T2KK solves all the neutrino parameter degeneracy

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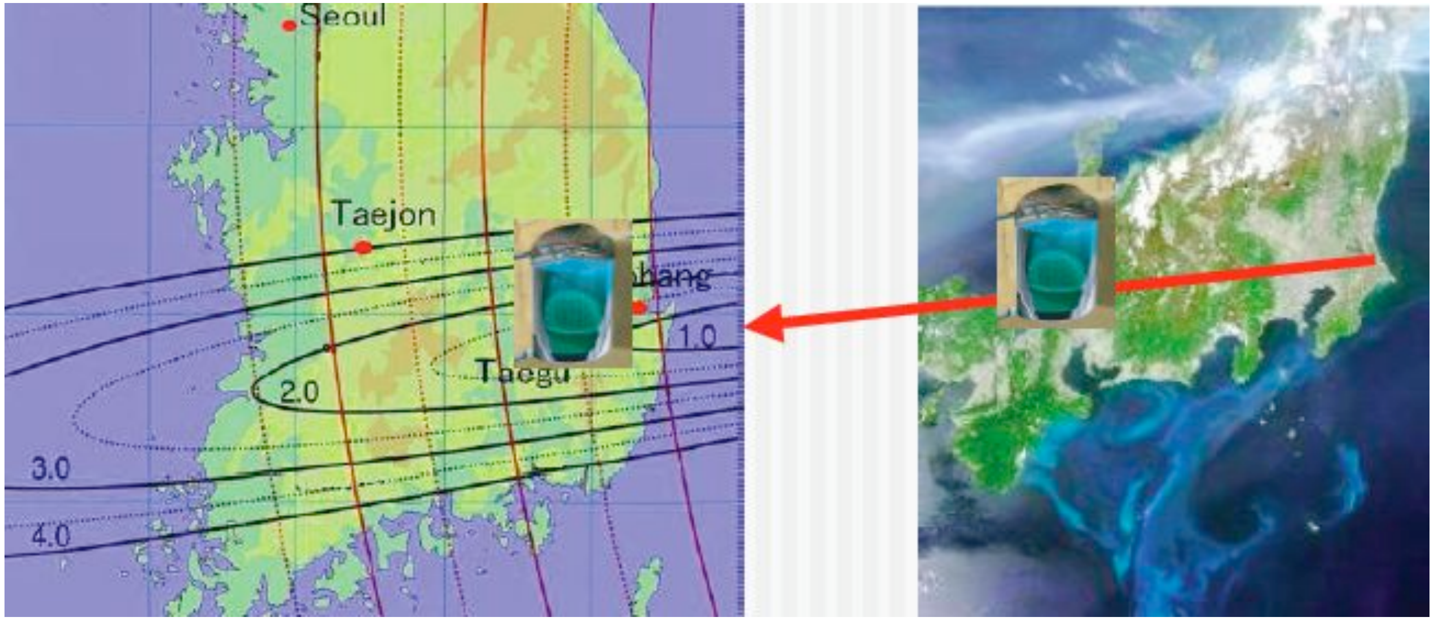
T2KK; Tokai-to-Kamioka-Korea identical two-detector complex

Ishitsuka et al. 05, Kajita et al. to appear

- T2KK (without reactor) solves 8-fold parameter degeneracy!



