Status, results and future prospects on the neutrino oscillation experiments

"The new, the rare and the beautiful"
Zürich, 6th-8th January 2010
F. Juget, LHEP Bern

Neutrino oscillation experiments

- The 1rst idea of neutrino oscillations was put forward by Pontecorvo in 1957
- First experiment Homestake in 1967 using solar neutrino leading to the so-called "Solar Neutrino Problem"

- Natural neutrino sources
  - Solar neutrinos
    - Homestake, SAGE/GNO, Super-Kamiokande, SNO, Borexino
  - Atmospheric neutrinos
    - Super-Kamiokande

- Artificial neutrino sources
  - Reactor neutrinos
    - Chooz (1 km), KamLAND (180 km)
  - Long baseline accelerator experiments
    - K2K (250km), MINOS (730 km), OPERA (730 km)

3-flavour oscillation parameters

The neutrino oscillation probability depends on the 4 mixing parameters (θ_{23}, θ_{12}, θ_{13}, δ_{cp}), the masses differences ($\Delta m^2_{ij} = m^2_i - m^2_j$) and the energy E and the distance L from the source (matter effect).

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

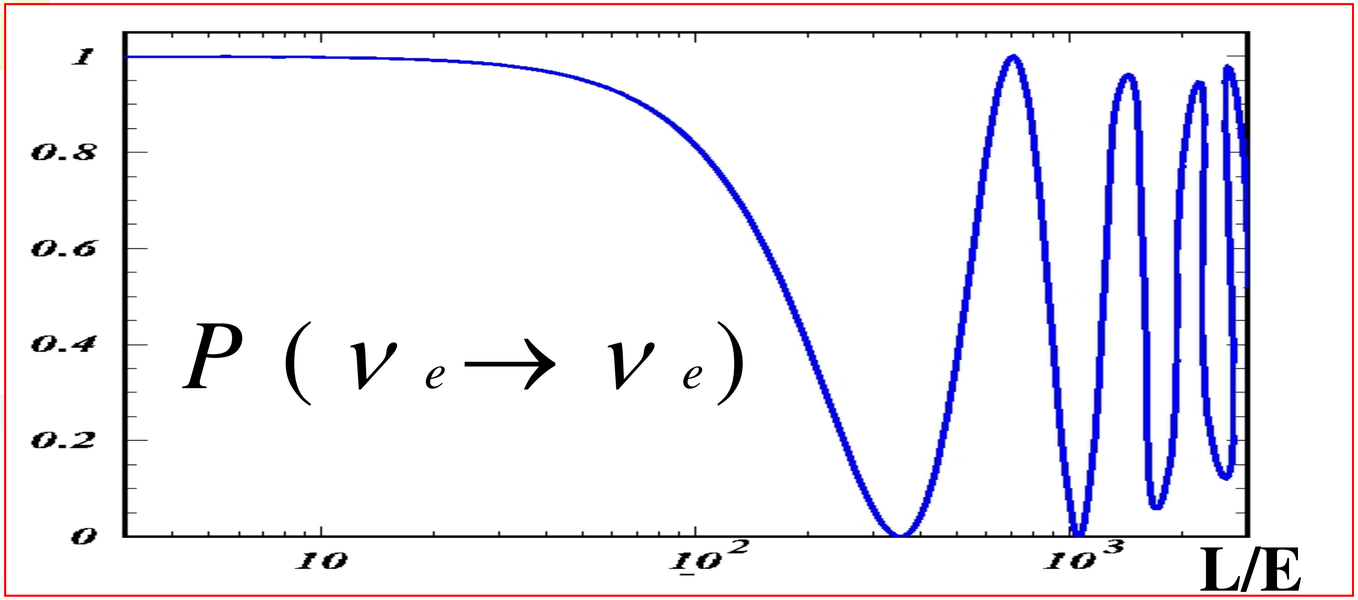
Flavor eigenstates | θ_{23} | θ_{13}, δ | θ_{12} | Mass eigenstates

$C_{ij} = \cos(\theta_{ij})$
$S_{ij} = \sin(\theta_{ij})$

$$P(\nu_\ell \to \nu_{\ell'}) = |\sum_i U_{\ell i} U^*_{\ell' i} e^{-i(m_i^2/2E)L}|^2$$

$$= \sum_i |U_{\ell i} U^*_{\ell' i}|^2 + \Re \sum_i \sum_{j \neq i} U_{\ell i} U^*_{\ell' i} U^*_{\ell j} U_{\ell' j} e^{i\frac{|m_i^2 - m_j^2|L}{2E}}$$

Oscillation probability



neutrinos: $\left.\begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}\right\} \xrightarrow{\text{oscillation}} \left\{\begin{matrix} \nu_e \Rightarrow e^- \\ \nu_\mu \Rightarrow \mu^- \\ \nu_\tau \Rightarrow \tau^- \end{matrix}\right.$

anti-neutrinos: $\left.\begin{matrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{matrix}\right\} \xrightarrow{\text{oscillation}} \left\{\begin{matrix} \bar{\nu}_e \Rightarrow e^+ \\ \bar{\nu}_\mu \Rightarrow \mu^+ \\ \bar{\nu}_\tau \Rightarrow \tau^+ \end{matrix}\right.$

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

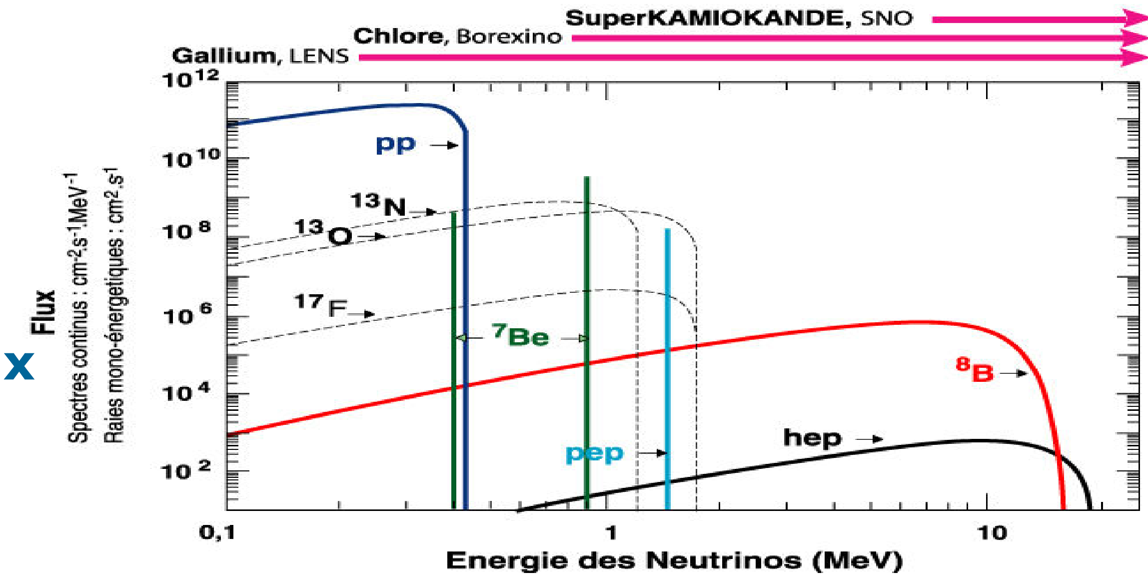
Neutrino flavor at L is given by lepton identification in CC interaction

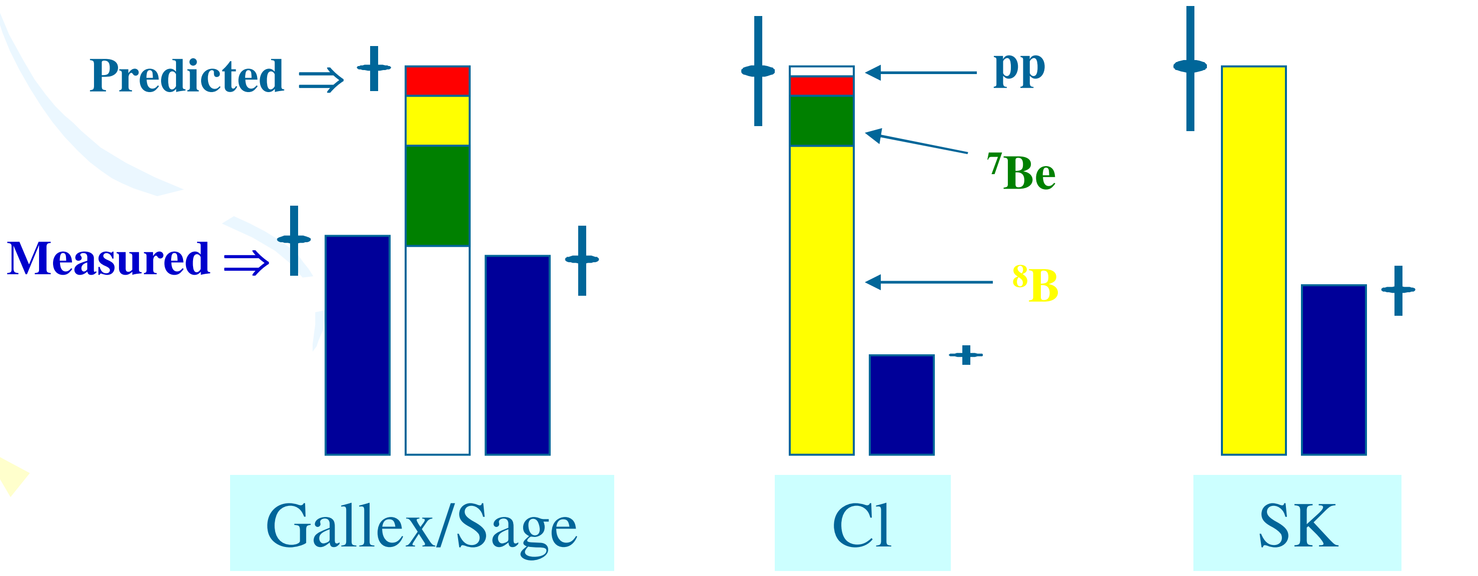
Solar neutrinos experiments

Experiments only sensitive to ν_e flavor **(CC interaction)**
Homestake – SK - Gallex/GNO - Sage

$\Rightarrow$**Deficit of predicted ν_e flux is measured**

"Solar Neutrino Problem"





