XVI International Workshop on Neutrino Telescopes

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Europe/Rome timezone

Neutrino Oscillations: Past, Present and Future

Gianluigi Fogli

Dipartimento di Fisica, Università di Bari and INFN, Sezione di Bari

Venice, March 2nd, 2015

The Past (the milestones on the route of neutrino oscillation physics)

1. Going deeply back in time…
2. The long-standing "Solar Neutrino Problem"
3. The first breaktrough: the "atmospheric neutrino anomaly"
4. 2002: "annus mirabilis" of solar neutrino physics
5. The Long Baseline Neutrino experiments
6. The hunt to θ_{13}, the last mixing angle
7. The Short Baseline Reactor experiments

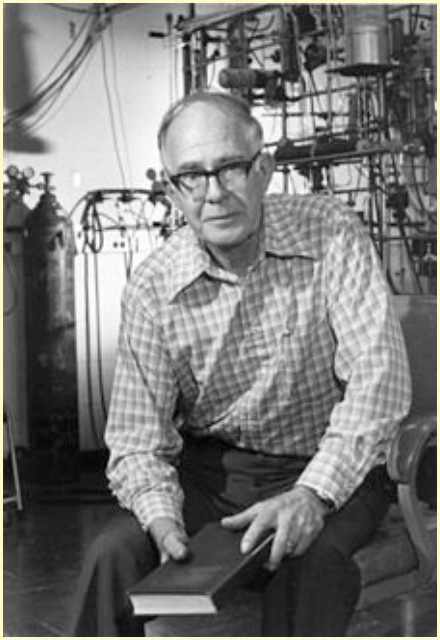
1. Going deeply back in time…

Two protagonists

A vivid and firm theoretical intuition …

Bruno Pontecorvo

and



Raymond Davis Jr.

… a challenging experimental quest

Bruno Pontecorvo mentions for the first time neutrino oscillations in 1957, in his paper about muonium ↔ antimuonium ($\mu^- e^+ \leftrightarrow \mu^+ e^-$) transition(*), the same year in which

- parity violation is discovered (Wu et al.)
- the two-component theory of massles neutrino is proposed (Landau, Lee and Yang, Salam).

Pontecorvo comes back to neutrino oscillations ten years later, in 1967, when

- The phenomenological V-A theory is well established (Feynman and Gell-Mann, Marshak and Sudarshan).
- It has been shown that the neutrino is left-handed (Maurice Goldhaber, 1957).
- The Brookhaven experiment (1962) has revealed that at least two types of neutrino, ν_e and ν_μ, exist (Lederman, Schwartz and Steinberger).

In this paper(§) he fixes the conditions at which neutrino oscillations are possible.

(*) B. Pontecorvo, "Muonium and Antimuonium", Zh. Eksp. Teor. Fiz. 33 (1957) 549.

(§) B. Pontecorvo, "Neutrino experiments and the Question of Leptonic Charge Conservation" Zh. Eksp. Teor. Fiz. 53 (1967) 1717.

Two years later, in 1969, **Gribov and Pontecorvo** consider explicitly a model in which:

$$\nu_{eL} = \cos\theta\, \nu_{1L} + \sin\theta\, \nu_{2L}$$

$$\nu_{\mu L} = -\sin\theta\, \nu_{1L} + \cos\theta\, \nu_{2L}$$

In the same paper

- Oscillations of solar neutrinos in vacuum are discussed.
- The survival probability of ν_e is explicitly derived.

Quite independently, in 1962 Maki, Nagakawa and Sakata, in the context of a model of the elementary particle structure, also introduce the mixing of two neutrinos, called "weak" neutrinos and identified as ν_e and ν_μ, in terms of two massive neutrinos ν_1, ν_2, called "true" neutrinos.

This is the origin of what is now called PMNS (Pontecorvo-Maki-Nakagawa-Sakata) neutrino mixing matrix.

2. The long-standing "Solar Neutrino Problem"

In the meantime, **Raymond Davis** is preparing his famous **Homestake experiment** on the detection of **solar neutrinos**, based on the radiochemical method proposed by Pontecorvo in 1946:

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

John N. Bahcall did the theoretical calculations for the expected solar fluxes. The experiment becomes operative in 1967.

The Davis experiment operates continuously until 1994. The flux measured is about 1/3 of the expected flux calculated by Bahcall.

Further experiments (Kamiokande, SAGE, GALLEX/GNO, SNO, and recently Borexino) also found a deficit … but at that time (the first 90's) it was not clear if the problem was related to particle physics (oscillations?) or to astrophysics (the solar model?).

On the other hand, since the 80's, **oscillations in matter**, the **MSW** (Mykheev-Smirnov-Wolfenstein) effect, were theoretically able to provide a quite attractive particle physics solution.

Let us show the situation of MSW solutions at that time.

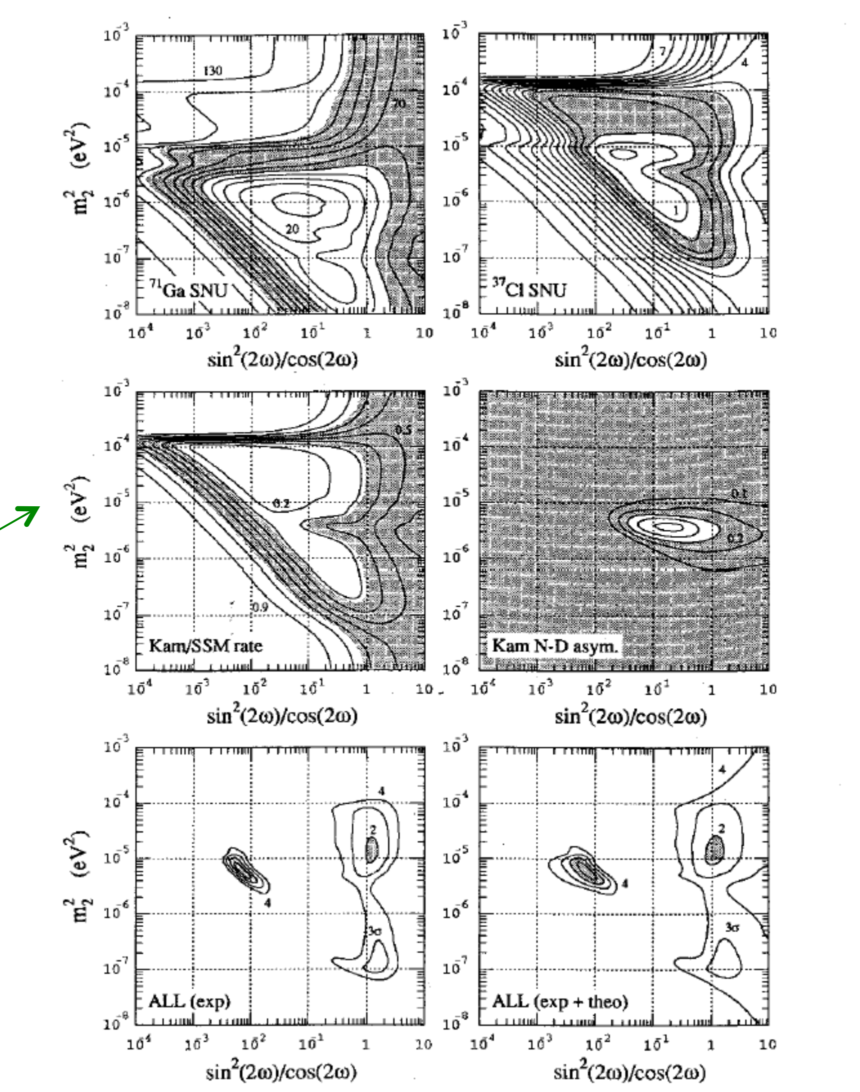
A comprehensive analysis of solar, atmospheric, accelerator and reactor neutrino experiments in a hierarchical three-generation scheme

G.L. Fogli [a], E. Lisi [a,b] and D. Montanino [a]

[a] *Dipartimento di Fisica di Bari, Bari, Italy*
Sezione INFN di Bari, Bari, Italy

[b] *Theory Division, CERN, Geneva, Switzerland*

Phys. Rev. D 49 (1994) 3626.



Regions allowed at the 2σ level, for each experiment separately in the upper four figures, for their combination in the lower two (θ_{13} = 0 is assumed here).

Both small and large mixing angle solutions (SMA and LMA) are allowed…

No a definite solution to the "solar neutrino problem" is found

3. The first breaktrough: the "atmospheric neutrino anomaly"

The so-called "atmospheric neutrino anomaly", is the unexpected difference between measured and predicted muon-to-electron flavor composition of the atmospheric neutrino flux, appeared in the first 90's.

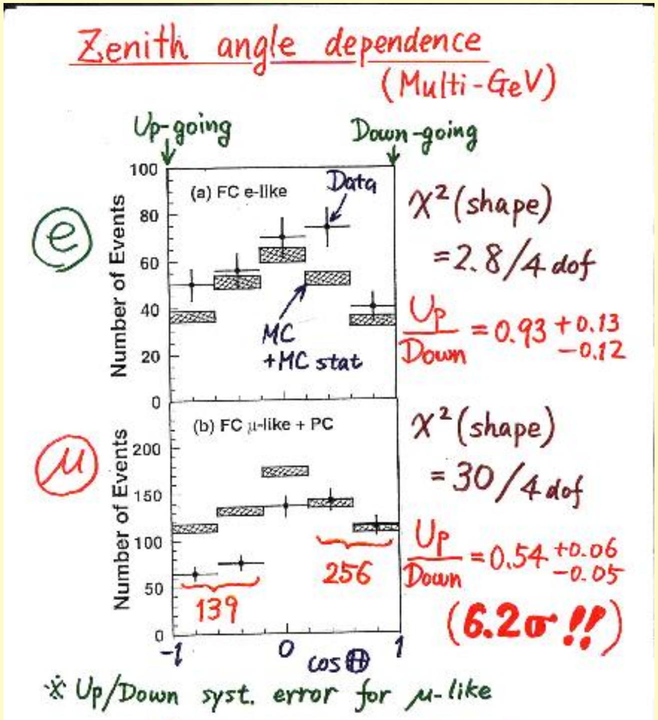
Once again: is it a problem of particle physics (oscillations?) or of astrophysics (primary cosmic ray fluxes?)

... but in 1998 ... the breakthrough!

The atmospheric neutrino flux shows a strong zenith angle dependence!

Takaaki Kajita for Super-Kamiokande Collab. at Neutrino '98, Takayama

a 6.2σ effect!



(Also: Francesco Ronga for MACRO Collab.)

RESULTS SK zenith distributions

SGe	Sub-GeV electrons
MGe	Multi-GeV electrons
SGμ	Sub-GeV muons
MGμ	Multi-GeV muons
USμ	Upward Stopping muons
UTμ	Upward Through-going muons

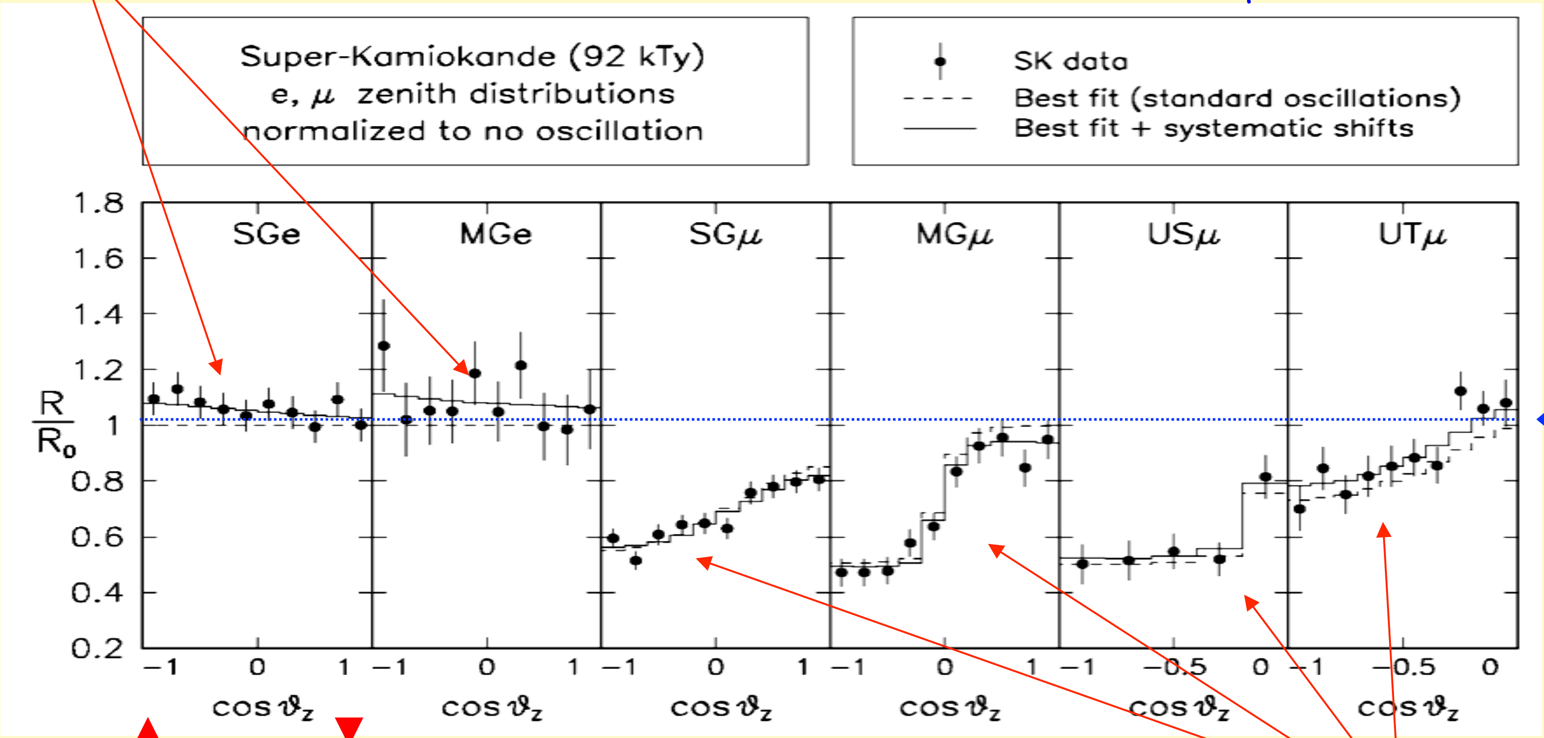
Super-Kamiokande atmospheric neutrino data, zenith distributions, and three-flavor oscillations

G. L. Fogli, E. Lisi, A. Marrone, and G. Scioscia
Dipartimento di Fisica and Sezione INFN di Bari, Via Amendola 173, I-70126 Bari, Italy

Phys. Rev. D 59 (1999) 033001; hep-ph/9808205

electrons ~ weak effect

A clear indication of $\nu_\mu \rightarrow \nu_\tau$ oscillation !



no osc.

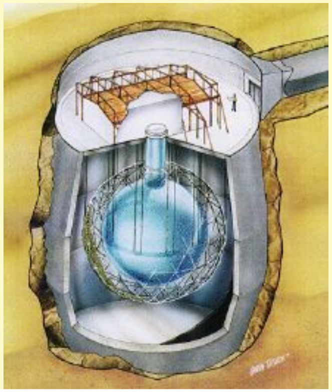
up

down

muon deficit from below

In the meantime, what about the "**solar neutrino problem**"?

As in the best western movies, a new experiment comes to rescue:



Sudbury Neutrino Observatory experiment (using a heavy-water target)

Why deuterium

In deuterium one can separate **CC** events (induced by ν_e only) from **NC** events (induced by ν_e, ν_μ, ν_τ), and double check via **ES** (Elastic Scattering events, due to both NC and CC)

$$\begin{aligned} \mathrm{CC}: &\quad \nu_e + d \to p + p + e \\ \mathrm{NC}: &\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau} \\ \mathrm{ES}: &\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau} \end{aligned}$$

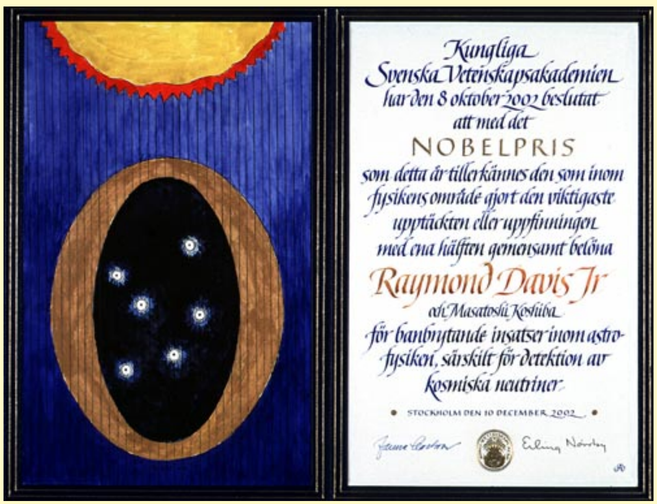
The experimental breakthrough

➡ CC/NC ~ 1/3 < 1
"Smoking gun" proof of flavor change. Solar model OK!

