Reactor measurement of θ_{13} and its complimentarity to LBL experiments

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1. Introduction

Oscillation parameters in $N_\nu = 3$ framework

$$(\underbrace{\Delta m^2_{21}, \theta_{12}}; \underbrace{|\Delta m^2_{32}|, \theta_{23}}; \underbrace{\text{sign}(\Delta m^2_{32}), \theta_{13}, \delta})$$

⇧ $\nu_\odot + \nu_{KamLAND}$

$$\begin{pmatrix} \Delta m^2_{21} \sim O(10^{-5} eV^2) \\ \sin^2 2\theta_{12} \sim 0.8 \end{pmatrix}$$

KamLAND ⇩ LMA

⇧ ν_{atm}

$$\begin{pmatrix} |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3} eV^2 \\ \sin^2 2\theta_{23} \simeq 1.0 \end{pmatrix}$$

⇧ things to do in the future

Final goal in ν oscillation physics is measurement of $\not{CP}$ (only possible for LMA)

$$\text{Prob}(\not{CP}) \propto J = \frac{c_{13}}{8} \underbrace{\sin 2\theta_{12}}_{\sim\sqrt{0.8}} \underbrace{\sin 2\theta_{13}}_{\lesssim\sqrt{0.1}\ \text{unknown}} \underbrace{\sin 2\theta_{23}}_{\simeq 1.0} \underbrace{\sin\delta}_{\text{unknown}}$$

As a first step, we need to know the magnitude of $\sin 2\theta_{13}$

	parameter degeneracy	sensitivity
Long Base Line exp.	some	$\sin^2 2\theta_{13}$(JHF) $\gtrsim O(10^{-3})$
Reactor exp.	none	$\sin^2 2\theta_{13} \gtrsim O(10^{-2})$

2. Reactor measurement of θ_{13}

F. Suekane, K. Inoue) are thinking of the possibity to measure θ_{13} by a reactor experiment at Kashiwazaki - Kariwa Nuclear Power Plant.

Experimental Conditions for θ_{13}

Optimization of Baseline

SK Result: $\Delta \overline{m}^2_{23} \approx 2.5 \times 10^{-3} eV^2$

$$\int f_\nu(E)\sigma(E)\sin^2\frac{\Delta m^2 L}{4E}dE = \max$$

$\Downarrow$

L~1.7km

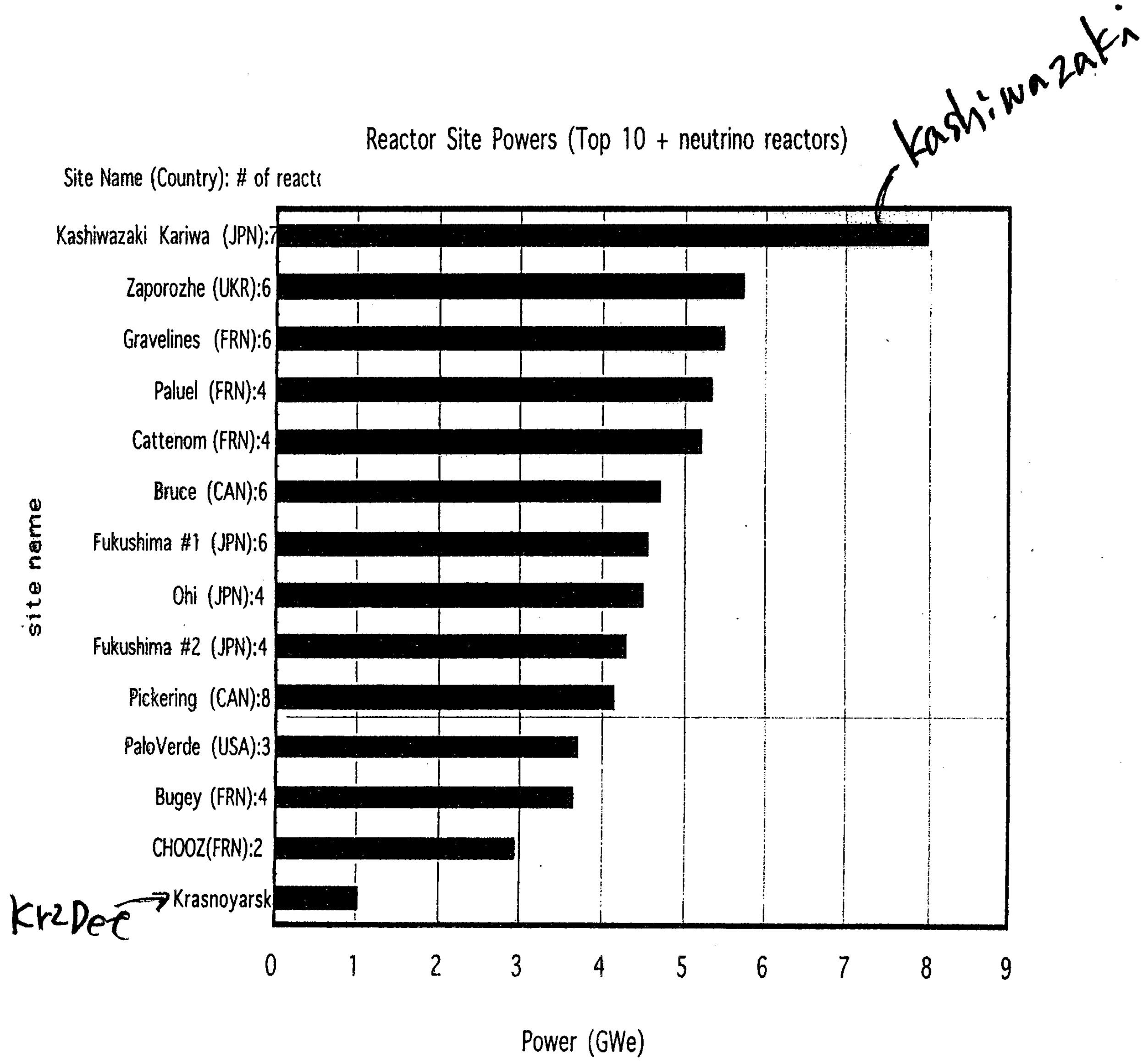
$\Downarrow$

N_ν~150/year/target-ton/GW_{th}

1% stat. error/year

$\Downarrow$

M_{Target}*$P_{Reactor}$=70[ton*GW_{th}]



(Overvies of the World Nuclear Power, Nuclear Training Centre Jozef Stefan Institute (Slovenia); 17.Sept.2001)

Kashiwazaki-Kariwa NPP (24.3GW_{th})

⇓

Largest Nuclear Reactor Site in the World.

Net M_{Traget}~5tons for 80% reactor and 70% detection efficiency (=Just CHOOZ size).

Issues at CHOOZ and solutions

(1) Systematic Error=2.7%

Comes from {
rate prediction: 2.3%
detection efficiency:1.5%

<u>Solution</u>:

Identical Front and Far Detectors

⇓

most of the systematics cancel out

How good is the cancellation?