Solar neutrinos experiments

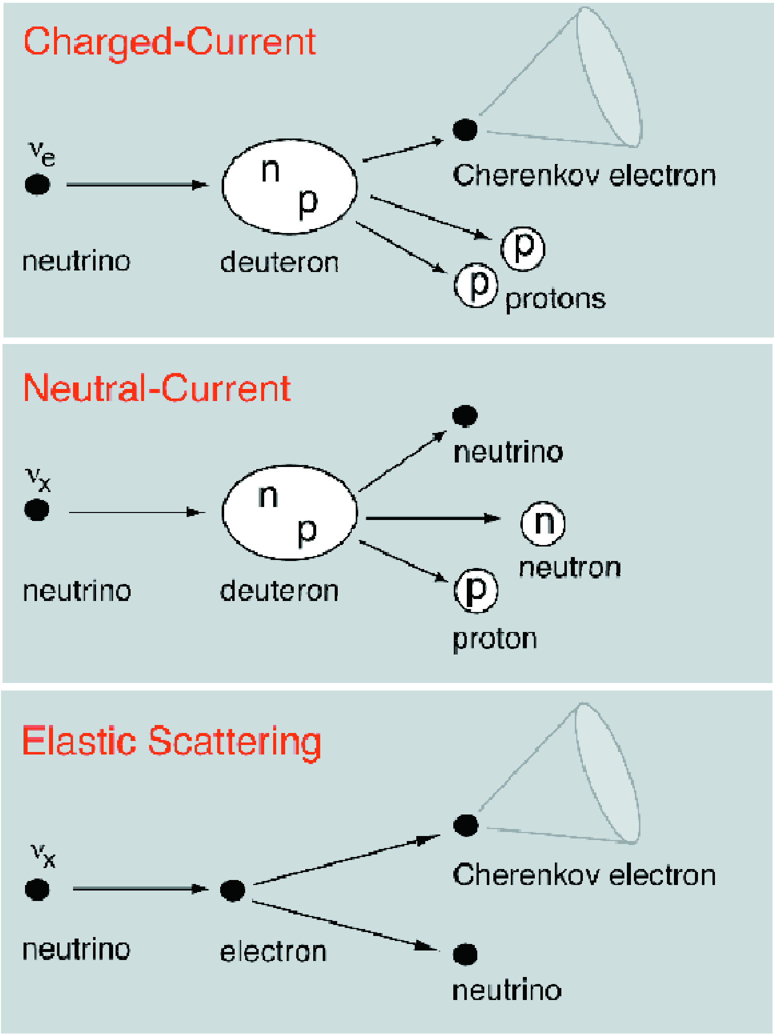
- **SNO:** Experiment sensitive to 3 flavors (CC+NC interactions)

CC $\nu_e + d \rightarrow p + p + e^-$

NC $\nu_x + d \rightarrow p + n + \nu_x$

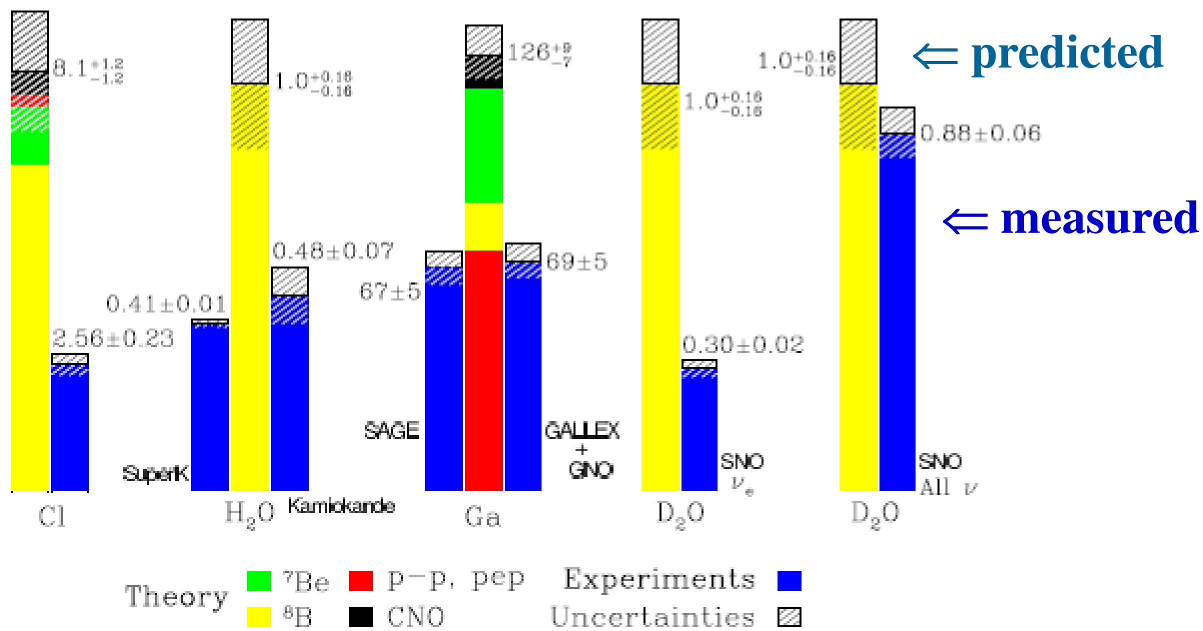
- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors

ES $\nu_x + e^- \rightarrow \nu_x + e^-$



Solar neutrinos experiments

- **SNO:** Experiment sensitive to 3 flavors (CC+NC interactions)



In 2001, deficit of ν_e flux is also measured, but the total flux is measured using the 3 flavors ⇒ absence of deficit

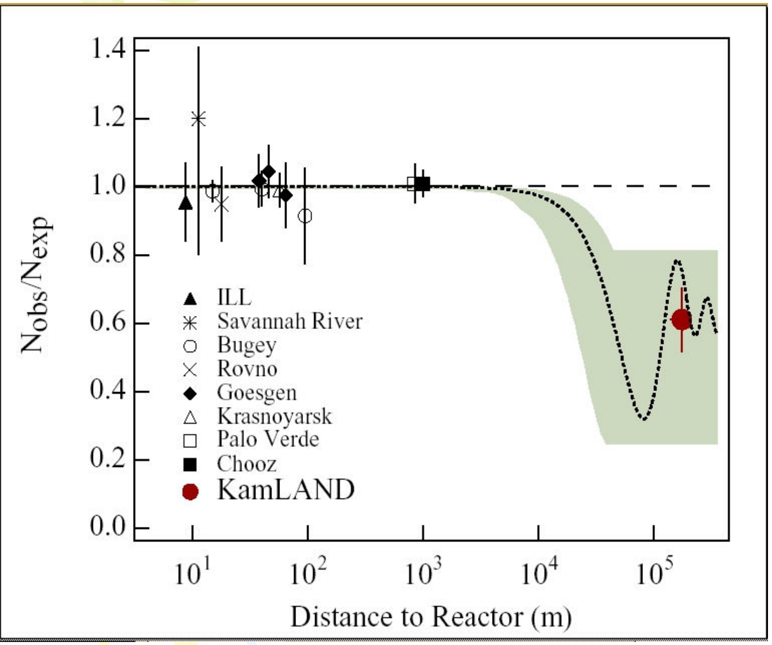
$$\frac{CC}{NC} = \frac{flux(\nu_e)}{flux(\nu_e + \nu_\mu + \nu_\tau)} = 0.301 \pm 0.033$$

⇒ Neutrino oscillates

$$\nu_e \longrightarrow \nu_{\mu,\tau}$$

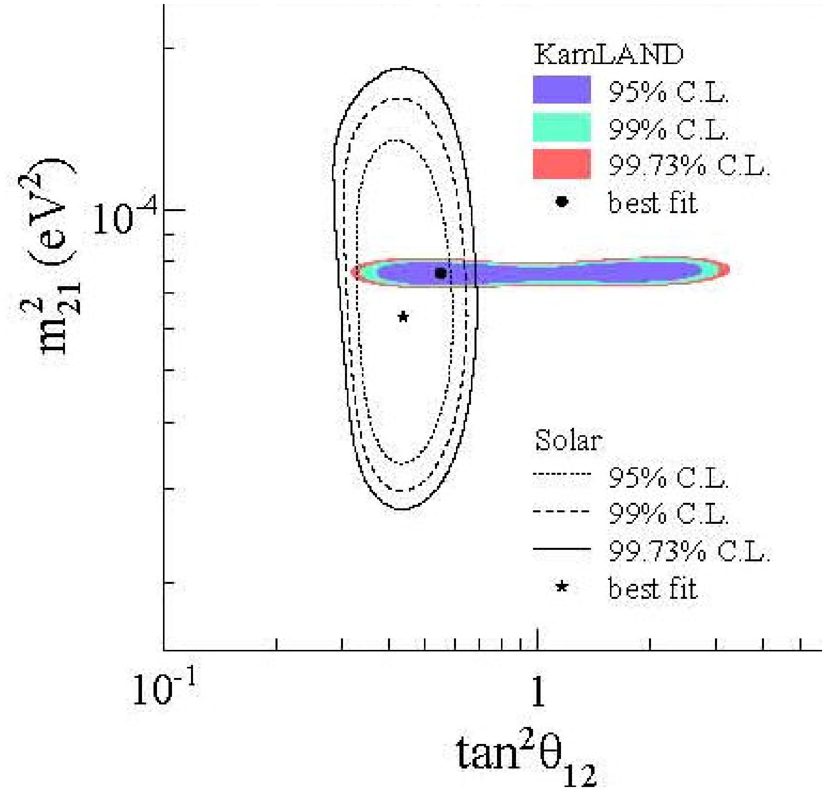
Solar neutrinos experiments

Confirmation with the KamLAND experiment (reactor ν's)



258 events observed
365.2 ± 23.7 expected

(Disappearance confirmed at 99.99%)



