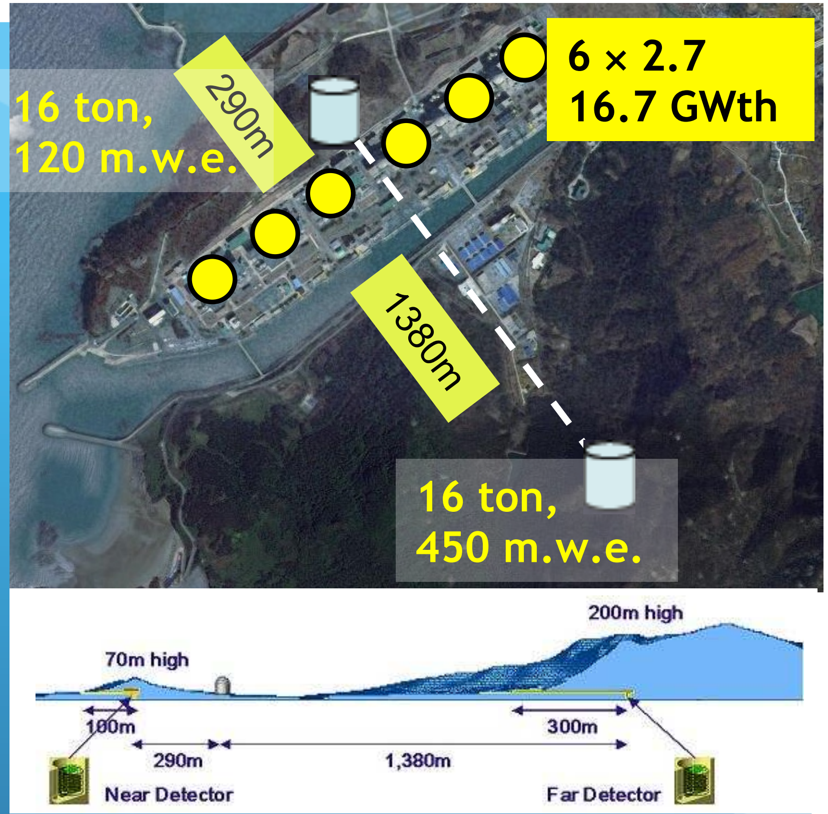
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

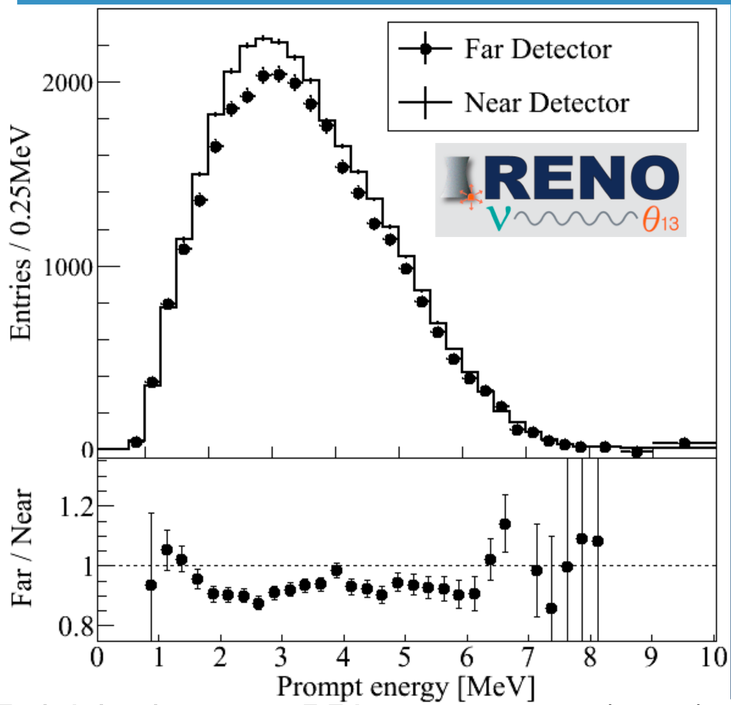
$$\chi^2/N_{\text{DoF}} = 162.7/153$$

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$

Reactor experiments: RENO

- Yeonggwang power plant in South Korea
- started operation in 2011
- rate results published, rate+shape analysis in progress





RENO 2013 resuts (402 days of data collection)
(improved energy calibration, background estimation/reduction)

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat) \pm 0.009(syst)$$

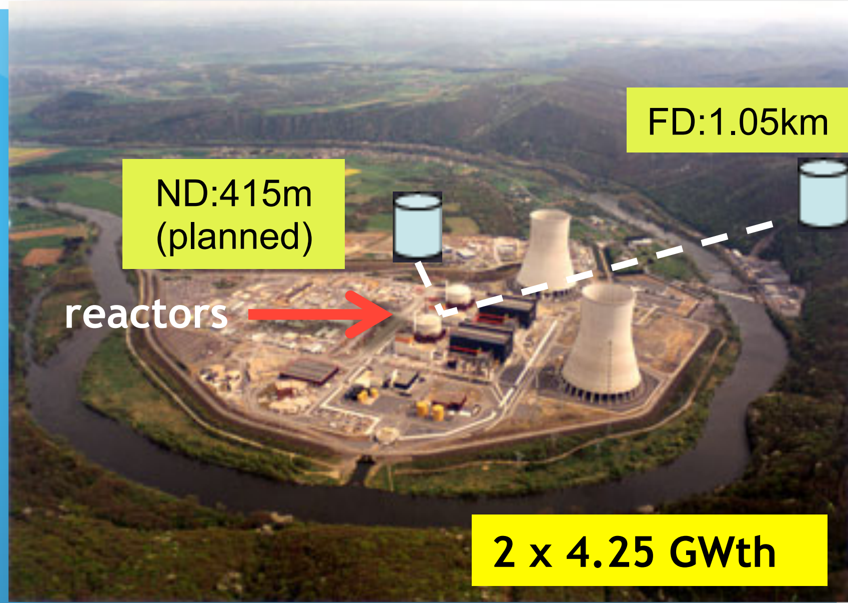
$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.015(syst)$$

