Complementarity of Terrestrial Neutrino Experiments in Searching for θ_{13}

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P.M., F. Terranova Phys. Lett. B 563 (2003) 73
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Outline

- Definition of "on-peak" and "off-peak" experiment
  - Two families scheme
  - Three families scheme
- Possible scenarios after first results of the planned experiments and implications
  - θ_{13} is so small the all give null result
  - θ_{13} is larger than 7°
  - $4° < \theta_{13} < 7°$
- Conclusion

Two families scheme

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

Maximum oscillation rate at $\Delta m^2 L/4E = \pi/2 \Rightarrow$ **on peak**

In principle very easy, in practice very difficult!

Δm^2 versus YEAR

Atmospheric exps

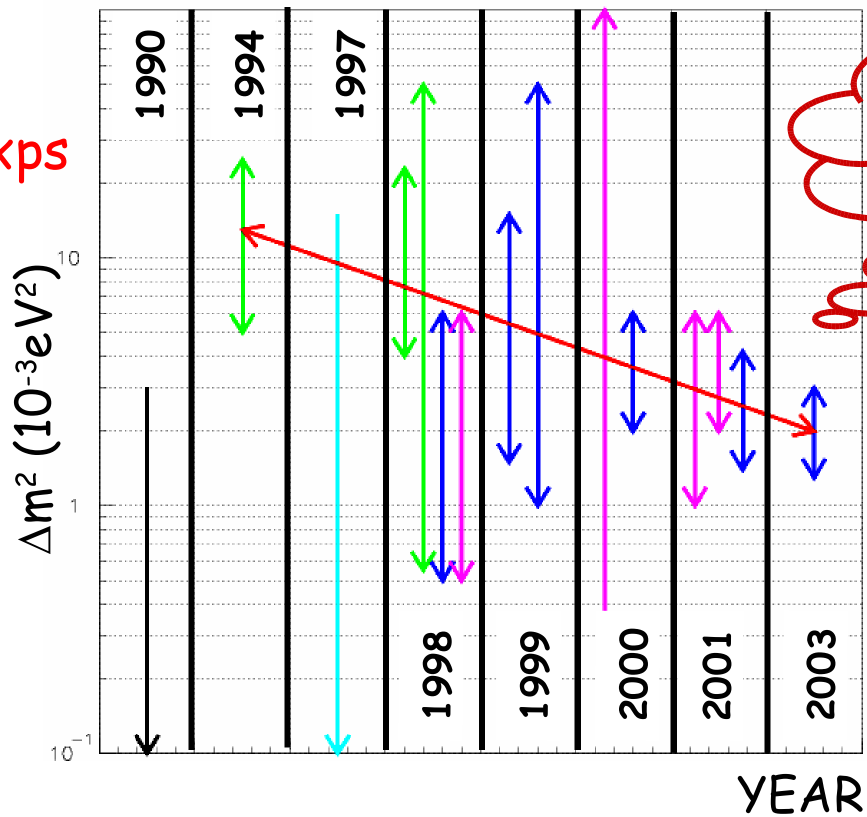
Frejus

Kamiokande

IMB

Super-K

Macro



90% allowed regions for different exps as a function of the time

NB

P_{osc} goes like $(\Delta m^2)^2$

From '94 to '03 it decreased by a factor 100!!

Very difficult the tuning at the atmospheric mass scale!

Impact both on $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillation searches

Comparing different scenarios in a two families scheme

Limits at 90% C.L. on $\sin^2 2\theta_{13}$ and θ_{13}

($\Delta m^2_{23}=2.5\times10^{-3}$ eV^2; $\sin^2 2\theta_{23}=1$)

Experiment	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	<0.14	<11°
MINOS 2yr	<0.06	<7.1°
ICARUS 5yr	<0.04 (LI) <0.03(HI)	<5.8° <5.0°
OPERA 5yr ≡ CNGS	<0.06(LI) <0.05(HI)	<7.1° <6.4°
ICARUS+OPERA 5yr	<0.03(LI) <0.025(HI)	<5.0° <4.5°
JHF 5yr	<0.006	<2.5°

LI = nominal CNGS; HI = nominal CNGS x 1.5

Phase I exps

NB The CNGS sensitivity is limited by statistics
⇒ very important high intensity proton beam

Comment

Historically different projects have been compared by looking at the sensitivity computed assuming the two families scheme. However, this approximation is to simple: neutrino are at least three and are connected among them.