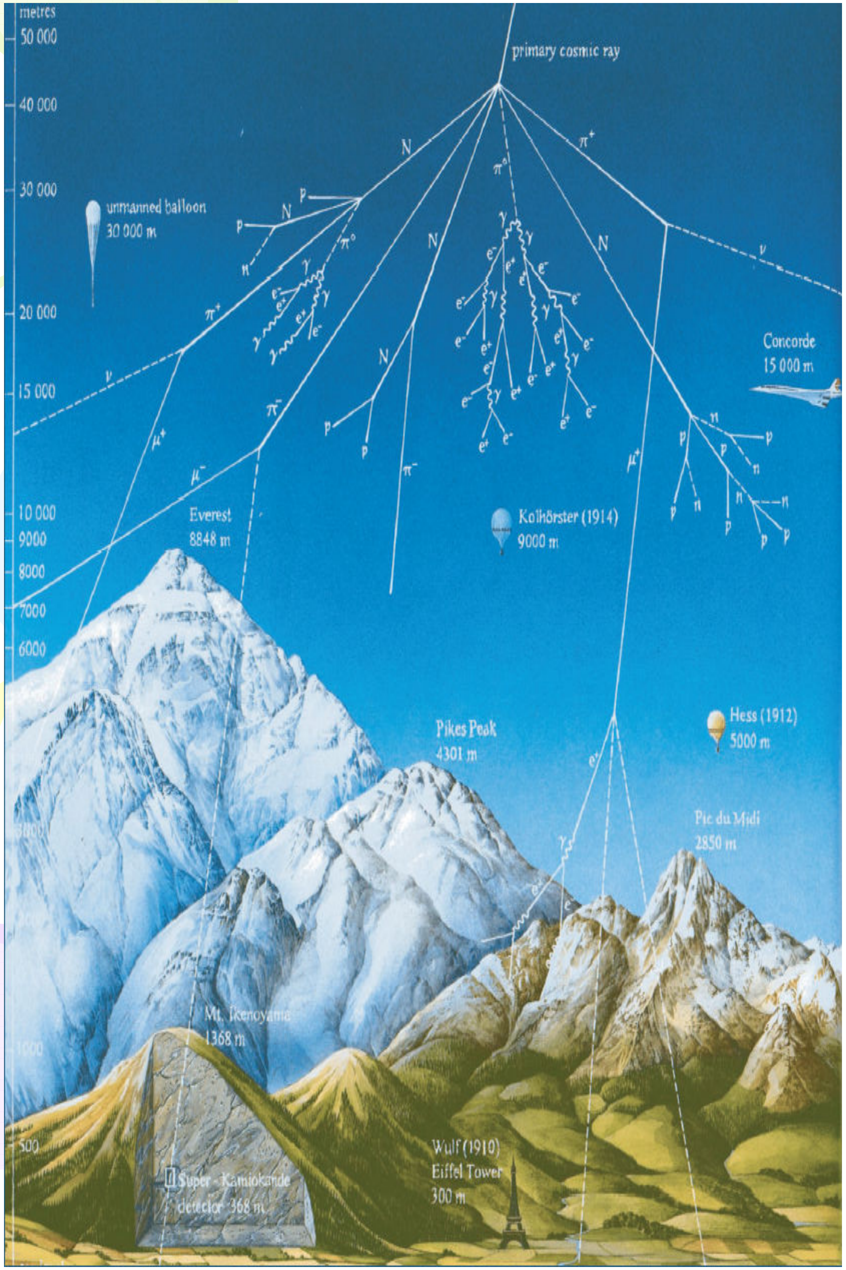
$$\Delta m^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5} \text{ eV}^2$$

$$\theta_{12} = 34.4^{+1.3}_{-1.2} \quad \text{degrees}$$

Phys.Rev.Lett.101:111301,2008

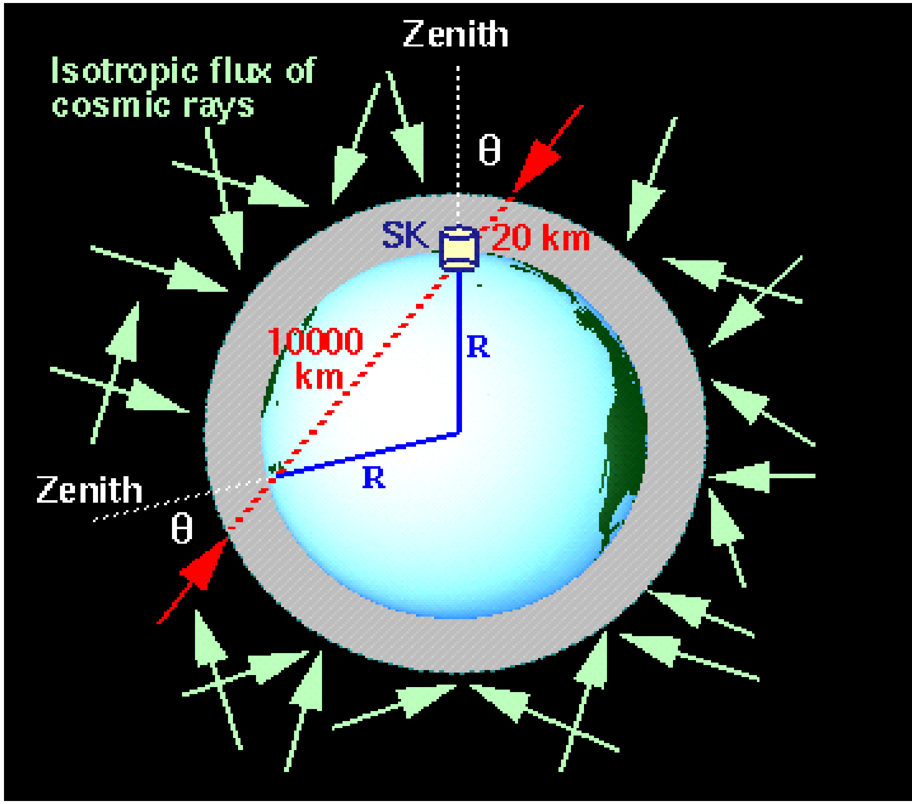
SOLAR + KAMLAND (Reactor ν's)

Atmospheric neutrinos experiments



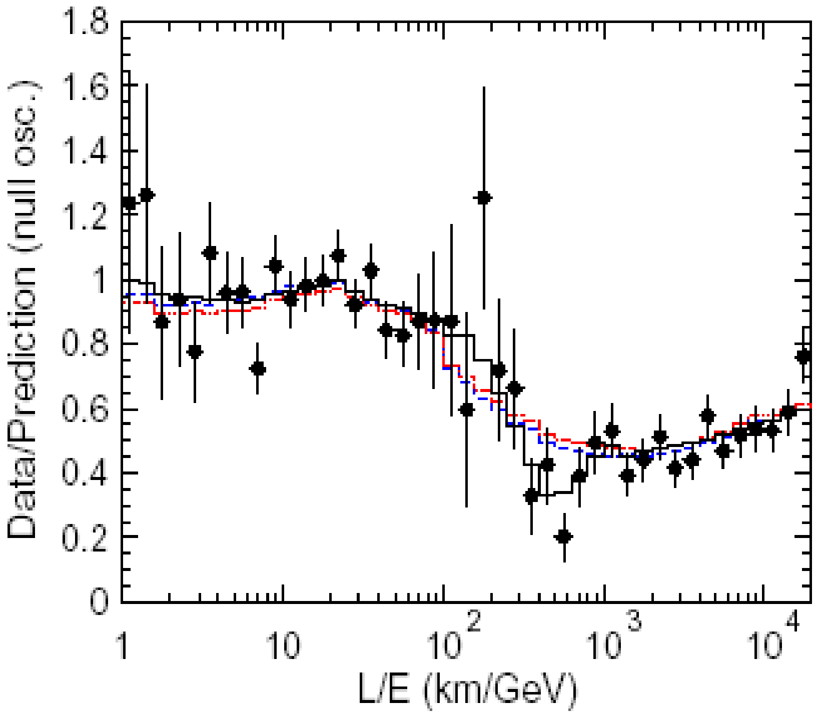
- «up-down» symetry of the flux
- L is linked to zenith angle θ
- Flux mainly ν_μ for high energy

  ($\nu_\mu / \nu_e \sim 2$ for $E < 1$ GeV)



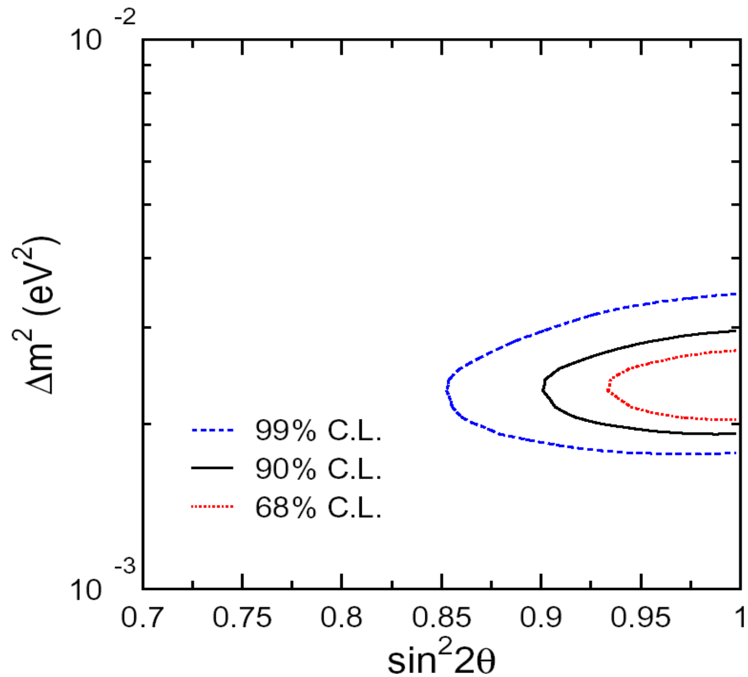
Atmospheric neutrinos experiments

Super-Kamiokande



- L/E dependance
- The observed deficit favors the $\nu_\mu \rightarrow \nu_\tau$ oscillation

(No appearance of ν_e flavor is observed)

