On-peak and off-peak neutrino oscillation experiments

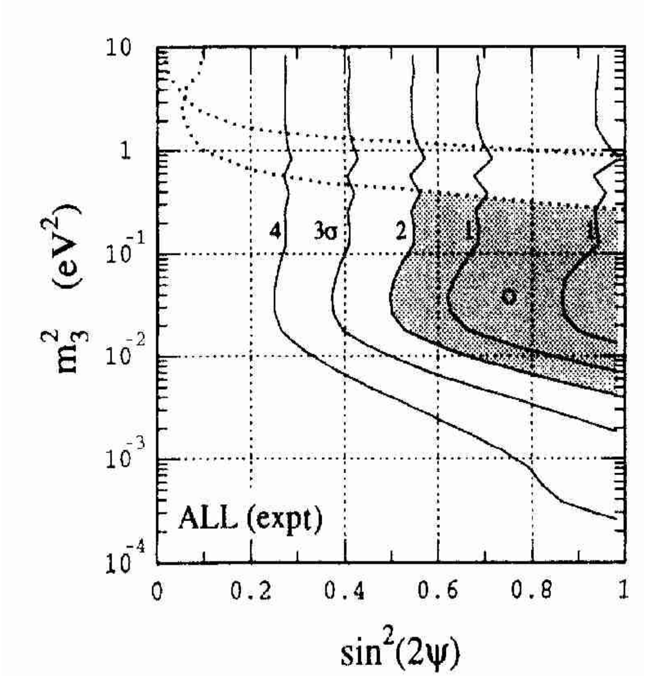
- Synergies among long-baseline experiments: a peculiar problem of the PMNS precision era.

- Three scenarios:
  - $\nu_\mu \rightarrow \nu_e$ unaccessible to Phase I superbeams
    (null result in next 10 years!)
  - Early observation of $\nu_\mu \rightarrow \nu_e$
    (evidence at MINOS/ICARUS/OPERA)
  - $\nu_\mu \rightarrow \nu_e$ observed only by Phase I superbeams
    (evidence at JPARC-Ph1 or NuMI-OA)

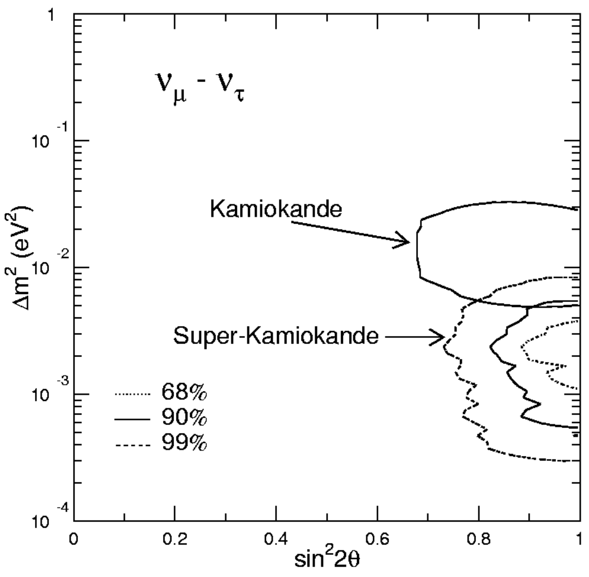
Two-family optimal tuning

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

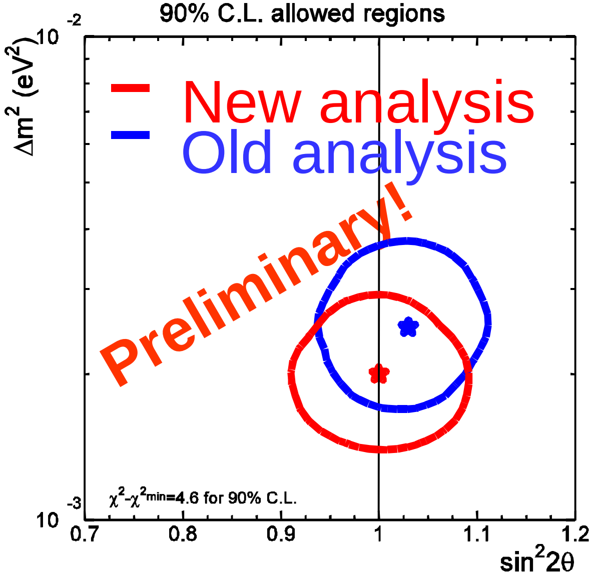
In practice it turned out to be a tough job... especially at the atmospheric scale!



1993



1998



2003

MINOS — beam retuning: compromise between being "on-peak" and flux

CNGS — need to run "off-peak": L fixed, E high enough to overcome the kinematic threshold for τ production

$\nu_\mu \to \nu_e$ in the full PMNS scenario

Taylor expansion around $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\vartheta_{13}$ for constant matter density:

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

O_1 (leading term)

$$-\alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin\Delta \frac{\sin[\hat{A}\Delta]}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

O_2 ($\sim \sin\Delta$)

$$+\alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos\Delta \frac{\sin[\hat{A}\Delta]}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

O_3 ($\sim \cos\Delta$)

$$+\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2[\hat{A}\Delta]}{\hat{A}^2}$$

O_4 (suppressed by α^2)

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

$$\hat{A} \equiv 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2_{31}}$$

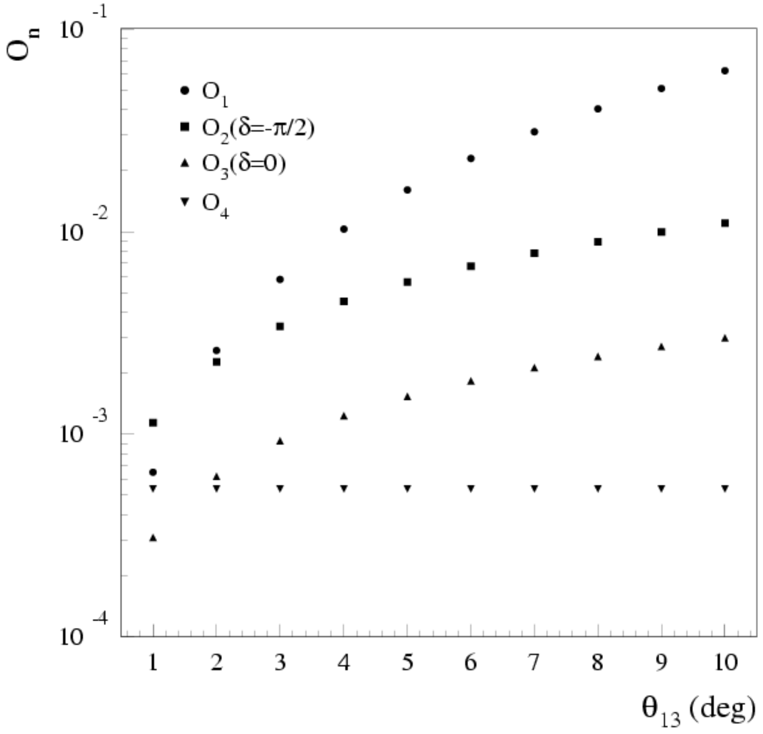
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