There is still room for improvement: syst. error can be reduced to 0.05 for 3 yrs of data (5.6σ->12σ)

Published results: PRL 108, 191802 (2012), 2013 from NuTel conference

Reactor experiments: Double Chooz

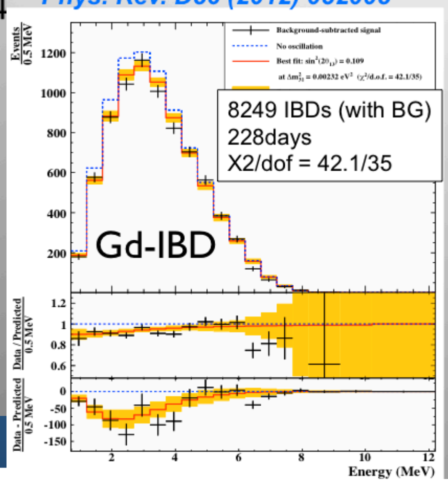
- North border of France
- Measurements utilizing only far detector (near detector in construction, starts taking data in 2014)



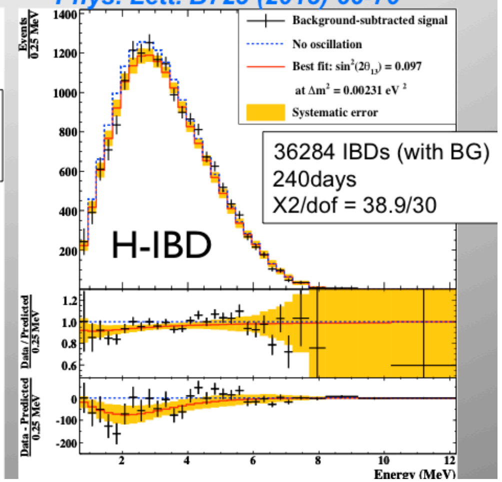
- Robust results with "independent" analyses
  - Gd-capture (rate+shape): $\sin^2(2\theta_{13}) = 0.109 \pm 0.039$
  - H-capture (rate+shape): $\sin^2(2\theta_{13}) = 0.097 \pm 0.048$
  - Nuclear power variation (Gd): $\sin^2(2\theta_{13}) = 0.10 \pm 0.04$
  - Nuclear power variation (H): $\sin^2(2\theta_{13}) =$ 0.13 ± 0.07
- New Combined fit results:
  - Rate and shape: $\sin^2(2\theta_{13}) =$ 0.109 ± 0.035
  - Nuclear power variation: $\sin^2(2\theta_{13}) =$ 0.097 ± 0.035
- Currently working on improved analysis (Gd+H)
- First results with near detector in 2014 (final precision ≈ 10%)

Rate+shape analysis:

Phys. Rev. D86 (2012) 052008

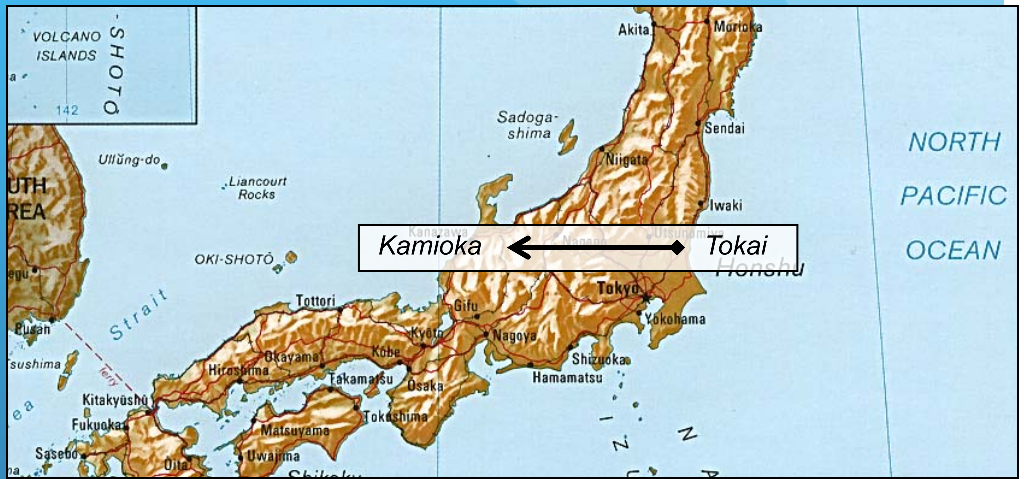


Phys. Lett. B723 (2013) 66-70



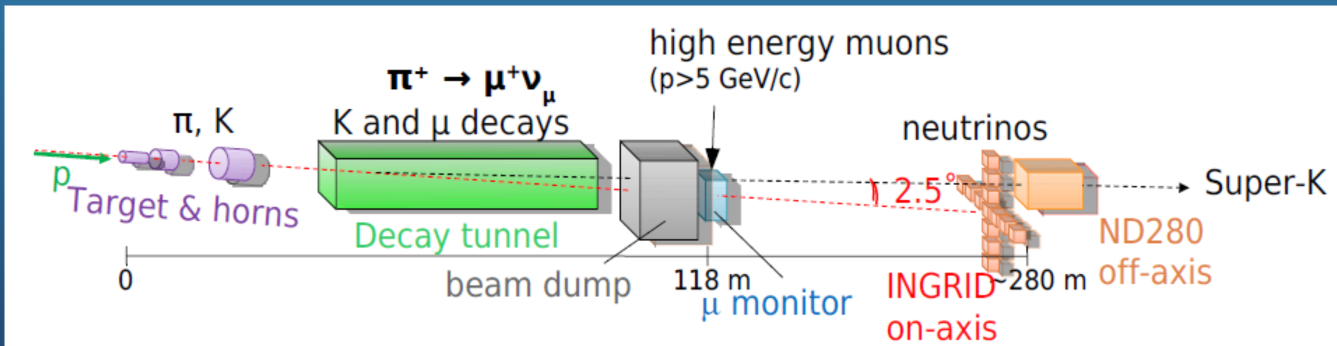
Accelerator experiments: T2K

- **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**



The T2K Collaboration

~500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wrocław U.