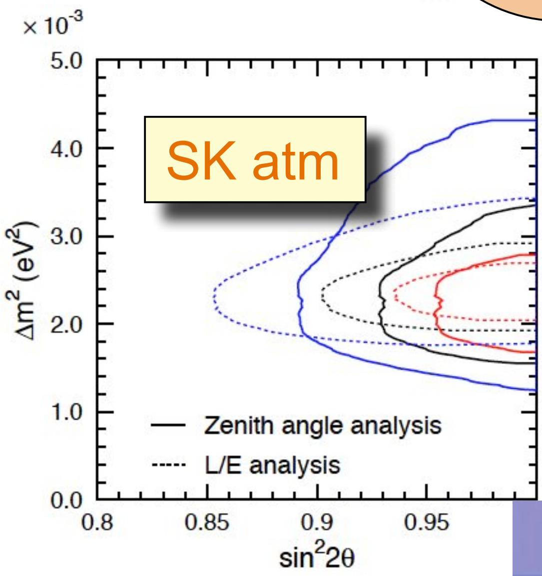
Exploring the MNS matrix

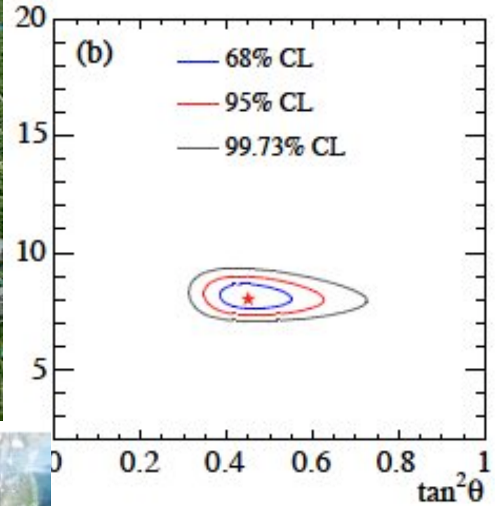
$\nu_\alpha = U_{\alpha i}\, \nu_i$

Atm + accel ν =>

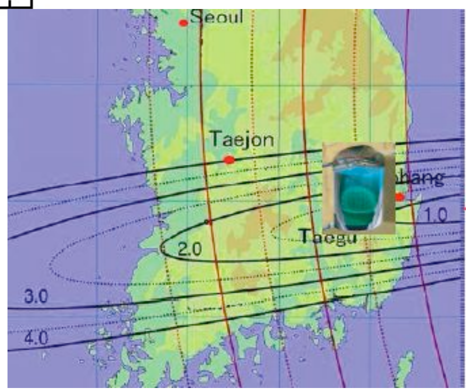
$$U \equiv U_{\rm MNS} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \mathrm{diag}(1, e^{i\beta}, e^{i\gamma})$$