The hierarchy among the O's 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



→ O_1

→ O_2

On-axis / Off-axis synergy:
build experiments with different O_1 , O_2 patterns

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

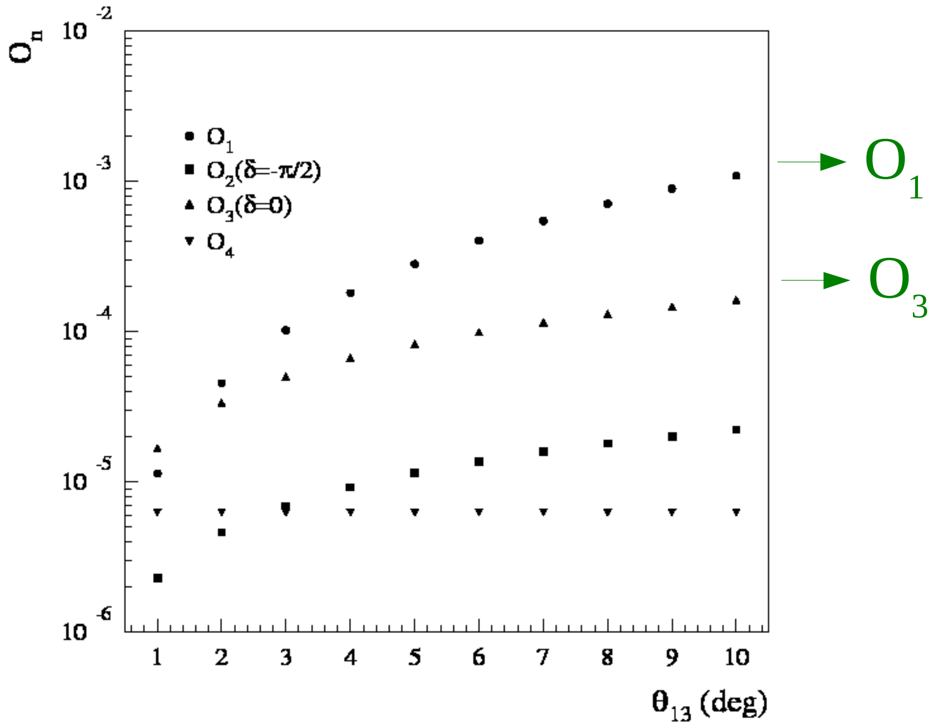
$$P(\nu_\mu \to \nu_e) \simeq \Delta^2 [\sin^2 2\theta_{13} A_1 - \sin\delta \sin 2\theta_{13} \alpha \Delta A_2 + \cos\delta \sin 2\theta_{13} \alpha A_3 + \alpha^2 A_4]$$

Dominance of O$_1$ and O$_3$:

O$_1$ is CP and matter independent

O$_3$ is CP <u>even</u> and <u>odd</u> under

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



An (obvious) warning:

The $O_1 O_3$ dominance is a by-product of the main physics case:

observation of ν_τ appearance

OPERA alone (5 years run @ 6.76×10^{19} pot / year)

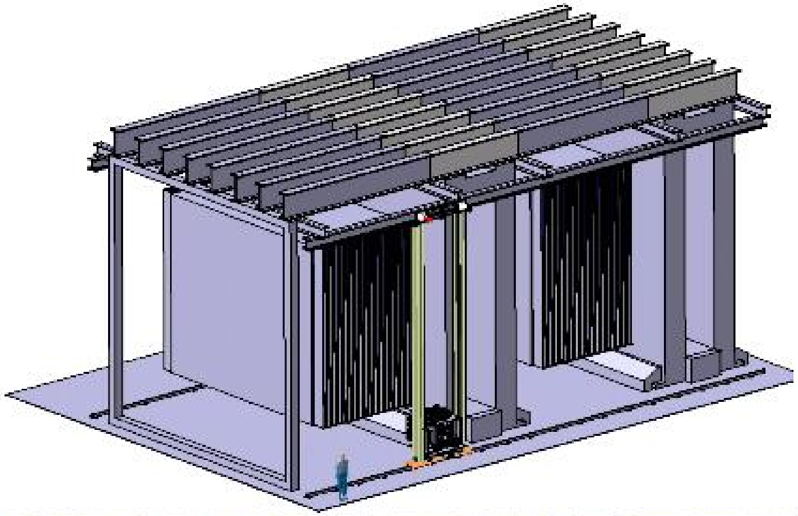
Channel	Δm^2 (10^{-3} eV^2)			(eff x BR)	Bkg
	1.3	2.0	3.0		
$\tau \to e$	1.8	4.1	9.2	3.4%	0.31
$\tau \to \mu$	1.4	3.4	7.6	2.8%	0.33
$\tau \to h$	1.5	3.5	7.8	2.9%	0.42
Total	4.7	11.0	24.6	9.1%	1.06