Study BUGEY(3 identical detectors) case
Bugey detectors are modular type
(Intrinsically worse systematics than bulk type)

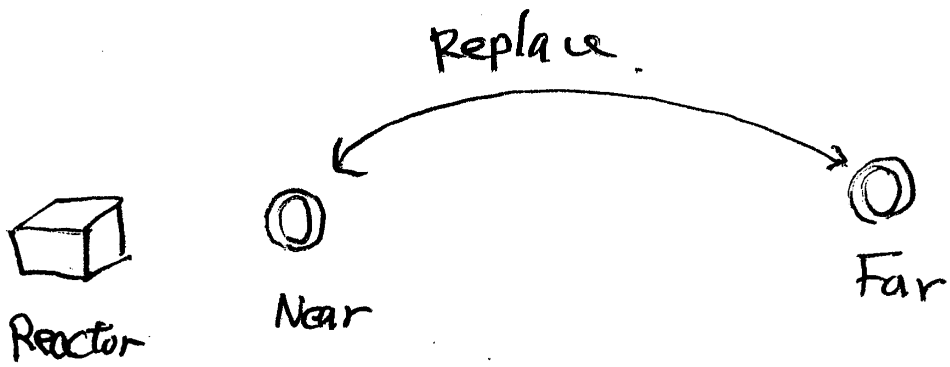
Example,

	BUGEY Case: (modular detectors)	CHOOZ projection: (same fraction assumed)
σf_{ν}	2.8%→0%	2.1%→0%
N_p	1.9%→0.6%	0.8%→0.3%
L^2	0.5%→0.5%	---
ε	3.5%→1.7%	1.5%→0.7%
Total	4.9% → 2%	2.7%→0.8%

(Kr2Det expects $\sigma_{sys} = 0.5\%$)

CHOOZ detector is (in principle) Movable.

If front and far detectors are exchanged during the experiment, the individualities of the detectors are canceled and it is expected that the systemetic error is further reduced to~ 0.5%.



We assume here :

24.3 GWth

80% operation efficiency

70% detection efficiency @ ($L = 1.7$ km, $L = 0.3$ km)

energ spectrum: 14 bins of 0.5 MeV $\Delta m^2_{32} = 2.5 \times 10^{-3} eV^2$

Results :

in the negative case

Excluded region (analysis w/ d.o.f. = 1)

$\sigma_{sys} = 2\%$, 5 t·yr

$\sin^2 2\theta_{13} \lesssim 0.027$

$\sigma_{sys} = 0.8\%$, 20 t·yr

$\sin^2 2\theta_{13} \lesssim 0.013$

in the affirmative case

The experimental error in $\sin^2 2\theta_{13}$ is almost independent of the central value

$\sigma_{sys} = 2\%$, 5 t·yr

$\delta(\sin^2 2\theta_{13}) = 0.034$

$\sigma_{sys} = 0.8\%$, 20 t·yr

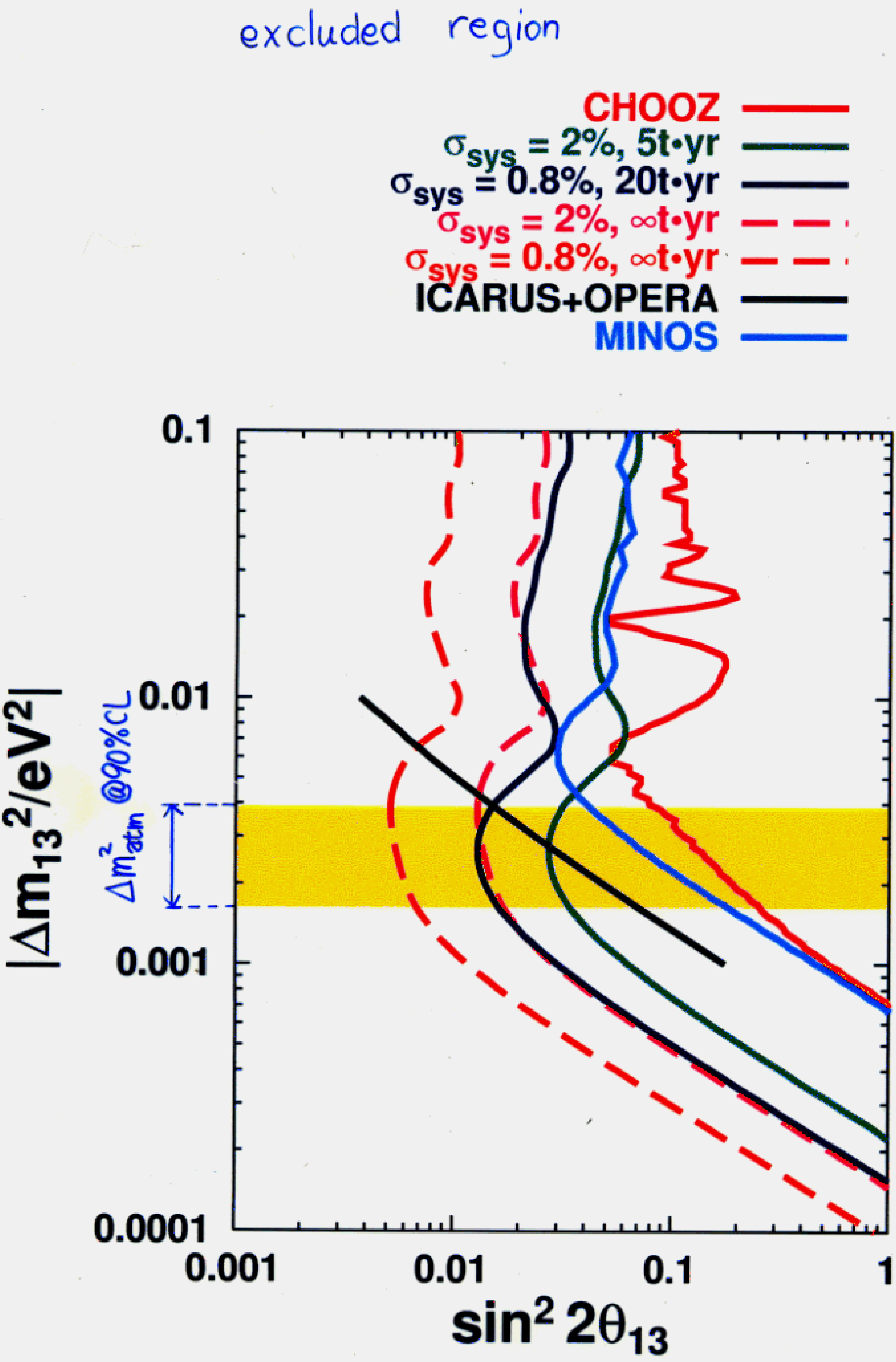
$\delta(\sin^2 2\theta_{13}) = 0.015$

} d.o.f. = 2

If JHF determines Δm^2_{32} to $10^{-4} eV^2$ then analysis becomes approximately 1-dimensional (w.r.t. $\sin^2 2\theta_{13}$ only)