<= solar + reactor ν

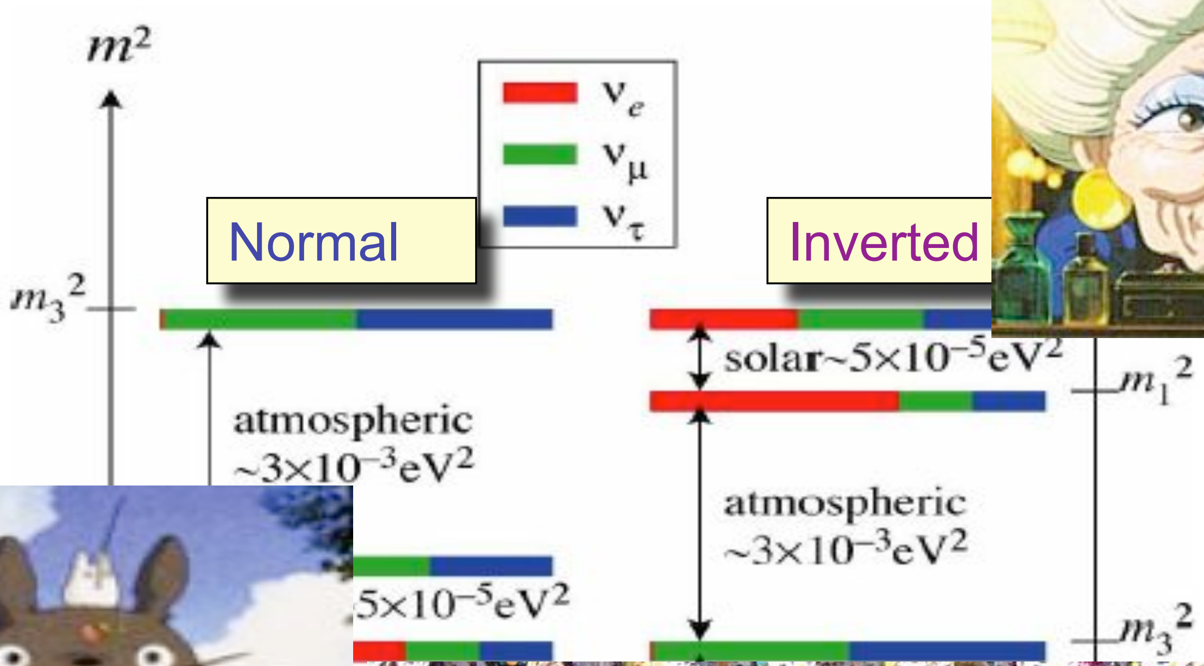




solar+KamLAND

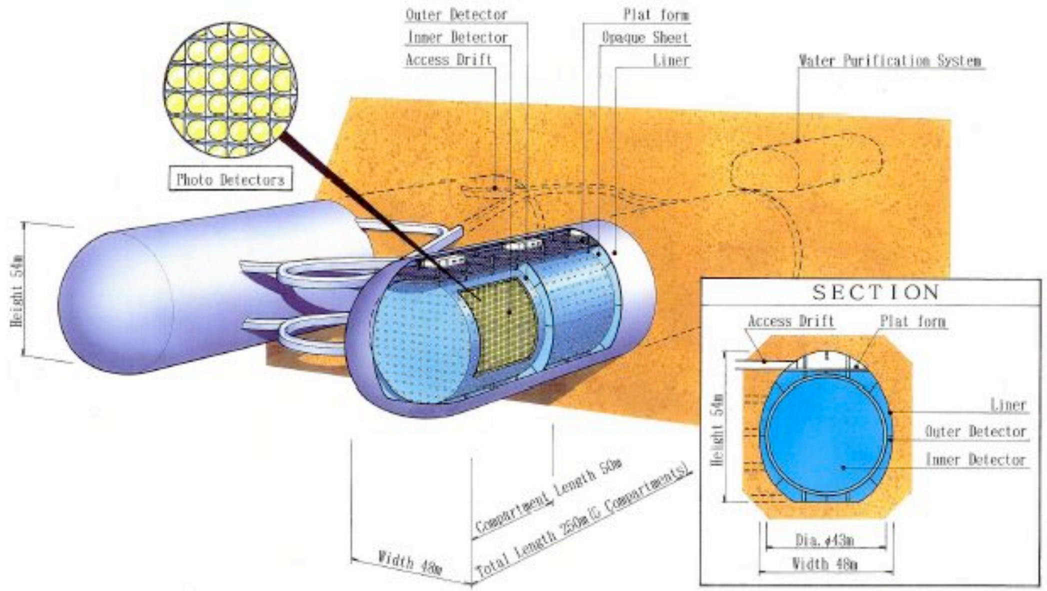


ν mass hierarchy & absolute mass scale

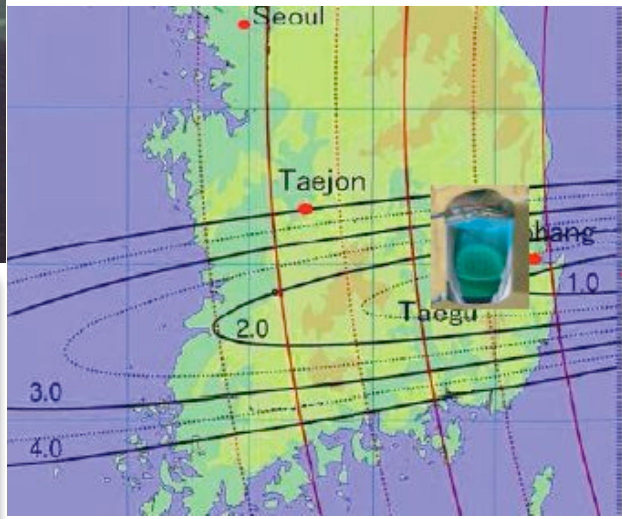


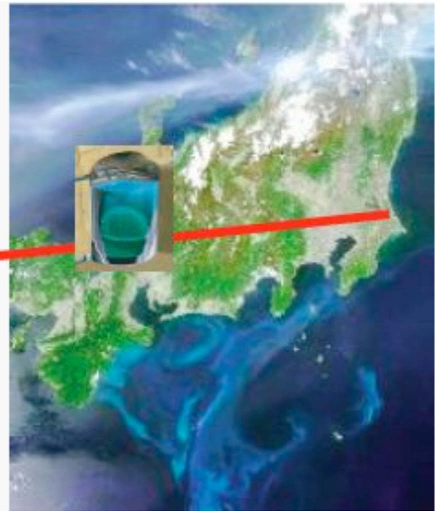
What's good in T2KK?

#1. Current design of Hyper-Kamiokande contains 2 tanks !



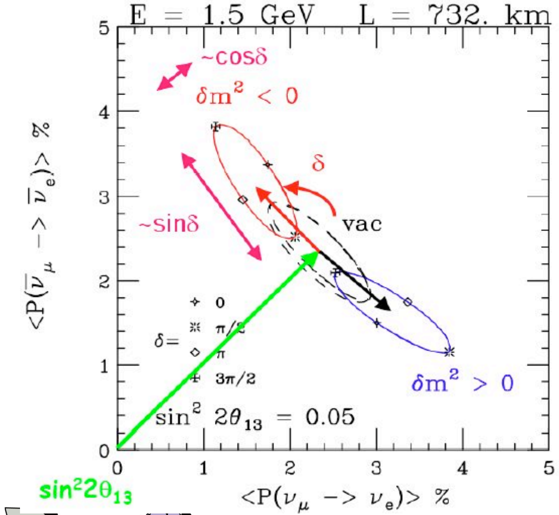
Why don't you bring one of the 2 tanks to Korea?