➡ CC/NC ~ P_{ee} ~ $\sin^2\theta_{12}$ (LMA) ~1/3 < $\frac{1}{2}$
Evidence of mixing in first octant + matter effects

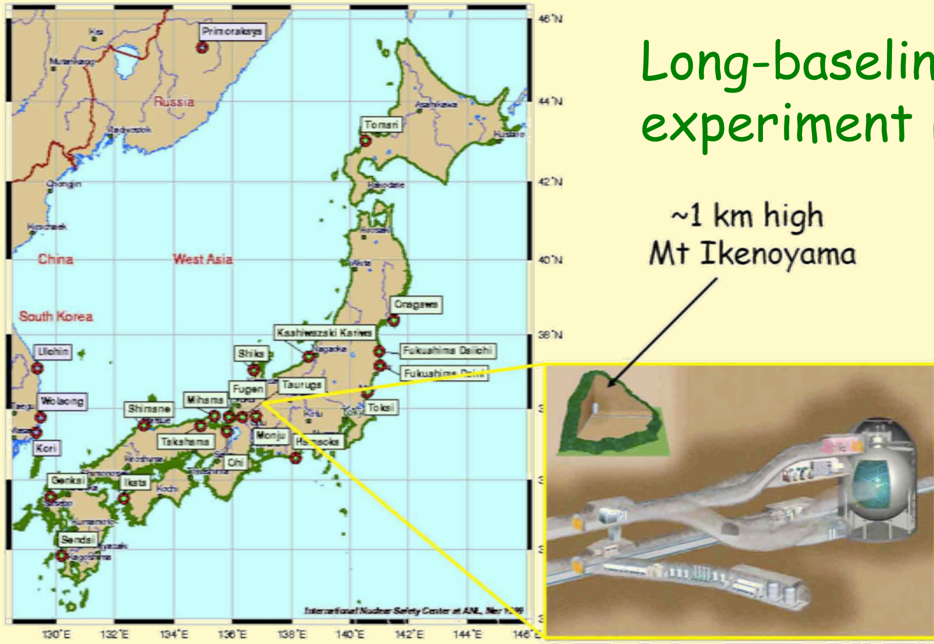
4. 2002: "annus mirabilis" of solar neutrino physics

2002
Nobel Prize



Motivation: "for their pioneering contributions to the detection of cosmic neutrinos …"

Again in 2002… KamLAND: aim of reproducing "solar ν oscillations" in Laboratory



Long-baseline reactor experiment in Japan

~1 km high
Mt Ikenoyama

1000 ton mineral oil detector, "surrounded" by nuclear reactors producing anti-ν_e

$A/\delta m^2 \ll 1$ in Earth crust
(so vacuum approx. OK)

$L \sim 100$-200 km

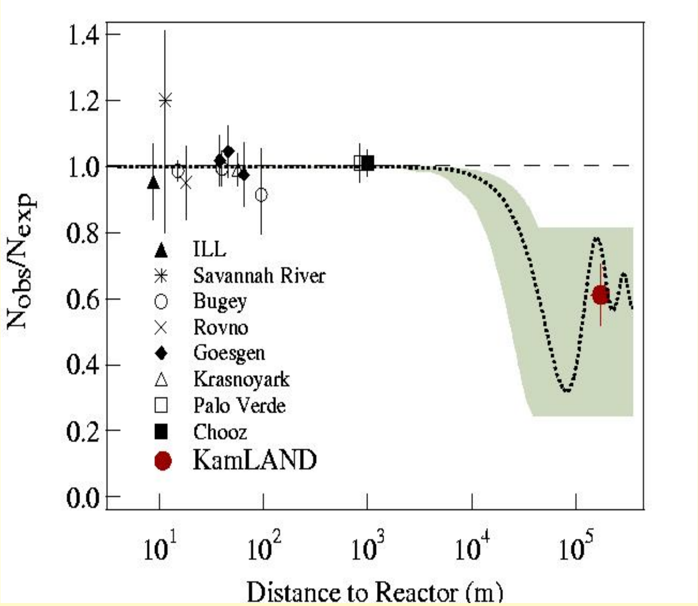
$E_\nu \sim$ few MeV

⇨

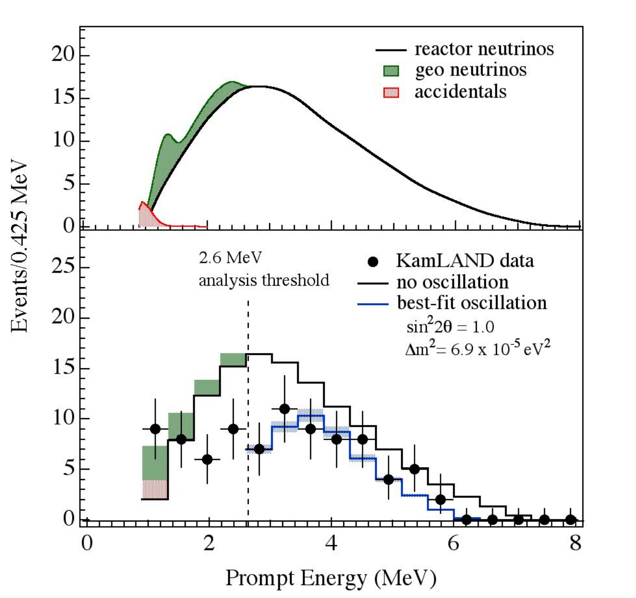
With previous $(\delta m^2, \theta_{12})$ parameters it is $(\delta m^2 L/4E) \sim O(1)$ and reactor neutrinos should oscillate with large amplitude (large θ_{12})

KamLAND results in 2002

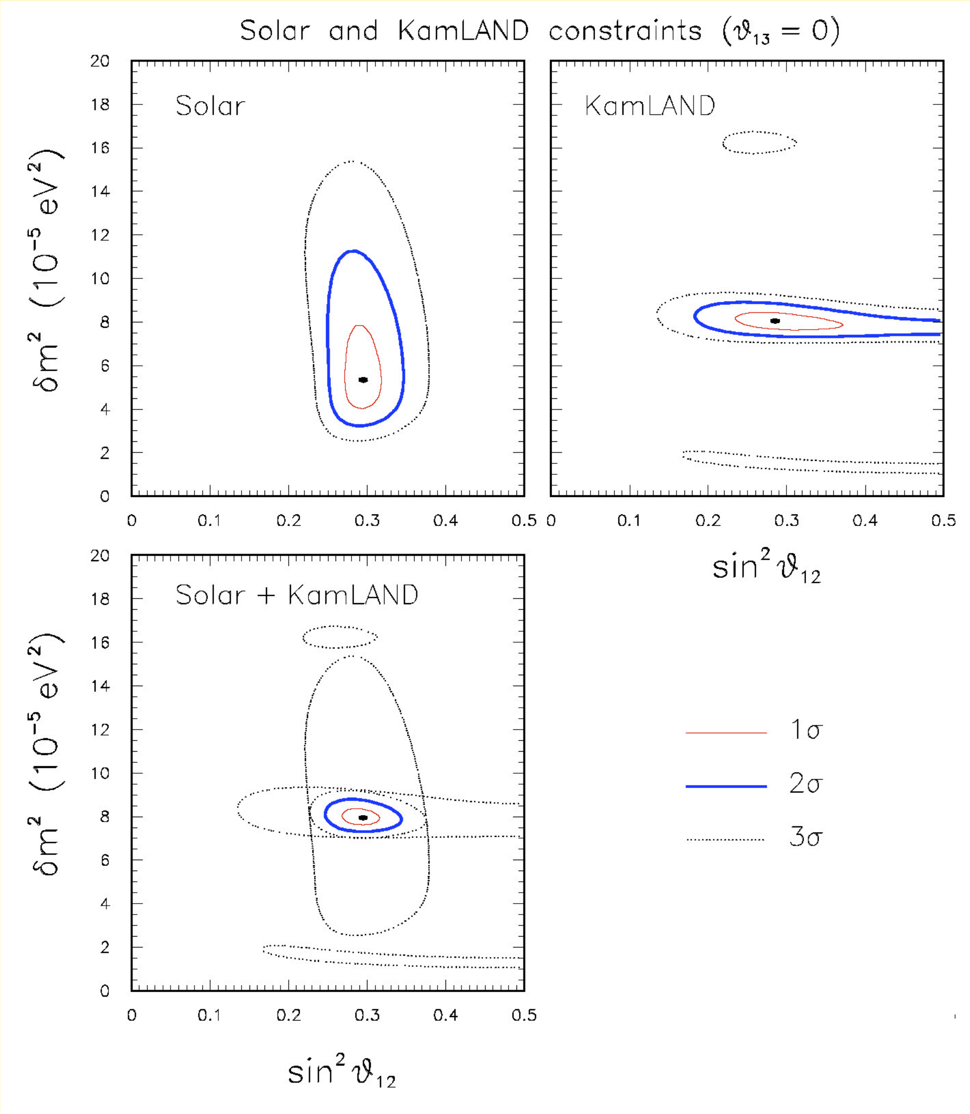
2002: electron flavor disappearance observed



2002: best fit of oscillation parameters



2004: by combining Solar and KamLAND data, only one solution very well identified (Large Mixing Angle solution)



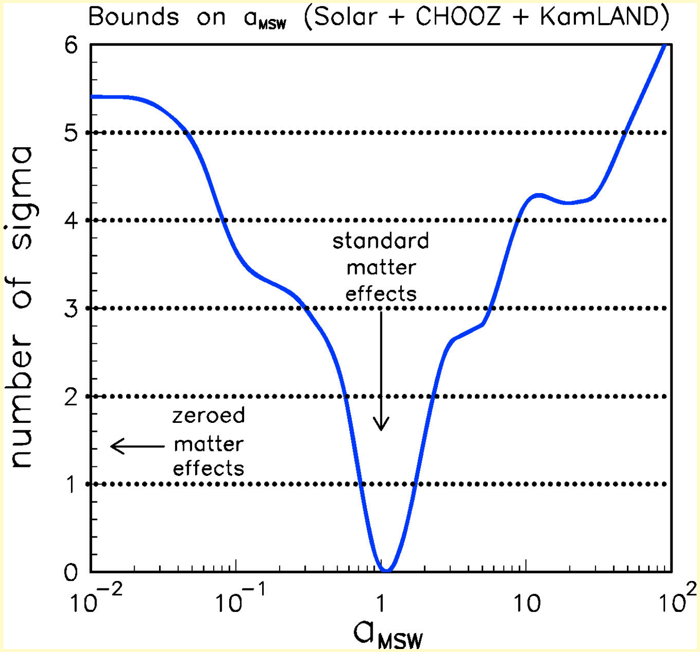
Solar neutrino oscillations have been succesfully reproduced through long baseline reactor oscillations

The "solar neutrino problem" is solved!

What can we say about the MSW effect?

What can we say about the MSW effect?

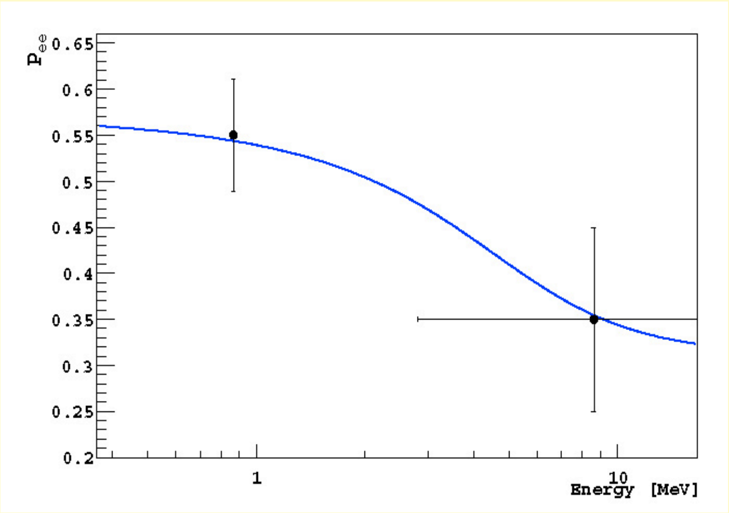
MSW effect (2006)



a_{MSW} free parameter "measuring" MSW effect

GLF, E. Lisi, A. Marrone, A. Palazzo,
Progr. Part. Nucl. Phys. 57 (2006)

MSW (Borexino, 2008)

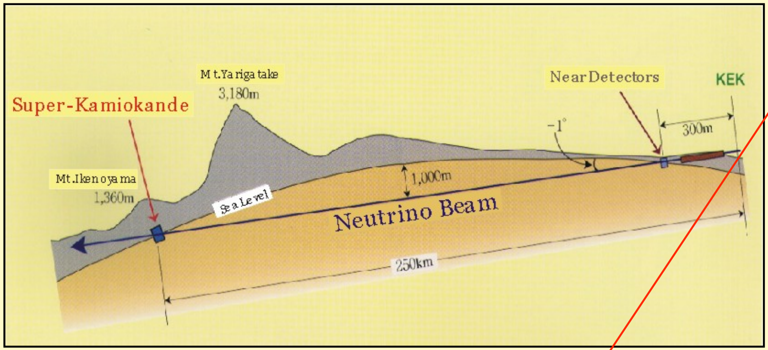


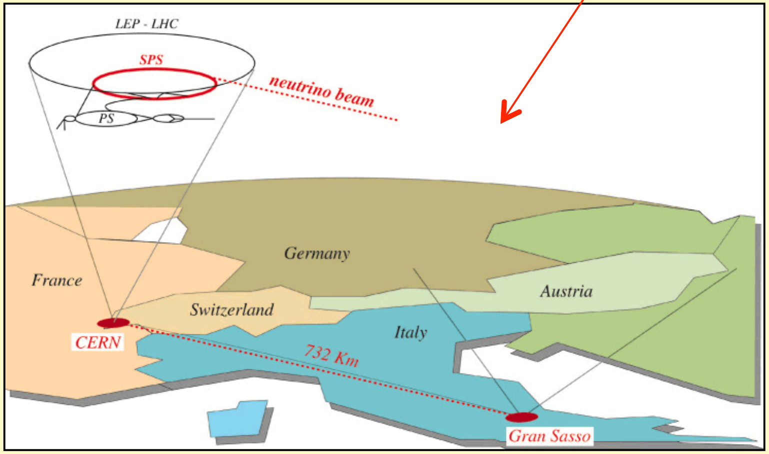
Behavior of P_{ee} (ν_e survival probability) with E_ν

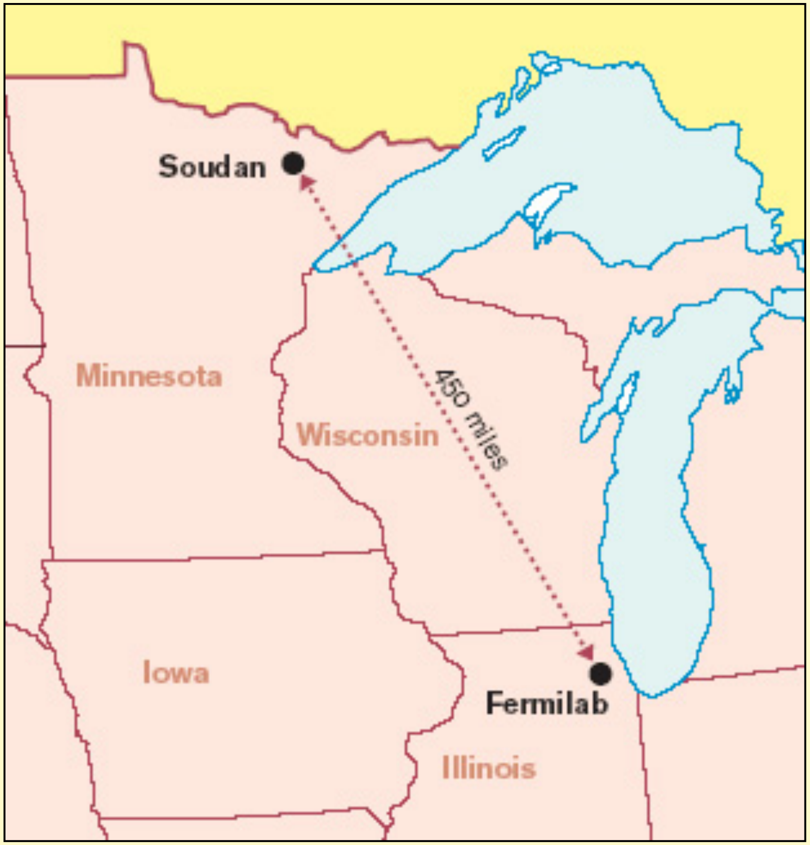
5. Long Baseline Neutrino experiments: aim of reproducing "atmospheric ν oscillations" in Laboratory

Several experiments are projected and realized with the aim of reproducing "atmospheric ν oscillations" in Labs, with a proper choice of neutrino beam **energy** and **baseline**.