$\Rightarrow$ Interplay between θ_{13} and the *CP* phase

$\Rightarrow$ The sensitivity depends on solar parameters

The oscillation probability in the full PMNS scenario

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

O_1 leading term

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

O_2: 1 at osc. max

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

O_3: 0 at osc. max

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

O_4: suppressed by α^2

$$\alpha \equiv \frac{\Delta m^2_{21}}{\left|\Delta m^2_{13}\right|} \quad \xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \approx O(1)$$

$$\hat{A} \equiv 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2_{13}} \qquad \Delta \equiv \frac{\Delta m^2_{13} L}{4E}$$

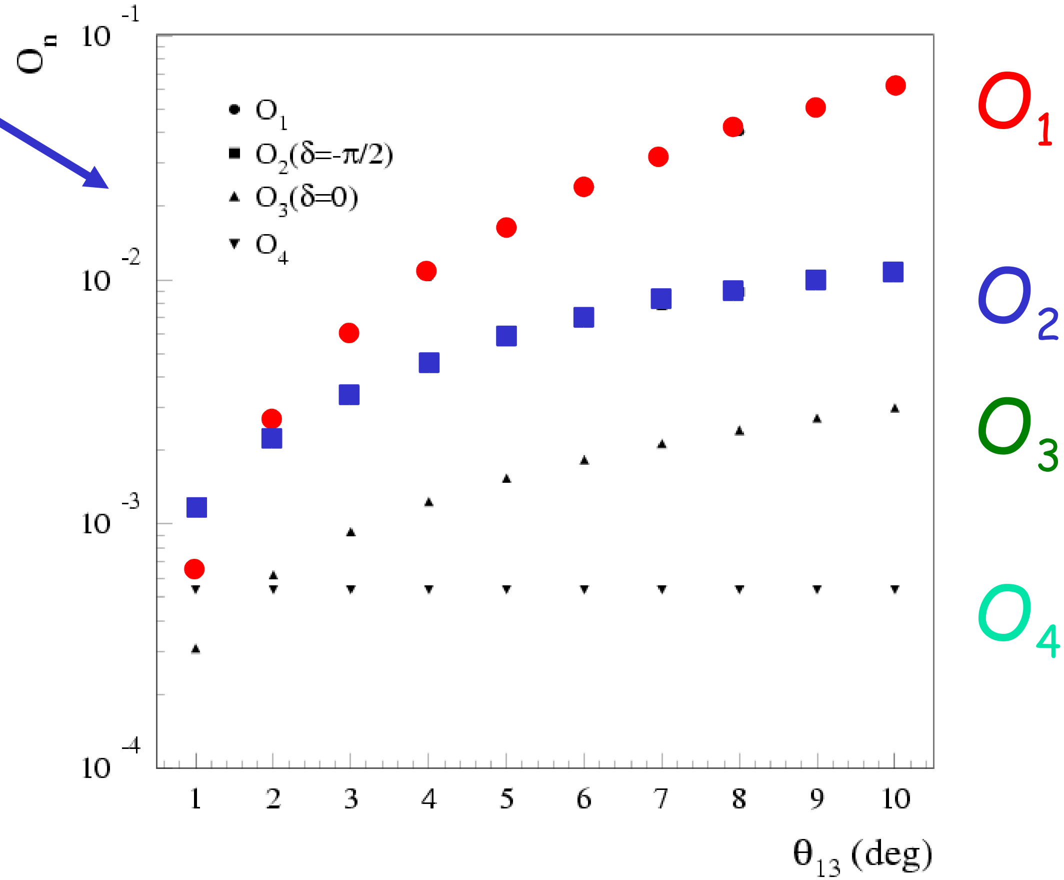
The hierarchy among the different O terms depends on the "on peak"-"off peak" choice

On peak, "short" baseline experiments (JHF-SK) ⇒

dominance of O_1 and O_2 terms and low sensitivity to sign of Δm^2_{31} (small matter effects)

$$P(\nu_\mu \to \nu_e) \simeq \sin 2\theta_{13}(\sin 2\theta_{13} A_1 - \sin\delta\,\alpha\, A_2) \quad ; \quad A_1, A_2 \sim O(1)$$

On peak, longer baseline experiments (NuMI-Off Axis) ⇒ dominance of O_1 and O_2 and higher dependence on sign(Δm^2_{31}) larger matter effect



Different dependence on sign(Δm^2_{23})

⇒ Possible sinergy between JHF and NuMI-OA

Off-peak experiments (e.g. CNGS)