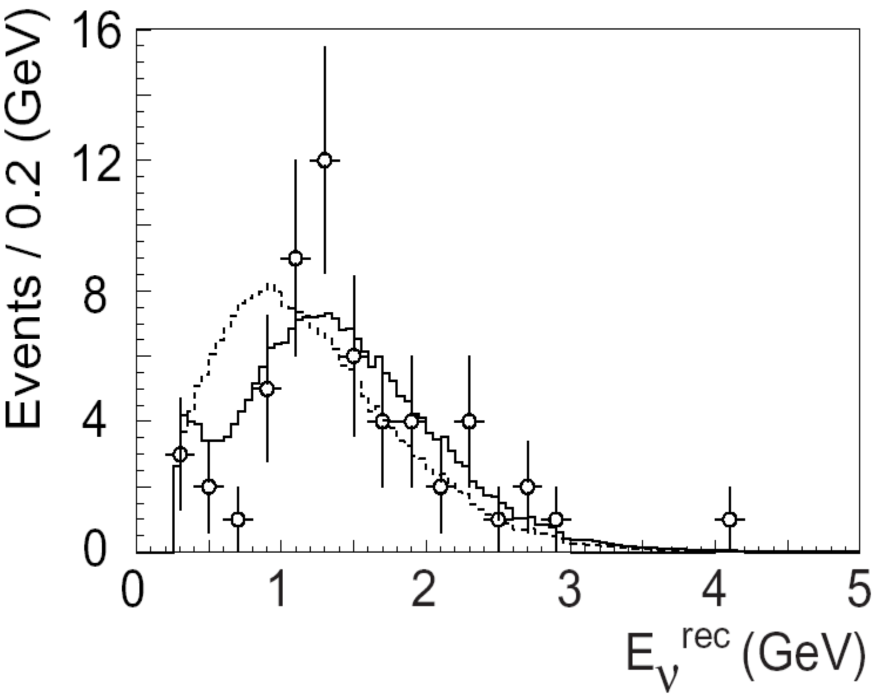


$$1.9\ 10^{-3} < \Delta m^2_{23} < 3.0\ 10^{-3}\ eV^2$$

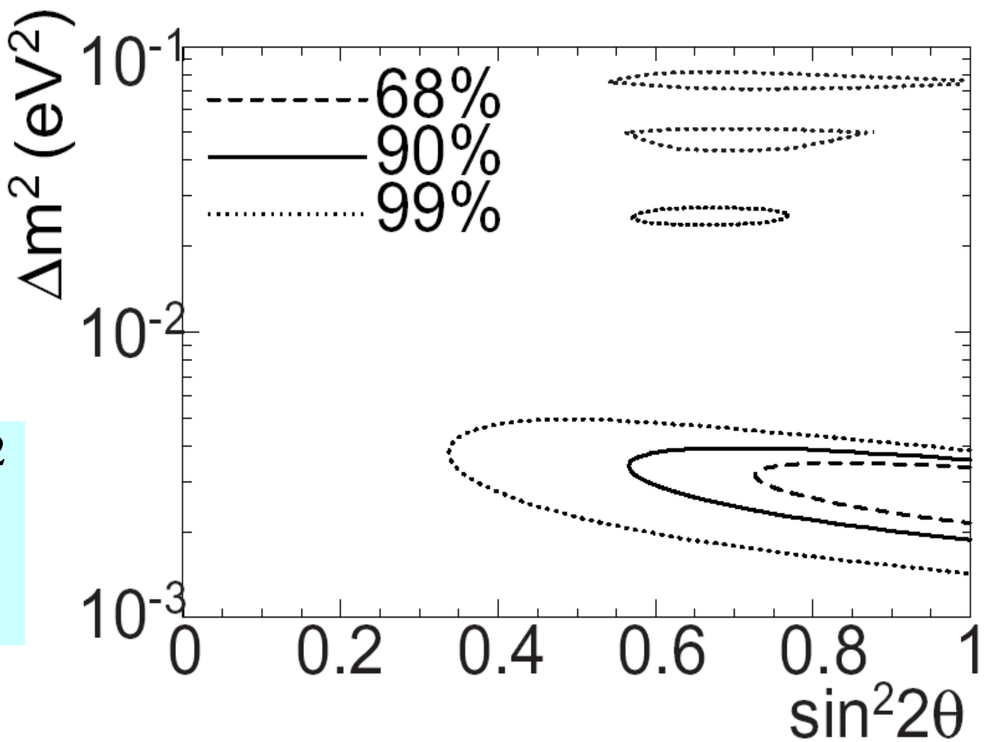
$$\sin^2 2\theta_{23} > 0.9 \qquad (90\%\ CL)$$

Atmospheric neutrinos experiments

Confirmed by K2K (accelerator neutrino's)



112 events observed
158.1 ± 9 expected without oscillation

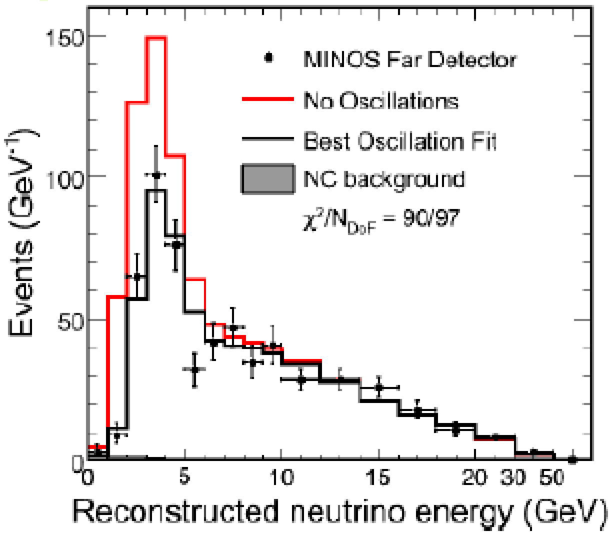


$$1.9\ 10^{-3} < \Delta m^2_{23} < 3.5\ 10^{-3}\ \mathrm{eV}^2$$

for $\sin^2 2\theta_{23} = 1$ (90% CL)

Atmospheric neutrinos experiments

- Confirmed by MINOS (accelerator neutrino's)



Unconstrained fit:

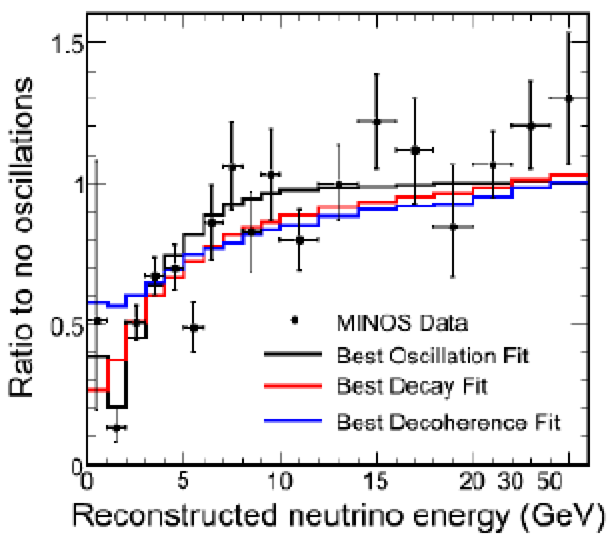
$|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

$\sin^2(2\theta) > 0.95$ [χ^2/ndof = 90/97, 68% C.L.]

Constrained ($\sin^2(2\theta)$=1.) fit:

$|\Delta m|^2 = 2.33 \times 10^{-3}\ eV^2$

$\sin^2(2\theta)$=1.07 [$\Delta\chi^2$=-0.6]



Decay

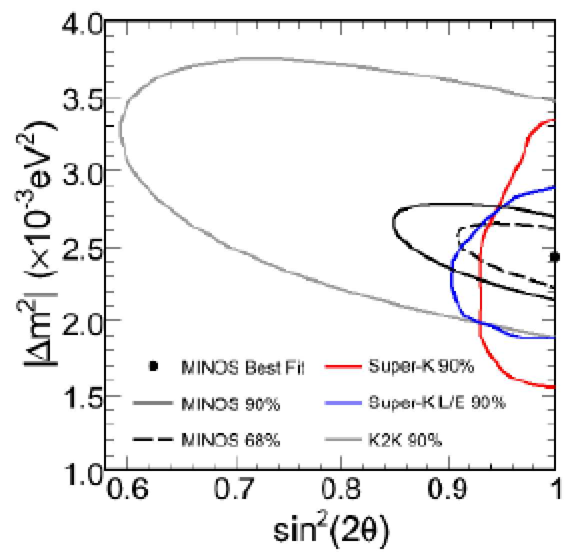
$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence

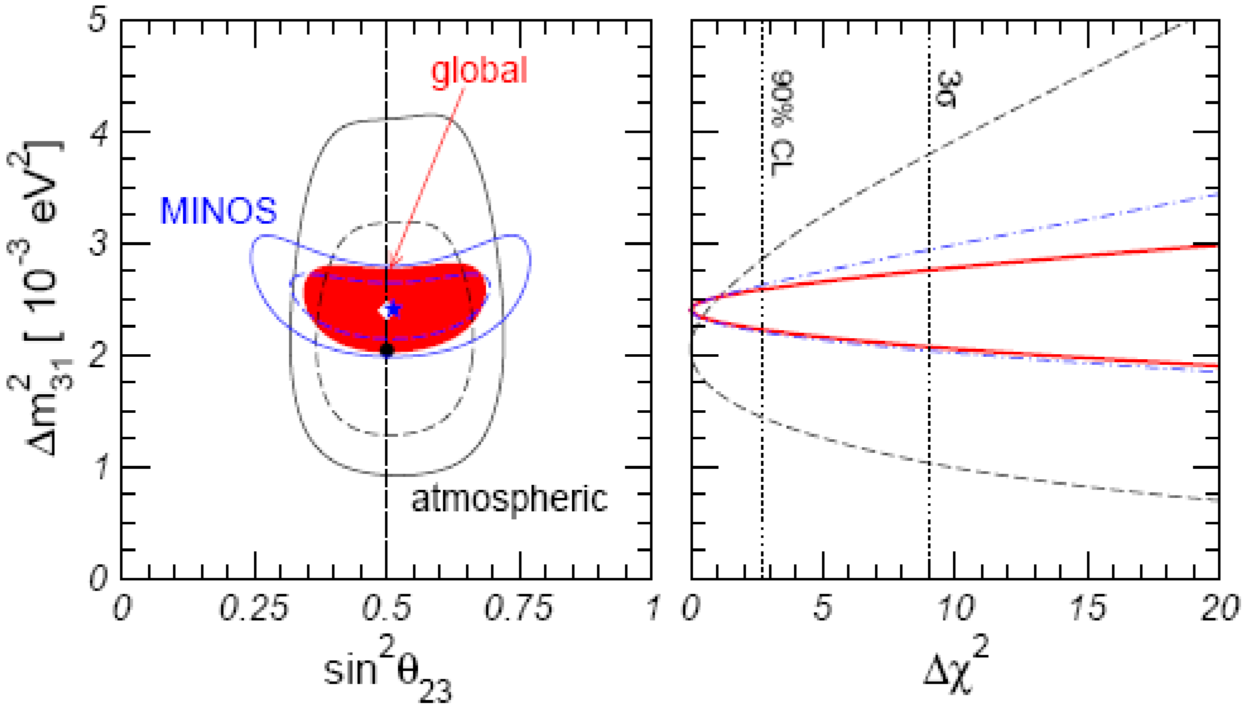
$\Delta\chi^2 = 33$

disfavored at 5.7σ



Atmospheric neutrinos experiments

- Global results with Super-K, K2K and MINOS data



$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06} \qquad |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$

The CHOOZ experiment

- Mesurement of the ν_e flux from nuclear reactor (at 1km)
  - Search for ν_e disappearance