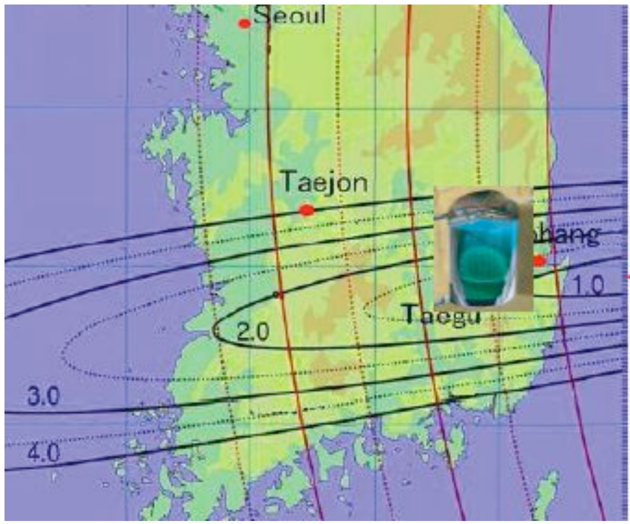


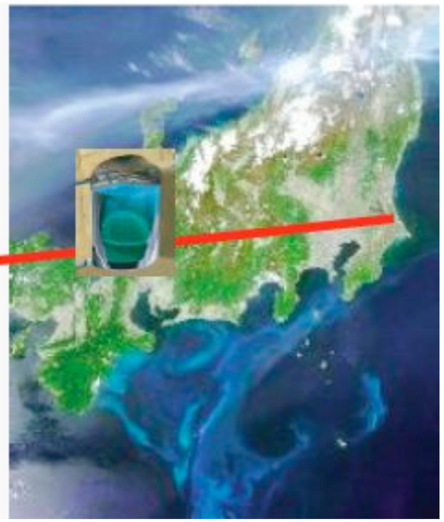


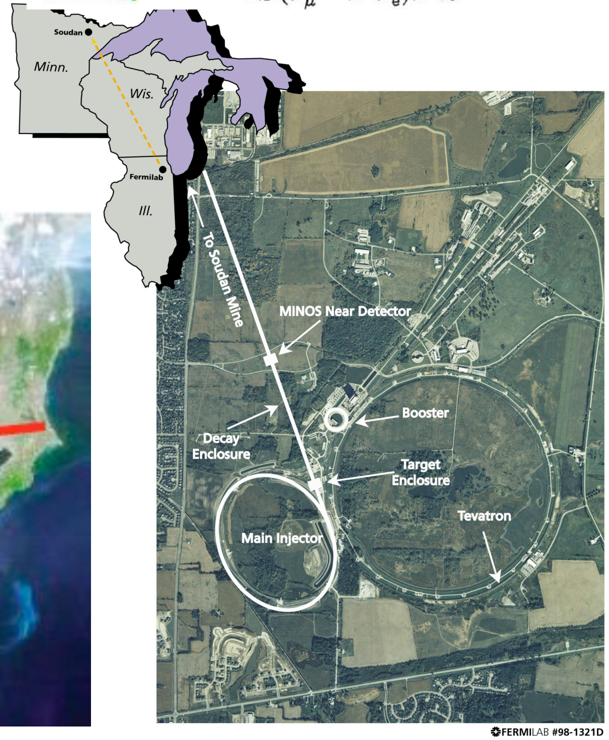
#2. Sign-Δm^2 degeneracy

- Resolution of sign-Δm^2 degeneracy requires the matter effect
- Requires baseline ~1000 km
- 2nd detector seems required to go down to $\sin^2 2\theta_{13}$=.02