Russia
INR

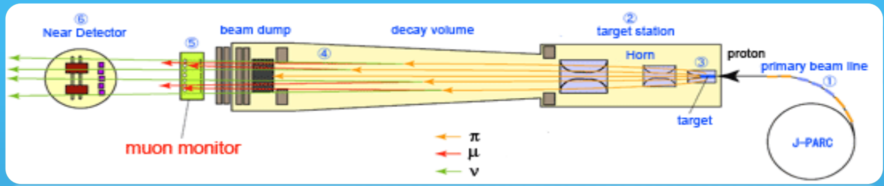
Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

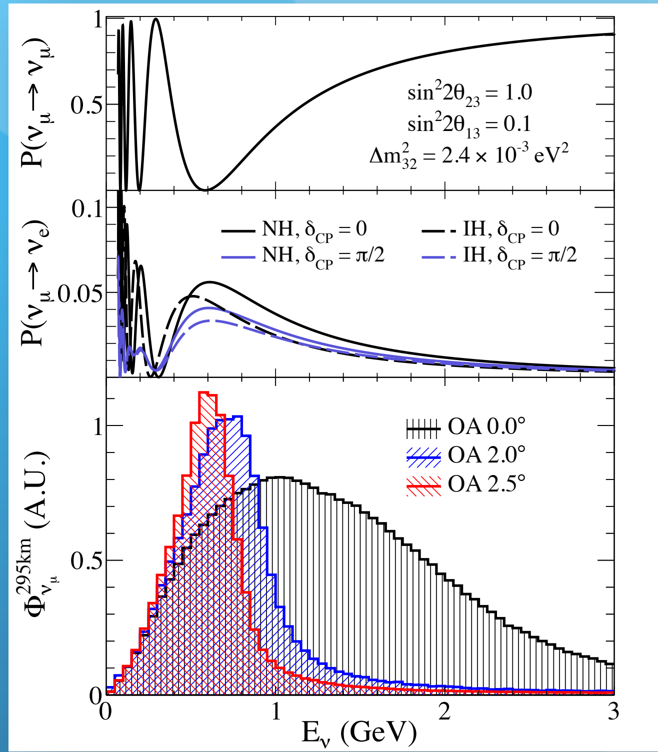
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

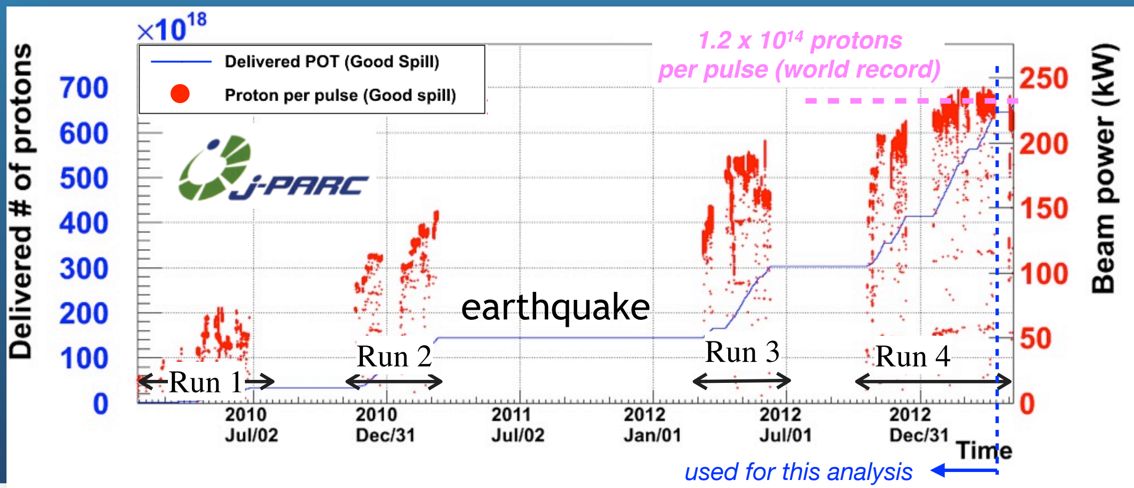
T2K: beam



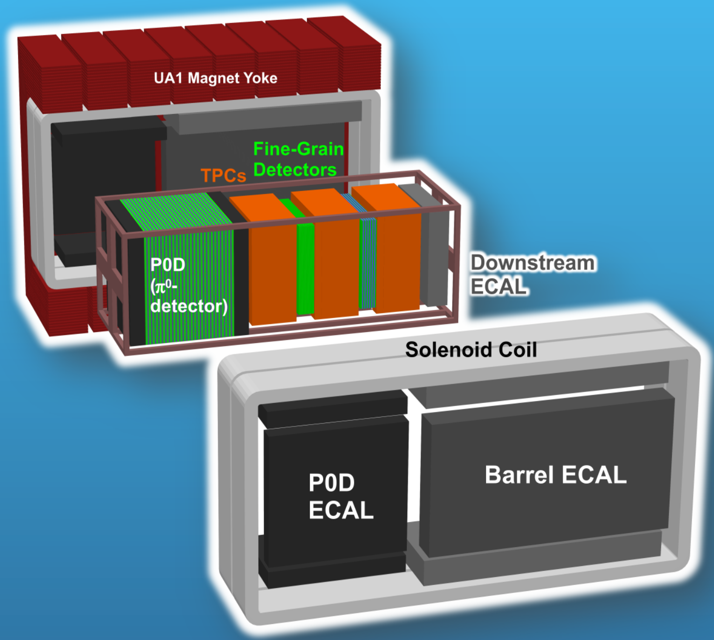
- Proton beam hits the target, produces hadrons, mainly pions
- **The pions decay:** $\pi^+ \to \mu^+ + \nu_\mu$
- **Beam contamination:** $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$, $K^+ \to \pi^0 e^+ \nu_e$
- Detectors positioned off-axis to get favorable spectrum shape
- Hadron production measured with target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