Leading term: signal rate suppressed $|(1-\hat{A})\Delta| \ll 1$

$$\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \simeq \Delta^2$$

Matter effects cancel out at LO even if CNGS is an high energy beam

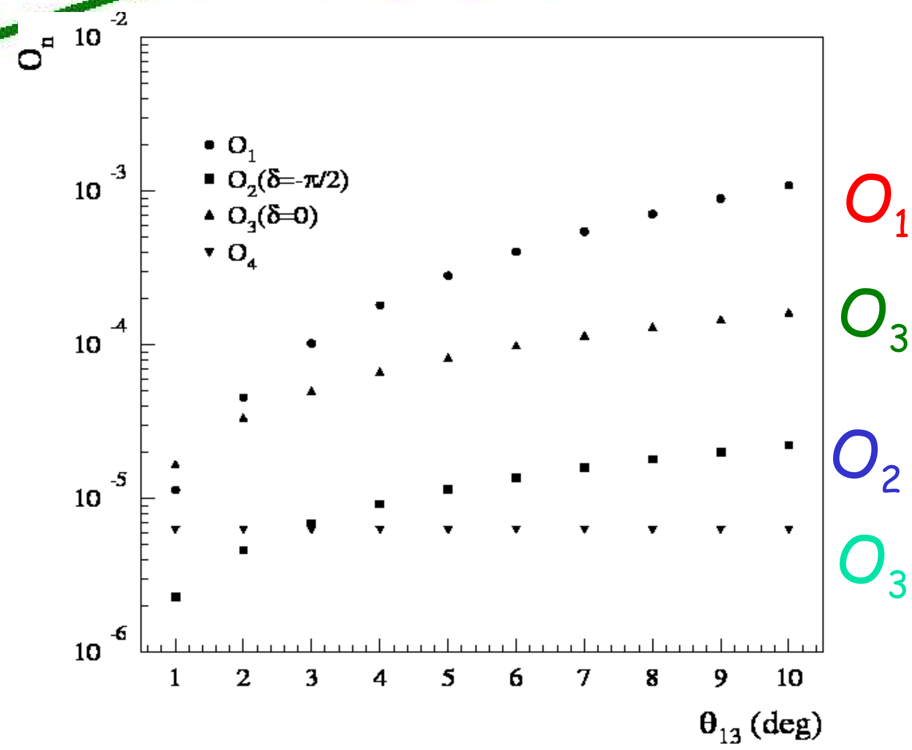
$$P(\nu_\mu \to \nu_e) \simeq \Delta^2[\sin^2 2\theta_{13} A_1 - \sin\delta \sin 2\theta_{13} \alpha \Delta A_2 + \cos\delta \sin 2\theta_{13} \alpha A_3 + \alpha^2 A_4]$$

Dominance of O_1 and O_3:

O_1 is CP and matter independent

O_3 is CP even and odd under

$\Delta m^2_{31} \to -\Delta m^2_{31}$ transformation



Different hierarchy of O terms

⇒ Possible synergies between "on" and "off" –axis exps.

All Phase I exps give null result

Can we start the construction of future facilities (Super-Beams, Neutrino Factories) on firm bases?

Can we safely exclude large values of θ_{13} such that CP is not visible at future facilities (i.e. stop future programs)?

The answer is no!

Some considerations

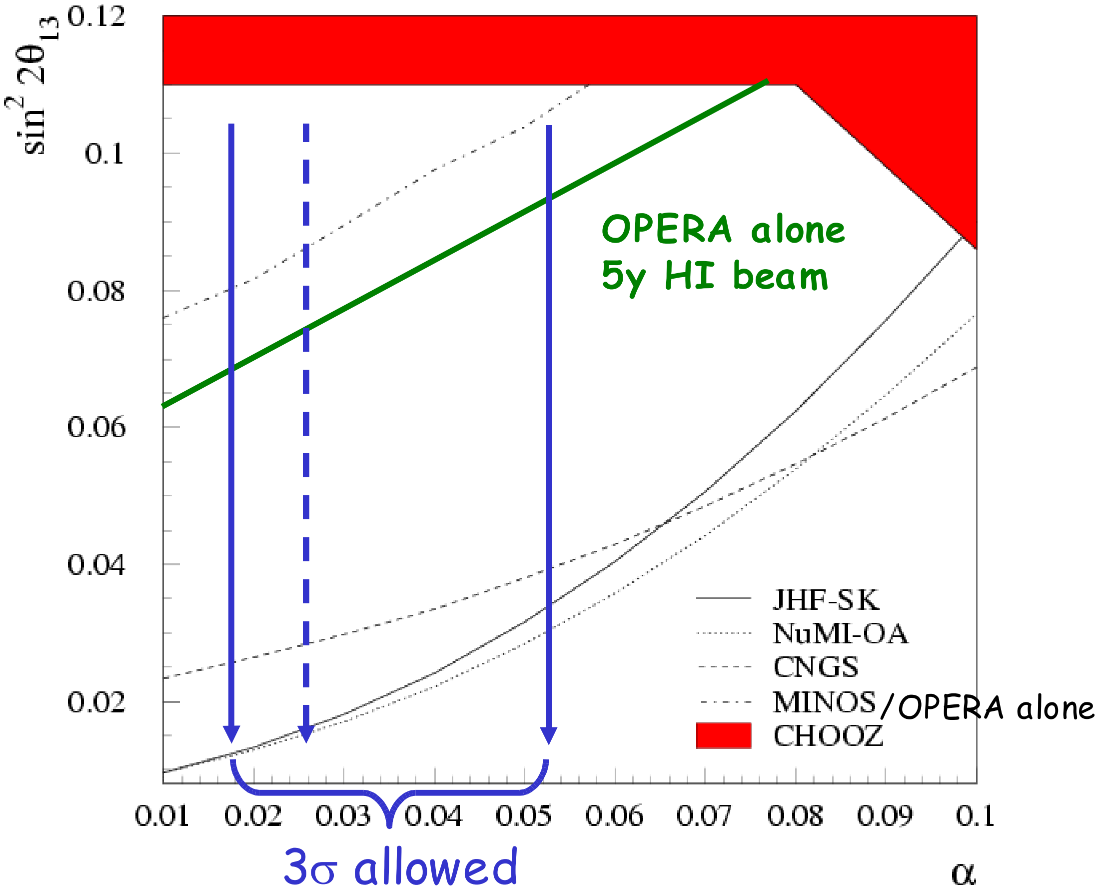
To have an unambiguous answer the exps should