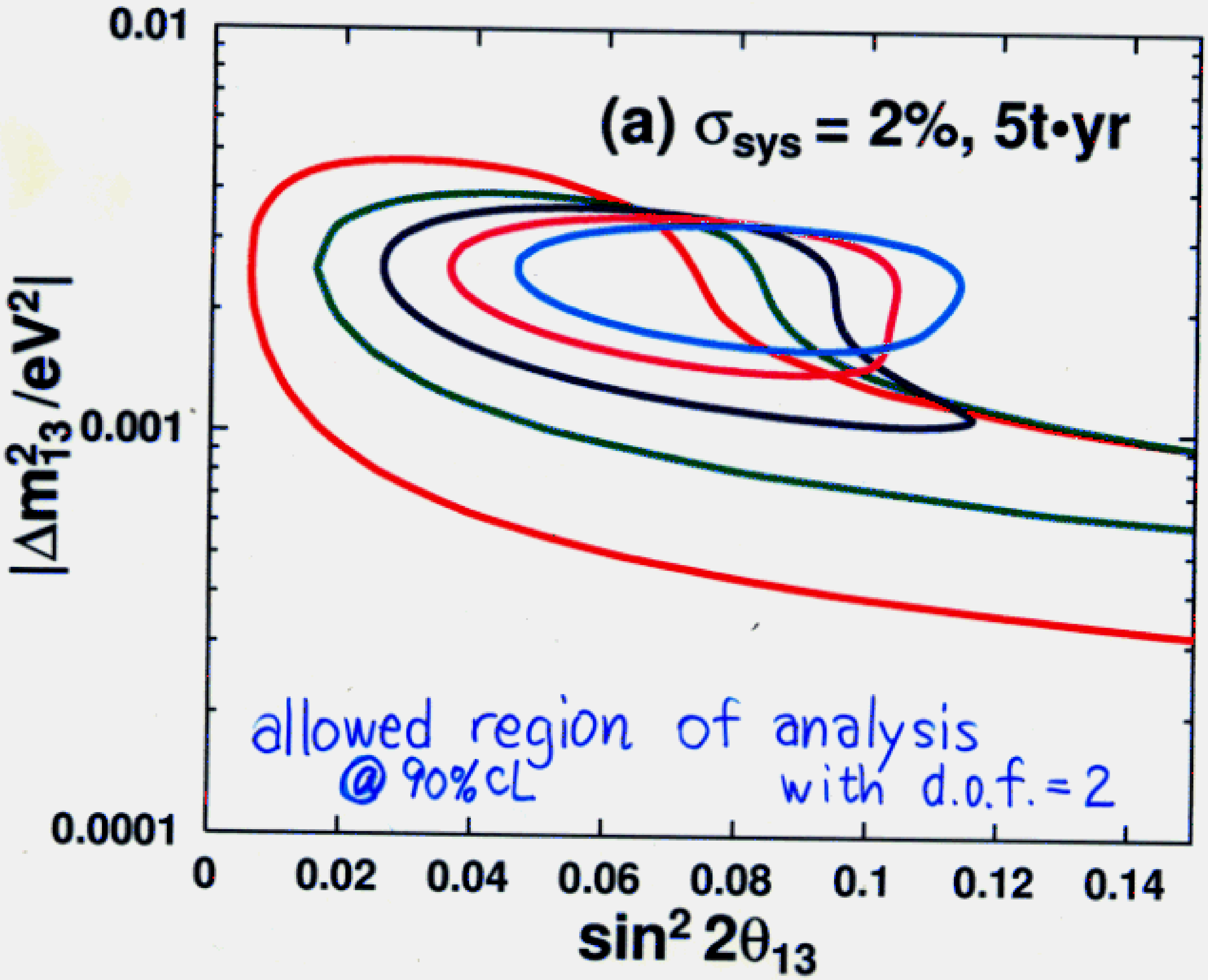
→ $\sigma_{sys} = 0.8\%$, 20 t·yr

$\delta(\sin^2 2\theta_{13}) = 0.012$ (d.o.f. = 1)

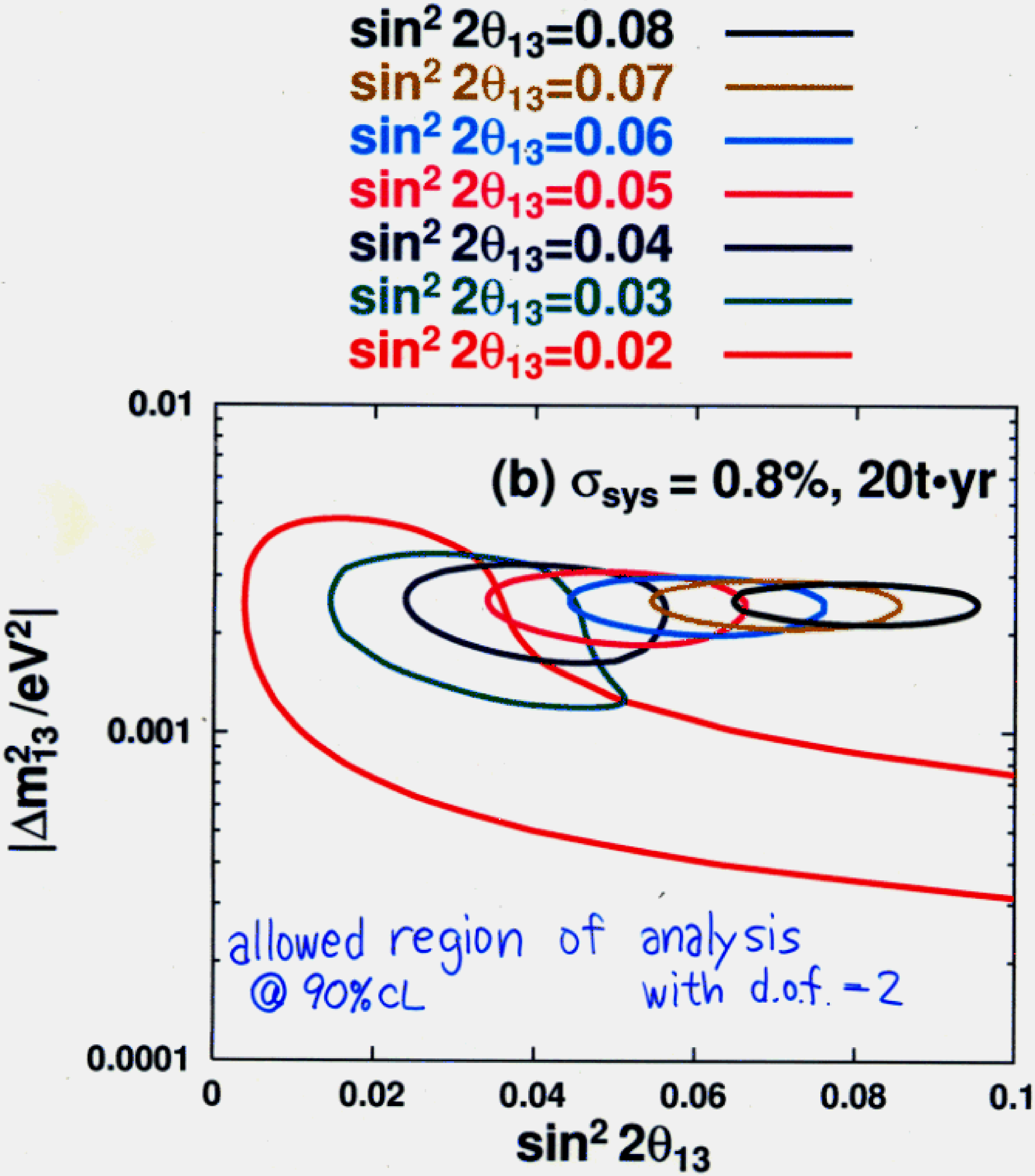

excluded region
CHOOZ
σsys = 2%, 5t•yr
σsys = 0.8%, 20t•yr
σsys = 2%, ∞t•yr
σsys = 0.8%, ∞t•yr
ICARUS+OPERA
MINOS
0.1
0.01
0.001
0.0001
1
$|\Delta m_{13}^2/eV^2|$
Δm^2_{atm} @90%CL
$\sin^2 2\theta_{13}$

$\delta(\sin^2 2\theta_{13}) = 0.034$

$\sin^2 2\theta_{13}=0.08$ (blue)
$\sin^2 2\theta_{13}=0.07$ (red)
$\sin^2 2\theta_{13}=0.06$ (black)
$\sin^2 2\theta_{13}=0.05$ (green)
$\sin^2 2\theta_{13}=0.04$ (red)



$\delta(\sin^2 2\theta_{13}) = 0.015$ → 0.012 (d.o.f.=1)



3. Parameter degeneracy

Measurement of θ_{13} can be done naively by LBL experiments:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

$$|U_{\mu 3}|^2 = C_{13}^2 S_{23}^2$$

$$P(\nu_\mu \to \nu_e) \simeq S_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

From these channels, one can naively determine θ_{13} & θ_{23}.

However, there are 3 kinds of parameter degeneracy:

(1) intrinsic $(\delta, \theta_{13}), (\delta', \theta_{13}')$ — Burguet-Castell et al ('01)

(2) sign (Δm_{32}^2) — Minakata-Nunokawa ('01)

(3) $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ — Fogli-Lisi PRD54 ('96) 3667; Barger-Marfatia-Whisnant ('02)

→ 8-fold degeneracy

Hereafter I assume that accelerator beams are approximately <u>monochromatic</u>.