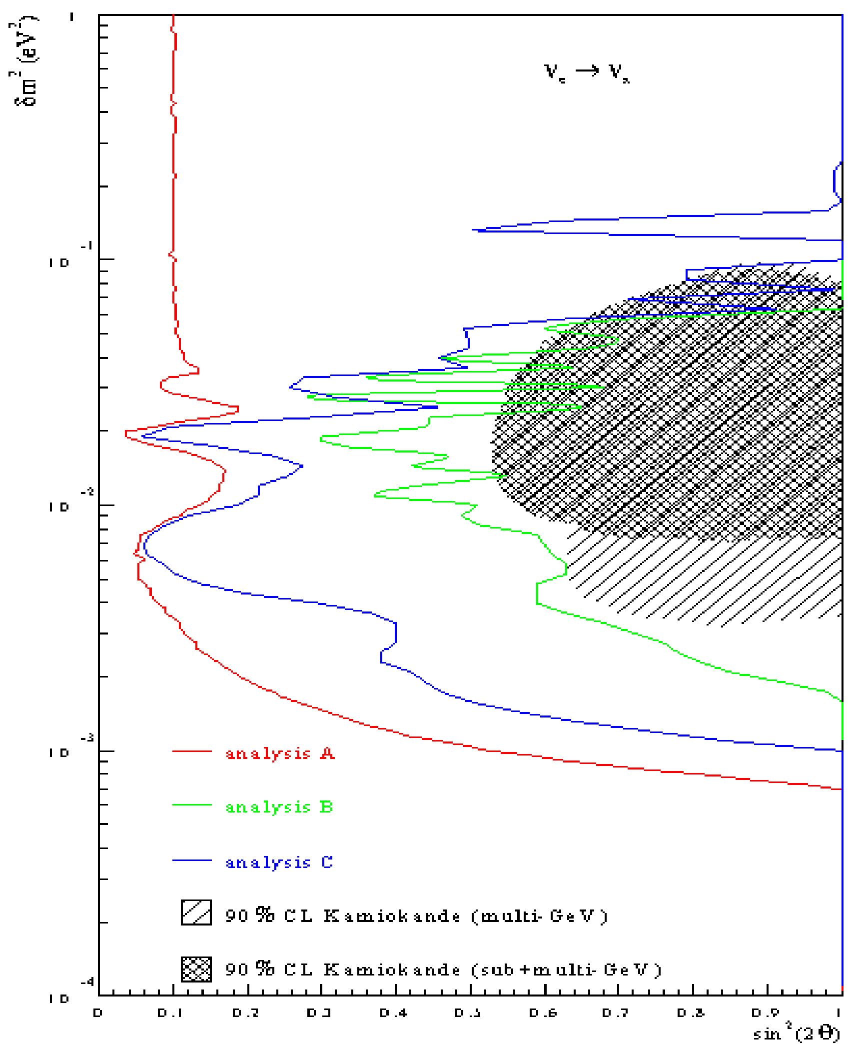
No observation of oscillation $\nu_e \rightarrow \nu_x$

Confirmation of the non observation of $\nu_\mu \rightarrow \nu_e$ from atmospheric neutrinos

$\Rightarrow$ Limite on θ_{13}

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

$\Rightarrow \theta_{13} < 11°$ (90% CL)



3-flavor oscillation parameters

parameter	Ref. [1] best fit $\pm 1\sigma$	Ref. [1] 3σ interval
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.05–8.34
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$\pm 2.40^{+0.12}_{-0.11}$	$\pm$(2.07–2.75)
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056

[1] Schwetz, Tortola and Valle, arXiv:0808.2016

Where are we?

What do we know:

- There are **three** families of active, light neutrinos *(LEP)*
- Solar neutrino oscillations: $\theta_{12} \sim 30^0$ $\Delta m_{12}^2 \sim 7\ 10^{-5} eV^2$
- Atmospheric ($\nu_\mu \rightarrow \nu_\tau$?) oscillations: $\theta_{23} \sim 45^0$ $\Delta m_{23}^2 \sim 2.5\ 10^{-3} eV^2$
- Electron neutrino oscillations are small: $\theta_{13} < 10^0$

What we do not know:

- Several unknown parameters: θ_{13} (only a limit)
  δ_{cp}
  mass hierarchy sign(Δm_{23}^2)

- Why θ_{12} and θ_{23} angles are large and θ_{13} seems very small or null ?
- Is there any CP violating phase in the mixing matrix ?
- Absolute mass values? (beta or double beta experiments)

Where do we go?

- **What is currently running**
  - Improve the precision on the atmospheric parameters θ_{23} and Δm_{23}^2
    - ν_μ disappearance: MINOS (also ν_e appearance)
    - ν_τ appearance: OPERA

- **Short term (in the next years 2010-2015)**
  - θ_{13} measurement $\theta_{13} < 3°$
    - reactor experiments $(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

      Double-Chooz, Daya Bay, Reno

    - Superbeam experiments: $(\nu_\mu \rightarrow \nu_e)$

      T2K, NOνA

- **Longer term (>2015?)**
  - New beams: β-beam, ν-fact

    θ_{13}, CP violation δ_{cp} , mass hierarchy $\mathrm{sign}(\Delta m_{23}^2)$

The OPERA experiment

<u>Goal:</u> First observation of ν_τ appearance in a pure ν_μ beam

- **CNGS (CERN to Gran Sasso) beam**

ν_μ beam tuned for the τ appearance at LNGS (730 km away from CERN)

Mean ν_μ energy : 17 GeV

Requested to deliver : 22.5 x 10^{19} pot (5 years)

The OPERA detector is installed in LNGS (Italy) which is the largest underground laboratory in the world

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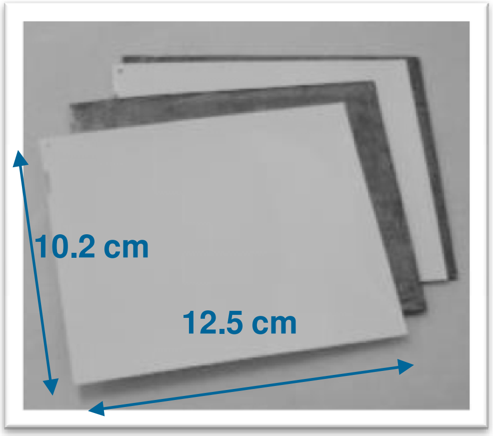
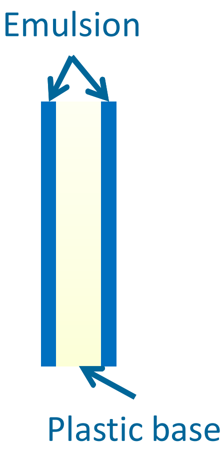
- **The OPERA target**

Basic component: OPERA Brick = 57 nuclear emulsion films interleaved by 1 mm thick lead plates





Film : 2 emulsion layers (44 μm thick) poured on a 205 μm plastic base

($\delta x \sim 1\ \mu m$ $\delta\theta \sim 1$ mrad)

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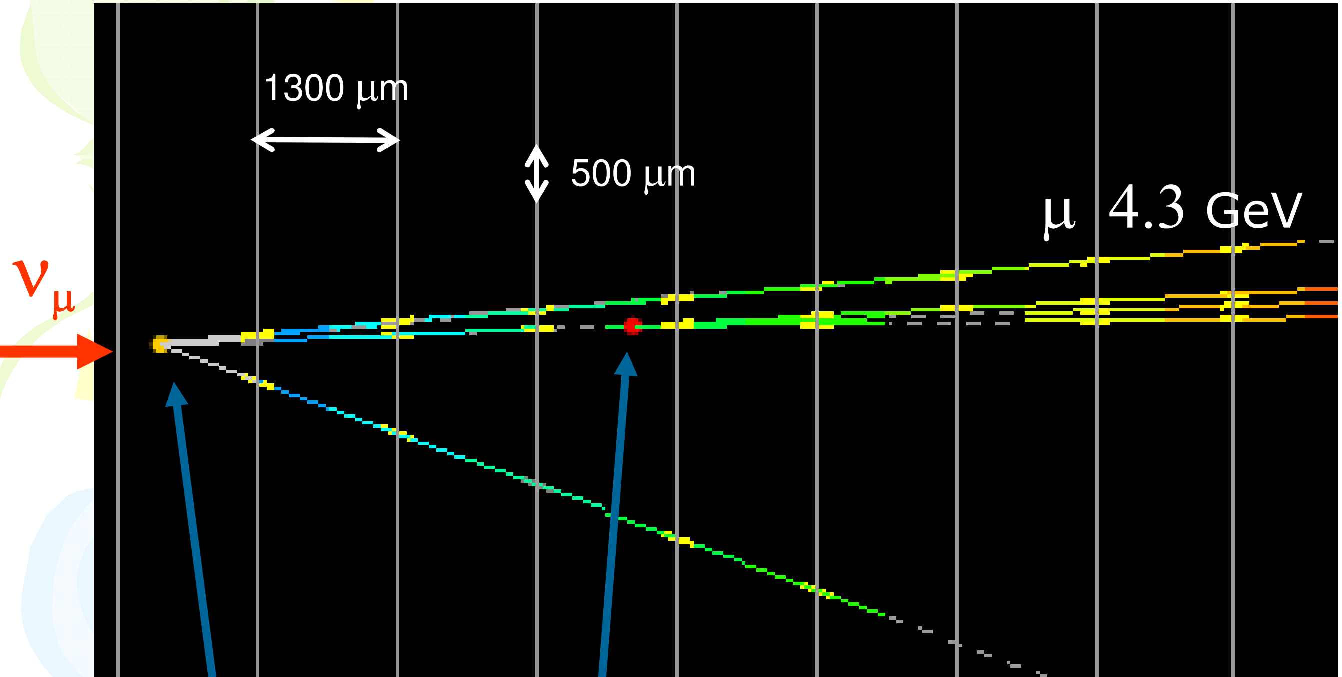
The OPERA target is composed of 150,036 bricks

Total target mass : 1.25 kt

...sion layers ... thick) ... on a ... plastic base

($\delta x \sim 1\ \mu m$ $\delta\theta \sim 1$ mrad)