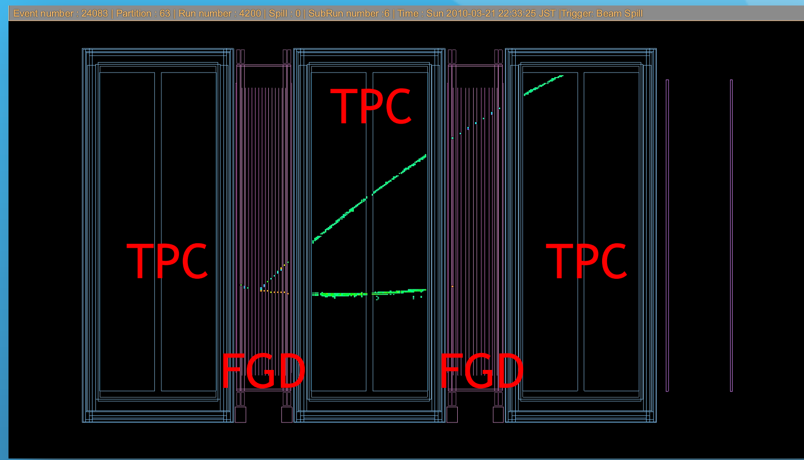


Off-axis angle chosen: 2.5 degrees



T2K, near detector: ND280





- **FGD** detectors- target for neutrino interactions, proton identification
- **TPCs** - identification and momentum reconstruction for muons, protons, charged pions and electrons

ND280 role:

- beam monitoring
- cross-section measurements
- Measurement of muon neutrino momentum for non-oscillated beam, electron neutrino contribution estimation

ND280 role in neutrino oscillation analysis:

- Constrains flux estimates (external constraints from NA61 experiment)
- Constrains cross-section parameters