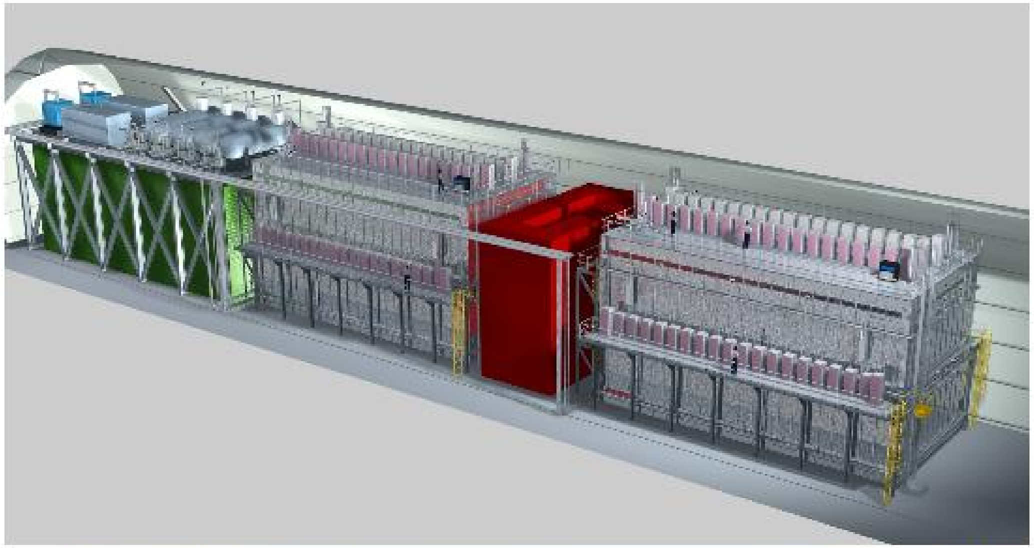
OPERA alone (5 years run @ 4.5×10^{19} pot / year)

Total	3.1	7.3	16.4	9.1%	0.71

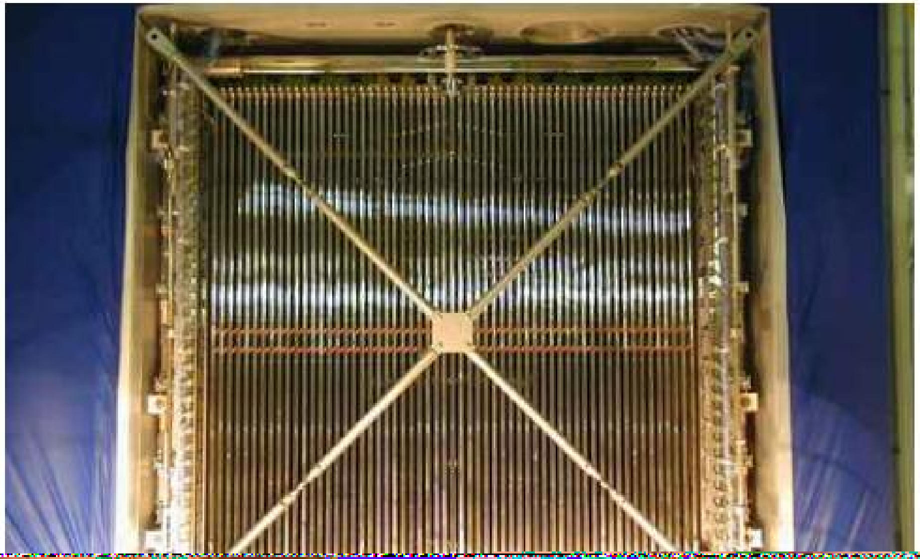
Can we get anything good from the $O_1 O_3$ dominance to study the (1,3) sector of the PMNS matrix?

Overcoming the Δ^2 suppression factor





Hall C Gran Sasso
Sep 2003



OPERA: 1.7 kton fiducial

ICARUS: 2.4 kton fiducial

Tau detection through kink id. or kinematical analysis: <u>outstanding granularity</u>

Can we use it for ν_e appearance?

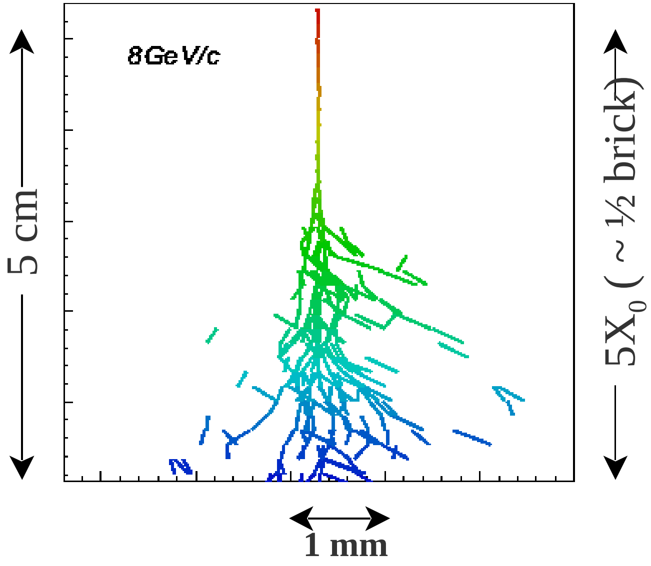
OPERA

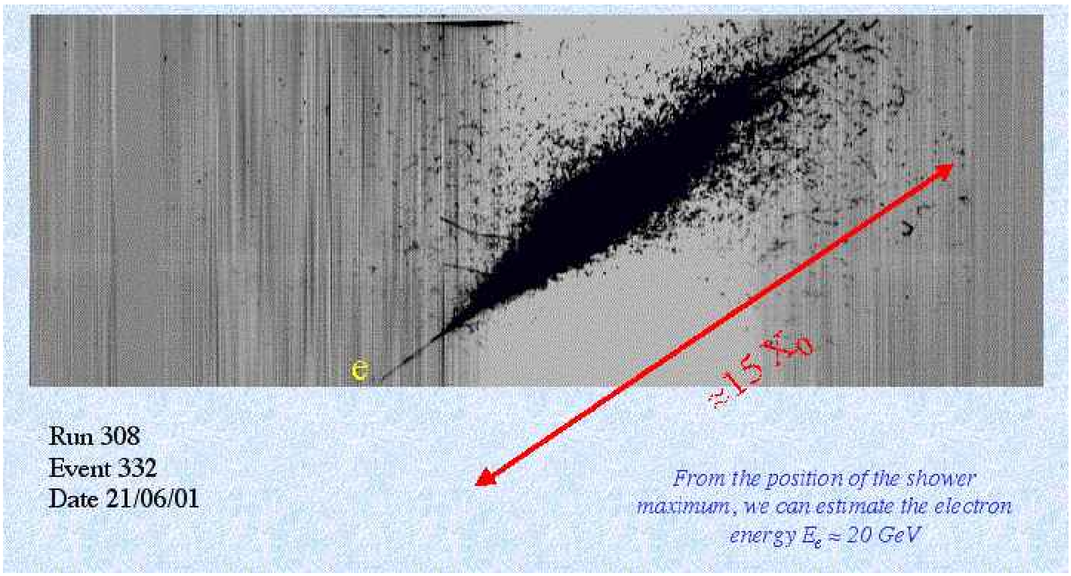
- Removal of ν_τ contamination on event-by event basis (kink finding)
- π^0/e separation through grain counting
- BUT
- Low mass