K2K **OPERA** **MINOS**



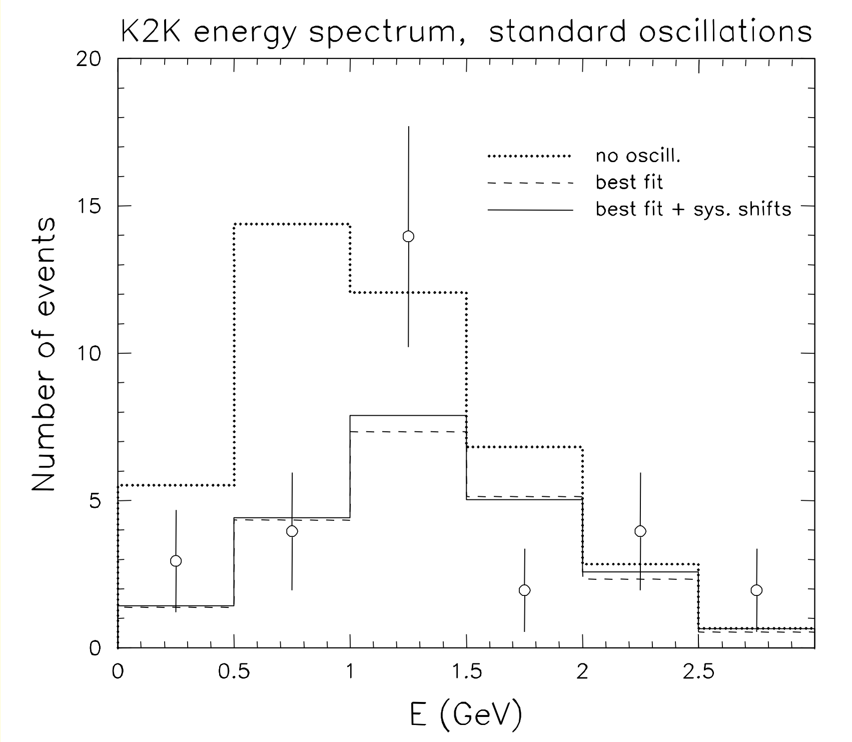


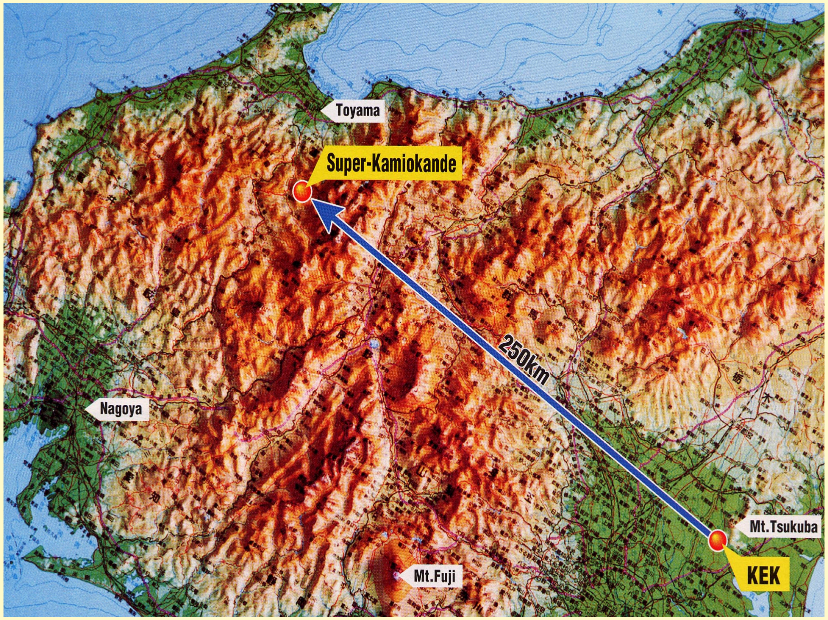


KEK-to-Kamioka (K2K)

Aimed at testing disappearance of accelerator ν_μ in the same range probed by atmospheric ν:

$(L/E)_{K2K} \sim (250 \text{ km}/1.3 \text{ GeV}) \sim (L/E)_{ATM}$

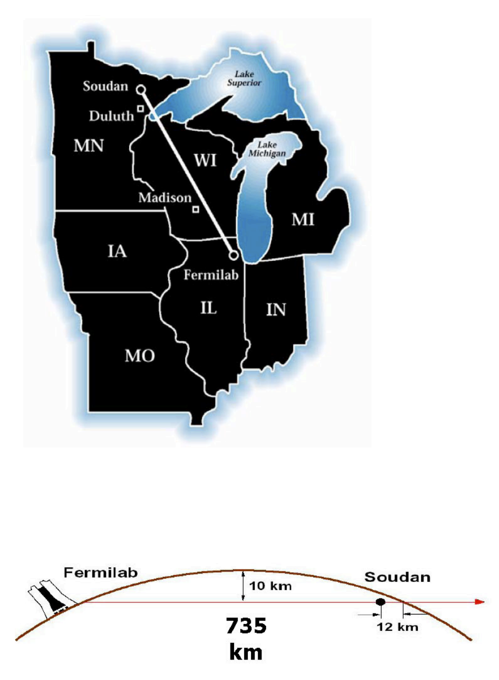


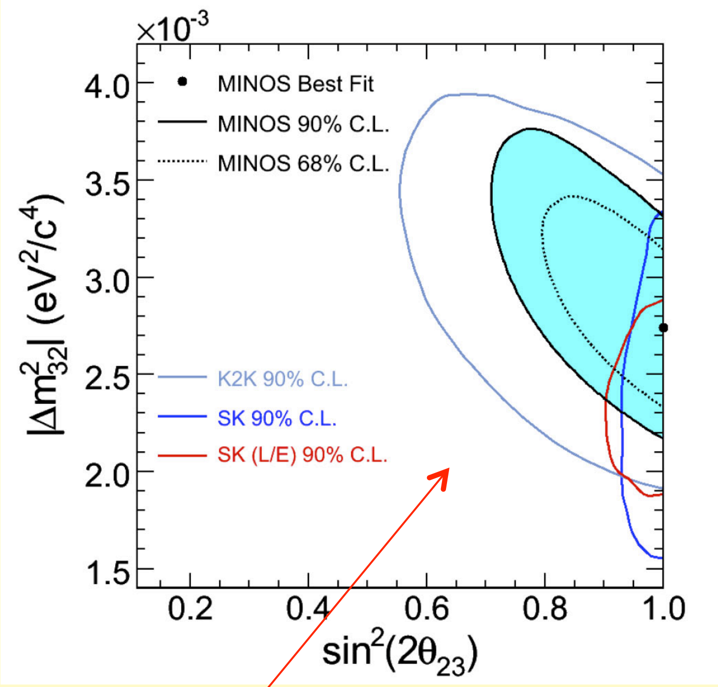


2002: muon disappearance observed at > 99% C.L.

no electron appearance

MINOS (2006)



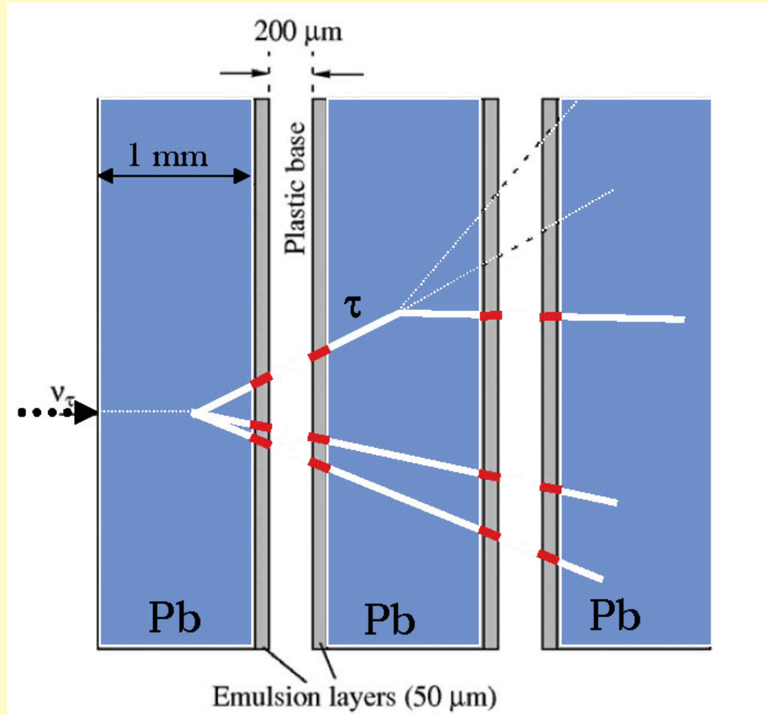


Comparison of K2K and MINOS results
(in muon disappearance mode)
with the SuperKamiokande measurements

OPERA

K2K and MINOS agree about muon flavor disappearance and no electron appearance, but there is still a missing piece …

direct observation of ν_τ **appearance in a ν_μ beam**!



Simulated tau event

Beam, tuned to relatively high E, suppresses oscillations (small L/E) but enhances **tau production**.

First observation of $\nu_\mu \to \nu_\tau$ oscillation in appearance mode. 4 ν_τ candidates found, with 0.23 of background: no-oscillation hypothesis excluded at 4.2 σ.

2007: PMNS mixing after about 40 years of research ...

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Atmospheric" sector	"Interference" sector	"Solar" sector
Large rotation (~ maximal)	Small rotation (maybe null ?)	Large rotation (< maximal)
$\sin^2\theta_{23} \sim 1/2$	**$\sin^2\theta_{13} \sim 0$?**	**$\sin^2\theta_{12} \sim 1/3$**
$\Delta m^2 \sim 3\times10^{-3}$ eV^2		**$\delta m^2 \sim 8\times10^{-5}$ eV^2**

Open questions ...

How can we measure θ_{13}? And δ afterwards?
And finally the hierarchy, i.e. **sign($\pm\Delta m^2$)**?

6. The hunt to θ_{13}, the last mixing angle

Indeed, the hunt to θ_{13} is crucial in neutrino research, in order to plan future CP violation searches!

In 2006 the upper bound still comes from

CHOOZ expt. $\Rightarrow$ **$\sin^2\theta_{13}$ < few %**

But, in the meantime, some weak hints of lower bounds have appeared …

1. From a 3ν analysis of atmospheric data (+ long-baseline accelerator experiments + CHOOZ) by considering **subleading "solar term" effects**.

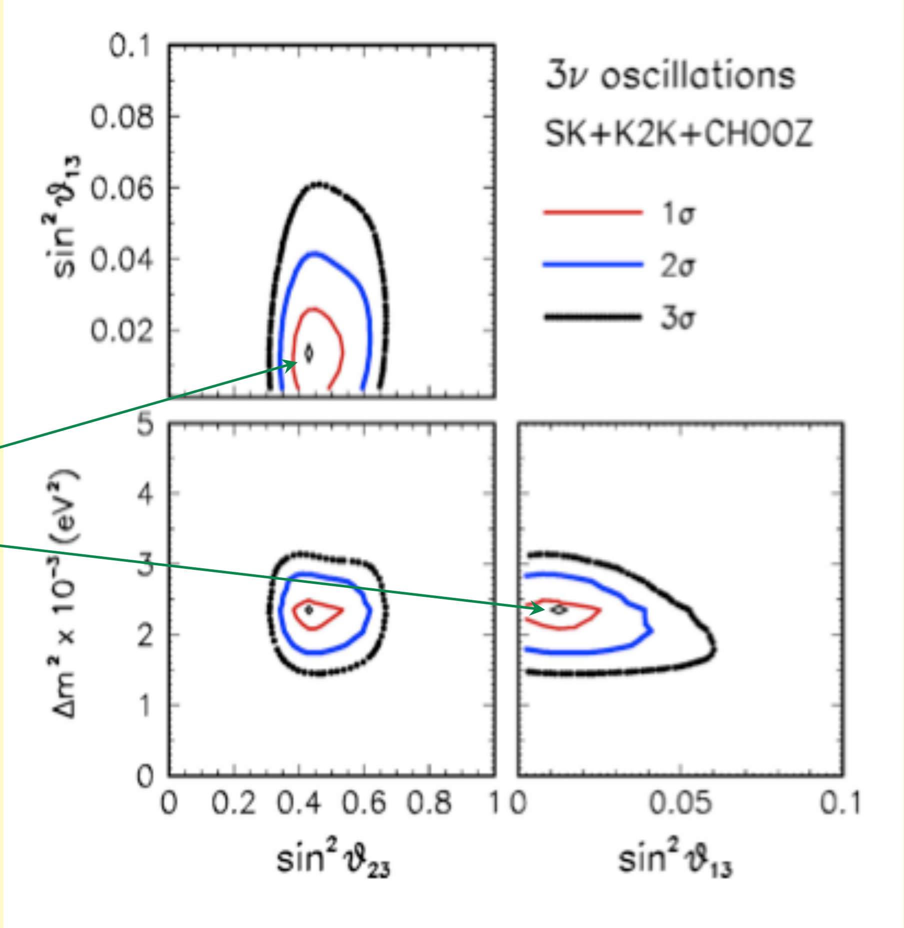
2. From an accurate comparison within a 3ν approach of **solar** (SNO dominated) and **KamLAND** data.

1 An old (but persisting) hint for $\theta_{13} > 0$ comes from the 3ν analysis of atmospheric + LBL + Chooz data …

[GLF, Lisi, Marrone, Palazzo, Progr. Part. Nucl. Phys. 57, 742 (2006)]

… mainly due to subleading "solar term" effects which help fitting atmospheric electron event data (especially sub-GeV).

best fit ~ 1 sigma away from zero

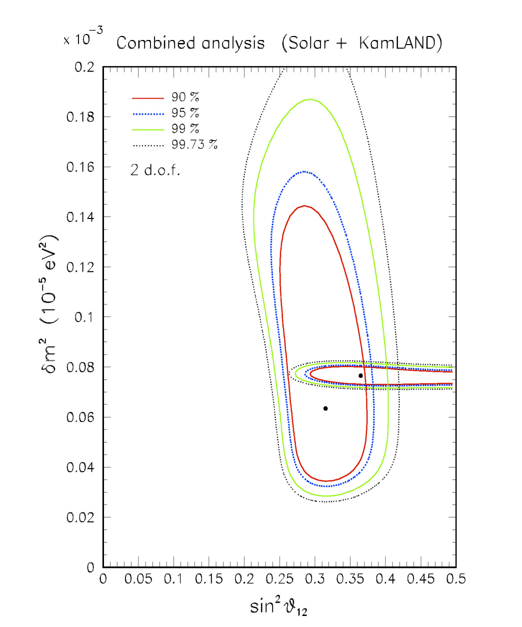


(2) Slight disagreement between

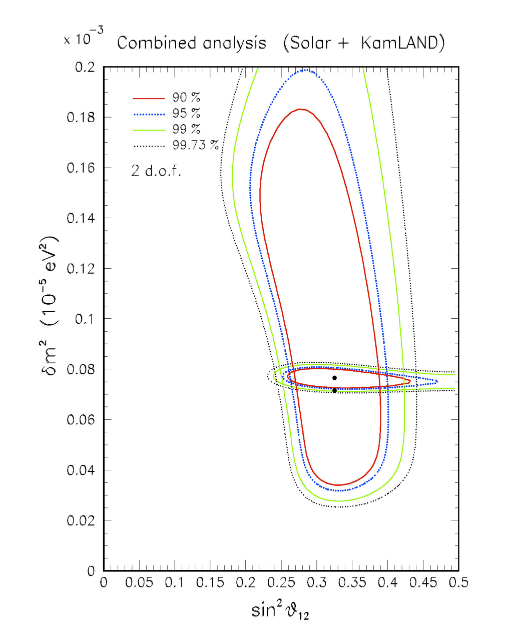
- Solar data (SNO dominated)
- KamLAND data (at $\sin^2\theta_{13} = 0$)

Disagreement reduced if $\sin^2\theta_{13} > 0$ is assumed …

… thanks to the different **correlation** between θ_{12} and θ_{13} in KamLAND and SNO data.