- Perform a pure measurement of θ_{13} (e.g. reactors)
- Be able to disentangle θ_{13}-δ intrinsic correlations which could result into an apparent suppression of θ_{13} (e.g. neutrino + anti-neutrino run)
- Have maximal θ_{13} sensitivity for maximal CP violation

The only thing we can do with the proposed experiments is to OPTIMIZE THE DATA TAKING!

Three families analysis:

$\sin^2 2\theta_{13}$ as a function of solar and atmospheric Δm^2



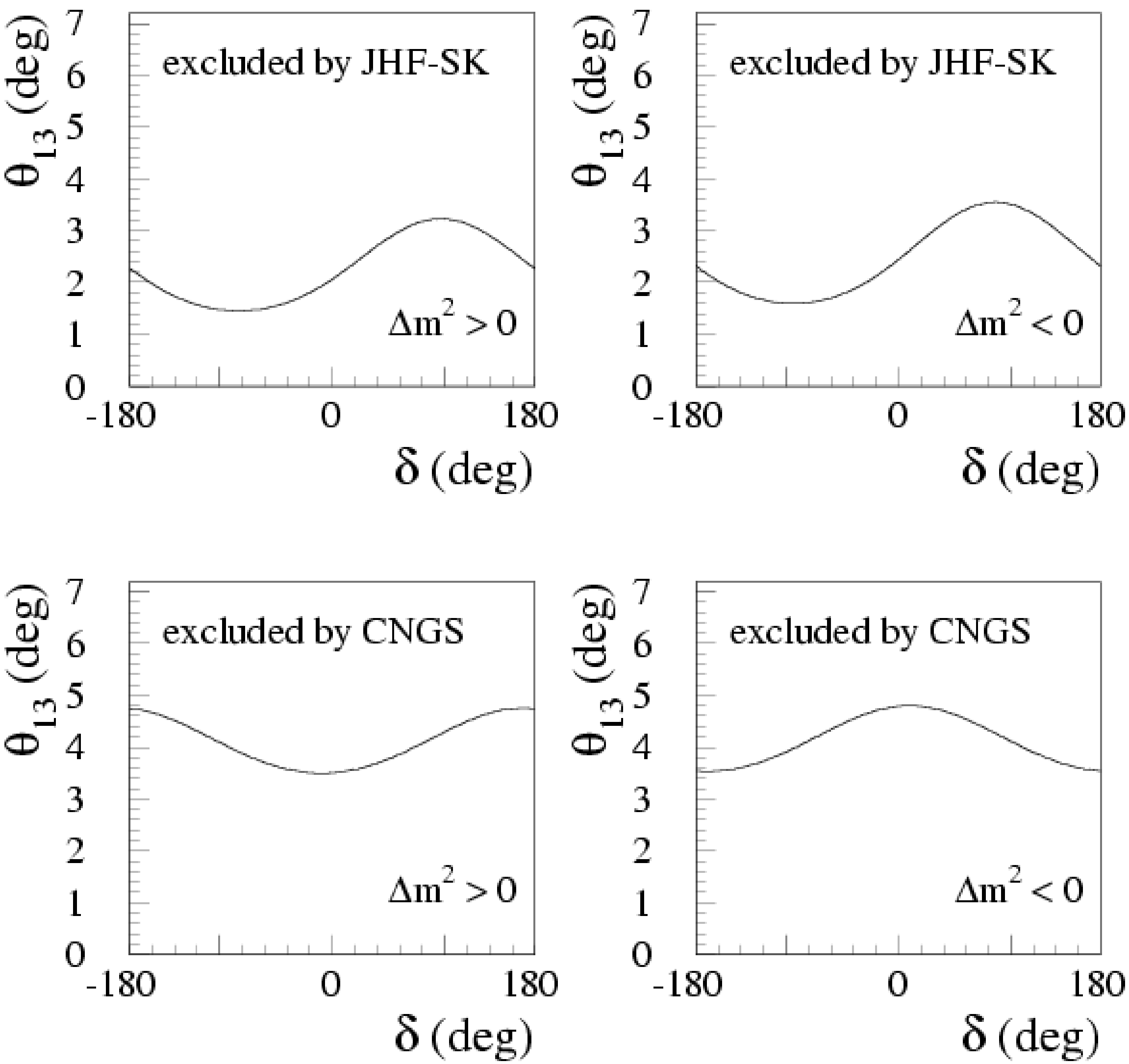
$$\alpha = \Delta m^2_{sol} / |\Delta m^2_{atmo}|$$