ICARUS

- More massive than OPERA
- π^0/e separation through g conversion vertex id (Ar has low X_0)
- BUT
- Higher ν_τ contamination

ECC exposure at CERN-PS

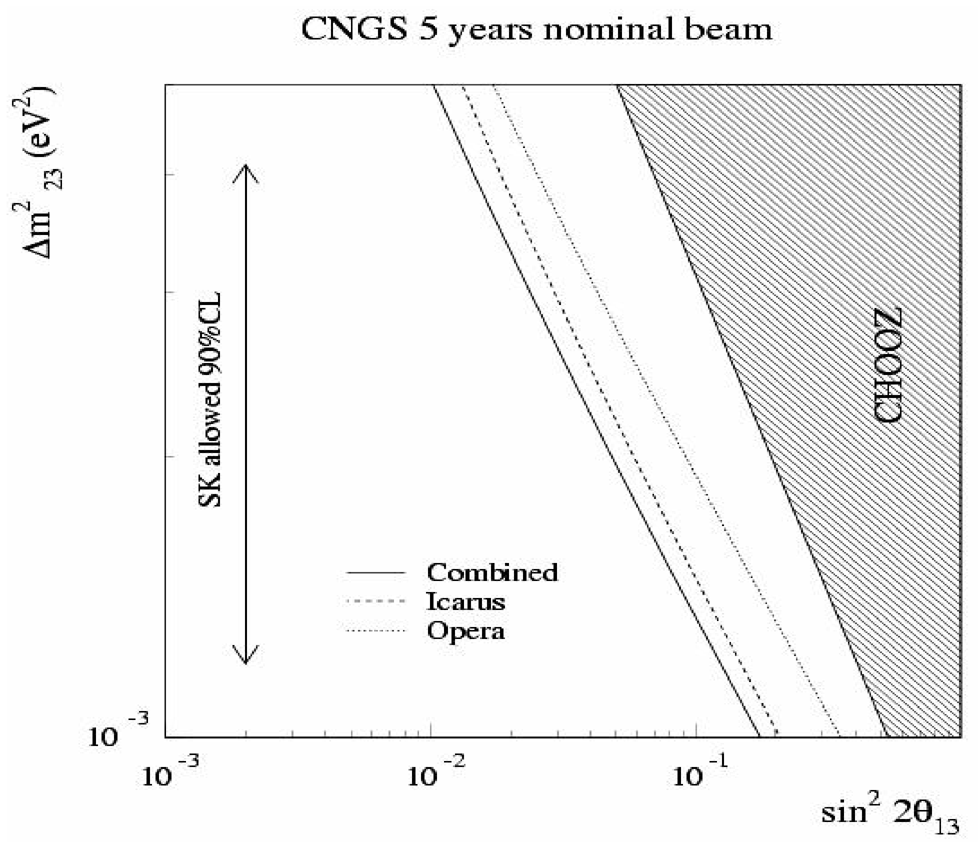




From the position of the shower maximum, we can estimate the electron energy $E_e \approx 20$ GeV

Two family approximation

$P(\nu_\mu \rightarrow \nu_e) = O_1$



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	<0.06 (LI) <0.05 (HI)	<7.1° <6.4°
ICARUS+OPERA	<0.03 (LI) <0.025 (HI)	<5.0° <4.5°
JHF 5yr	<0.006	<2.5°

$\Delta m^2 = 2.5\ 10^{-3}\ \mathrm{eV}^2$
LI = nominal CNGS flux (proposal)
HI = 6.76×10^{19} pot/y = 1.48 x LI

The null hypothesis and the Phase I $\rightarrow$ Phase II strategy

Since the physics reach of High Intensity Superbeams (e.g. JPARC-PhII) and NuFact depends critically on the size of $\sin^2 2\vartheta_{13}$

Phase I experiments $\Rightarrow$ high $\sin^2 2\vartheta_{13}$ sensitivity

signal $\Rightarrow$ precision MNS physics at SB/NuFact

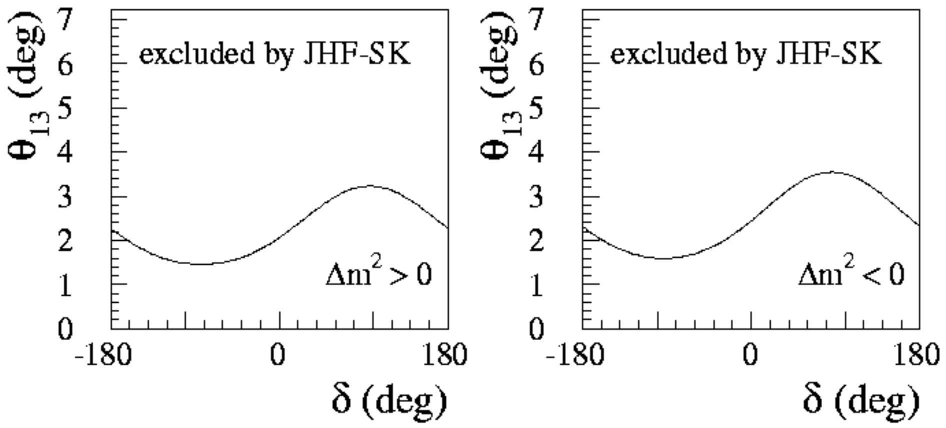
null result $\Rightarrow$ discourage the SB/NuFact physics programme

Three ways to build a good phase I experiment:

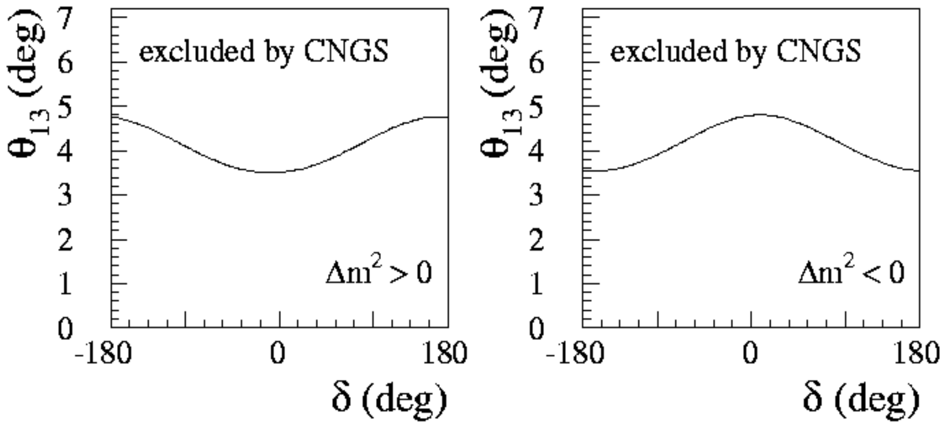
- A "pure" $\sin^2 2\vartheta_{13}$ experiments (e.g. Reactors)
- An experiment sensitive to δ_{CP} but able to disentangle δ–ϑ_{13} cancellation effects (JPARC-Ph1 + antineutrino runs)
- An experiment which has maximal ϑ_{13} sensitivity for maximal $\cancel{CP}$

What happens in $\nu_\mu \rightarrow \nu_e$ appearance experiments?

JPARC-Ph1 has the wrong pattern for $\delta>0$



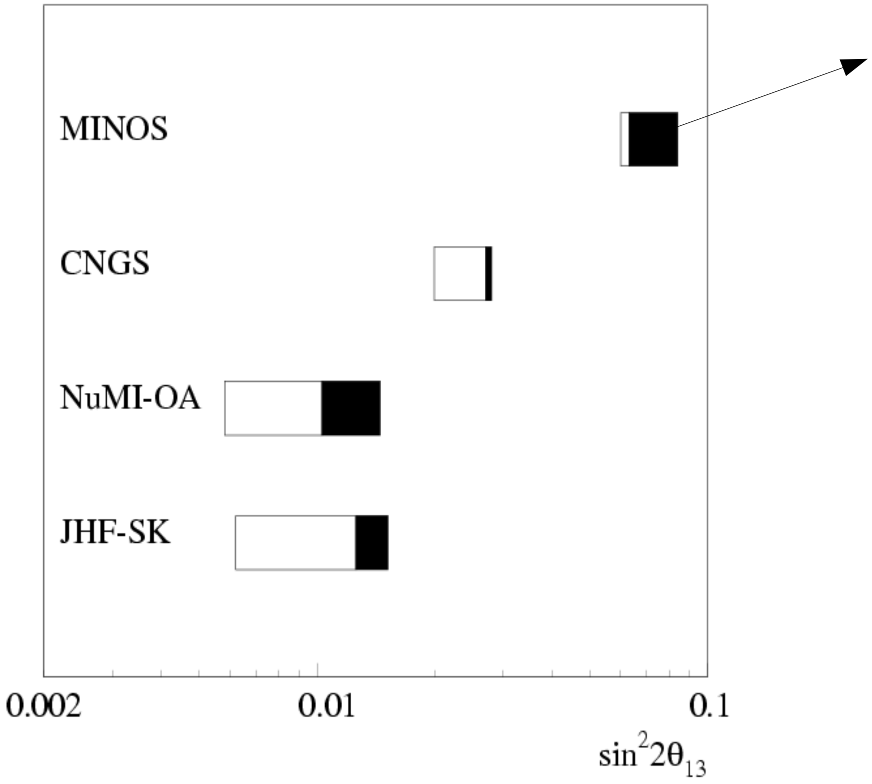
CNGS has the wrong pattern for $\Delta m^2_{31}>0$



5 years of data taking

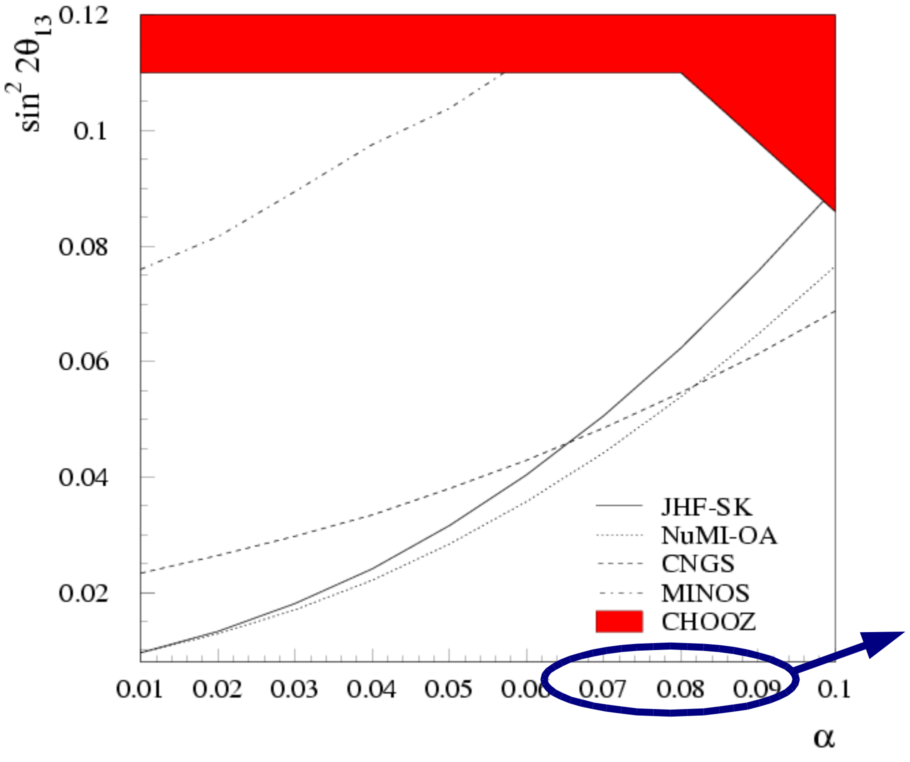
What can we say on Phase II if we observe a null result in JHF-SK?