$\sin^2\theta_{13} = 0$

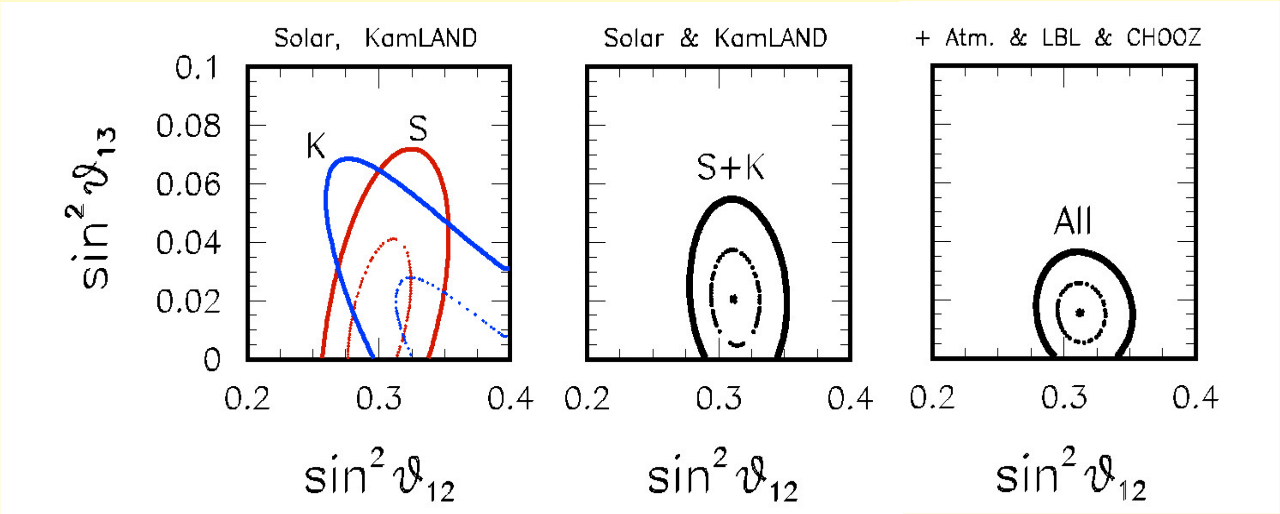


$\sin^2\theta_{13} = 0.03$

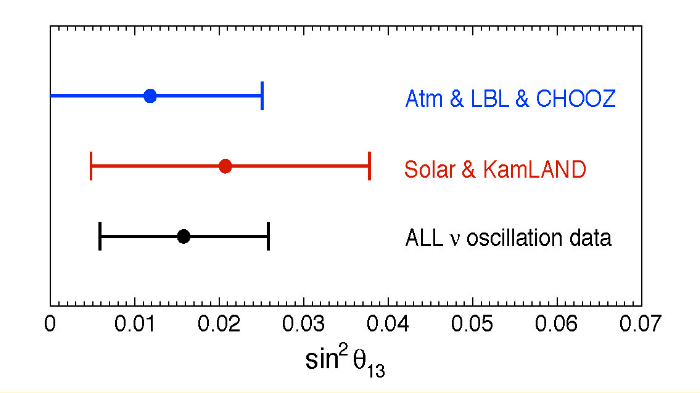
[Effect presented at the conference NO-VE 2008]

[Seen independently by Balantekin & Yilmaz, J.Phys. G 35 (2008)]

Taken together, the two hints (solar+KamLAND, and atmospheric+CHOOZ+LBL), provide a possible indication in favor of $\theta_{13} > 0$ at the level of ~ 1.6 sigma = 90% CL: not so bad!



By combining all data together …



$\sin^2\theta_{13} = 0.016 \pm 0.010$ (all data)

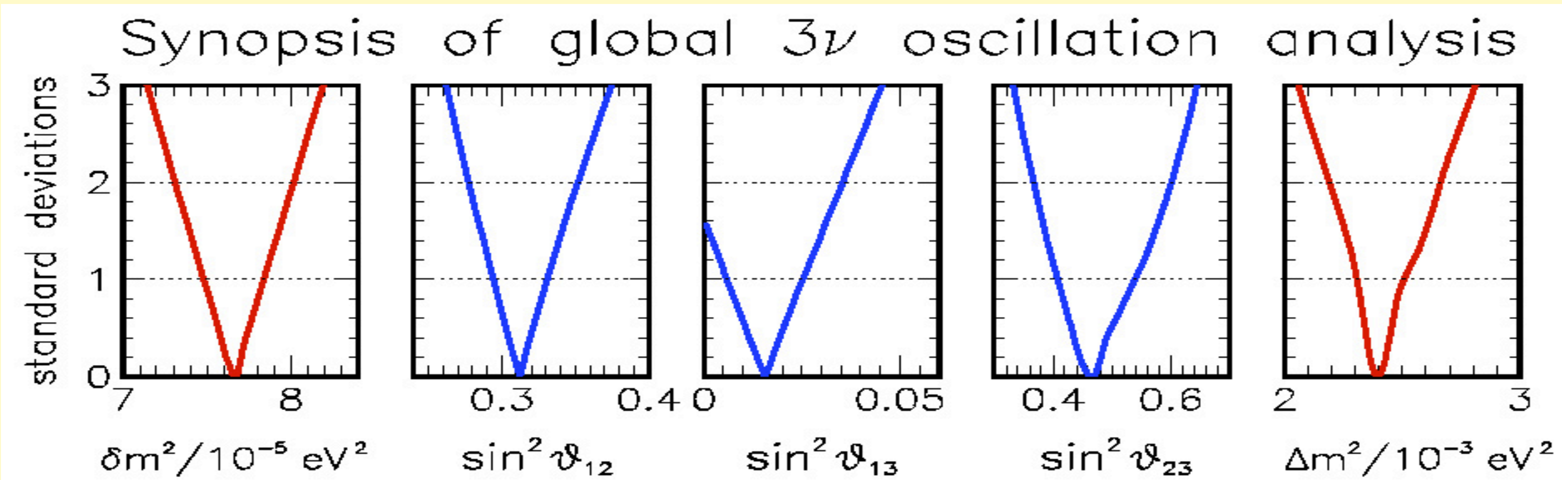
GLF, Lisi, Marrone, Palazzo, Rotunno
PRL 101, 141801 (2008) arXiv:hep-ph/0806.2649

Global analysis of mass-mixing parameters, 2008

PHYSICAL REVIEW D **78**, 033010 (2008)

Observables sensitive to absolute neutrino masses. II

G. L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] A. Melchiorri,[3] A. Palazzo,[4] A. M. Rotunno,[1,2] P. Serra,[5] J. Silk,[6] and A. Slosar[7]



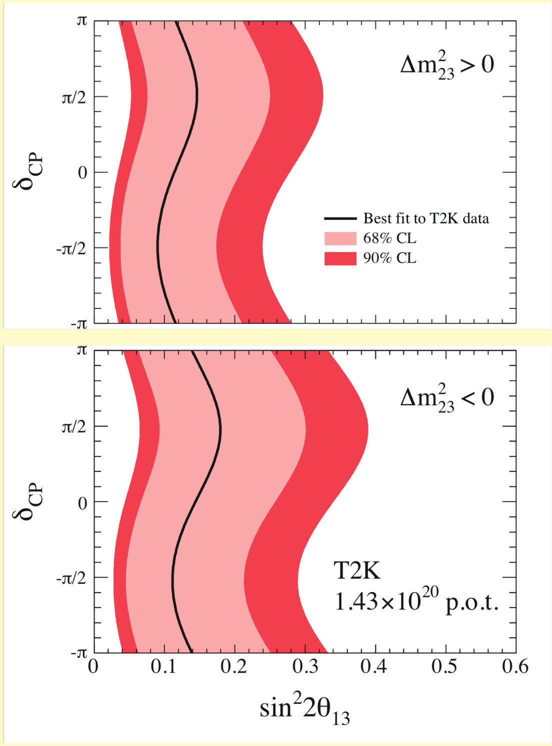
This in 2008. What happened next?

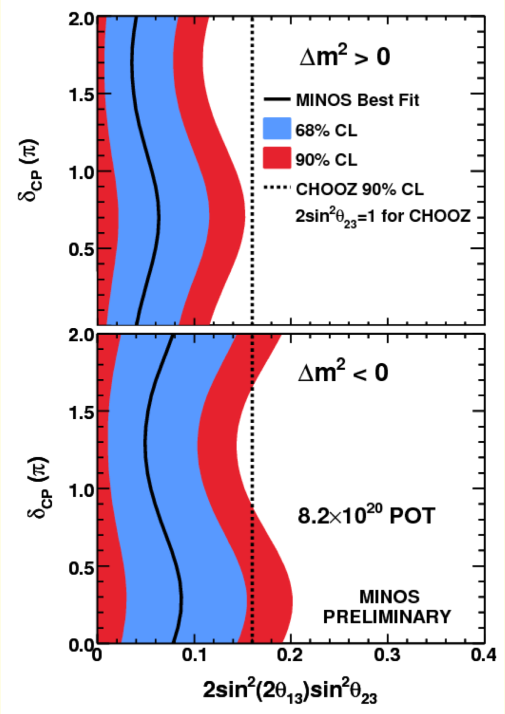
[Note that the θ_{13} hints have been debated at length, and have reached but not exceeded the statistical level of about 2σ]

Once again, new experimental results come to rescue! In 2011, **T2K** and **MINOS** found some electron event excess when running in appearance mode …

$\nu_\mu \rightarrow \nu_e$ oscillations, sensitive to θ_{13}

T2K



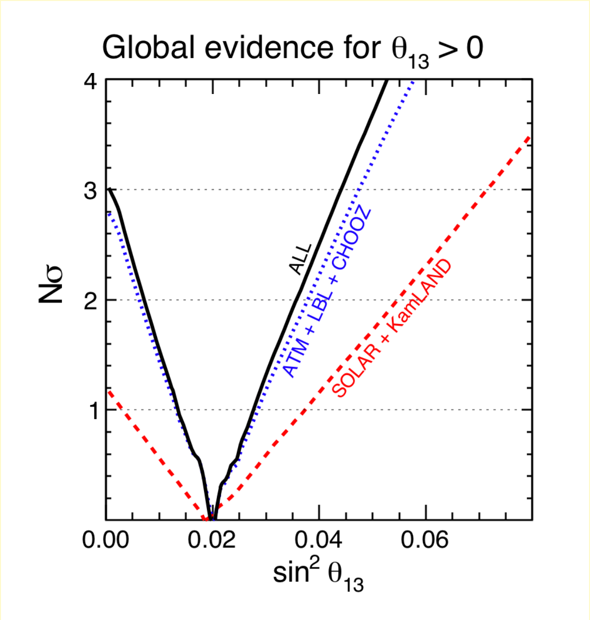


MINOS

Both experiments favor $\sin^2\theta_{13} \sim$ few % ! It makes sense to combine these with all the other oscillation data …

2011 Global results for $\sin^2\theta_{13}$, before the arrival of SBL reactors data

G.L.F., Lisi, Marrone, Palazzo Rotunno "Evidence of $\theta_{13}>0$ from global neutrino data analysis"
Phys. Rev. D84 (2011) 053007 [arXiv:1106.6028[hep-ph]]



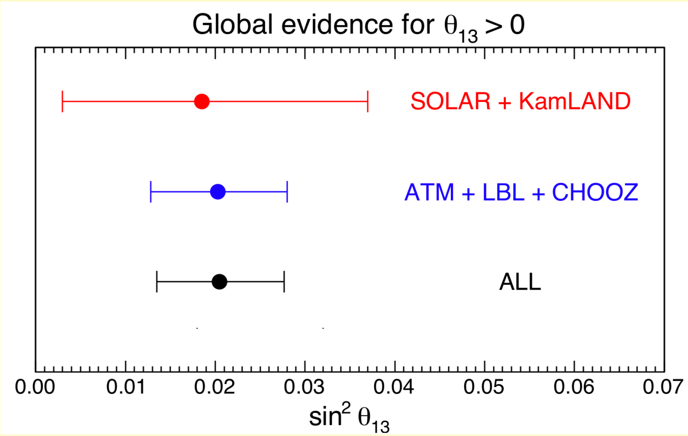
Note:

ATM+LBL+CHOOZ
now more significant that
Solar+KamLAND

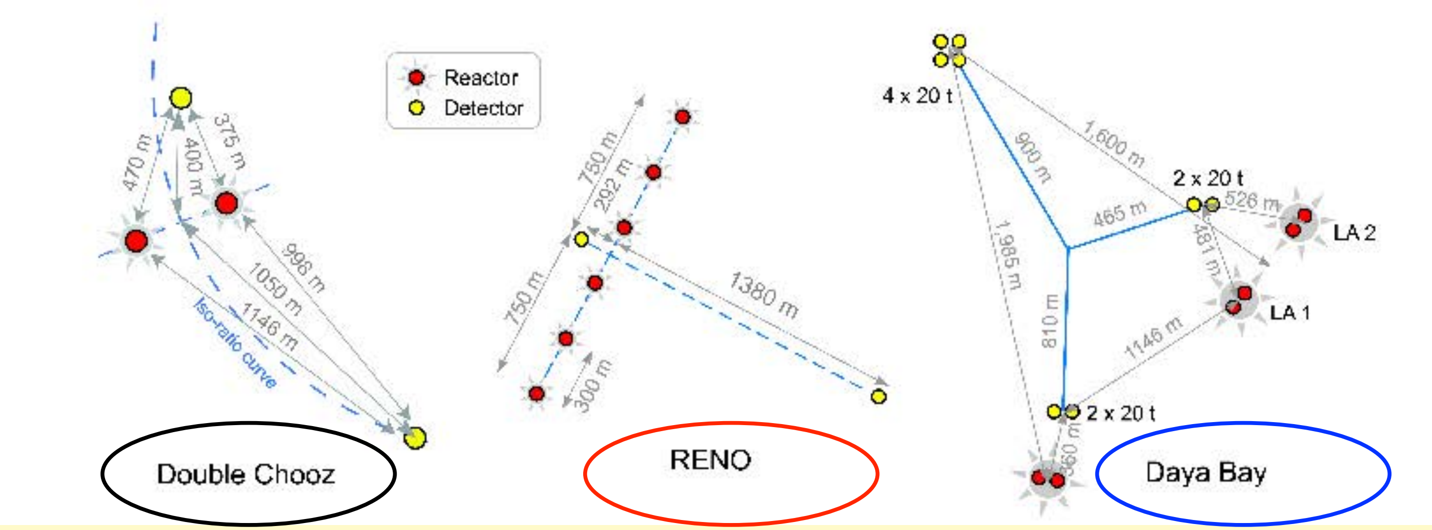
Astonishing conspiracy of
the two totally independent
sets of data

$\sin^2\theta_{13}=0.021\pm0.007$

Evidence for $\sin^2\theta_{13}>0$ at ~3σ !