This plot has been obtained in the worst case: the larger value of θ_{13} (varying δ_{CP}) is taken

Limits on α taken from a global fit to all available data: atmospheric+solar+reactor*

*M. Maltoni et al. hep-ph/0309130

Accelerator expts. sensitivity vs δ_{CP}



There are διπ values for which the sensitivity on θ_{13} is even better than the one compute in the 2-flavour approximation (δ_{CP}=0).

Notice the different behaviour on Δm^2 of the CNGS sensitivity

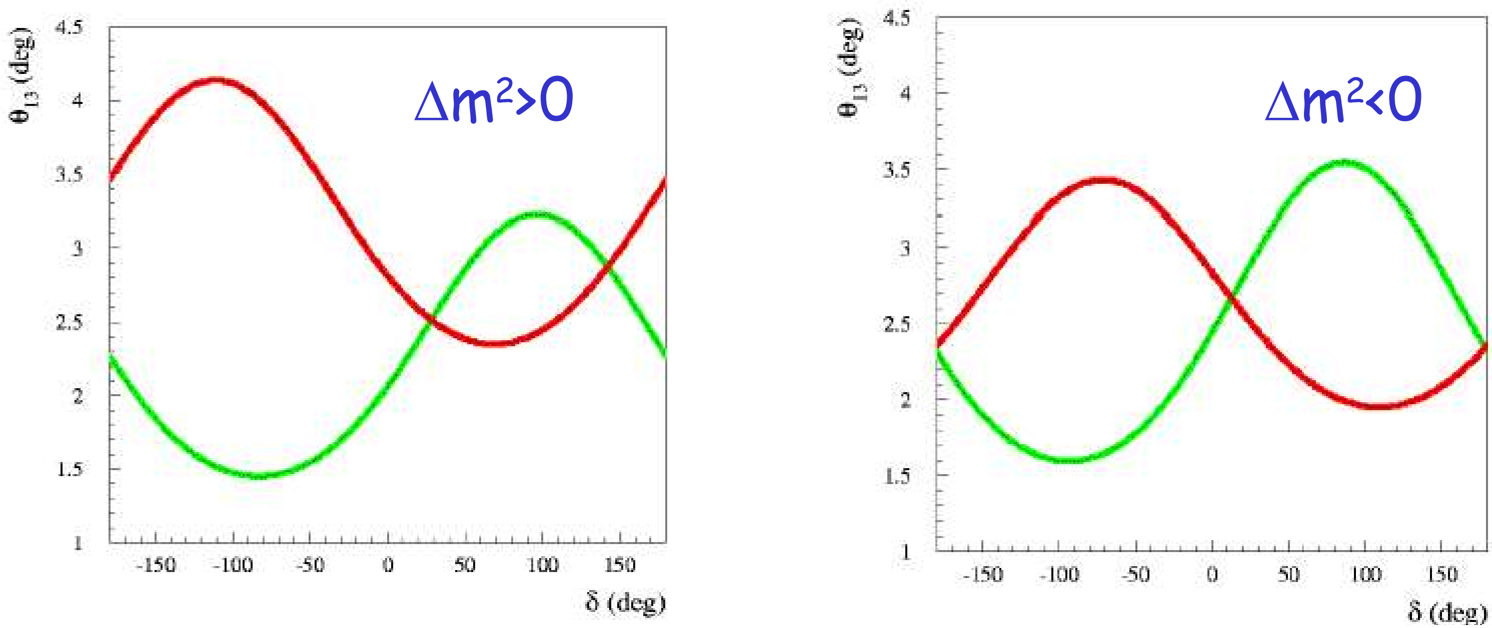
⇒ Possible measurement of the sign of Δm^2_{31}?