Assuming complete ignorance on δ_{CP} and using no other information to lift the ϑ_{13}-δ_{CP} ambiguity...



A bit unfair (2y only)...

Even worse for higher $\Delta m^2_{21}/\Delta m^2_{31}$



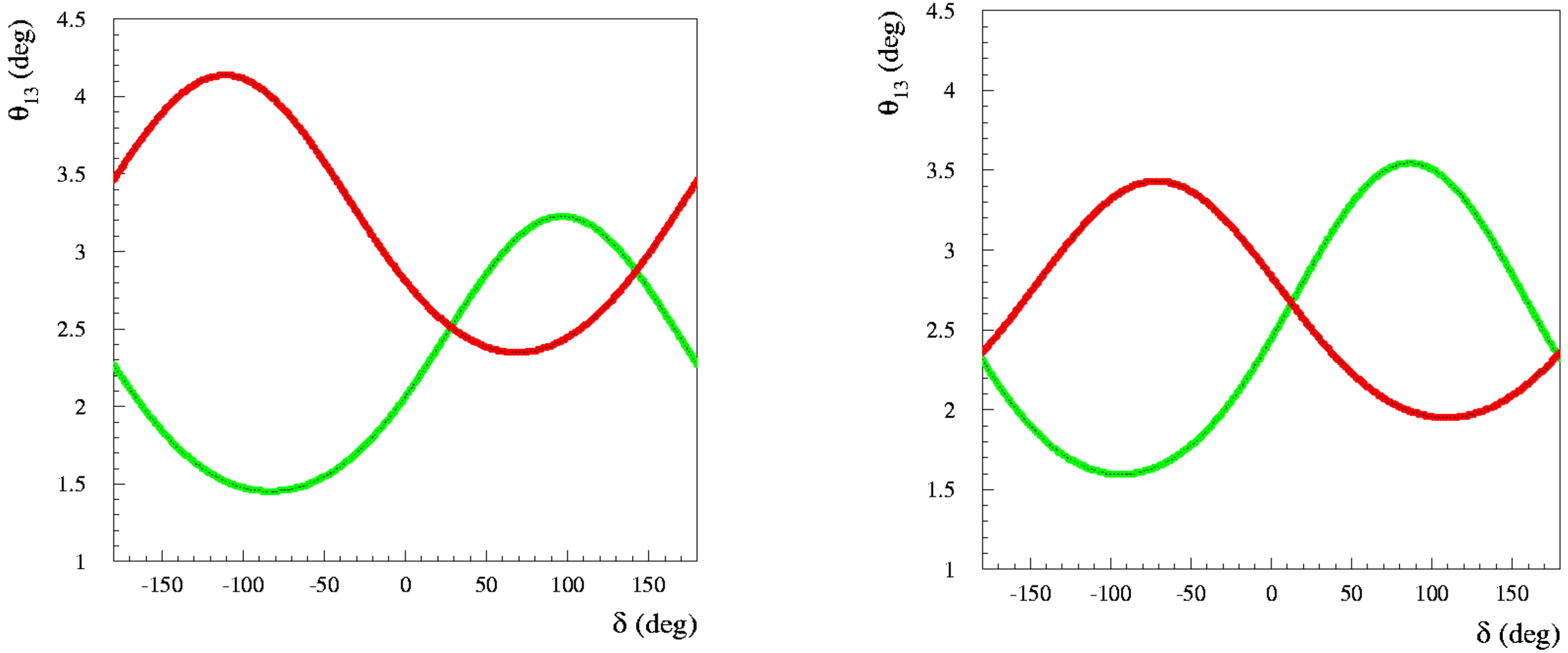
HLMA solution
(unfavored now)

In case of null result, JPARC-Ph1 <u>must</u> foresee an antineutrino run to fully exploit its outstanding sensitivity. Otherwise, we will not learn much more than CNGS!!

The case of NuMI-OA in anti-ν mode

An alternative: running NuMI-OA directly in anti-ν mode.

Chance to make the big discovery even starting later than JPARC-Ph1.



Normal hierarchy

Inverted hierarchy

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

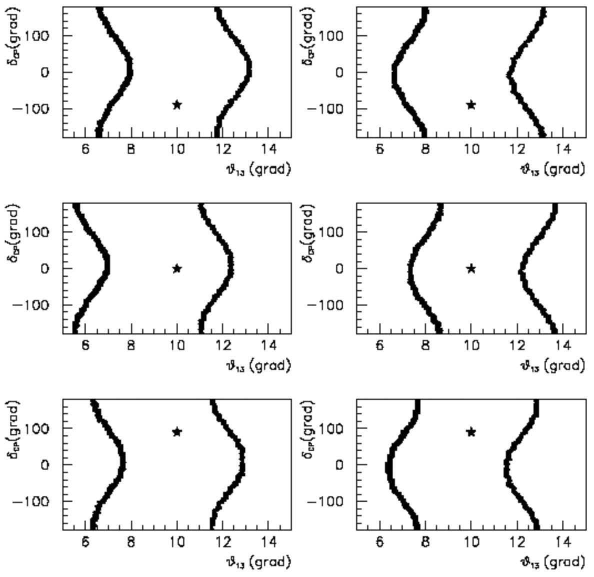
🟩 **JPARC-Ph1 in ν mode (5y)**

Just the opposite: $\vartheta_{13} > 7^0$

Accessible (3σ) to MINOS/ICARUS/OPERA at ANY value of δ

The situation before the first JPARC-Ph1 results (3y)?