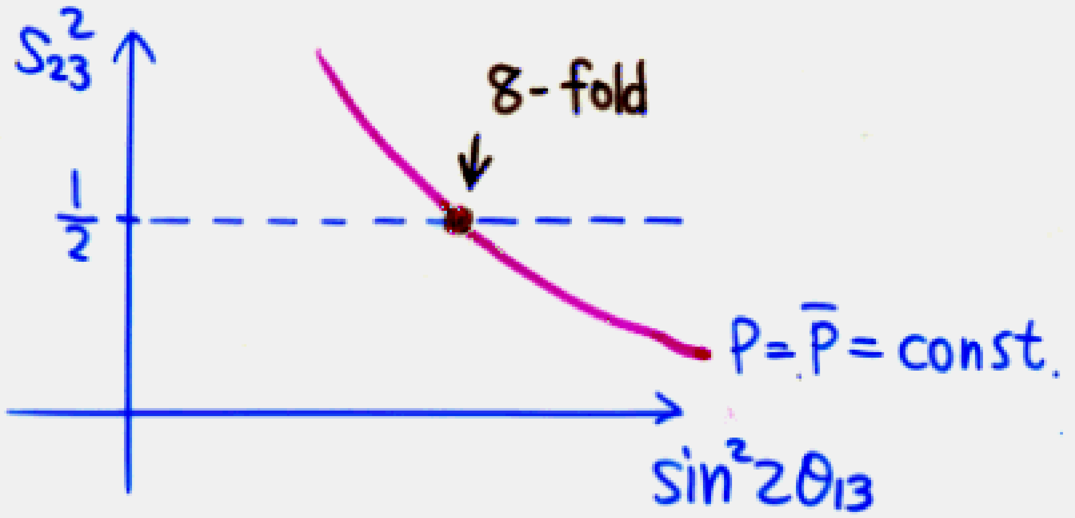
Also experimental errors are not taken into account.

8-fold degeneracy in the $(s_{23}^2, \sin^2 2\theta_{13})$ plane

Even if $P \equiv P(\nu_\mu \to \nu_e)$ and $\bar{P} \equiv P(\bar{\nu}_\mu \to \bar{\nu}_e)$ are given, there are 8 solutions.

① If $\theta_{23} = \frac{\pi}{4}$, $A \equiv \sqrt{2} G_F N_e = 0$, $\Delta m_{21}^2 = 0$

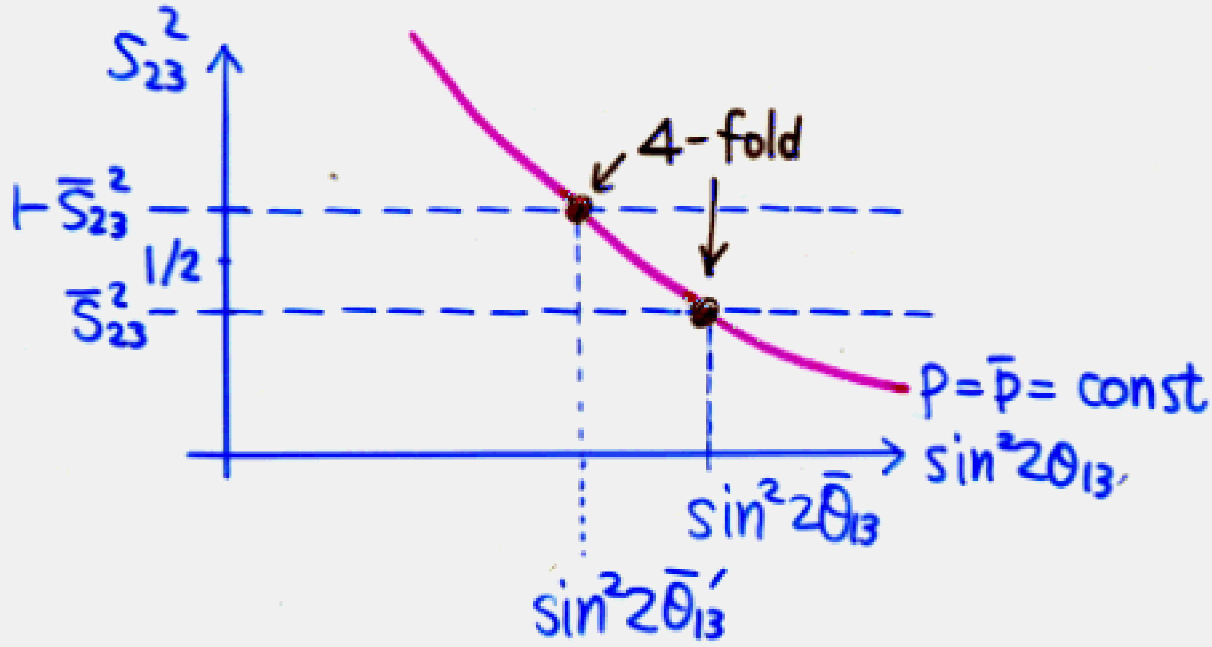
then all the 8 solutions are degenerated.



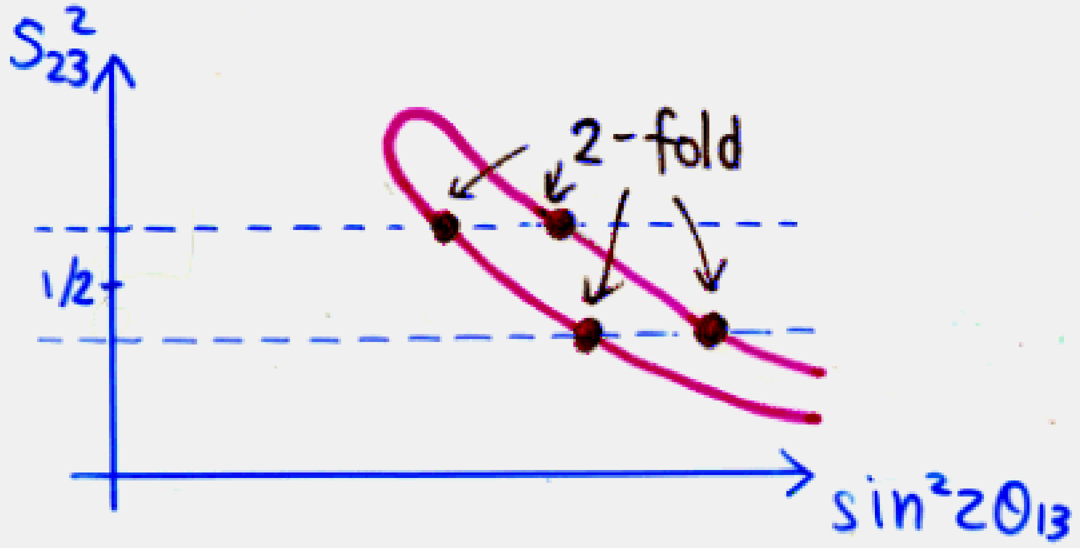
All the solutions give the same $\sin^2 2\theta_{13}$.

② If $\theta_{23} \neq \frac{\pi}{4}$, $A = 0$, $\Delta m_{21}^2 = 0$

then there 2 sets of 4-fold solutions which give 2 different values of $\sin^2 2\theta_{13}$.