These are used to calculate MC far detector prediction

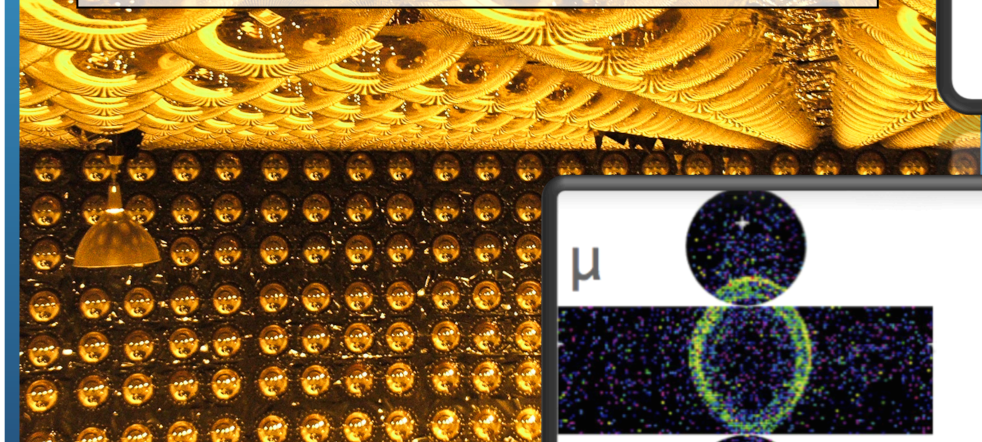
T2K: Super-Kamiokande

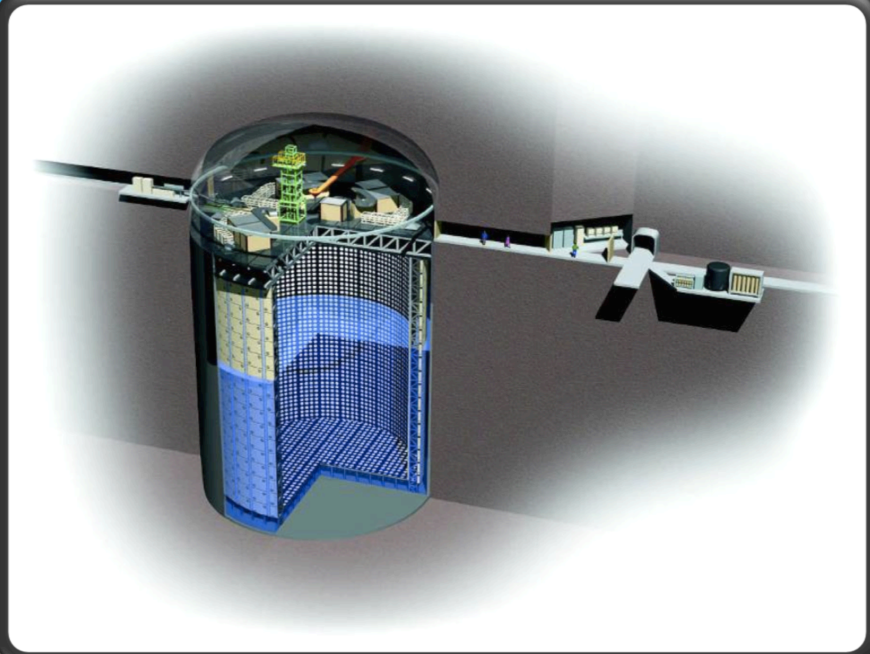
Large water Cherenkov detector

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

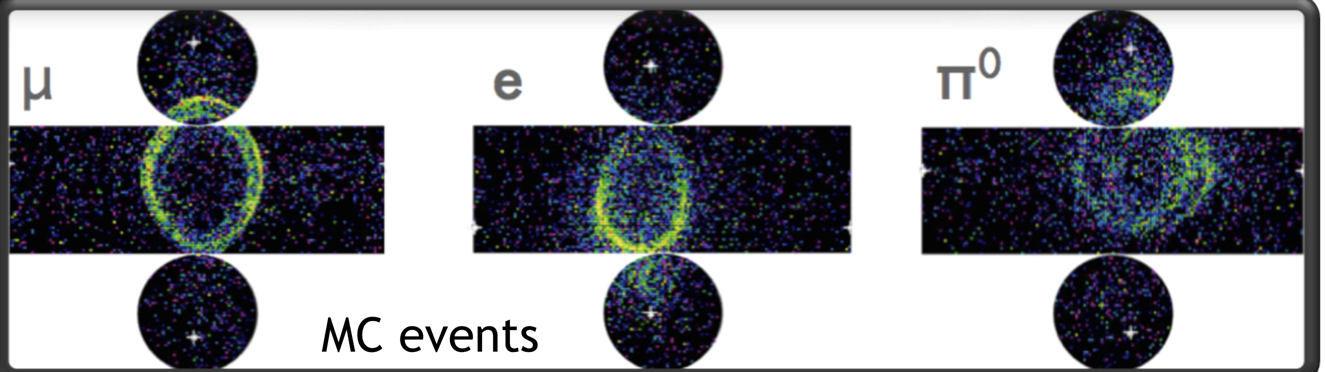
Many years of experience, very well known detection technique, systematic errors known and understood