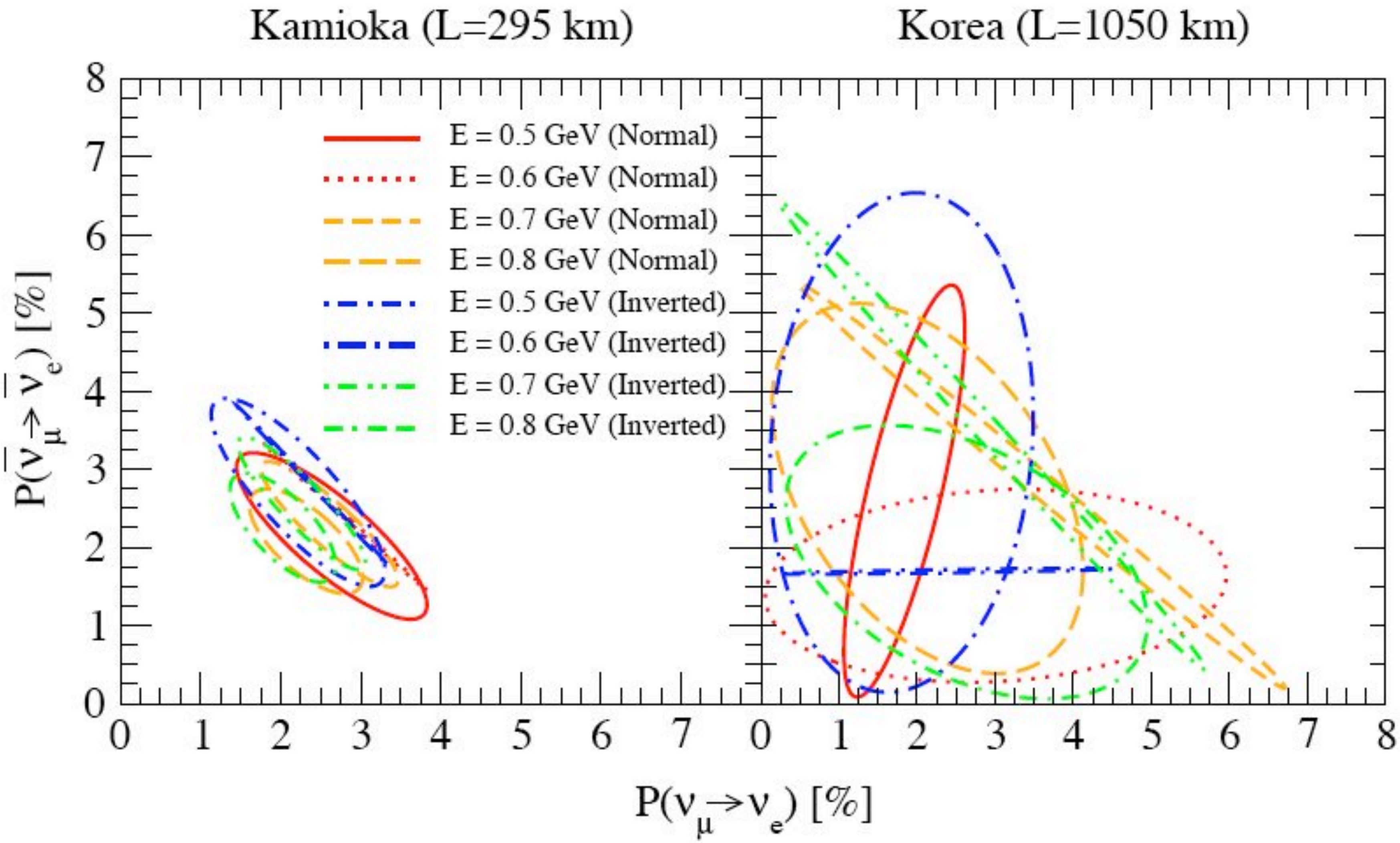








#3. Sensitive to δ because energy dependence is far more dynamic in 2nd oscillation maximum



#4. Sensitive to solar n oscillation; good for octant degeneracy

- Detect the effect of the solar term using a far detector in Korea, which has a longer baseline.

solar term

$$P[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] = \boxed{c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2}$$
$$+ \sin^2 2\theta_{13} s_{23}^2 \left[\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right.$$
$$\left. \pm \left(\frac{4Ea(x)}{\Delta m_{31}^2}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \mp \frac{a(x)L}{2} \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)\right]$$
$$+ 2J_r \left(\frac{\Delta m_{21}^2 L}{2E}\right) \left[\cos\delta \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \mp 2 \sin\delta \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right].$$