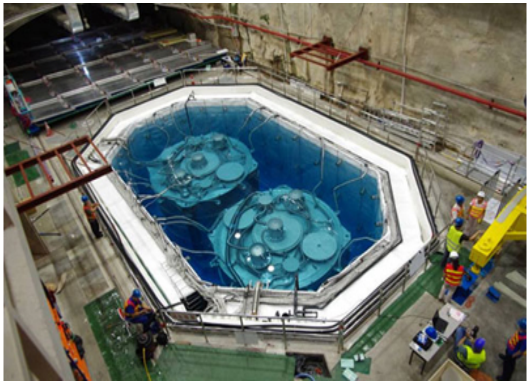
7. The Short Baseline Reactor experiments



Running with FD;
ND in construction

Running with
ND & FD

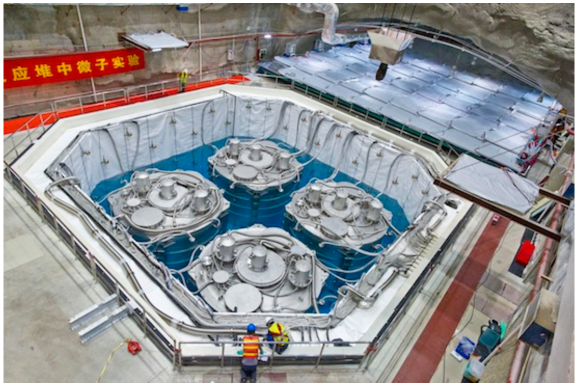
Running with
ND & FD



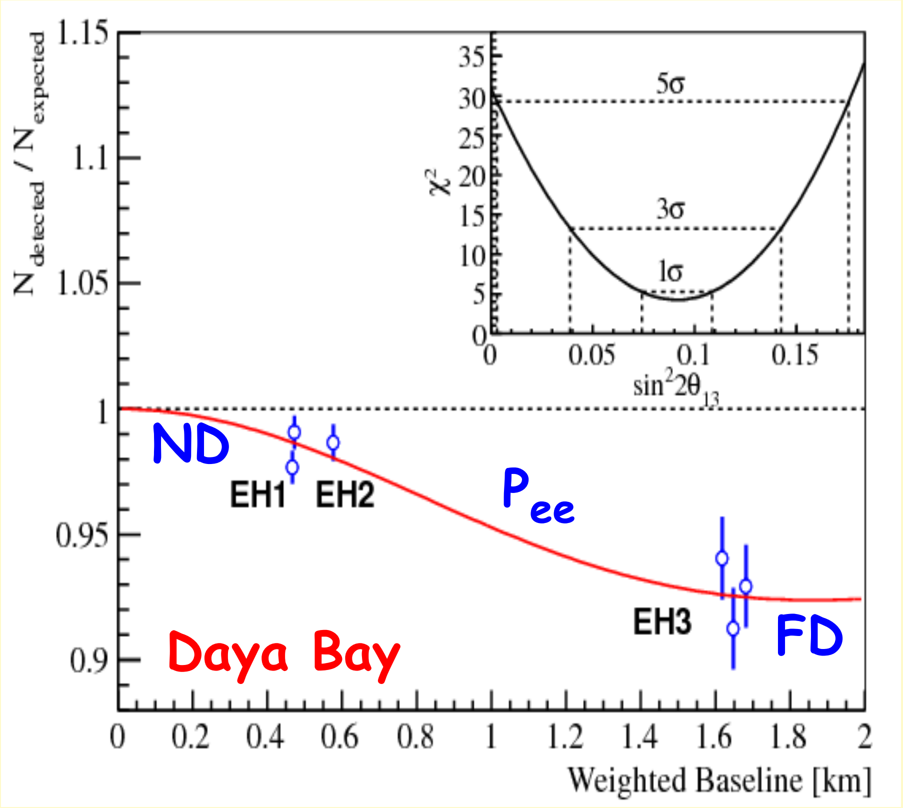
E.g, for
Daya Bay:

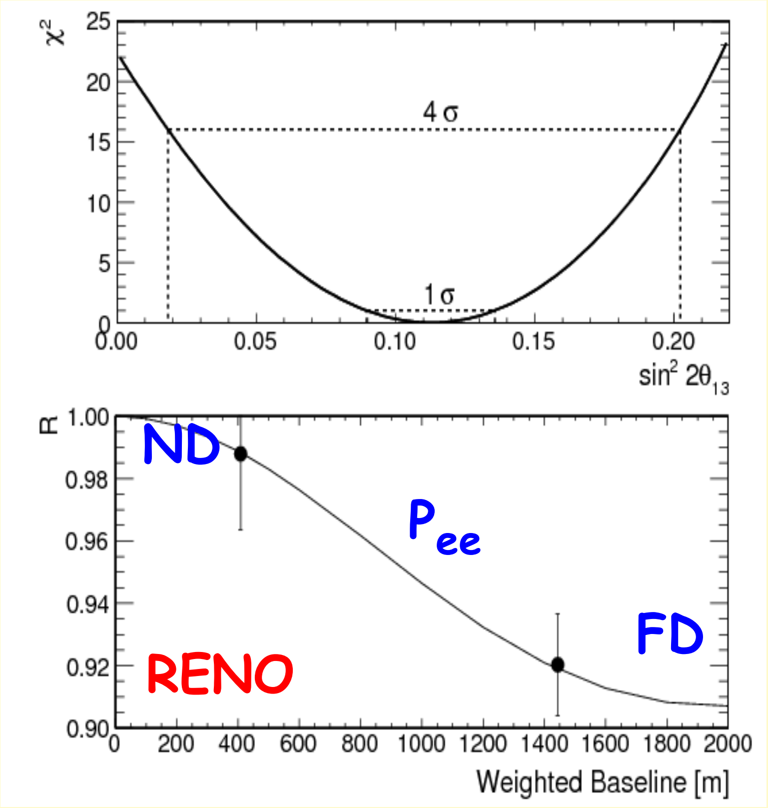
← ND

FD →



2012: experimental discovery of $\theta_{13}>0$! (value obtained at ~ fixed Δm^2)

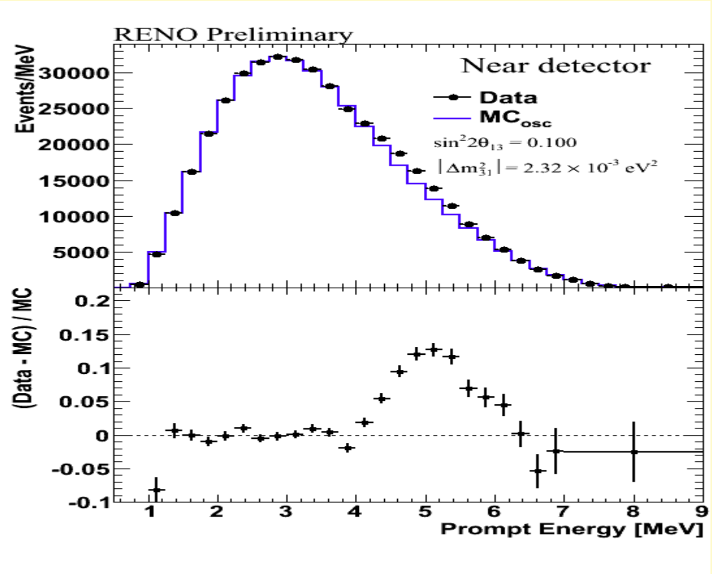




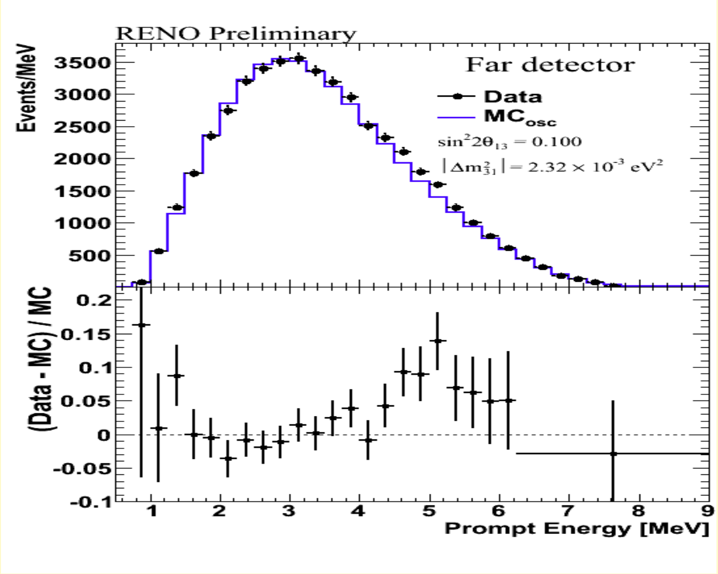
Clear disappearance at FD with respect to ~ unoscillated signal at ND. Double Chooz results (FD only) also consistent with Daya Bay & RENO.

Impressive improvement of the SBR data: spectra at ν 2014

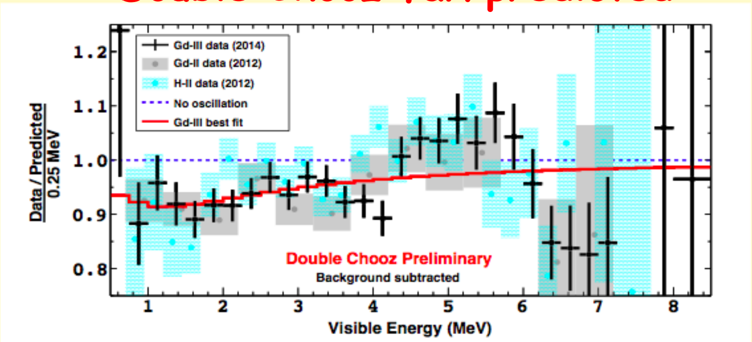
RENO near



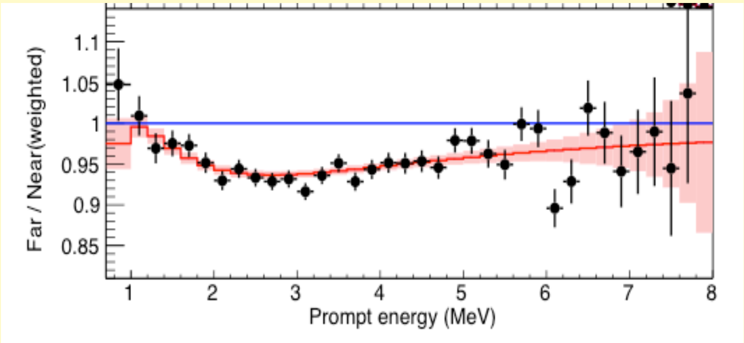
RENO far



Double Chooz far/predicted



Daya Bay far/near



The Present (a global analysis of neutrino oscillations data)(*)

1. The data set
2. A note about methodology
3. The global analysis
4. From variances to covariances: 2D plots

(*) F. Capozzi, G.L.F., E. Lisi, A. Marrone, D. Montanino, A. Palazzo, "Status of three-neutrino oscillation parameters, circa 2013", Phys. Rev. D 89, 093018 (2014) , [arXiv:1312.2878]

1. The data set

- Oscillation parameters are extracted with their correlations from solar, atmospheric, accelerator and reactor neutrino data.

- Data set:

LBL Accelerators	→	K2K + T2K + MINOS
Solar	→	Homestake, Gallex/GNO, SAGE, SK, SNO, Borexino
KamLAND	→	KamLAND reactor data
SBL Reactors	→	Double Chooz + RENO + Daya Bay
SK Atm	→	Super-Kamiokande Atmospheric data

- In particular they include neutrino appearance and disappearance data published in 2013 and at the beginning of 2014 from **T2K** and **MINOS,** together with the data of **SBL reactors** presented at Neutrino '14 in Boston.

- Full 3ν probabilities included, no approximation.

2. A note about Methodology

- **LBL Accelerator** data are dominantly sensitive to (Δm^2, θ_{23}, θ_{13}). But accurate constraints on these parameters do need (δm^2, θ_{12}) coming from **Solar + KL** in order to include and compute sub-dominant effects.

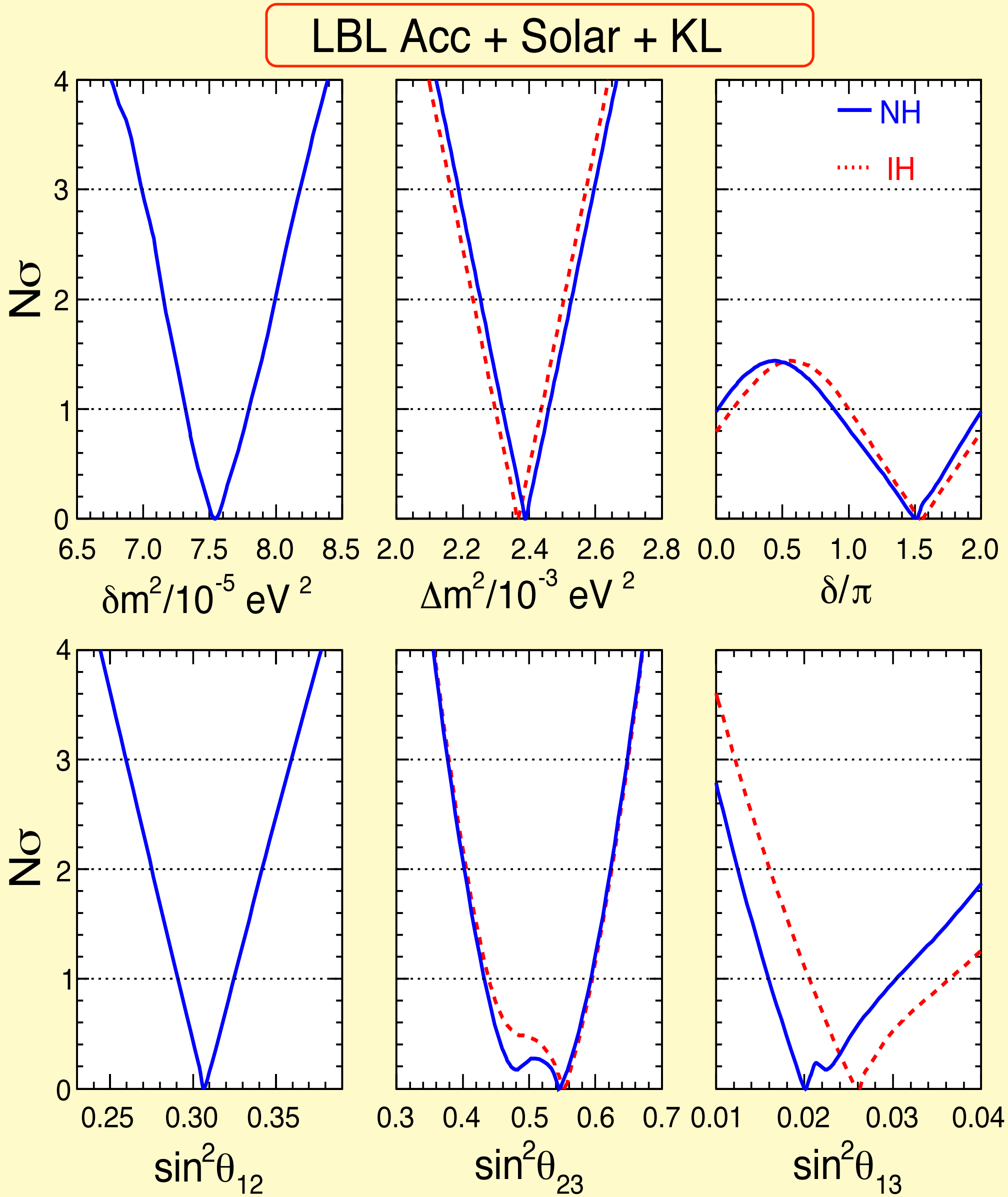
- Then, we combine first **LBL accelerator** data with **solar+KamLAND** data, since the latter provide the "solar parameters" needed to calculate the full 3ν LBL probabilities in matter. So, analysis includes increasingly rich data sets:

LBL Acc + Solar + KL

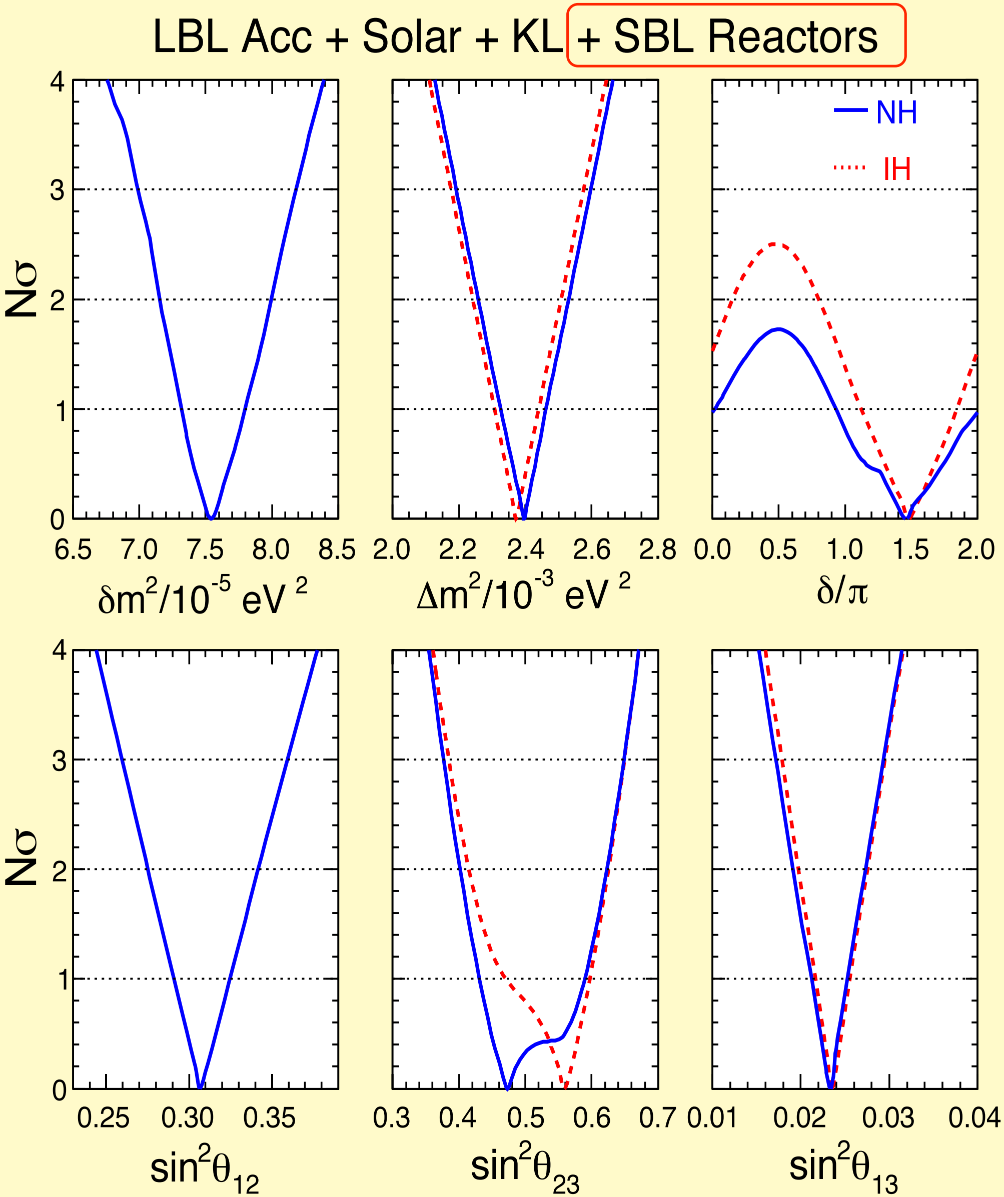
LBL Acc + Solar + KL + SBL Reactor

LBL Acc + Solar + KL + SBL Reactor + SK Atm.