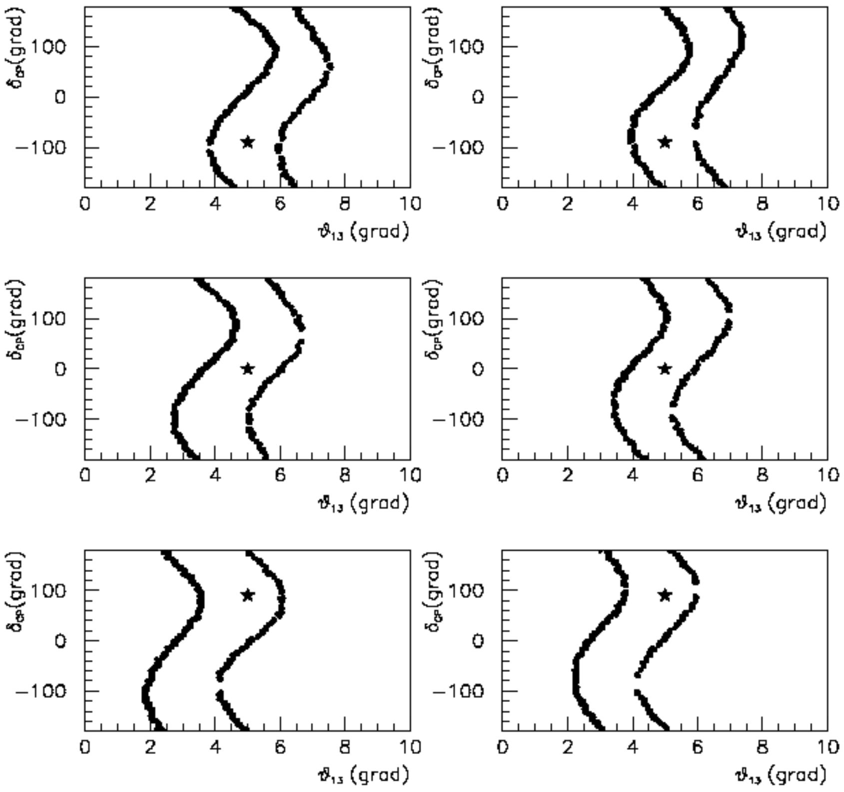
$\theta_{13}\vert_{true}$	$\theta_{13}\vert_{min}$	$\theta_{13}\vert_{max}$	
1°	---	5.5°	---
2.5°	---	5.8°	---
5.0°	---	7.0°	---
7.5°	1.2°	11.4°	(7.5+3.9-6.3)°
10°	5.6°	13.7°	(10.+3.7-4.4)°