What happens if an exp decides to start with anti-neutrinos?

At the present NuMI-OA is supposed to start data-taking with ν

BAD CHOICE: results similar to JHF, no synergies

GOOD CHOICE: would be data-taking with anti-ν, synergies!



NUMI-OA in anti-ν mode (5y). Yield corrected for σ(anti-n) and π-/π+ yield

JPARC-Ph1 in ν mode (5y)

θ_{13} issue

The measurement of θ_{13} is made complicated by the fact that oscillation probability is affected by matter effects and possible CP violation

Because of this, there is not a unique mathematical relationship between oscillation probability and θ_{13}

Especially for low values of θ_{13}, sensitivity of an experiment to seeing $\nu_\mu \rightarrow \nu_e$ depends very much on δ

Several experiments with different conditions and with both ν and anti-ν will be necessary to disentangle these effects

θ_{13} is larger than 7°

Signal already visible at MINOS/ICARUS/OPERA

CNGS at the start-up of JHF-SK

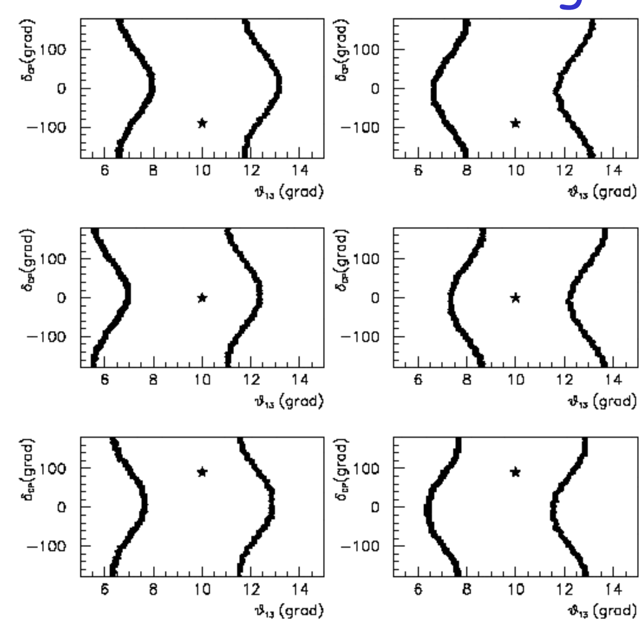
3 years data taking at the CNGS

Sensitivity: $\sin^2 2\theta_{13} < 0.035$ @ 90% C.L. (a factor 4 better than CHOOZ)

Indication (90% C.L) of ν_e appearance if $\theta_{13} > 7°$

$\theta_{13}\|_{true}$	$\theta_{13}\|_{min}$	$\theta_{13}\|_{max}$	
1°	---	5.5°	---
2.5°	---	5.8°	---
5.0°	---	7.0°	---
7.5°	1.2°	11.4°	(7.5+3.9-6.3)°
10°	5.6°	13.7°	(10.+3.7-4.4)°