Studies also atmospheric, solar neutrinos



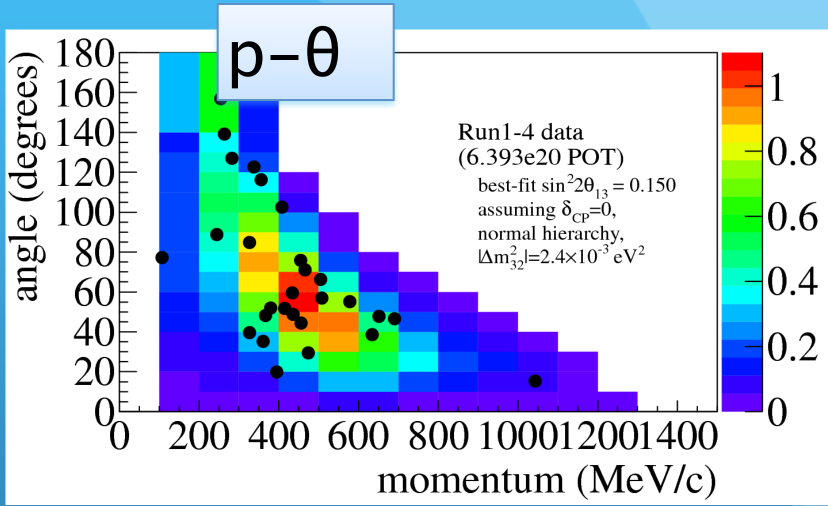


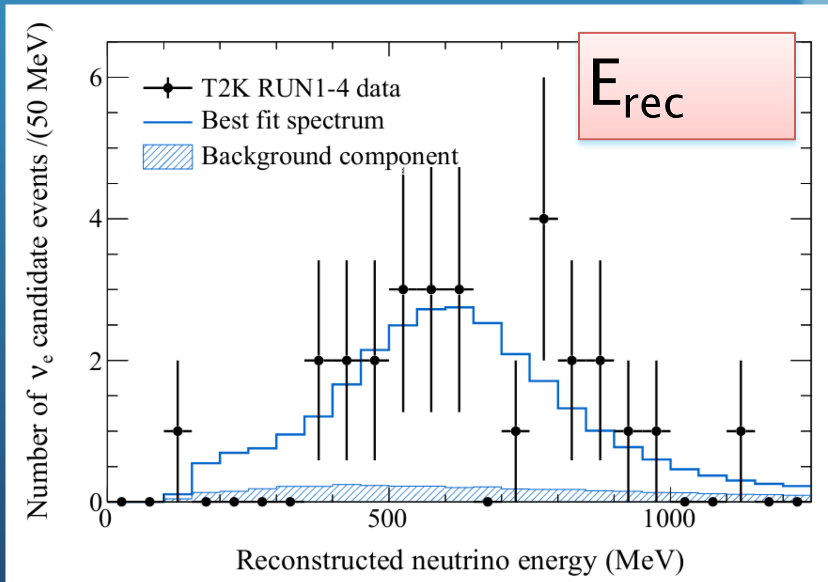
Good muon/electron separation



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

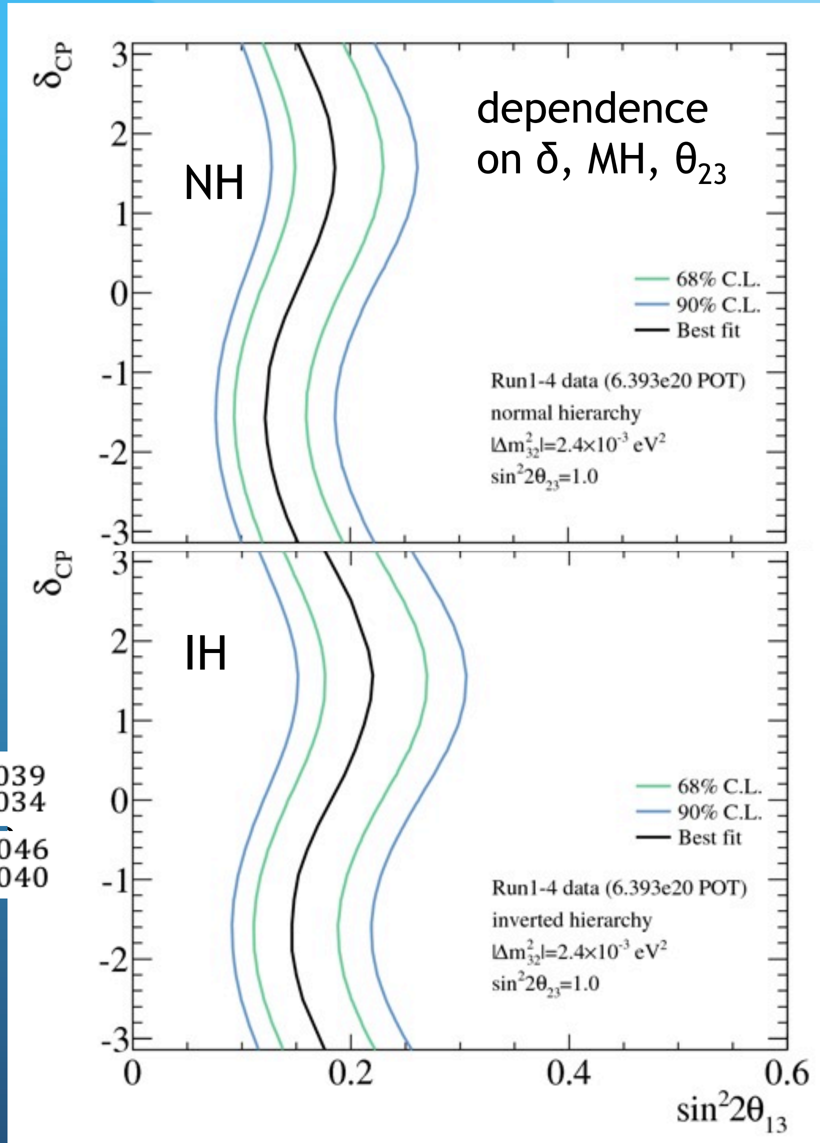




T2K: 2013 results

- 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

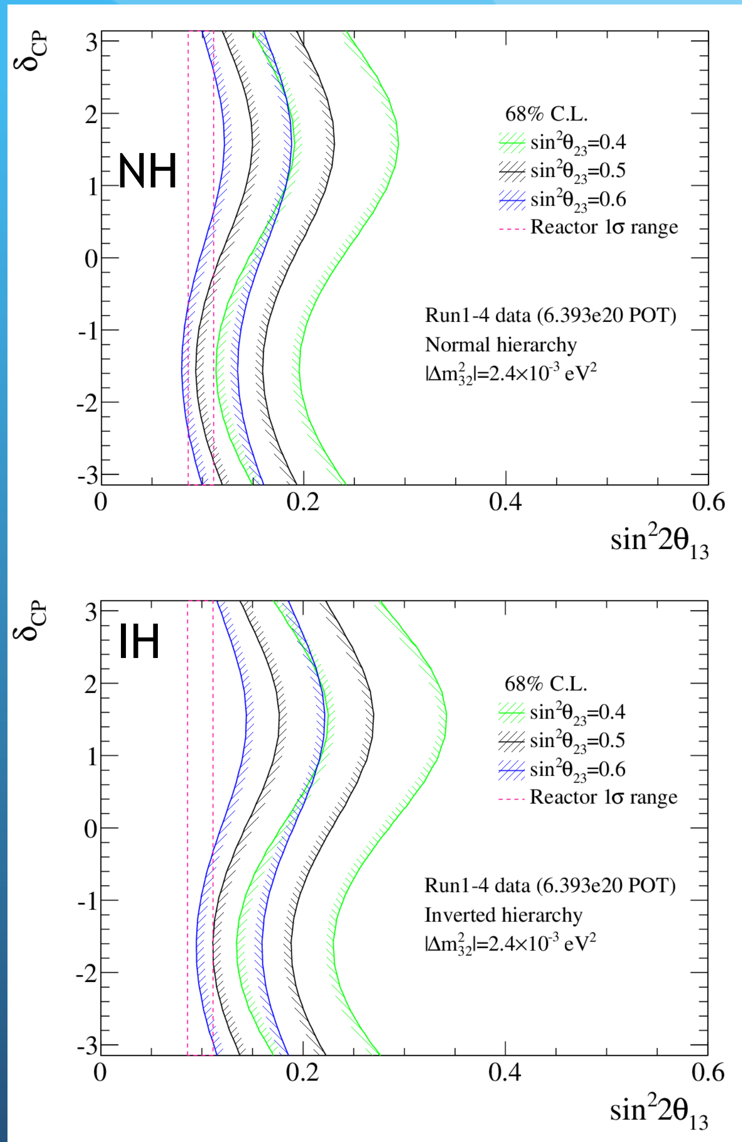
- ν_e appearance contours depend on the value of θ_{23}
- This needs to be determined more precisely by studying ν_μ dissapearance