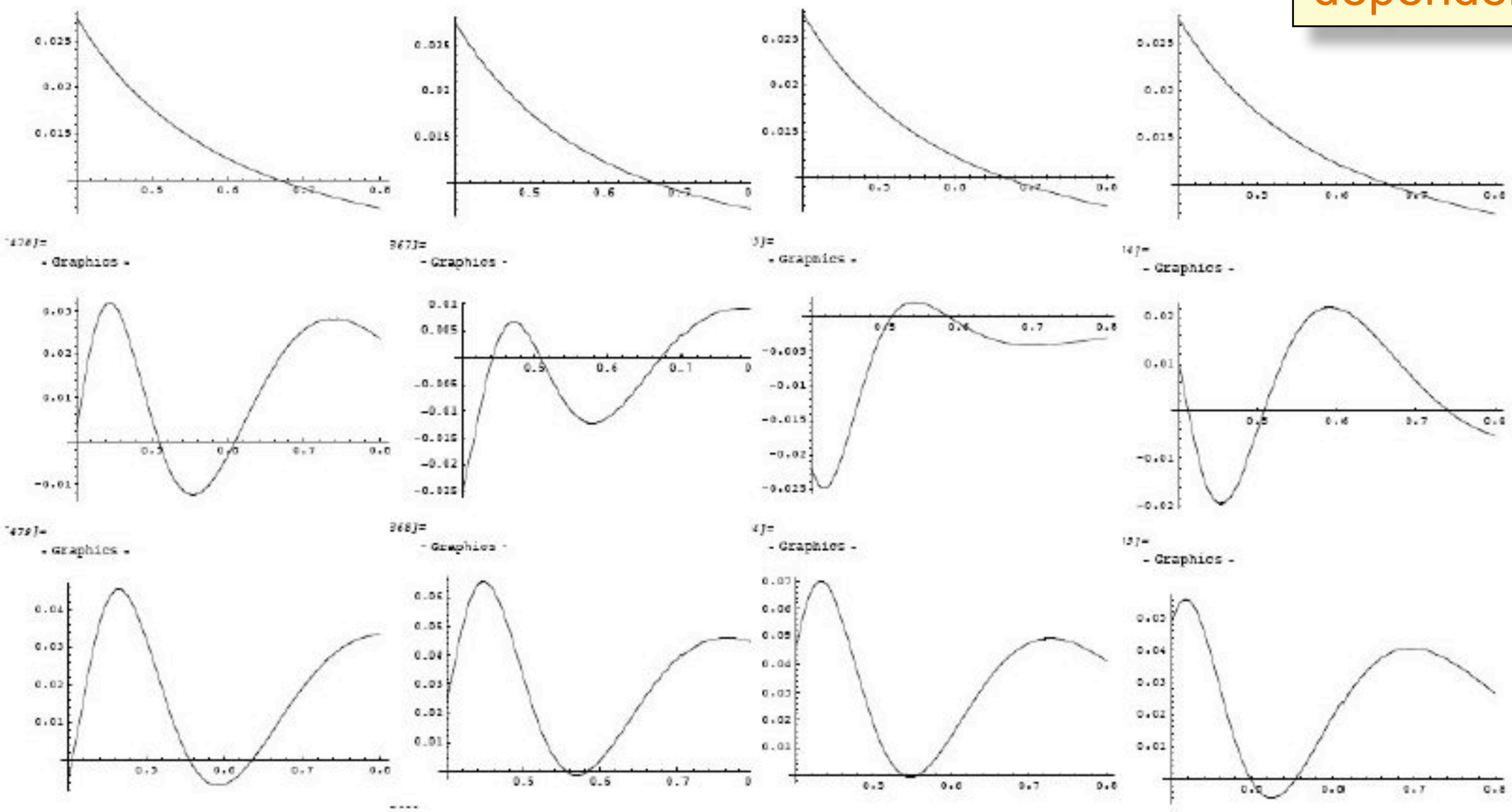
$a(x) = \sqrt{2} G_F N_e(x)$, $N_e(x)$: electron number density

$J_r \ (= c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23})$: reduced Jarlskog factor

Solar and atm. terms differ in energy dependences

From above: P_{solar}, P_{atm_ν}, $P_{atm\_\nu bar}$

All different in energy dependences !



$\delta=0, \pi/4, \pi/2, 3\pi/4$

Degeneracy;