The OPERA experiment



Primary vertex

ν_μ CC with 4 prongs

Secondary vertex

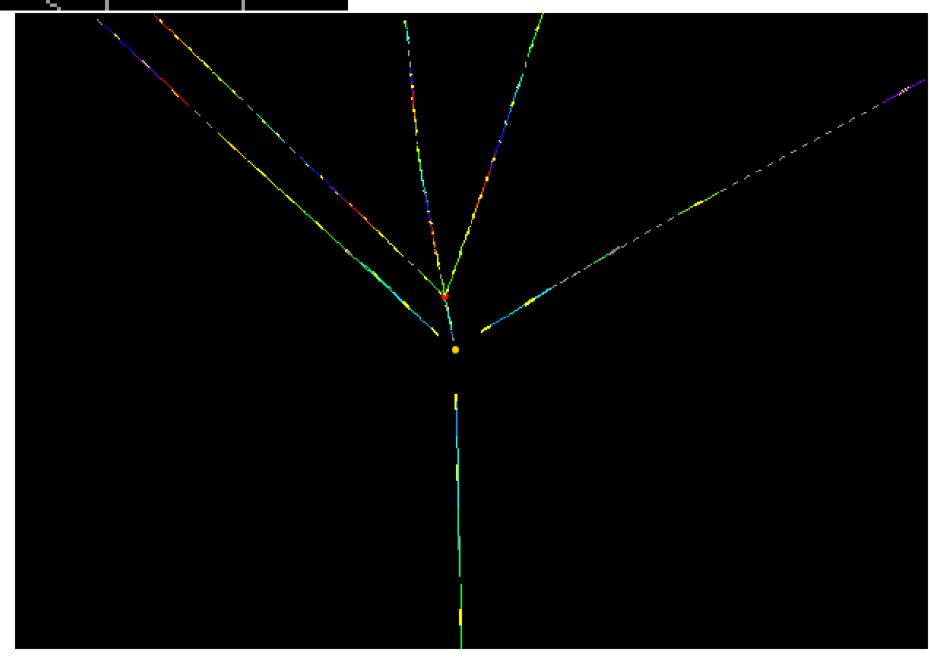
Charged Charm decay into 3 prongs

Charm flight length: 4.4 mm

Charm events from 2009 run

similar topology for ν_τ event

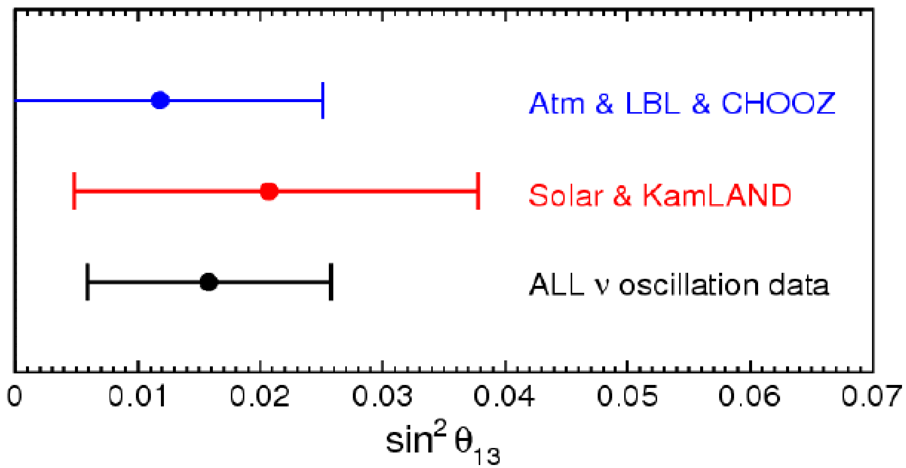
First τ event expected in 2010



θ_{13} measurement

- Hint of θ_{13} >0 in current data?

From solar+reactor+atmospheric

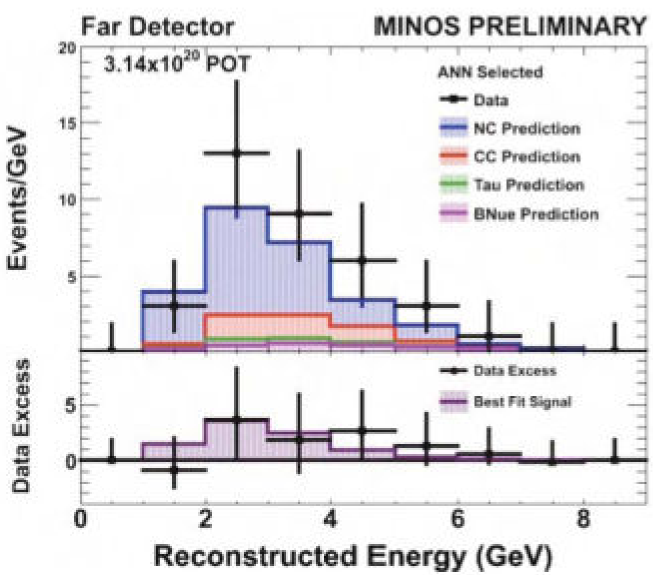


$$\sin^2\theta_{13} = 0.016 \pm 0.01 \quad (1\sigma)$$

Fogli, Lisi, Marrone, Palazzo, Rotunno, arxiv:0806.2649

From MINOS

Observation 35 events
Expected Background 27±5(stat)±2(sys)
for 3.14 x 10^{20} POT



Not really conclusive, effect is 1 or 1.5 σ
Early evidence or discovery with T2K or reactor exp.

θ_{13} measurement

- Two complementary approaches:
  - $\bar{\nu}_e$ disappearance reactor experiments: **Double Chooz, Daya Bay, Reno**

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

- Depends on $\sin^2(2\theta_{13})$ & Δm_{31}^2, weakly on Δm_{21}^2

- Measurement is independent of δ_{CP}

- negligible matter effect (1km) - independent of sign(Δm^2_{13})

$\Rightarrow$"clean" θ_{13} measurement

But neutrino beam is not well know (need near and far detectors)
Systematic error dominant

  - ν_e appearance in ν_μ beam: **T2K (250 km), NOνA (810 km)**

- **$P_{\mu e}$** is a complicated function depending on various parameters

  - θ_{13} measurement is correlated with δ_{CP} and sign(Δm^2_{13})

T2K experiment

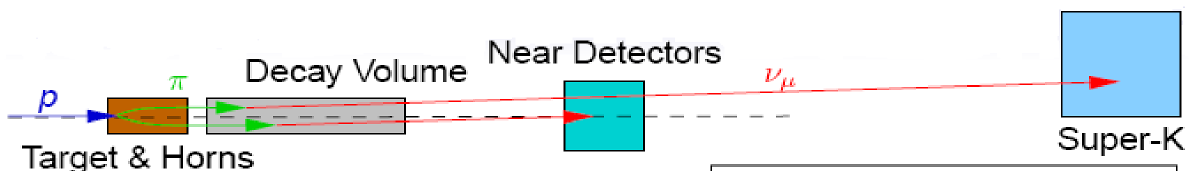
- <u>Main goal:</u> Discovery of non-zero θ_{13}
  - Increase the current sensitivity by a factor ~10

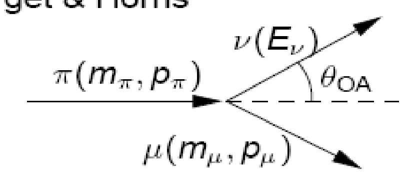
Off-axis beam (2.5°)

Quasi-monochromatic ν_μ beam
L/E tuned for max sensitivity
Small fraction of ν_e
Reduced high-E non-CCQE bckg

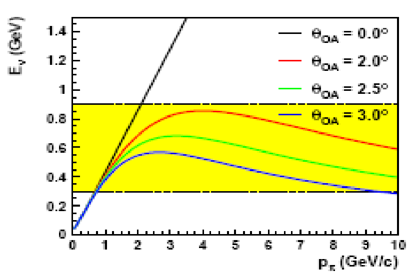
Near detector (ND280)
(beam characterization)

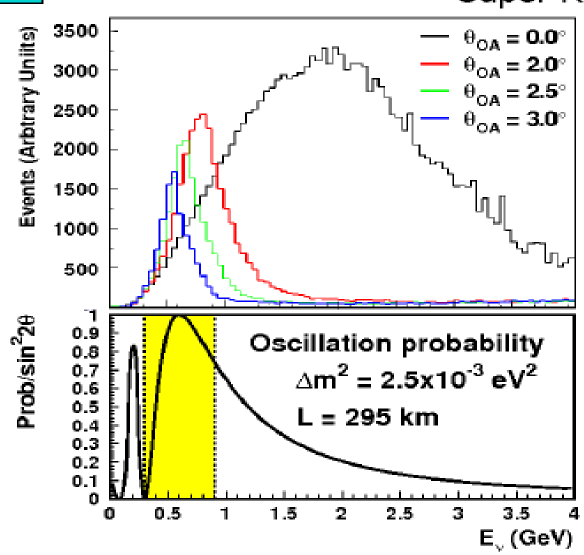
Far detector
(Super-Kamiokande)
250 km from source
Cherenkov detector
50 kton Water
20" PMT x 11000