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

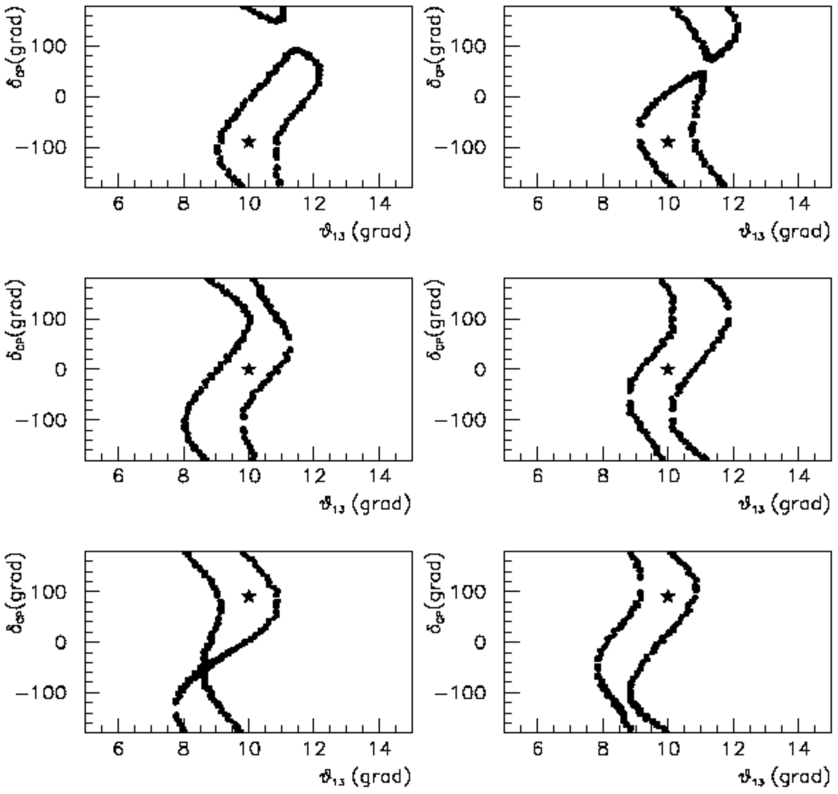
After JPARC-Ph1 data taking

θ_{13}=5°



Δm²<0 Δm²>0

θ_{13}=10°

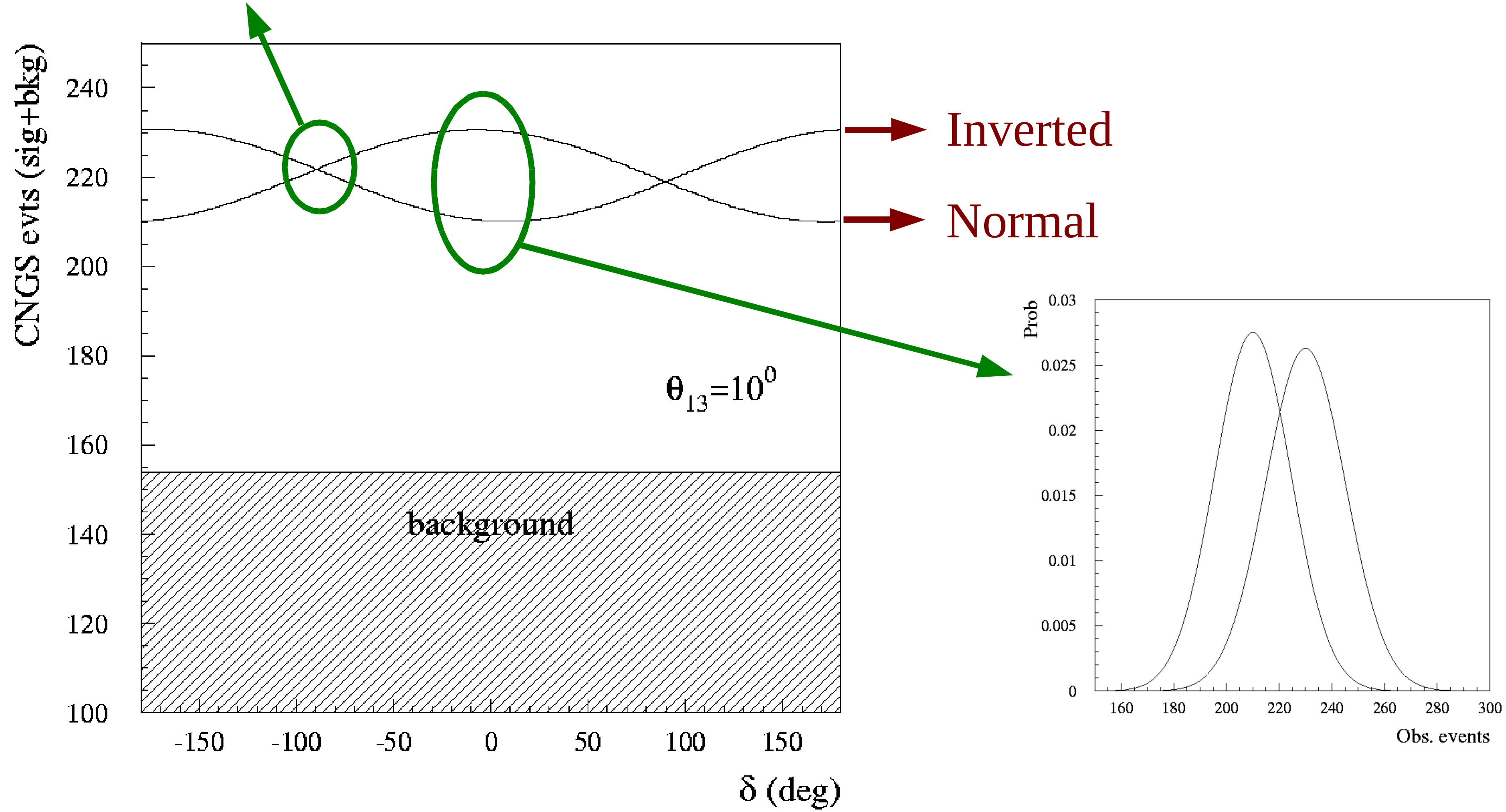


Δm²<0 Δm²>0

5y JPARC + 8y CNGS

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...

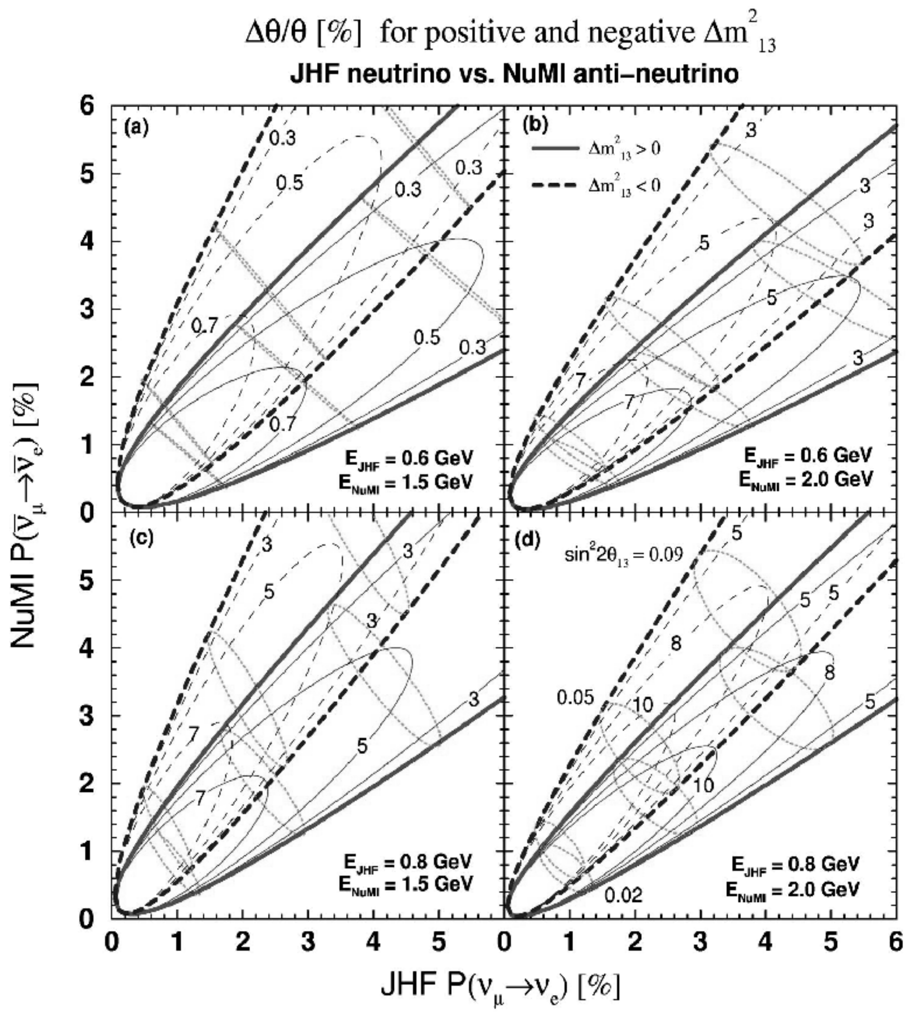
The intermediate case: about $4^0 < \vartheta_{13} < 7^0$

Off peak will not contribute (null result)

Retain classical results of:

- V.Barger et al., Phys.Lett. B560 (2003) 75
- P.Huber et al., Nucl.Phys. B654 (2003) 3
- H.Minakata et al., Phys.Rev. D68 (2003) 013010

- Better run JPARC in ν mode and NuMI-OA in anti-ν mode for high precision in the ϑ_{13}-δ_{CP} plane
- Run both of them in ν mode to focus on mass hierarchy



Conclusions

- Null result at JPARC-Ph1 : **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-nu choice (done after the nu 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 + JPARC-Ph1 + NuMI-OA:
  - to constrain (δ–ϑ_{13})
  - to determine the sign of Δm^2_{atm}

- $4^0 < \vartheta_{13} < 7^0$ **Another great season for Japanese neutrino physics!** Signal seen at JPARC. NuMI-OA contribute to precision measurement of (δ–ϑ_{13}) in anti-nu mode, sign Δm^2_{atm} in neutrino mode