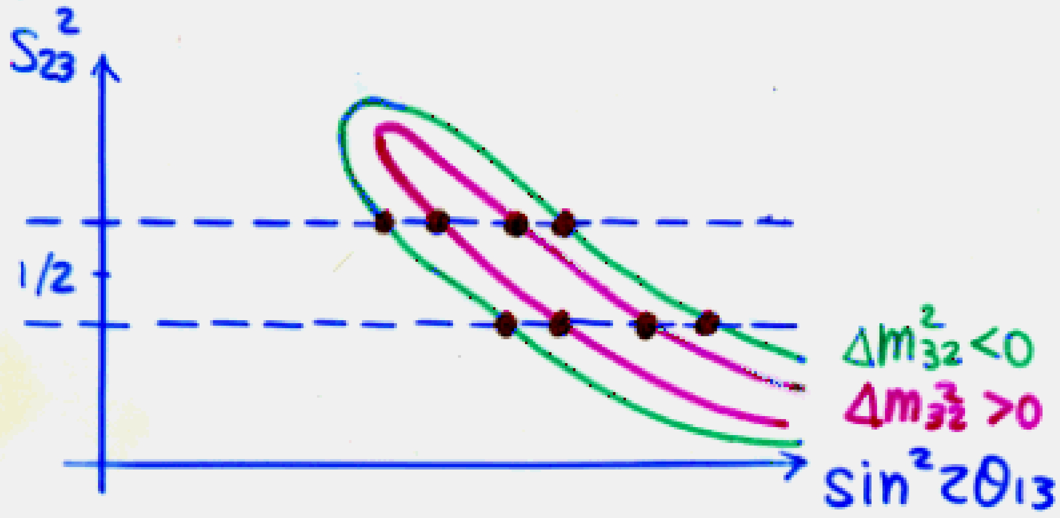


③ If $\theta_{23} \neq \frac{\pi}{4}$, $A=0$, $\Delta m^2_{21} \neq 0$
then there 4 sets of 2-fold solutions which give 4 different values of $\sin^2 2\theta_{13}$.



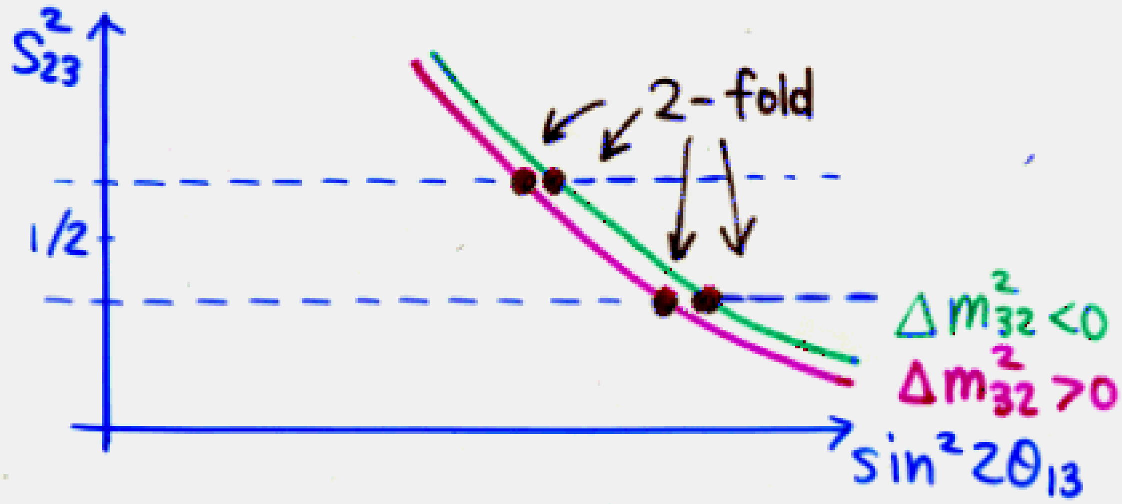
(The lines are given by :
$P = \text{const}$,
$\bar{P} = \text{const}'$)

④ If $\theta_{23} \neq \frac{\pi}{4}$, $A \neq 0$, $\Delta m^2_{21} \neq 0$
then degeneracy of all the 8 solutions is lifted, and they all give different values of $\sin^2 2\theta_{13}$.

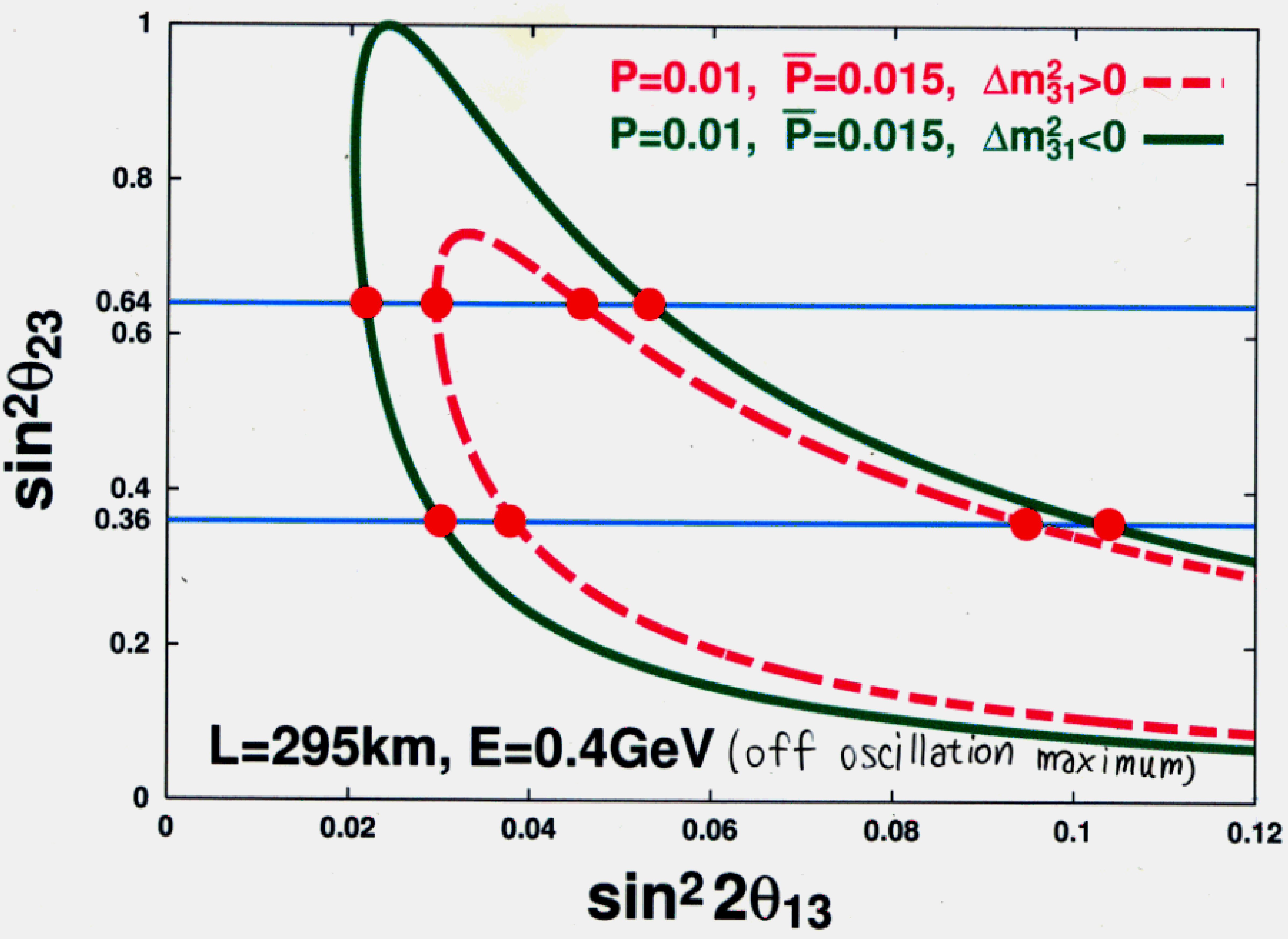


④' If $\theta_{23} \neq \frac{\pi}{4}$, $A \neq 0$, $\Delta m^2_{21} \neq 0$ done @ Oscillation Maximum, there is intrinsic degenercy, leaving 4 sets of 2-fold solutions.