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$

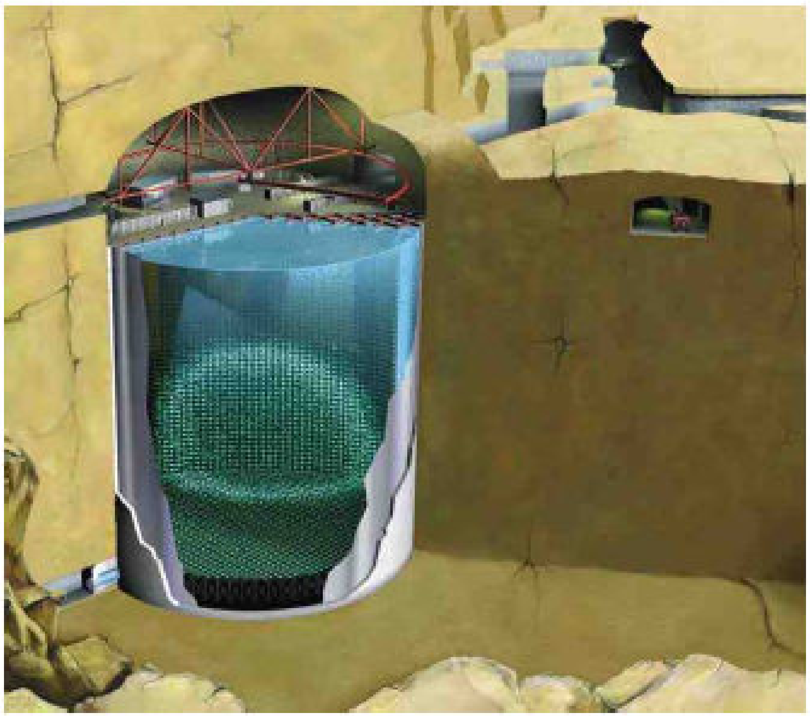




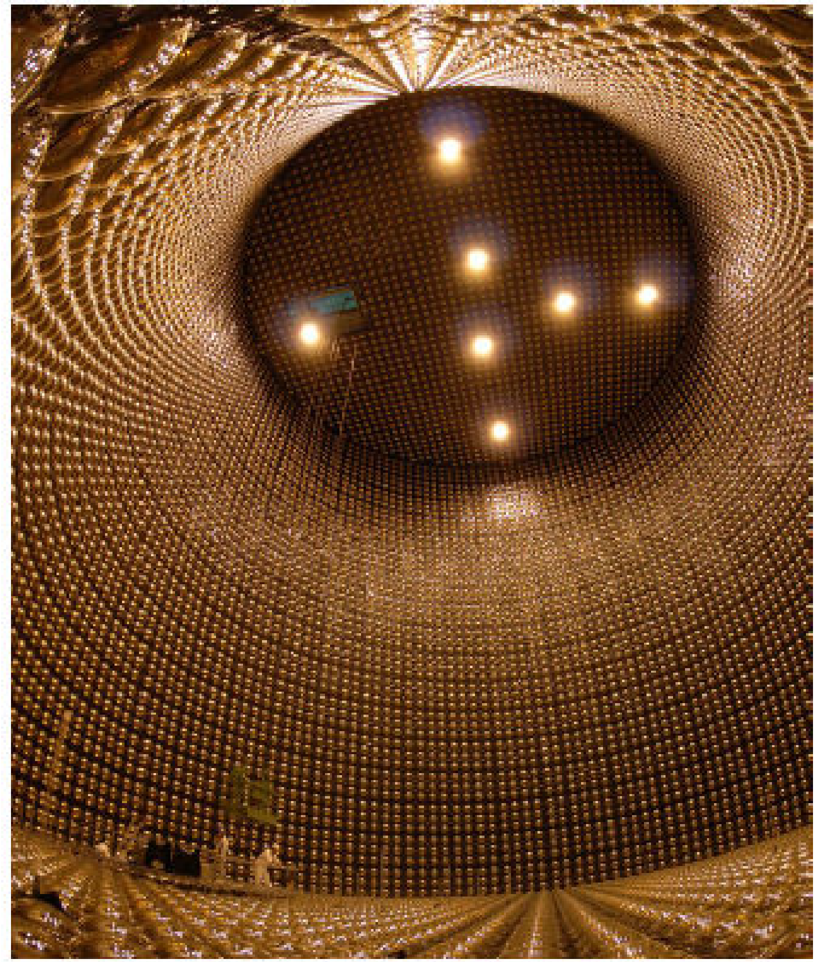
Data taking
Starts in 2010

T2K experiment

Far detector – Super-Kamiokande

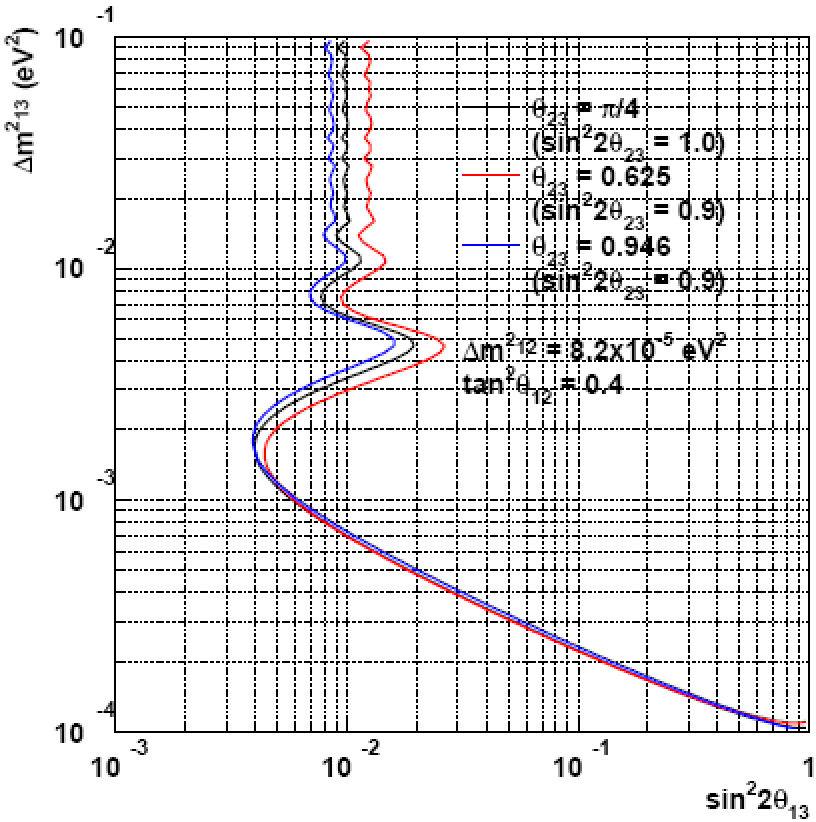


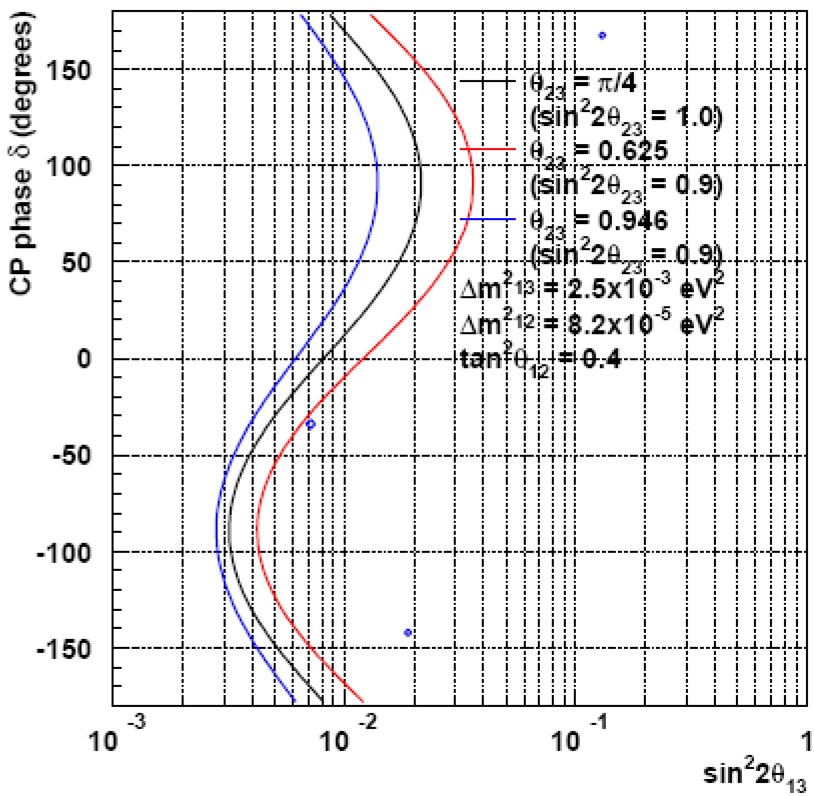
- $\phi \times h = 39\ \mathrm{m} \times 41\ \mathrm{m}$
- 11146(inner)+1885(outer) PMTs
- Fiducial volume 22.5 kt



T2K experiment sensitivity

- 5 years (10^{21} POT/year)
- Error on background estimation at 10%





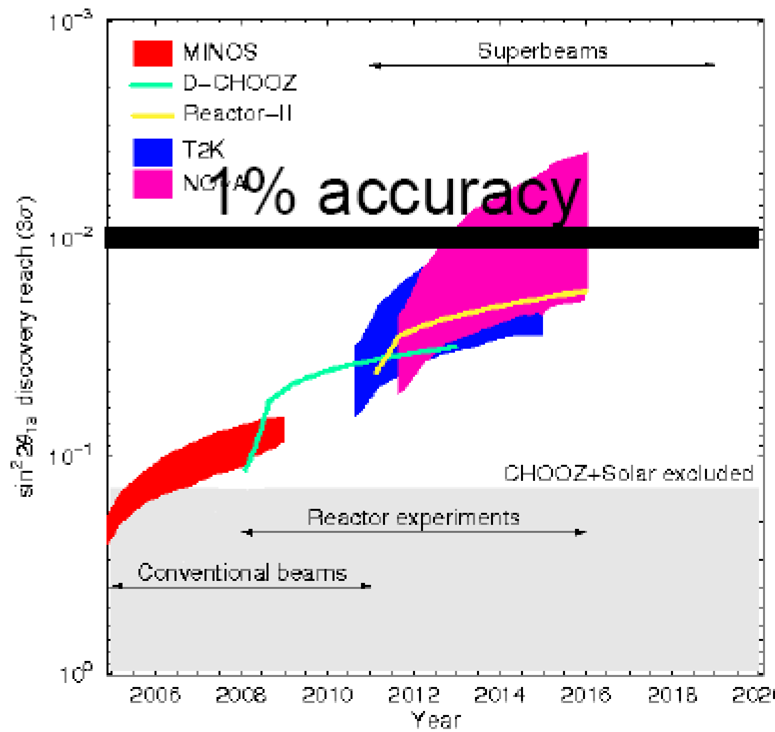
$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)
for: $\delta = 0$, $\Delta m^2_{13} = 2.5 \times 10^{-3}\ eV^2$, $\sin^2 2\theta_{23} = 1$

- Factor 10 improvement on CHOOZ limits (for any δ)

The next 5 years

- If $\sin^2 2\theta_{13} > 0.01$
  - evidence very soon
  - firm observation by 2015
  - CP search will be open:

    new detectors, upgraded beams



- If no evidence by 2015
  - Need new types of facility (ν-factory, β-beam)
    - measure the value of δ_{CP} (if $\theta_{13} \neq 0$!)
    - determine the mass hierarchy - sign(Δm^2_{13}) (earth matter effect)

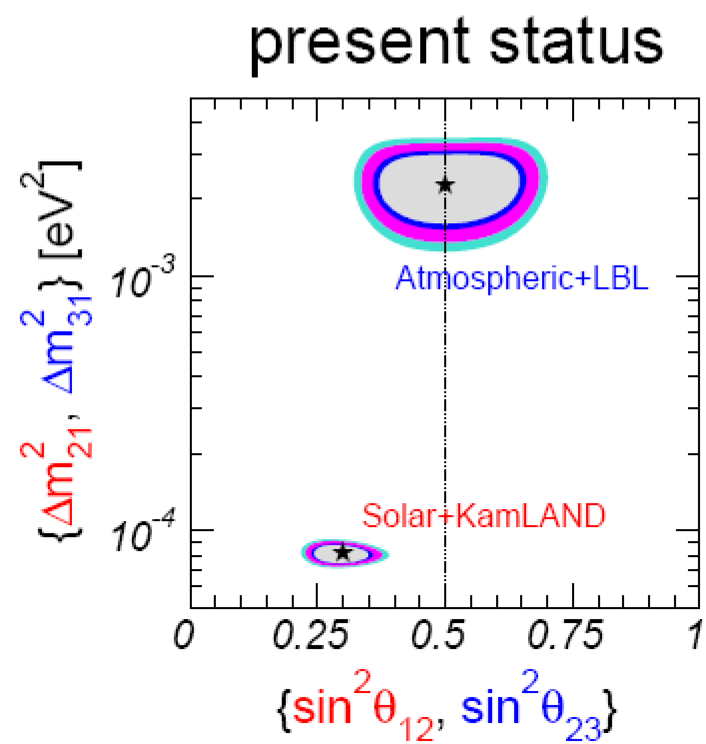
Conclusion

- Still unknown oscillation parameters: θ_{13} δ_{cp} sign(Δm^2_{13})
  - The others are measured with some accuracy

- Upcoming reactor and accelerator neutrino experiments will reach $\sin^2 2\theta_{13} \sim 0.01$ (within 5 years)

- Even with upgrades these experiments most likely cannot say much on CP violation and Mass Hierarchy
  - Need new facility and detectors (> 2015?)