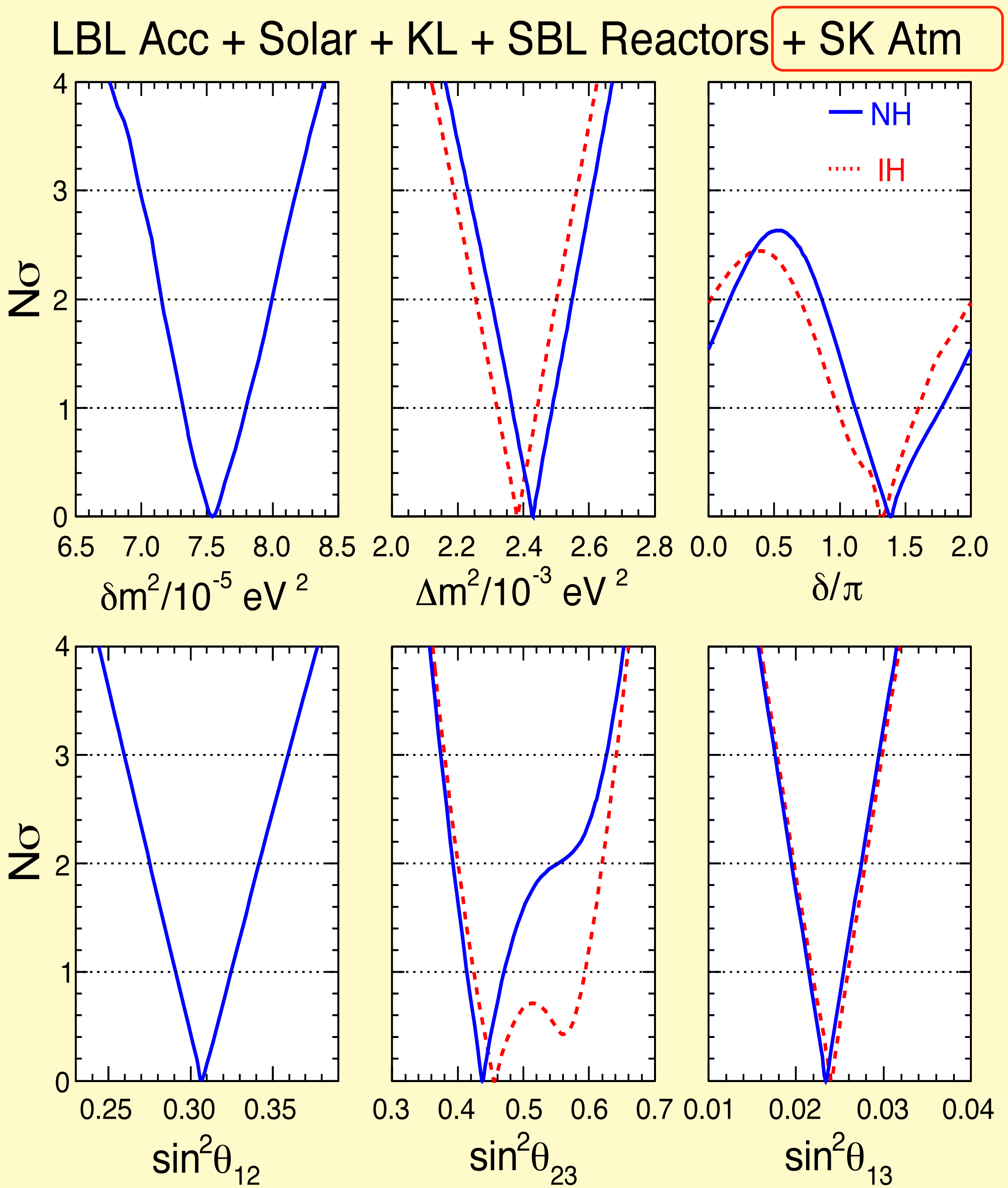
3. The global analysis



- Upper and lower bounds on all oscillations parameters but δ
- Slight preference for $\delta \sim 1.5\,\pi$
- Slight preference for θ_{23} non-maximal in the 2nd octant



- Strong θ_{13} bounds
- Still a preference for $\delta \sim 1.4\text{-}1.5\,\pi$
- Still a preference for non-maximal θ_{23} but octant flips with hierarchy



- Some effects on the $\nu_\mu \rightarrow \nu_\tau$ dominant parameters (Δm^2, θ_{23})
- Preference for $\delta \sim 1.4\,\pi$
- Preference for non-maximal θ_{23} and 1st octant in NH, much weaker in IH: somewhat fragile

Let us appreciate the improvement obtained by adding the new sets of data!

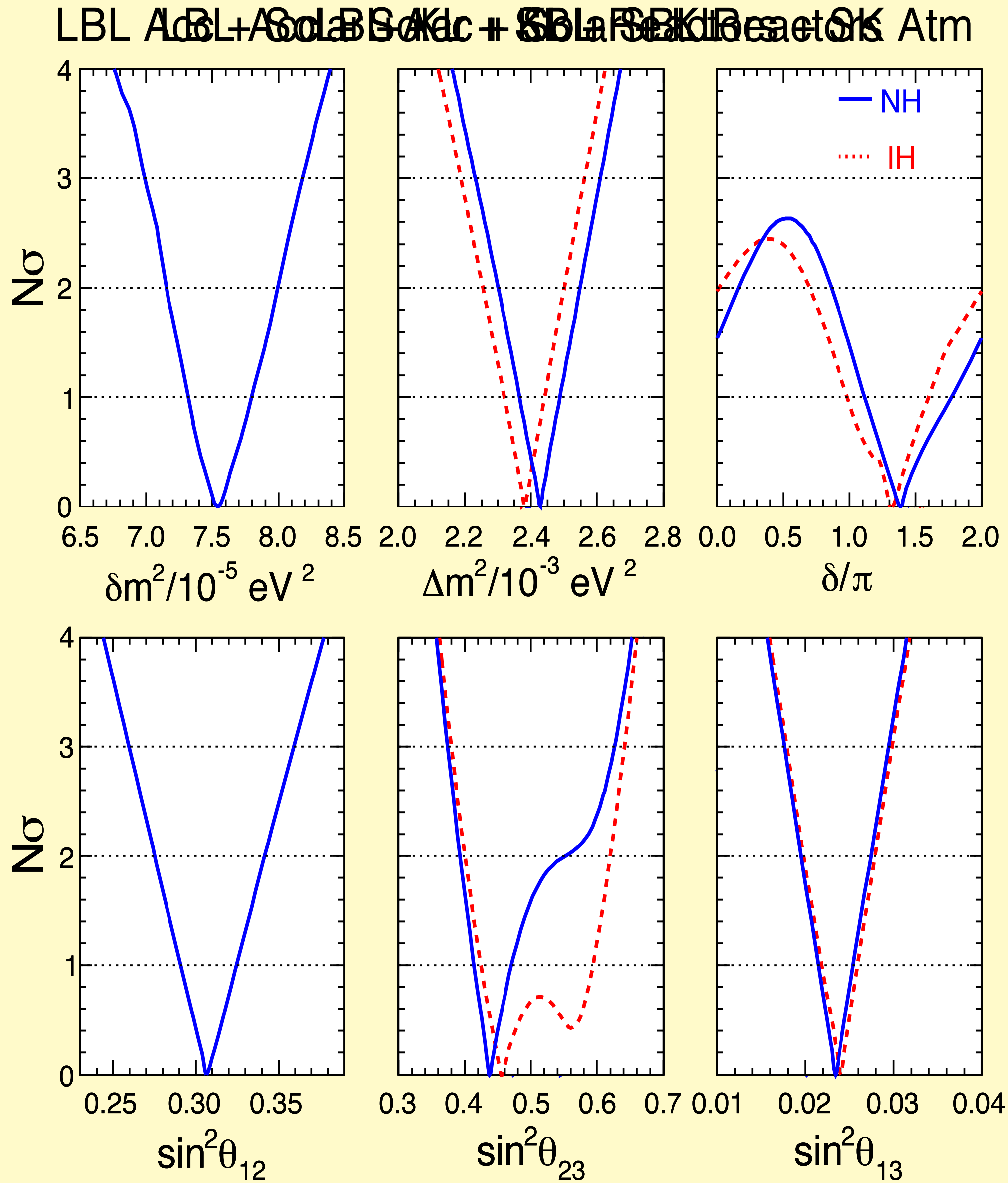
LBL Acc. + Solar + KamLAND

+

SBL reactors

+

SK atmospheric



Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.54	0.307	0.014	0.42	2.36
1σ range	7.32 – 7.79	0.291 – 0.325	0.006 – 0.023	0.38 – 0.51	2.26 – 2.48
2σ range	7.14 – 7.99	0.275 – 0.342	< 0.033	0.36 – 0.59	2.17 – 2.57
3σ range	6.98 – 8.17	0.259 – 0.360	< 0.042	0.33 – 0.64	2.07 – 2.67

Fractional 1σ accuracy [defined as 1/6 of $\pm 3\sigma$ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	~ 0.008	~12%	4.2%

Moreover …

- No significant hierarchy preference from the global fit [$\Delta\chi^2$(I-N) = -0.3]
- Weak preference for the 1st octant (more fragile after T2K 2014 data).
- Intriguing hint of nonzero CP violation, with $\sin\delta < 0$ …

  [Similar CP hint: Gonzalez-Garcia, Maltoni, Schwetz, Salvado 2013/14; SK, T2K official data analyses 2013/14]

About ~~CP~~ …

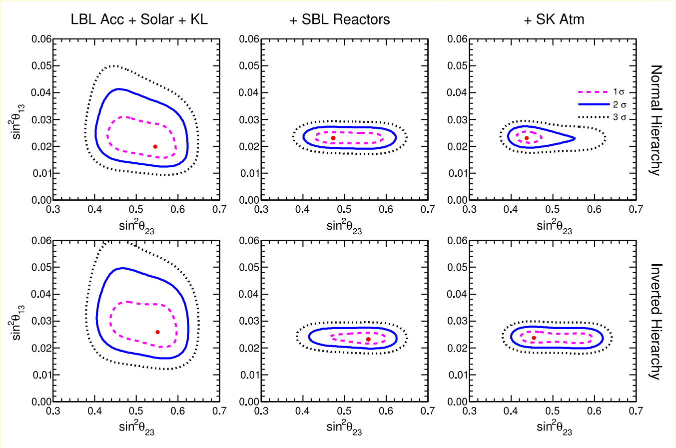
CP violation requires genuine 3ν oscillations, in particular …

- the 3 mixing angles should be nonvanishing ✔
- the 2 mass gaps should be nonvanishing ✔
- the Dirac phase should be nonvanishing …

It seems that also this last condition is realized !

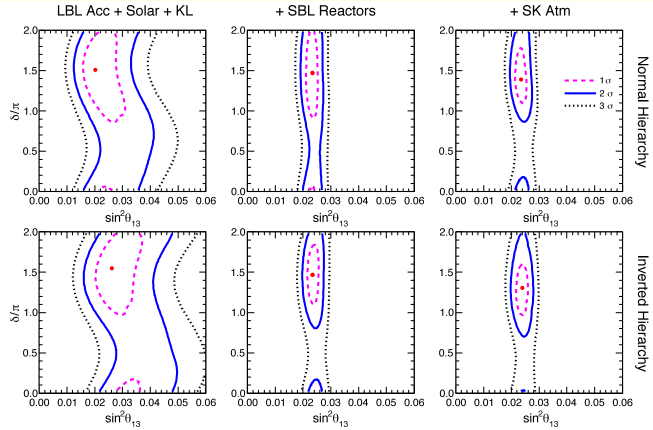
From variances to covariances: 2D plots

$\sin^2\theta_{13}$



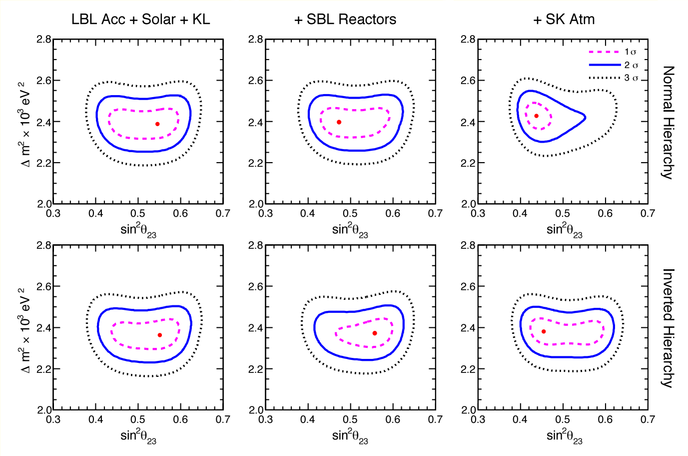
$\sin^2\theta_{23}$

δ/π



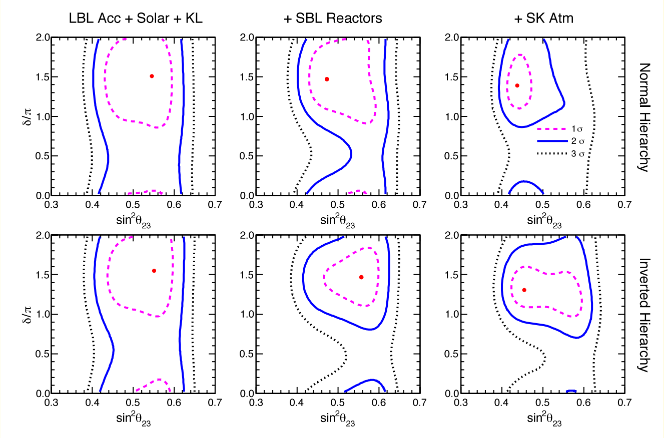
$\sin^2\theta_{13}$

Δm^2



$\sin^2\theta_{23}$

δ/π



$\sin^2\theta_{23}$

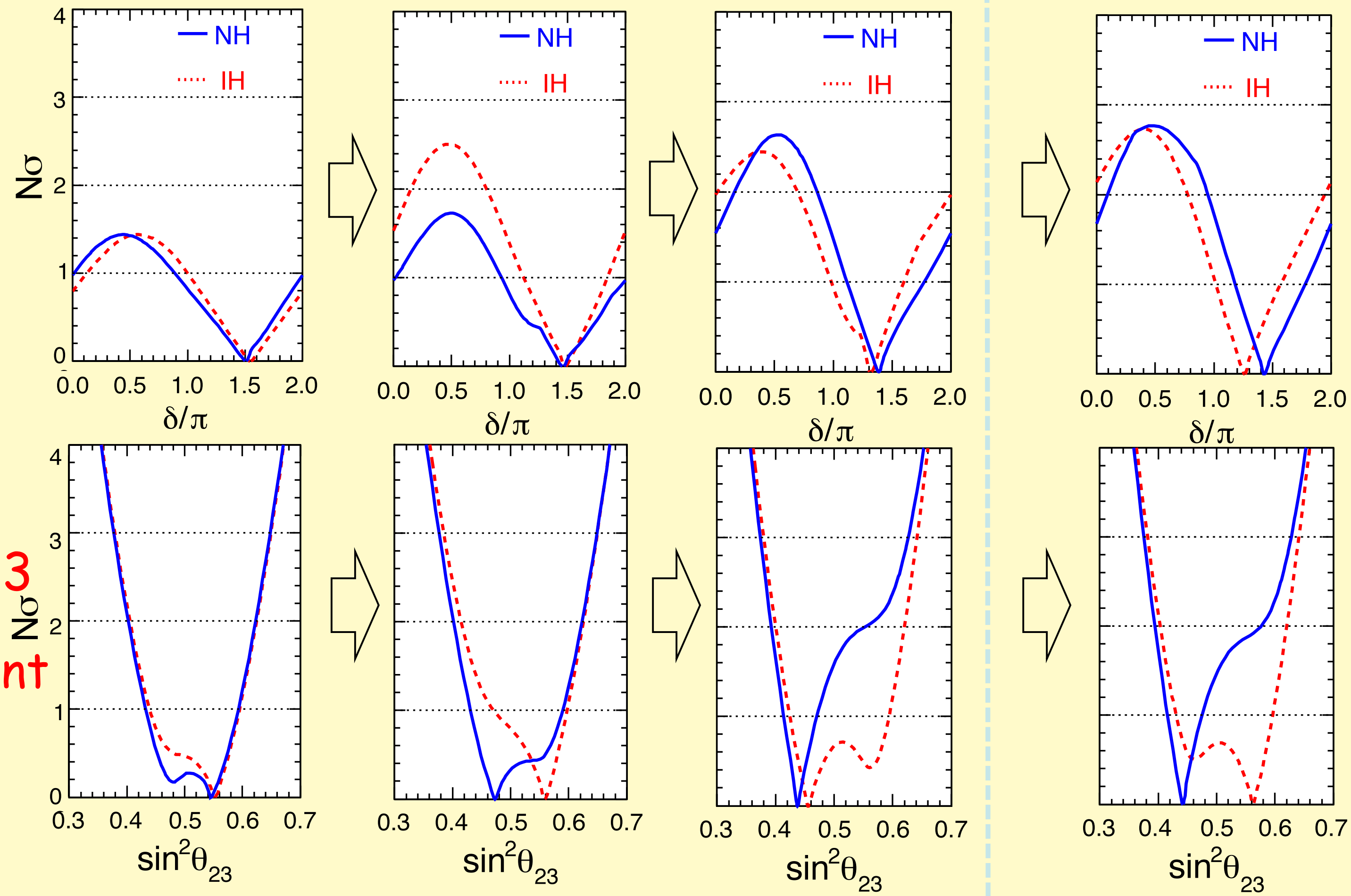
Recap on δ, θ_{23}, $\Delta\chi^2$(IH-NH)

pre-ν2014 | post-ν2014

LBL+Sol+KL → +SBL Reac → +SK atm → +Daya Bay '14

δ

θ_{23} octant



intriguing, $\sin\delta < 0$ favored

unstable, fragile

$\Delta\chi^2$ (IH-NH): -1.4 → -1.1 → -0.3 → -0.1

irrelevant

The Future (expectations about neutrino oscillation parameters)