a notorious obstacle

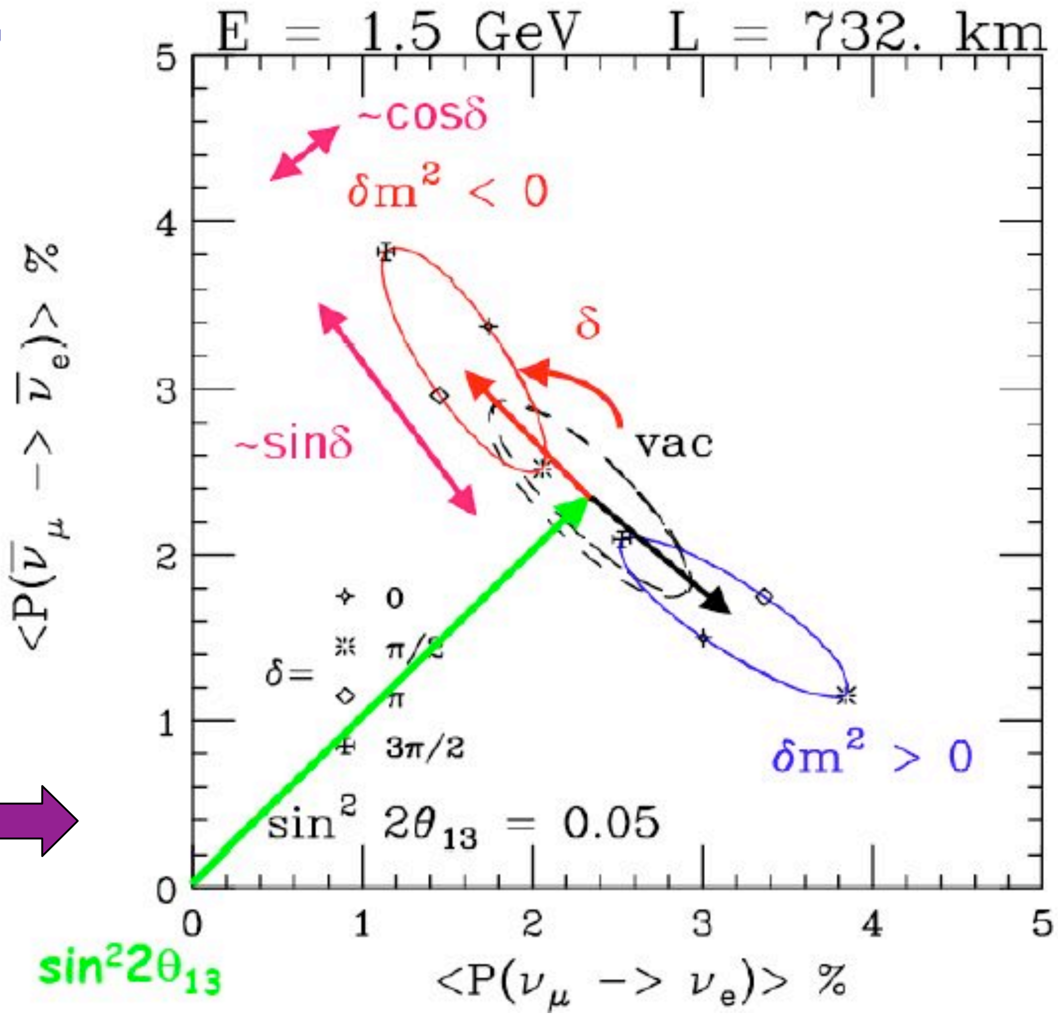
A machinery in my talk

Oscillation probability
- draw ellipse if plotted in bi-P plane

Role played by CP
- phase δ and the matter clearly distinguished

Art work by Adam Para

Two solutions of S_{23}^2 x



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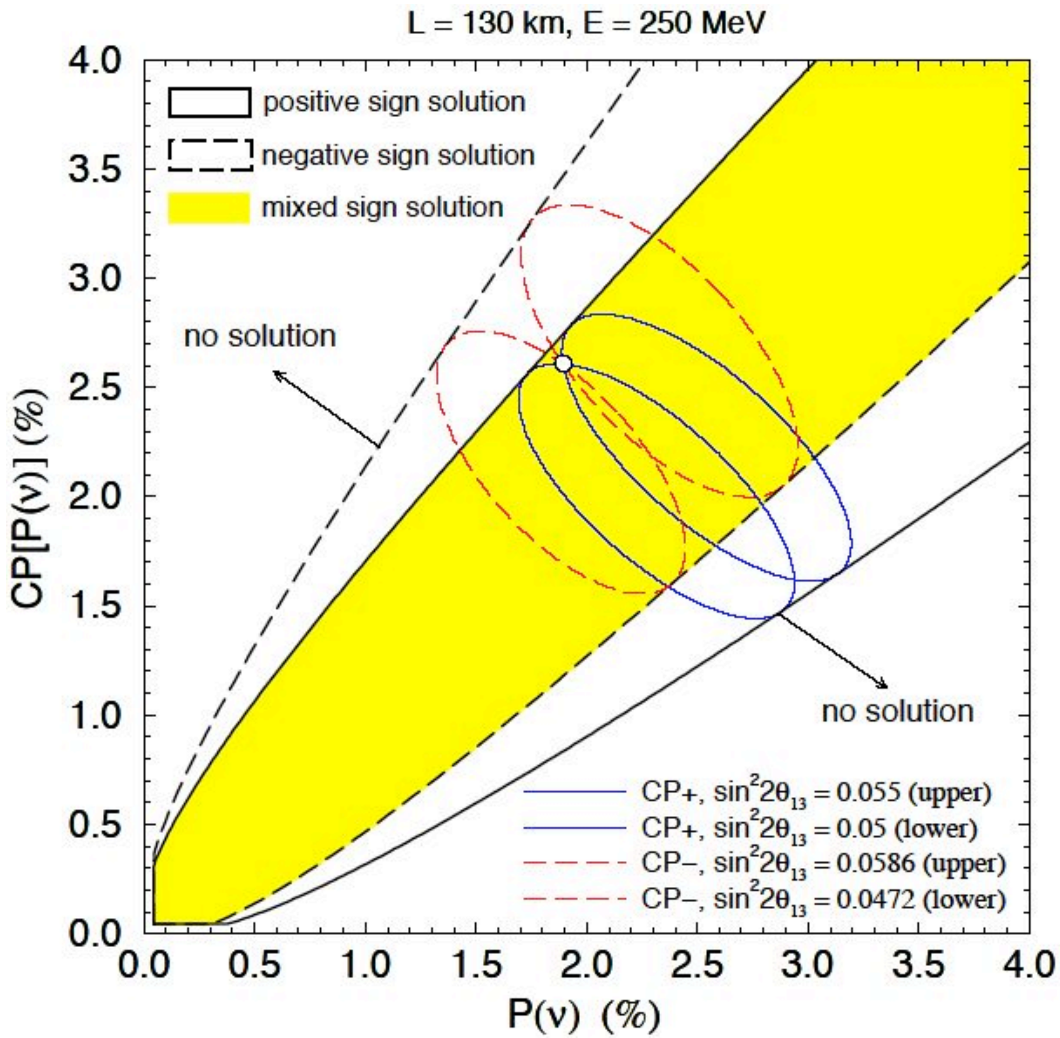
Cause of the degeneracy; easy to understand