(remark: Not taken into account LSND results)



The oscillation probability including matter effect

All effects are driven by θ_{13} !

$$P_{\nu_\mu \to \nu_e} \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)^2}$$

$$\Delta \equiv \frac{\Delta m_{13}^2 L}{4E}$$ → **Oscillation phase**

Neutrinos +

Anti Nu -

$$\mp \alpha \sin\theta_{13} \xi \sin\delta_{CP} \sin\Delta \frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}} \frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}$$

dominant « on peak »

$$+\alpha \sin\theta_{13} \xi \cos\delta_{CP} \cos\Delta \frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}} \frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}$$

$$+\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2\left(\hat{A}\Delta\right)}{\hat{A}^2}$$

$$\alpha \equiv \frac{\Delta m_{21}^2}{\left|\Delta m_{13}^2\right|}$$

2-3 10^{-2}

$$\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \approx O(1)$$

$$\hat{A} \equiv 2\sqrt{2} G_F n_e \frac{E}{\Delta m_{13}^2}$$

Matter effect sensitive to :

- **Sign of Δm^2_{13}**
- **neutrino versus anti-neutrino**

For the special case of $\nu_\mu \rightarrow \nu_e$ oscillations, we have: $P(\nu_\mu \to \nu_e) = \Sigma_{i=1,4} P_i$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$ atmospheric part

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$ solar part

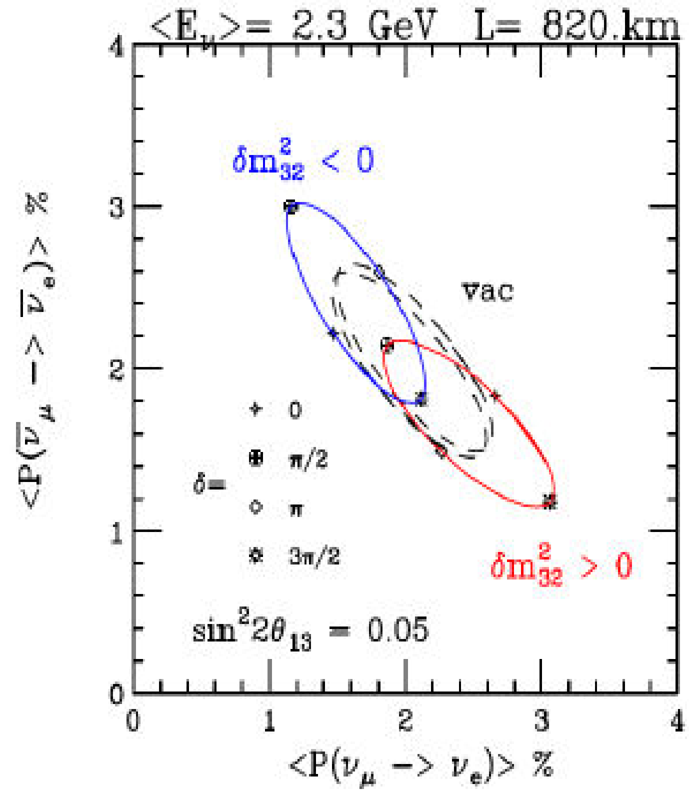
$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$ interference

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$ interference

where

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$
$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

and the $\pm$ signifies neutrinos or antineutrinos



In vacuum, at leading order:

$$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E}$$

Pin down CP phase and mass hierarchy

Detecting CP violating effects

Best method:
(in vacuum)

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

it requires: Δm^2_{12} and $\sin 2\theta_{12}$ large (LMA solar): OK !

larger effects for long L: 2nd oscillation maximum

however…

$$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13} \qquad A_{CP} \propto \frac{1}{\sin\theta_{13}}$$

$\sin^2 2\theta_{13}$ small: low statistics and large asymmetry

$\sin^2 2\theta_{13}$ large: high statistics and small asymmetry

impact on the detector design

…and:

$$P(\nu_\mu \to \nu_e) \propto \sin^2 \frac{\Delta m^2_{23} L}{4E}$$

oscillations are governed by Δm^2_{atm} , L and E:

$E \approx 5$ GeV → $L \approx 3000$ km

flux too low with a conventional LBL beam

Mass hierarchy from matter oscillations

Neutrinos oscillating through matter (MSW effect):

- different behavior of different flavors due to the presence of electrons in the medium
- additional phase contribution to that caused by the non zero mass states.
- asymmetry between neutrinos and antineutrinos even without CP violating phase in the matrix
- the related oscillation length L_M, unlike L_V (vacuum), is independent of the energy
- as an example L_M (rock) is ~ 10000 km while L_M (Sun) ~ 200 km

In the limit of Δm^2_{sol} approaching zero (for which there are no CP effects) and of running at the atmospheric oscillation maximum, the asymmetry between neutrinos an antineutrinos equal to

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{2E_\nu}{E_R} \quad \text{for low } E_\nu$$

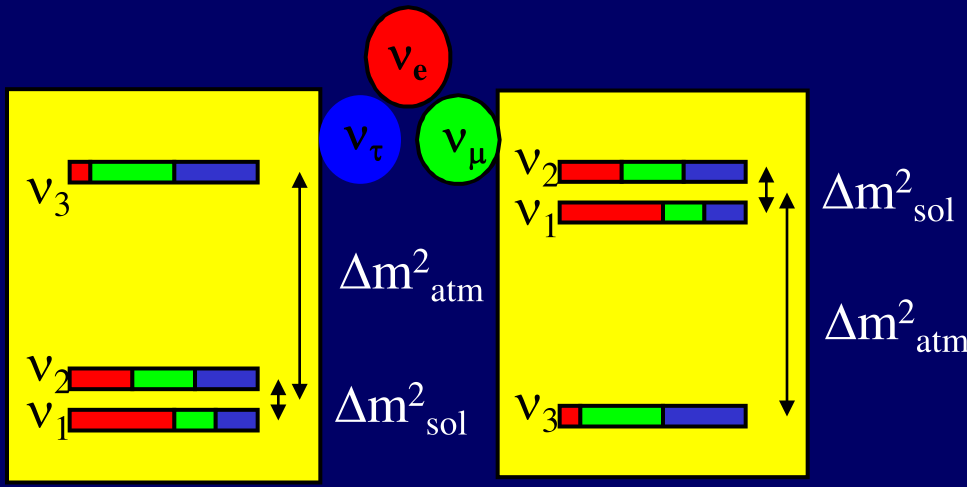
with

$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2}G_F \rho_e} \approx 11 GeV$$

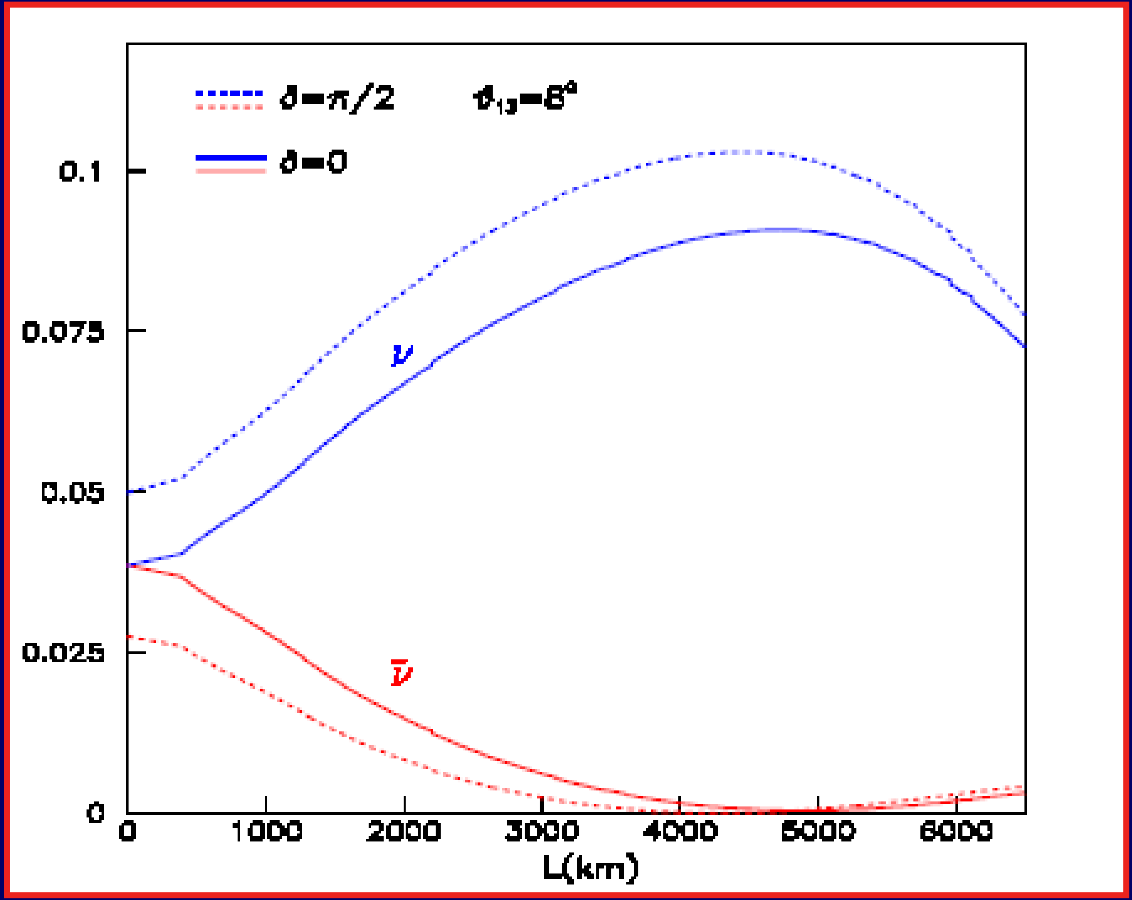
By the measurement of this asymmetry one can determine whether Δm^2_{23} is positive or negative (hierarchy)

$$\sin^2 2\theta_{13} \quad \Rightarrow \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{13}}{\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu} \right)^2$$

$$|\Delta m^2_{13}| \quad \Rightarrow |\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu|$$



For $E_\nu \sim E_R$ large amplification of $P(\nu_\mu \rightarrow \nu_e)$ at long distances



The NOνA experiment

- NuMI beam off-axis – 810 km
- Far detector 14 kton
- Near detector 222 tons
- Liquid scintillator (4x6 cm^2 cells)
- First data 2012 (2.5 kton)
- Full detector 2014

- Longer baseline (810 km)
  (mass hierarchy?)