1. θ_{13}
2. θ_{23} octant
3. δ_{CP}
4. The neutrino mass hierarchy: sign(Δm^2)

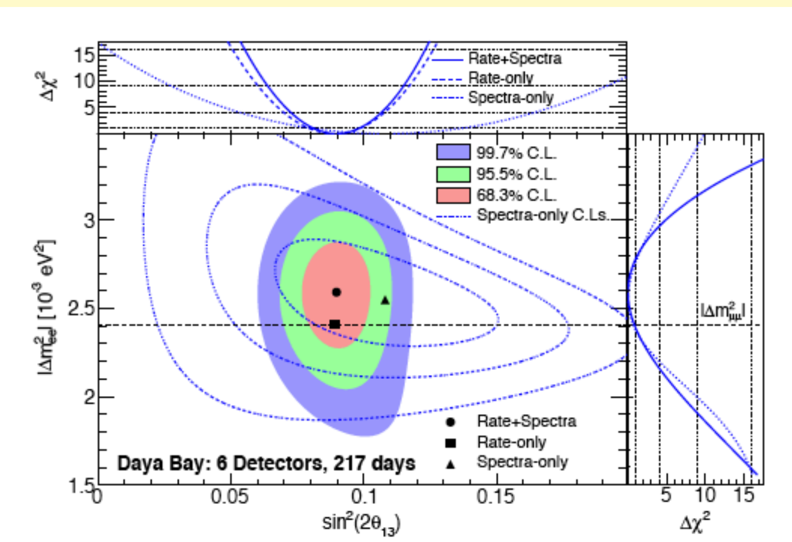
1. θ_{13}

Already well measured, but important to improve its estimate, since the measurements of the phase δ_{CP} and the mass hierarchy **sign(Δm^2)** are strongly sensitive to the precise determination of θ_{13}.

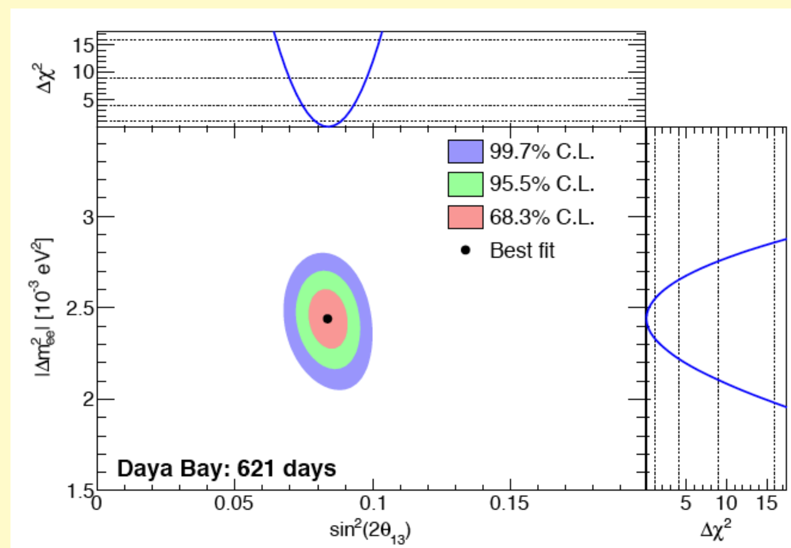
The estimate of **Daya Bay** has been recently improved. After **621** days of data taking

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

with an impressive improvement in the last year:



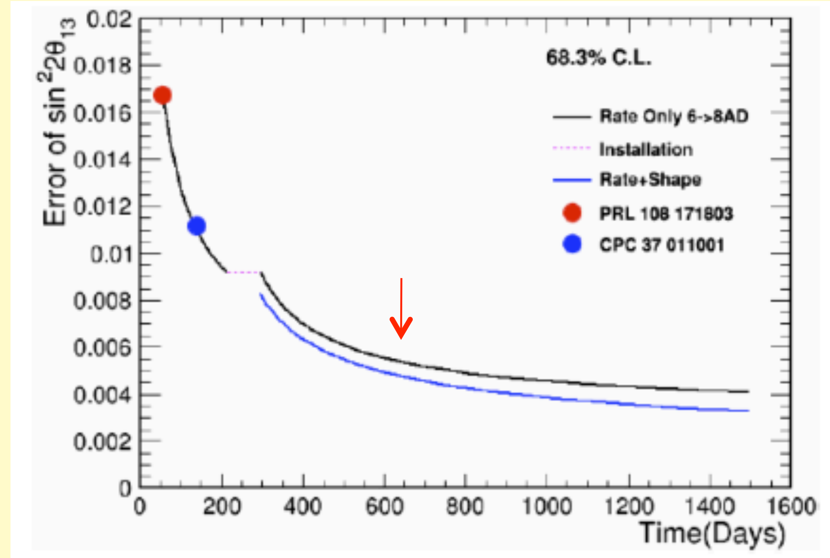
Daya Bay Collab., ArXiv: 1310.6732v2[hep-ex]



Chao Zhang for Daya Bay Coll., ArXiv: 1501.0499v1[hep-ex]

However, total uncertainty is still dominated by statistics. So, the measurement can be further improved.

Prospects for precision measurements of $\sin^2 2\theta_{13}$ with reactor antineutrinos at Daya Bay.

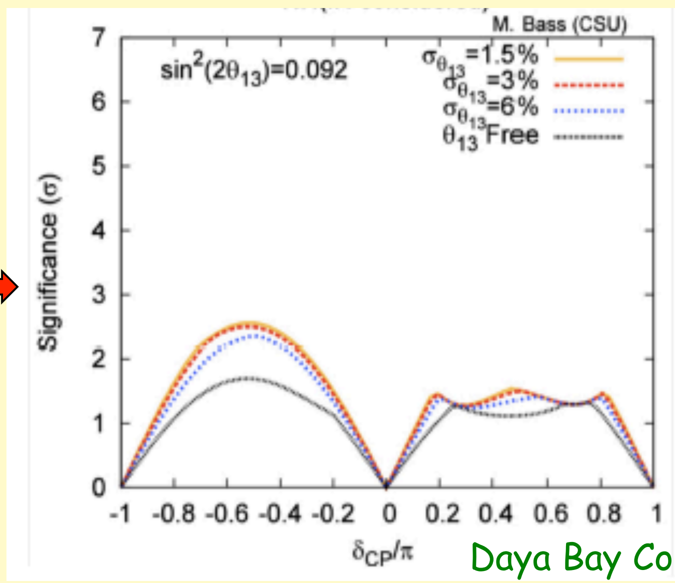


Daya Bay Collab. ArXiv: 1309.7961v1[hep-ex]

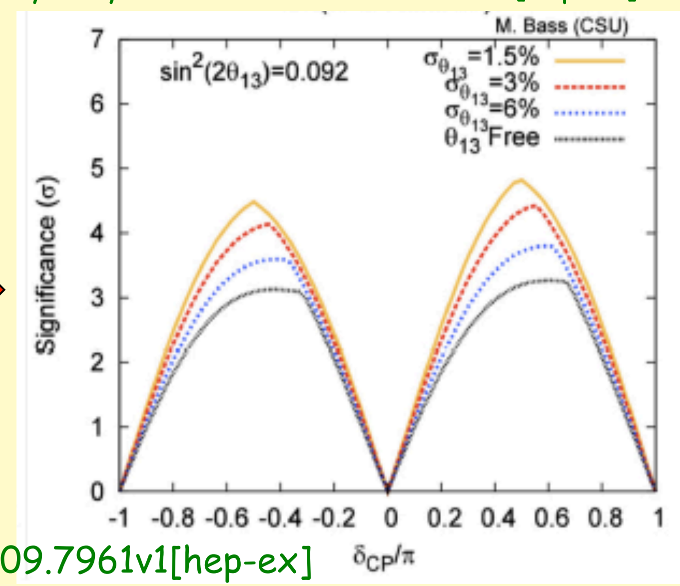
Accordingly, the **total uncertainty** can be reduced to **0.003** in 2 or 3 years.

With this uncertainty, it is evaluated the **significance** with which δ_{CP} can be observed by

NOvA + T2K



NOvA + T2K + LBNE



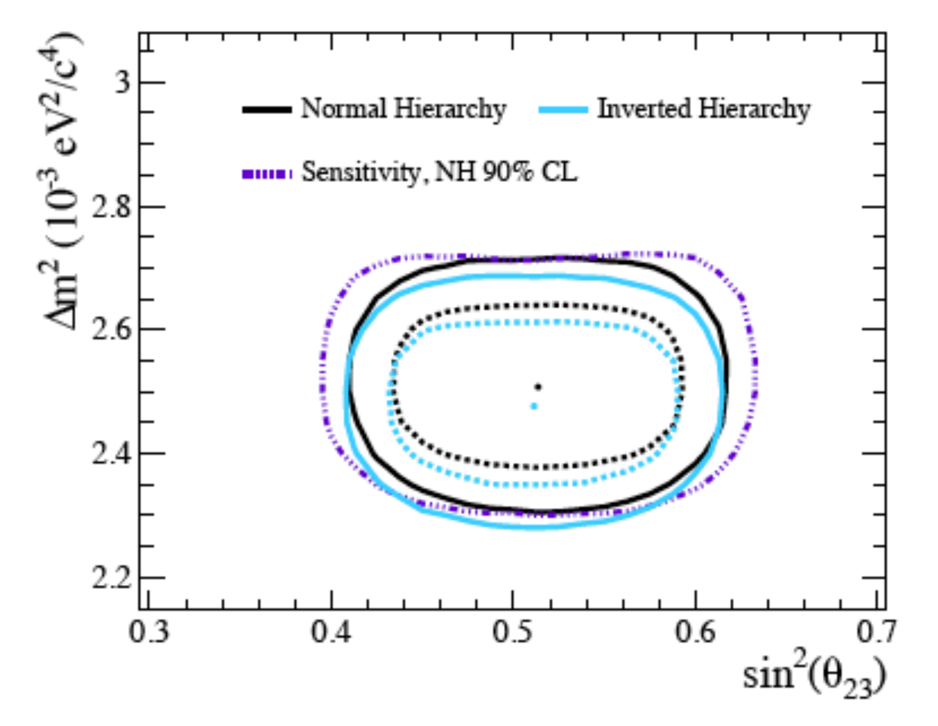
Daya Bay Collab. ArXiv: 1309.7961v1[hep-ex]

2. θ_{23} and its octant

From the ν_μ disappearance at LBL accelerators one can estimate Δm^2 and $\sin^2\theta_{23}$, using $\sin^2\theta_{13}$ measured at reactors (and then independent of δ_{CP}).

T2K Collaboration [arXiv: 1502.01550v1[hep-ex]]

The most recent measurement has been presented by T2K a few days ago.



68% and 90% C.L. regions of Δm^2 vs. $\sin^2\theta_{23}$, for NH and IH.

Note that these regions are smaller than the expected sensitivity. This since the best-fit point is near to the boundary of maximal disappearance.

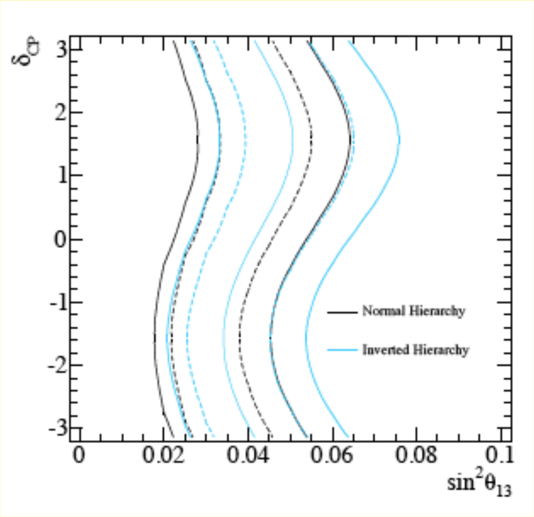
With the best point so near to the maximal disappearance, the θ_{23} octant degeneracy seems difficult to be solved.

3. δ_{CP}

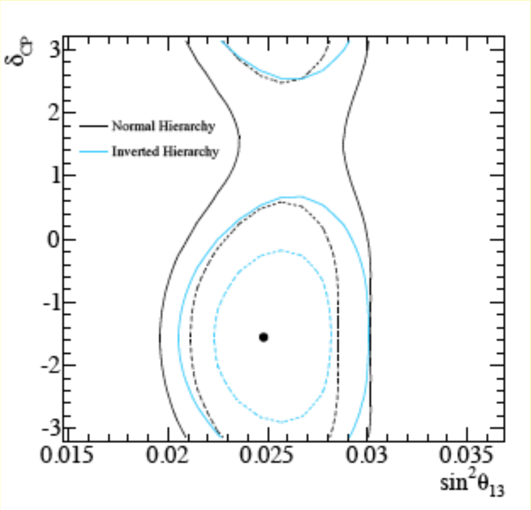
The ν_μ appearance measurements at LBL accelerators are particularly sensitive to δ_{CP}. Again T2K reports on a very recent estimate based on joint ν_μ disappearance and ν_e appearance analysis, with Δm^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$ and δ_{CP} unknown.

However, a similar analysis has little power to constrain δ_{CP} without the reactor measurements of $\sin^2\theta_{13}$. In order to constrain δ_{CP} it is mandatory to include the estimate of $\sin^2\theta_{13}$ coming from reactors.

In the figure δ_{CP} vs. $\sin^2\theta_{13}$, without and with the "ultimate" $\sin^2\theta_{13}$.