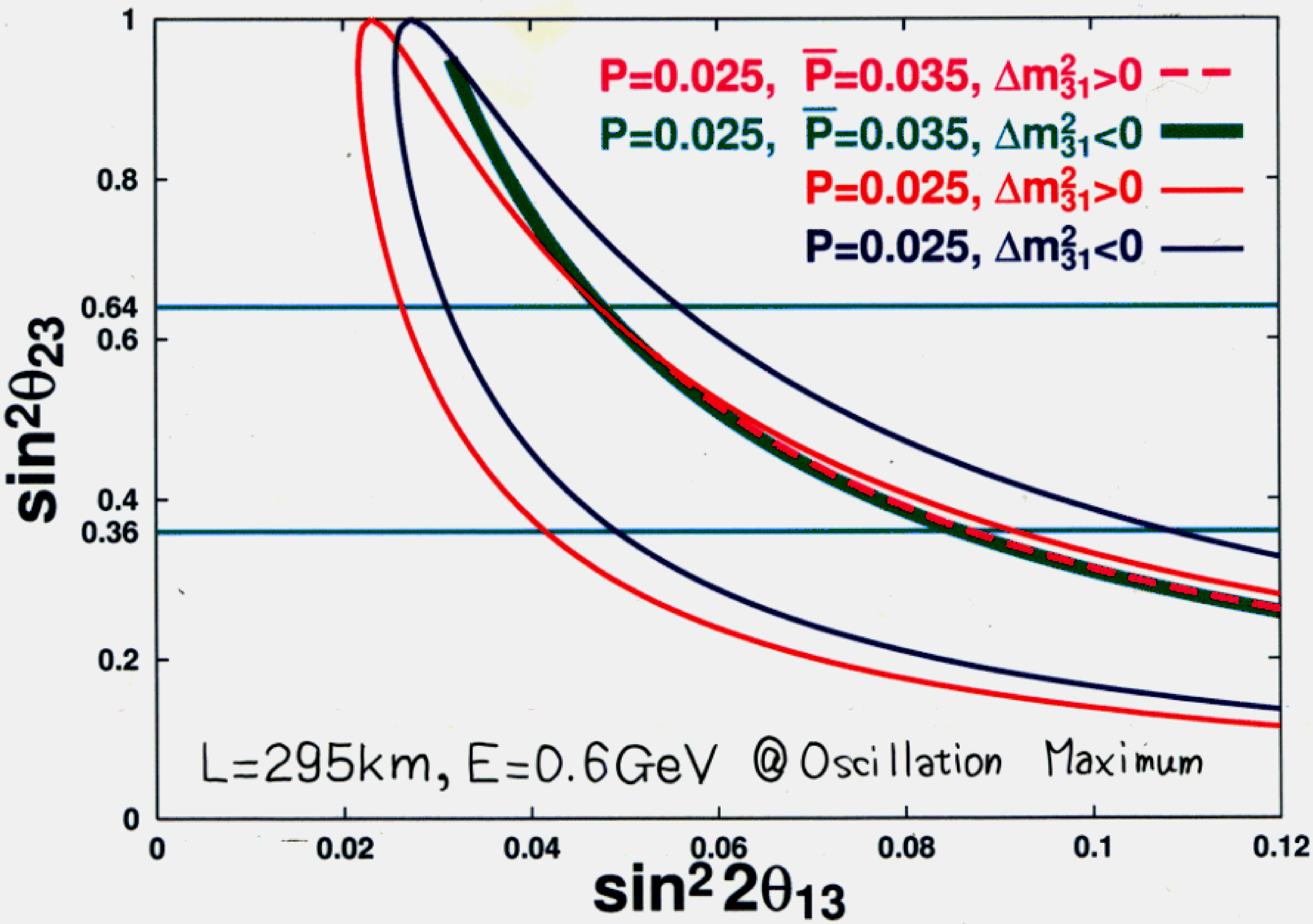
$$\frac{\Delta m^2_{32} L}{4E} = \frac{\pi}{2}$$



In the JHF case, the 2 lines are close, so there are approximately only 2 different values of $\sin^2 2\theta_{13}$.



P=0.01, $\overline{P}$=0.015, $\Delta m^2_{31}>0$
P=0.01, $\overline{P}$=0.015, $\Delta m^2_{31}<0$
L=295km, E=0.4GeV (off oscillation maximum)
$\sin^2\theta_{23}$
$\sin^2 2\theta_{13}$
1
0.8
0.64
0.6
0.4
0.36
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12

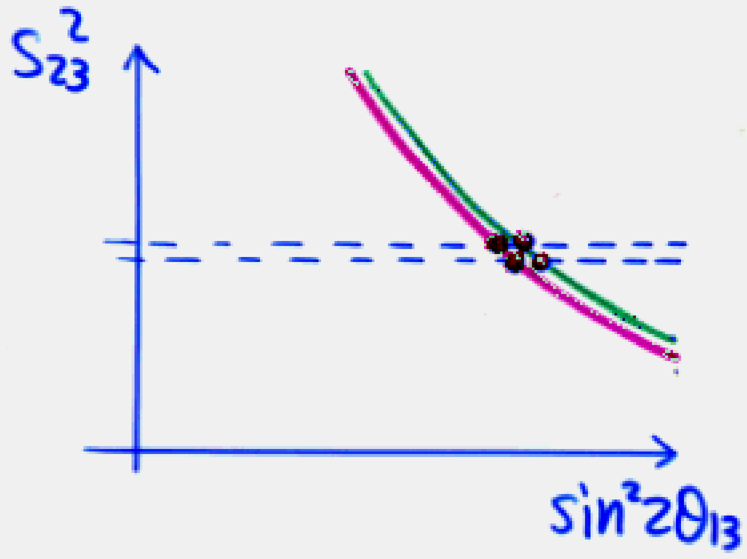

P=0.025, $\overline{P}$=0.035, $\Delta m^2_{31}>0$
P=0.025, $\overline{P}$=0.035, $\Delta m^2_{31}<0$
P=0.025, $\Delta m^2_{31}>0$
P=0.025, $\Delta m^2_{31}<0$
L=295km, E=0.6GeV @Oscillation Maximum
$\sin^2\theta_{23}$
$\sin^2 2\theta_{13}$
1
0.8
0.64
0.6
0.4
0.36
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12

At JHF we will know that θ_{23} satisfies either of the followings :

(A) $|1 - \sin^2 2\theta_{23}| <$ a few $\times 10^{-2}$

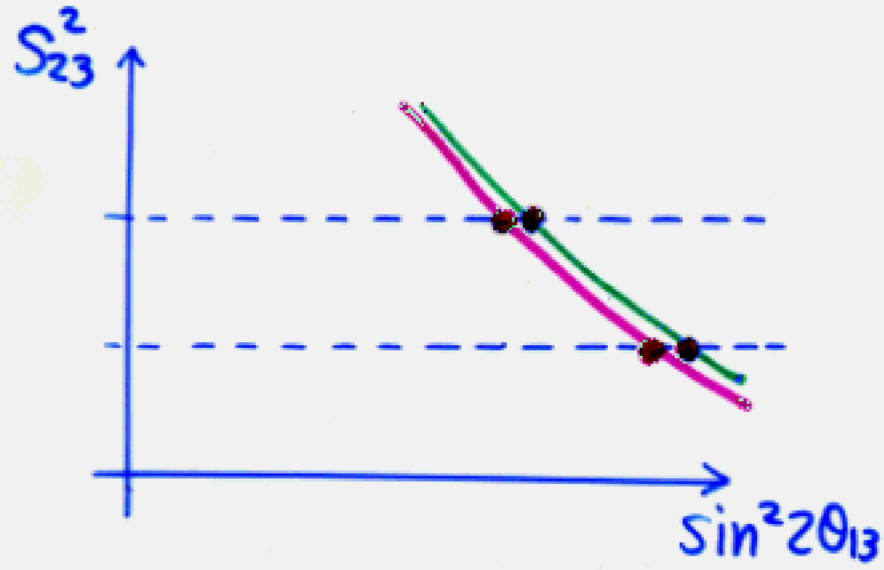
(B) $|1 - \sin^2 2\theta_{23}| \geq$ a few $\times 10^{-2}$