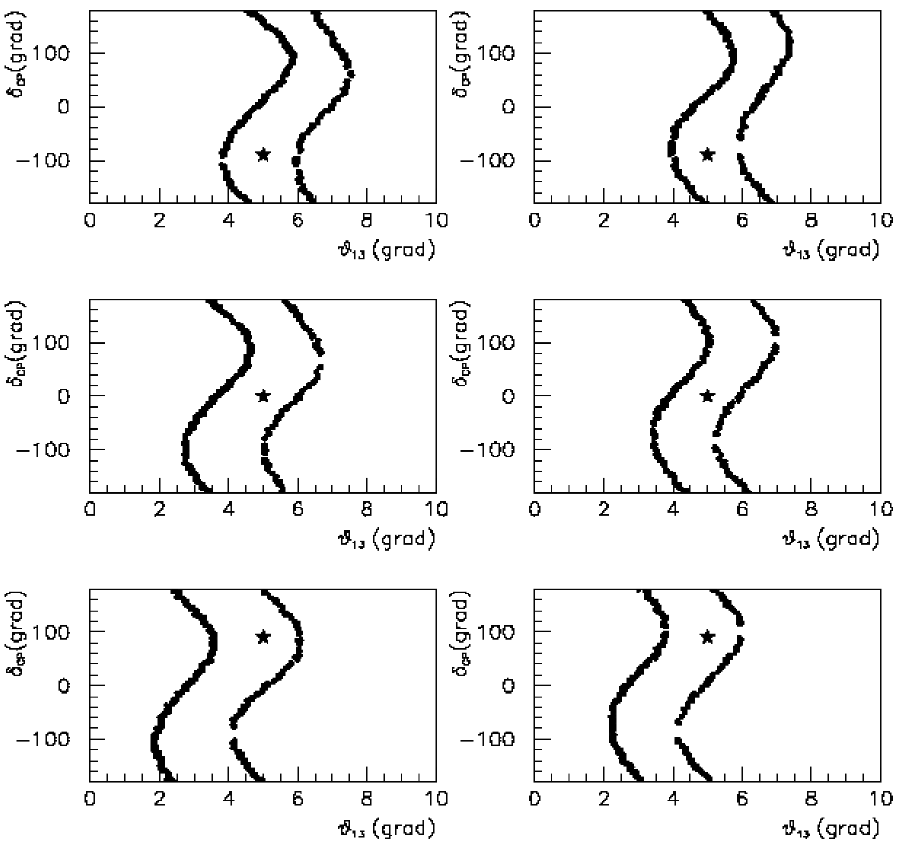
90% C.L. allowed region



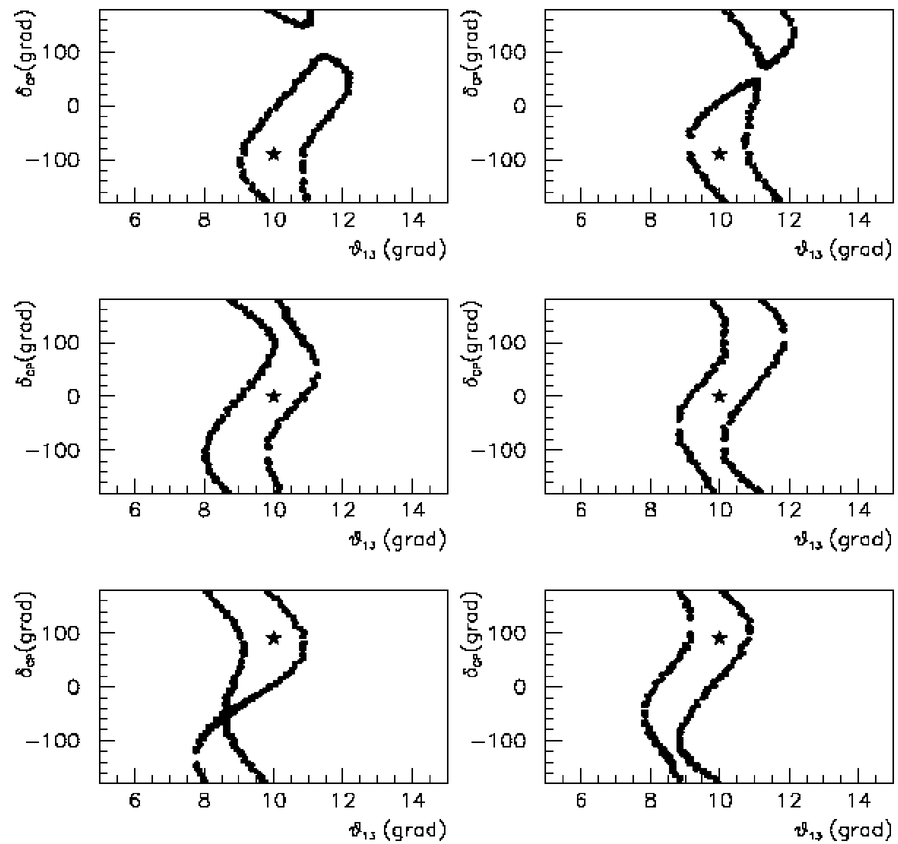
$\Delta m^2<0$ $\Delta m^2>0$

Allowed regions for JHF (5 years) + CNGS (8years)