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

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

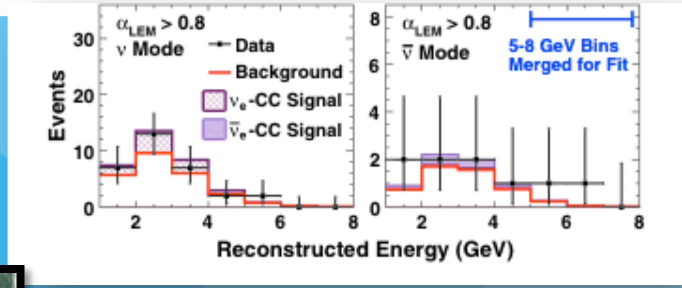
Leading terms

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

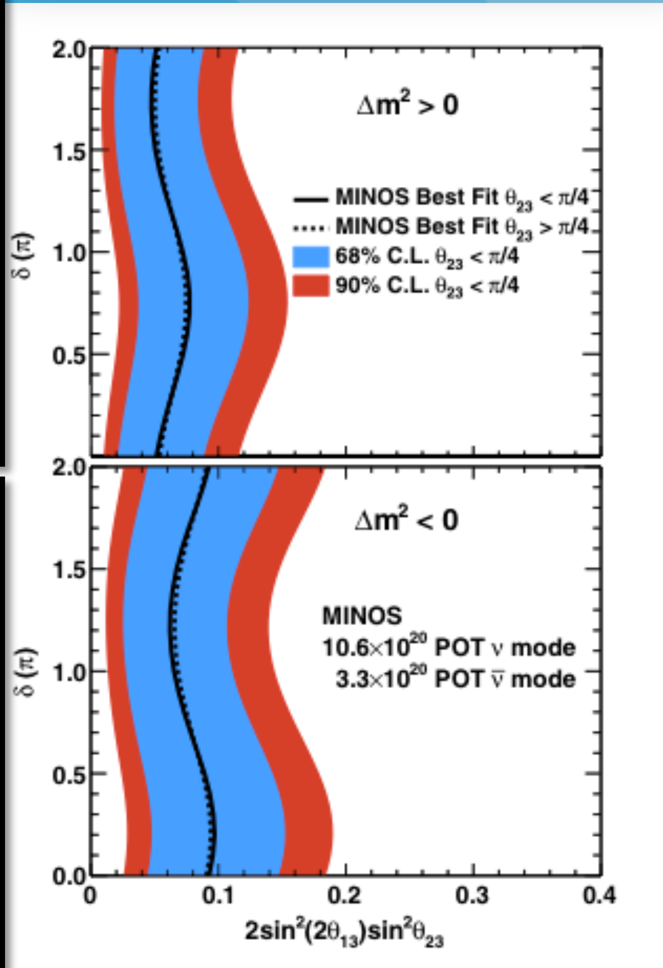
Accelerator exps: MINOS



- 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



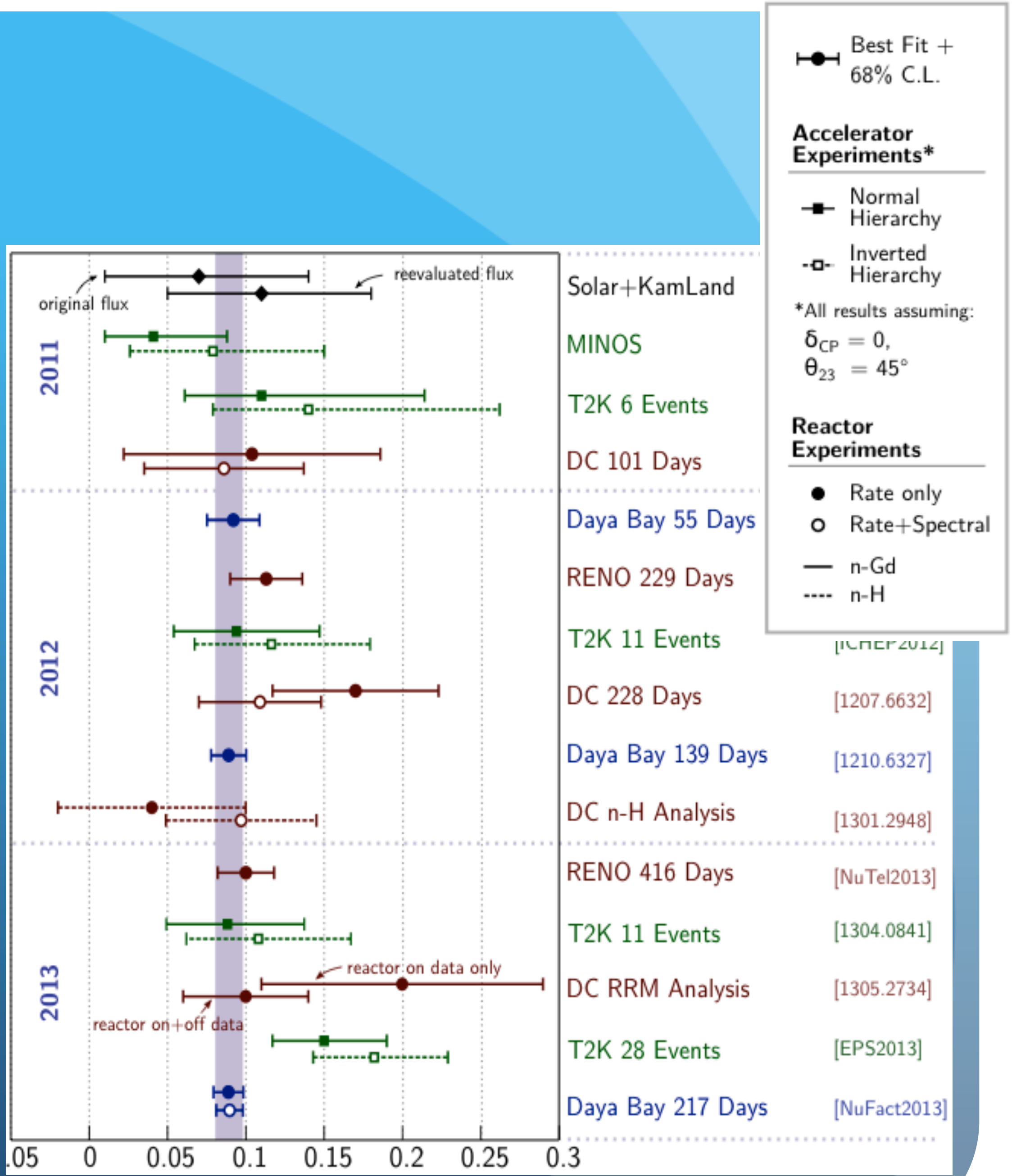
- Neutrino (10.6* 10^{20} POT) and antineutrino (3.3* 10^{20} POT) beam data collected