(A) With JHF @ OM we have the situation like



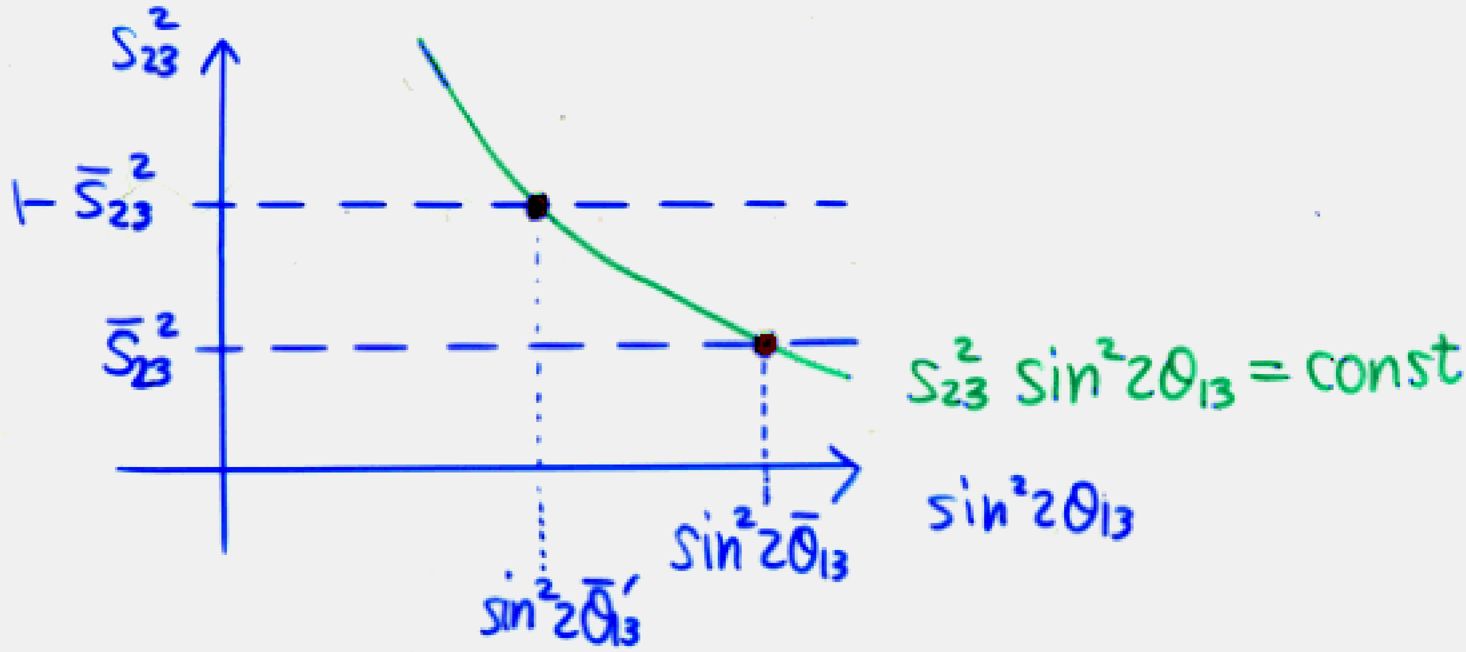
So the precise determination of $\sin^2 2\theta_{13}$ for the true solution is difficult, but the values of $\sin^2 2\theta_{13}$ for the 4 solutions are approximately the same.

(B) With JHF @ OM we have



The values of $\sin^2 2\theta_{13}$ for $\theta_{23} < \frac{\pi}{4}$ and for $\theta_{23} > \frac{\pi}{4}$ are quite different and it may be possible to determine $\sin^2 2\theta_{13}$ for the true solution by a reactor experiment.

We can estimate the ratio $\sin^2 2\theta_{13}' / \sin^2 2\theta_{13}$ assuming $A=0$, $\Delta m^2_{21}=0$ (this is not a bad approximation for JHF@OM):



$$(1-\bar{s}^2_{23})\sin^2 2\bar{\theta}_{13}' = \bar{s}^2_{23}\sin^2 2\bar{\theta}_{13}$$

$$\therefore \sin^2 2\bar{\theta}_{13}' = \tan^2\bar{\theta}_{23}\sin^2 2\bar{\theta}_{13}$$

relative errors

experimental ($\sigma_{sys}=0.8\%$, 20t·yr, d.o.f. = 1)

$$\frac{\delta(\sin^2 2\theta_{13})}{\sin^2 2\theta_{13}} = \frac{0.012}{\sin^2 2\theta_{13}}$$

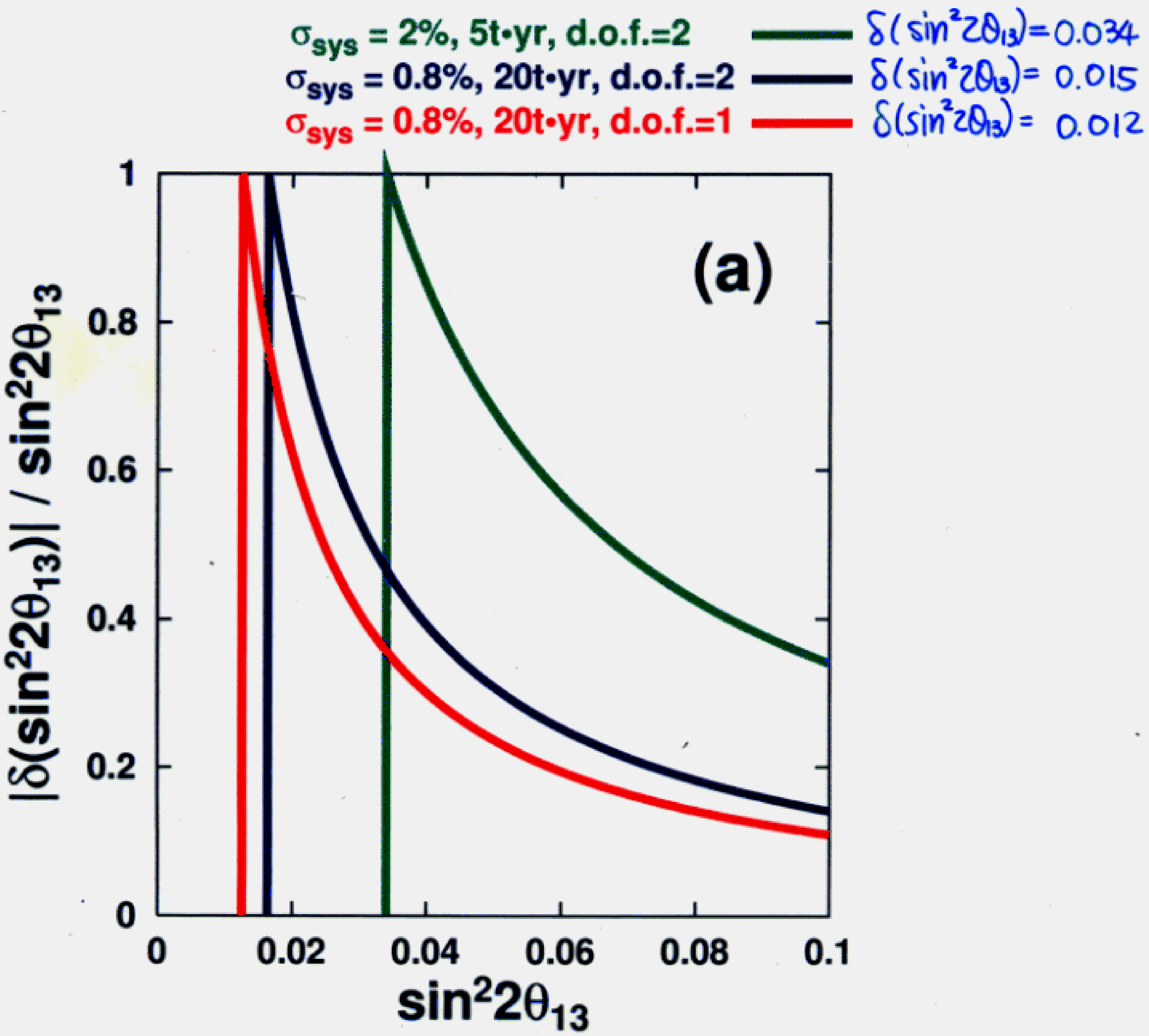
uncertainty due to $\theta_{23} \leftrightarrow \frac{\pi}{2}-\theta_{23}$ degeneracy