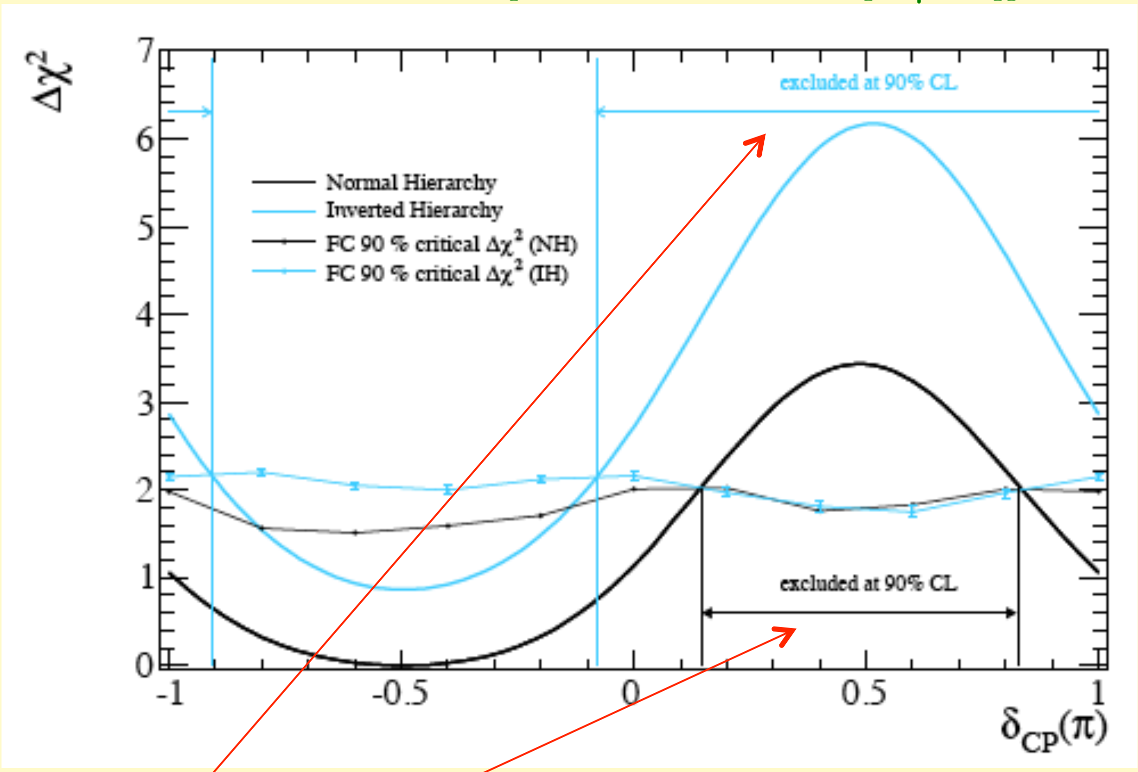
with $\sin^2\theta_{13}$ fixed at the "ultimate" reactor estimate



T2K Collaboration [arXiv: 1502.01550v1[hep-ex]]

Including **$\sin^2 2\theta_{13}$** as measured by reactors, T2K has estimated the **excluded regions** at the 90% C.L. in both NH and IH:

T2K Collaboration [arXiv: 1502.01550v1[hep-ex]]



IH δ_{CP}/π = [- 0.08,1.09] excluded at 90% C.L.

NH δ_{CP}/π = [0.15,0.83] excluded at 90% C.L.

It is interesting to estimate the sensitivity potential of LBL experiments in the measurement of δ_{CP}, using or not $\sin^2 2\theta_{13}$ measured at reactors.

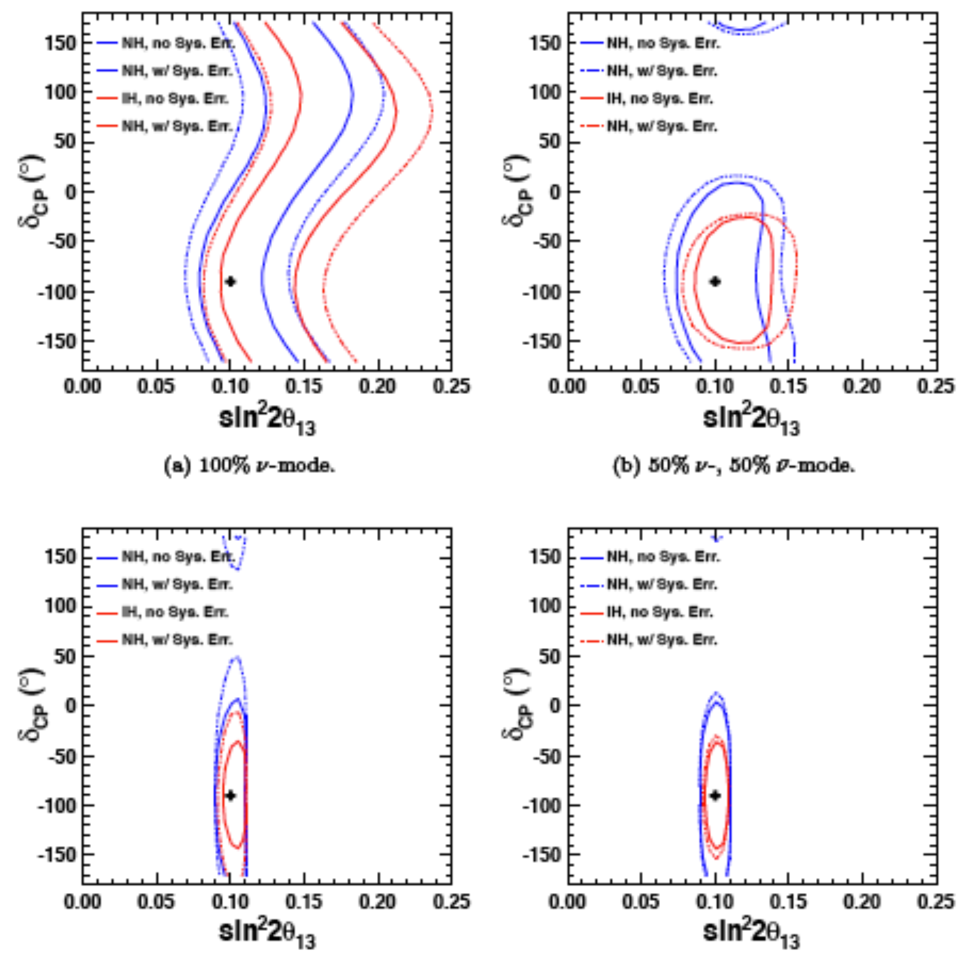
This has been recently performed by T2K, assuming for $\sin^2 2\theta_{13}$ a total uncertainty of **0.005** (assumed as "ultimate" reactor error).

The T2K analysis is performed including or not systematic errors, for different experimental setups, assuming the full T2K POT and

δ_{CP} = -90° , NH

The best result is obtained by combining both ν-mode and $\bar{\nu}$-mode data and with the ultimate reactor constraint.

T2K Collaboration [arXiv: 1409.7469v1]



(a) 100% ν-mode.

(b) 50% ν-, 50% $\bar{\nu}$-mode.

(c) 100% ν-mode, with ultimate reactor constraint.

(d) 50% ν-, 50% $\bar{\nu}$-mode, with ultimate reacto[r] constraint.

However, let us remind that **sensitivity** depends on the **true** values of the oscillation parameters, so different values of δ_{CP} could make things much harder.

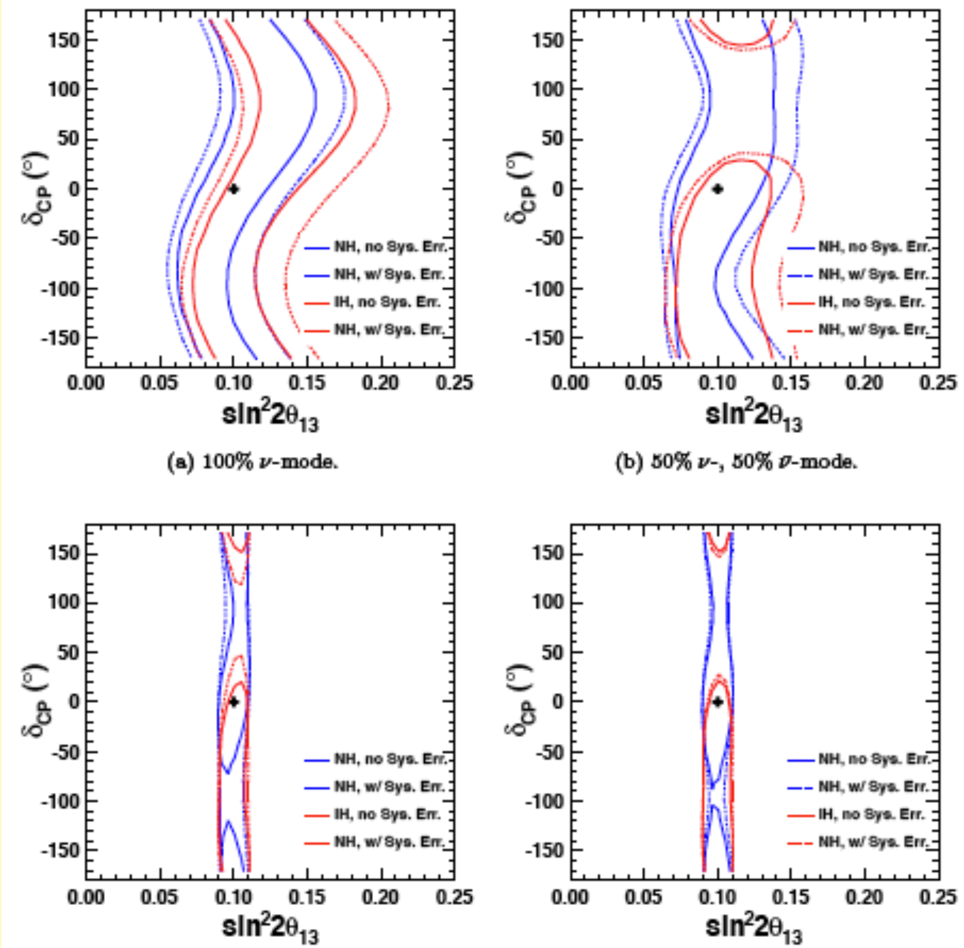
(*)T2K Collaboration [arXiv: 1409.7469v1]

These are the results of the same kind of analysis assuming

$\delta_{CP} = 0°$, NH

In this case sensitivity is not enough to resolve δ_{CP} degeneracy.

The ability of T2K to measure δ_{CP} would be greatly enhanced by the knowledge of **MH**, with a consequent breaking of the degeneracy.



(a) 100% ν-mode.

(b) 50% ν-, 50% $\bar{\nu}$-mode.

(c) 100% ν-mode, with ultimate reactor constraint.

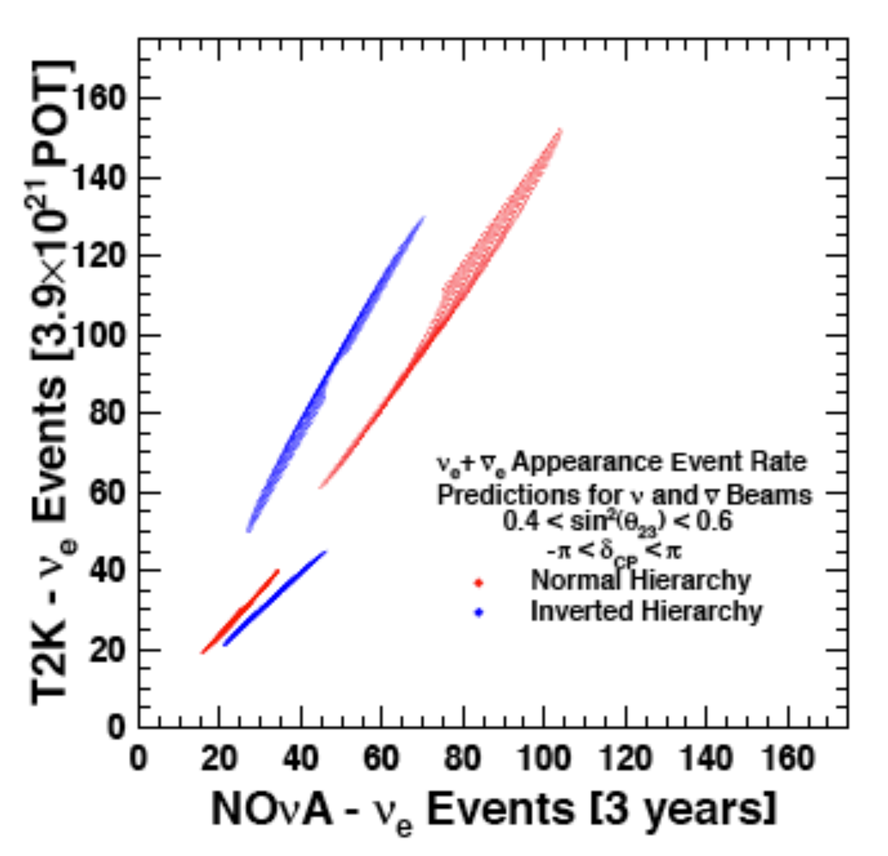
(d) 50% ν-, 50% $\bar{\nu}$-mode, with ultimate reactor constraint.

Unfortunately, **T2K** does not have sufficient sensitivity to determine the **mass hierarchy** by itself. But a similar sensitivity is achieved by **NOνA**, which has a longer baseline (810 km) and a higher peak neutrino energy (~ 2 GeV), which means a larger impact of the matter effects and a greater sensitivity to MH.

T2K Collaboration [arXiv: 1409.7469v1]

A comparison of the ν_e **appearance** data of the two experiments is foreseen.

In the figure the relation between the expected number of events in the two experiments for specific ranges of values of δ_{CP}, $\sin^2\theta_{23}$ and both the two **mass hierarchies**.



4. The neutrino mass hierarchy: sign(Δm^2)

Maybe the most fascinating item of neutrino physics. No indications so far from the current experiments, but we hope to solve this dilemma within the next ten years.

The following three types of experiments are expected to compete in determining the neutrino mass ordering:

- Medium baseline (MBL) reactor neutrino experiments, specifically JUNO, studying in vacuum the interference between solar and atmospheric oscillation amplitudes.

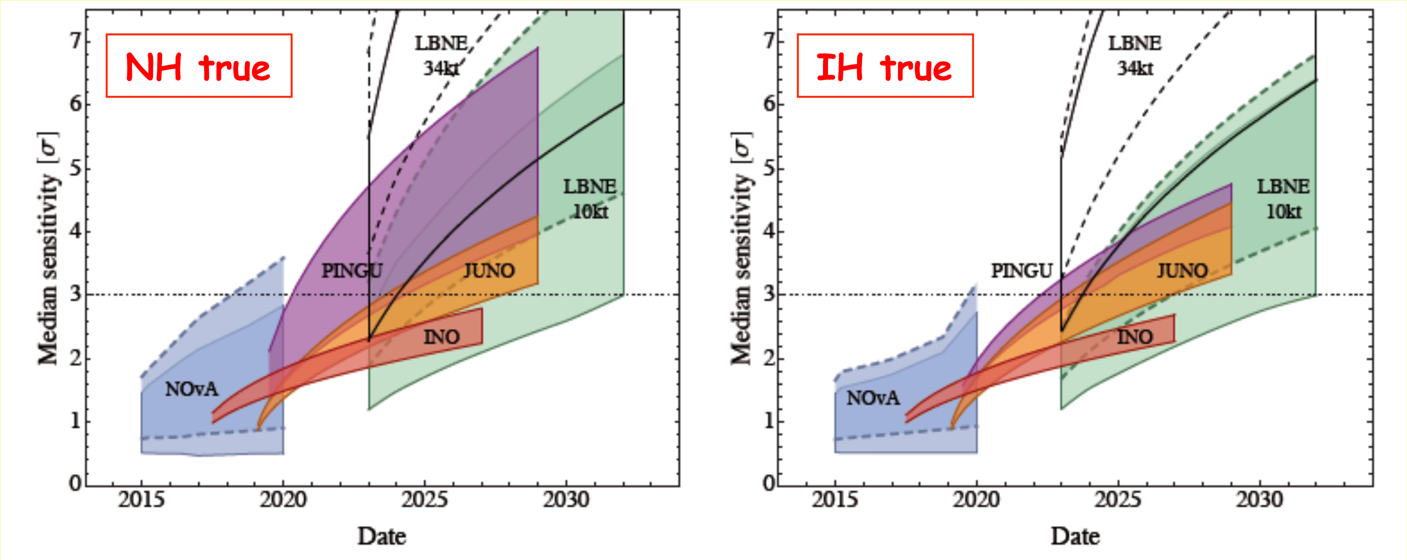
- Atmospheric neutrino experiments, as PINGU and INO, studying matter effects in atmospheric neutrino experiments.

- Long Baseline (LBL) accelerator neutrino experiments, as NOνA and LBNE, studying matter effects in $\nu_\mu \rightarrow \nu_e$ **appearance**.

A detailed discussion of **sensitivity** and **discovery potential** of these experiments is beyond the scopes of this talk. Many studies exist in literature, based on the available details of each experimental apparatus, taking into account efficiencies, energy resolution, angular resolution, systematics, etc.

We close with a recent detailed comparison of the **sensitivity** of each of the cited experiments, in terms of number of σ's, plotted in terms of the time-scale.

M. Blennow, P. Coloma, P. Huber and T. Schwetz, JHEP 02 (2014) 028 [arXiv:1311.1822v2[hep-ph]]



Due to the dichotomous character of the neutrino mass ordering, the **sensitivity** is plotted on the left for **rejecting IH** if **NH** is true, and viceversa on the right.

The width of each band depends on the range of values of the parameters relevant in the estimates, in particular:

- δ_{CP} and the true θ_{23} for LBL accelerator experiments, NOνA and LBNE
- θ_{23} for atmospheric experiments, INO and PINGU
- energy resolution for MBL reactor experiment, specifically JUNO

Arriving to the conclusion …

… it is suggestive to affirm, with a dash of optimism, that we are not so far from completing our knowledge of the parameters of neutrino oscillations.

Without excluding, of course, possible surprises, that in particle physics are always around the corner!

Thanks for your attention !