θ_{13}=5°



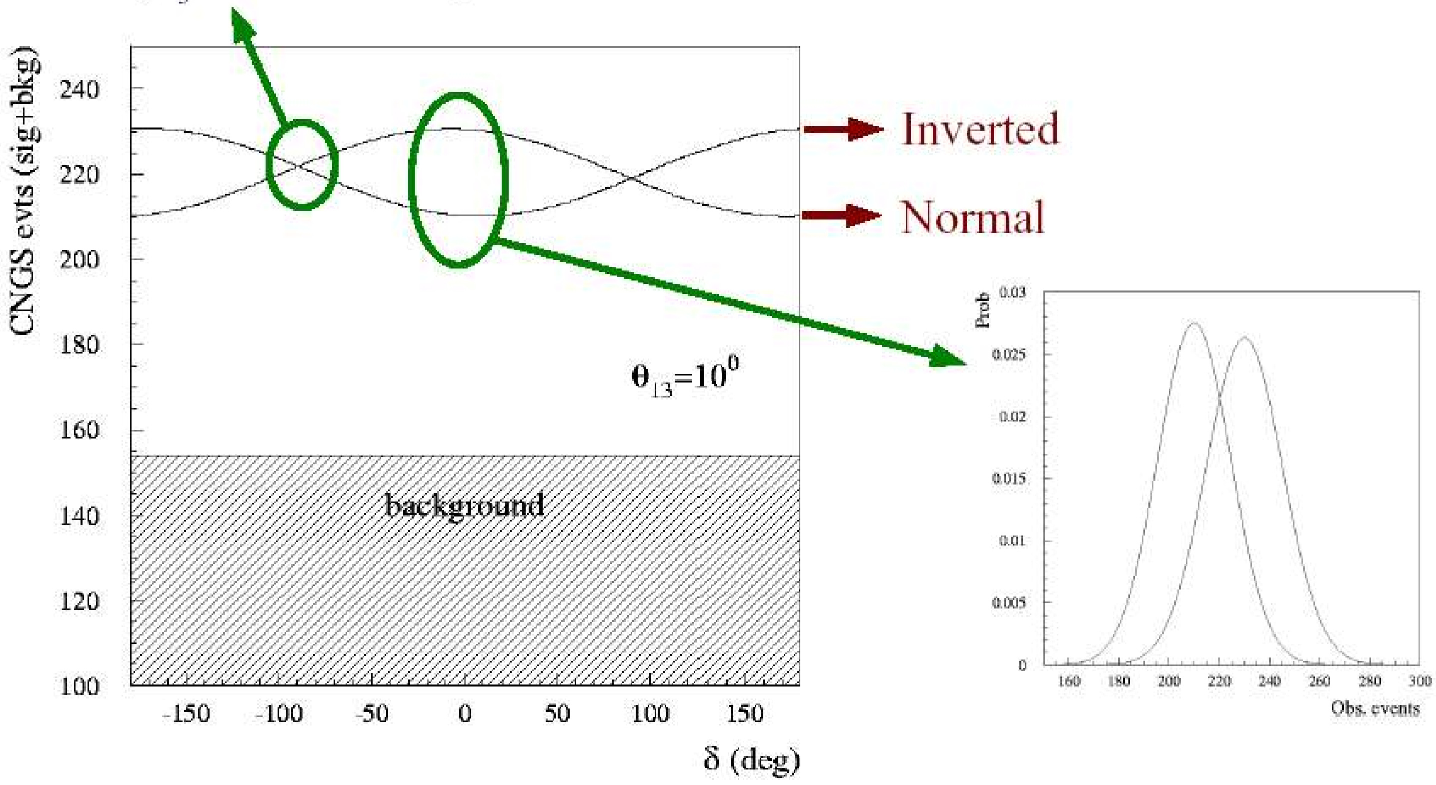
θ_{13}=10°



$\Delta m^2<0$ $\Delta m^2>0$ $\Delta m^2<0$ $\Delta m^2>0$

Mass hierarchy with CNGS?

Obvious! (O_3=0 for max CPV)



Marginal! More than 40% Type II error for 90% significance even assuming ϑ_{13} well measured by JPARC/NUMI

Would need a high-intensity off-peak experiment...

θ_{13} in the range 4° to 7°

Off-peak exps do not contribute to the θ_{13} business

Run JHF with ν and NuMI-OA with anti-ν will be the optimal solution to lift the δ-θ_{13} correlation

Run both JHF and NuMI-OA with ν in order to measure the sign(Δm^2_{23}) (e.g. the two exps have different matter effects)

V. Barger et al. Phys. Lett. B 560 (2003) 75

P. Huber et al. Nucl. Phys. B 654 (2003) 3

H. Minakata et al. Phys. Rev. D 68 (2003) 013010

Conclusion

Null result at Phase I exps : **WARNING!** δ_{CP} could be huge but hidden by the choice of the neutrino run. A dangerous manifestation of the (δ-θ_{13}) correlation!

The anti-ν choice (done after the ν run or in parallel by NUMI-OA) is mandatory to take decisions about the Phase II

Positive result at MINOS or CNGS: **Great time for oscillation physics!** Synergic use of MINOS+ CNGS + JHF + NuMI-OA:

- to constrain (δ-θ_{13})
- to determine the sign of Δm^2_{atm}

$4° < \theta_{13} < 7°$ **Another great season for Japanese neutrino physics!** Signal seen at JPARC. NuMI-OA contribute to precision measurement of (δ-θ_{13}) in anti-ν mode, sign Δm^2_{atm} in neutrino mode

Final remark

For a successful future one should first exploit and optimise the present