$$\frac{\delta(\sin^2 2\theta_{13})}{(\sin^2 2\theta_{13})_{average}} \equiv \frac{|\sin^2 2\theta_{13}' - \sin^2 2\theta_{13}|}{\frac{1}{2}(\sin^2 2\theta_{13}' + \sin^2 2\theta_{13})}$$

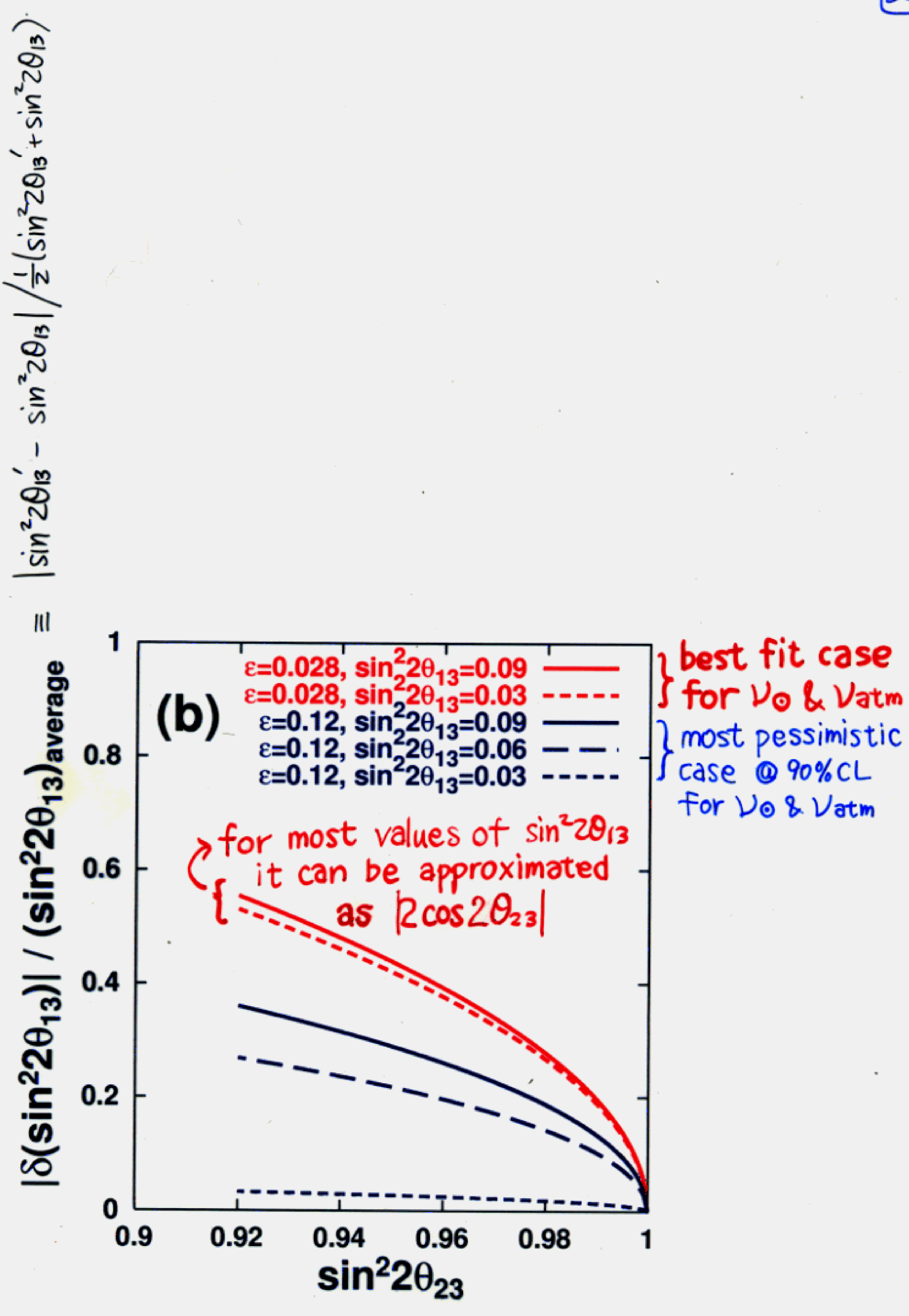
$$\simeq 2\,\frac{|t^2_{23}-1|}{t^2_{23}+1} = 2|\cos 2\theta_{23}|$$

Thus if $\dfrac{0.012}{\sin^2 2\theta_{13}} < 2|\cos 2\theta_{23}|$

then a reactor experiment may be able to determine $\sin^2 2\theta_{13}$ & s^2_{23} for the true solution.



σ_{sys} = 2%, 5t•yr, d.o.f.=2
σ_{sys} = 0.8%, 20t•yr, d.o.f.=2
σ_{sys} = 0.8%, 20t•yr, d.o.f.=1
$\delta(\sin^2 2\theta_{13})=0.034$
$\delta(\sin^2 2\theta_{13})=0.015$
$\delta(\sin^2 2\theta_{13})=0.012$
(a)
$|\delta(\sin^2 2\theta_{13})| / \sin^2 2\theta_{13}$
$\sin^2 2\theta_{13}$
0
0.2
0.4
0.6
0.8
1
0.02
0.04
0.06
0.08
0.1



$|\sin^2 2\theta_{13}' - \sin^2 2\theta_{13}| / \frac{1}{2}(\sin^2 2\theta_{13}' + \sin^2 2\theta_{13}) \equiv$
$|\delta(\sin^2 2\theta_{13})| / (\sin^2 2\theta_{13})_{average}$
(b)
ε=0.028, $\sin^2 2\theta_{13}$=0.09
ε=0.028, $\sin^2 2\theta_{13}$=0.03
ε=0.12, $\sin^2 2\theta_{13}$=0.09
ε=0.12, $\sin^2 2\theta_{13}$=0.06
ε=0.12, $\sin^2 2\theta_{13}$=0.03
best fit case for $\nu_\odot$ & ν_{atm}
most pessimistic case @ 90%CL for $\nu_\odot$ & ν_{atm}
for most values of $\sin^2 2\theta_{13}$ it can be approximated as $|2\cos 2\theta_{23}|$
0
0.2
0.4
0.6
0.8
1
0.9
0.92
0.94
0.96
0.98
1
$\sin^2 2\theta_{23}$

4. Summary

Reactor experiment on θ_{13}

* { much cheaper / may be done earlier } than JHF

* sensitivity

$\sin^2 2\theta_{13} \gtrsim 0.013$ for $\sigma_{sys} = 0.8\%$, 20 ton·yr (d.o.f.=1) @ KK-NPP

* free from degeneracy

if $\sin^2 2\theta_{23} \lesssim 0.96$ & $\sin^2 2\theta_{13} \gtrsim 0.06$

then a reactor experiment may be able to determine $\sin^2 2\theta_{13}$ & s^2_{23} for the true solution.