- Result:

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

Summary

- θ_{13} mixing angle has been succesfully measured in reactor and long-baseline experiments
- more precise measurements coming soon
- we can now study CP violation effects



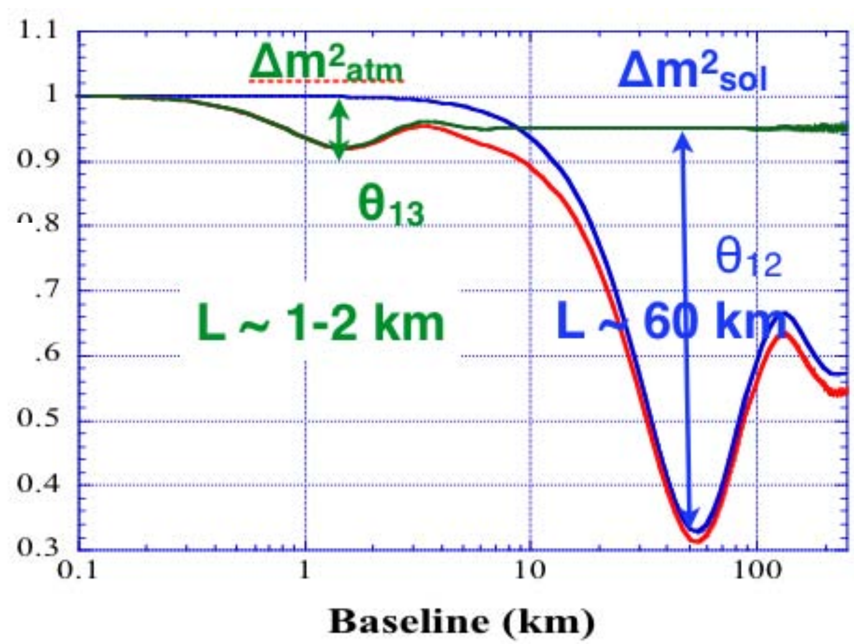
Plot taken from Soeren Jetter's Daya Bay talk (NuFact 2013)

backup

Reactor experiments

- probability for electron antineutrino dissapearance

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$



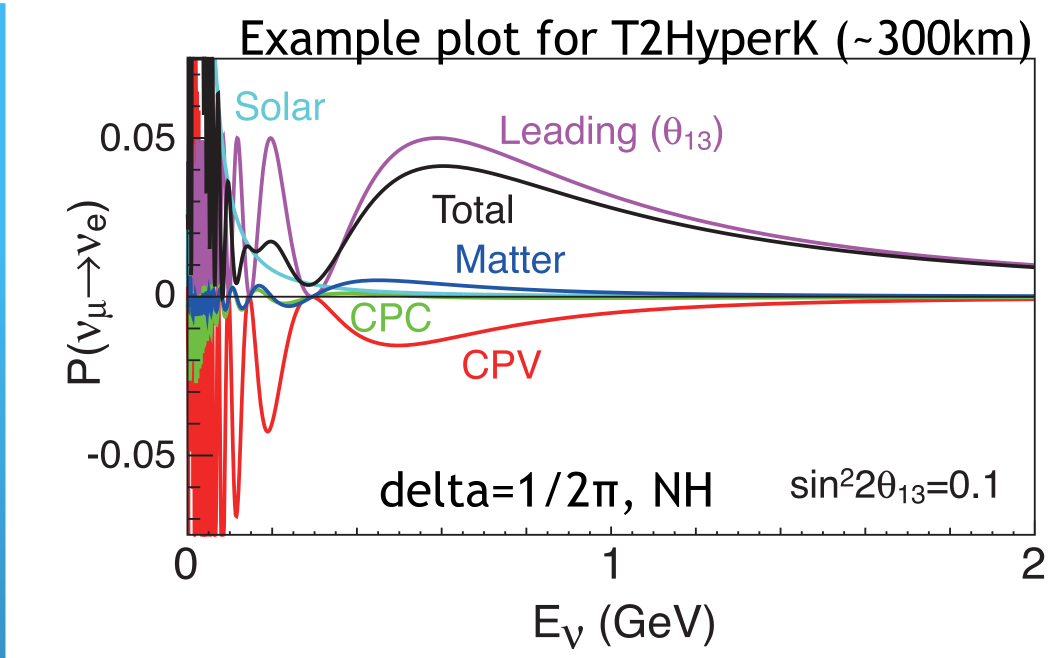
$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

$10{-}40\ keV$

$1.8\ MeV$: threshold

Long baseline experiments

- Probability of electron neutrino appearance



$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$
leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
CP conserving

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
CP violating

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$
solar term

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$
matter effects

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

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

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

Oscillation parameter values

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

$$\sin^2\theta_{23} = \begin{cases} 0.49^{+0.08}_{-0.05} & \text{for } \Delta \mathrm{m}^2_{31} > 0 \\ 0.53^{+0.05}_{-0.07} & \text{for } \Delta \mathrm{m}^2_{31} < 0 \end{cases}$$

$$\sin^2\theta_{12} = 0.320^{+0.015}_{-0.017}$$

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