- You can draw two ellipses from a point in P-Pbar space

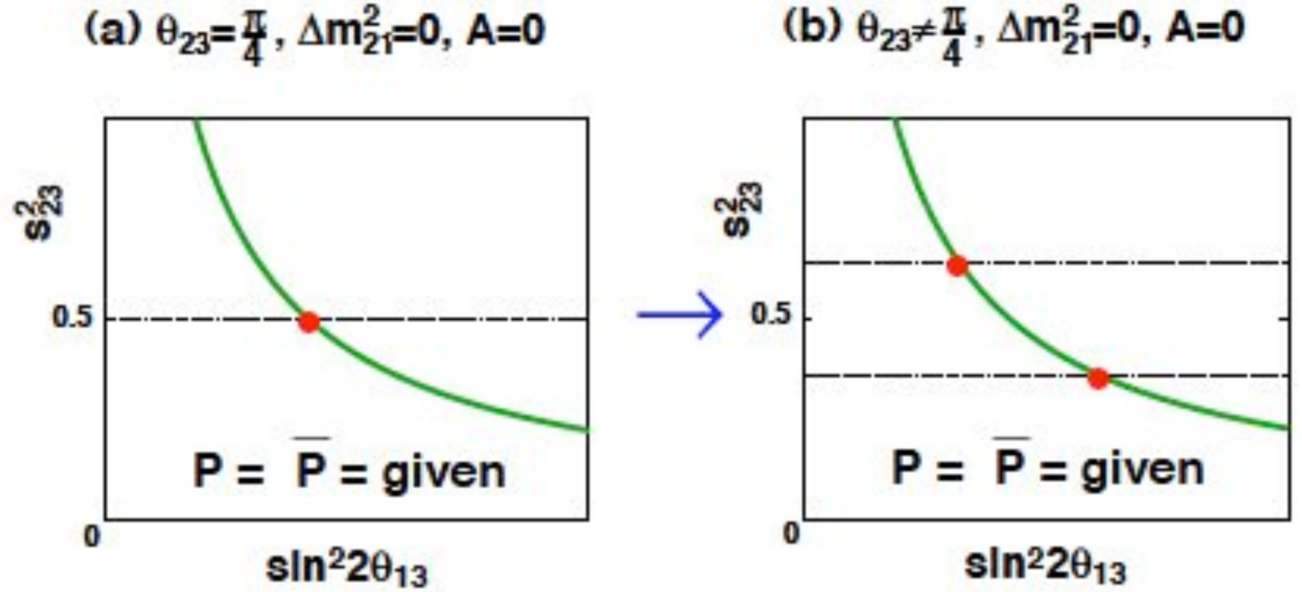
→ Intrinsic degeneracy

- Doubled by the unknown sign of Δm^2

→ 4-fold degeneracy



θ_{23} octant degeneracy

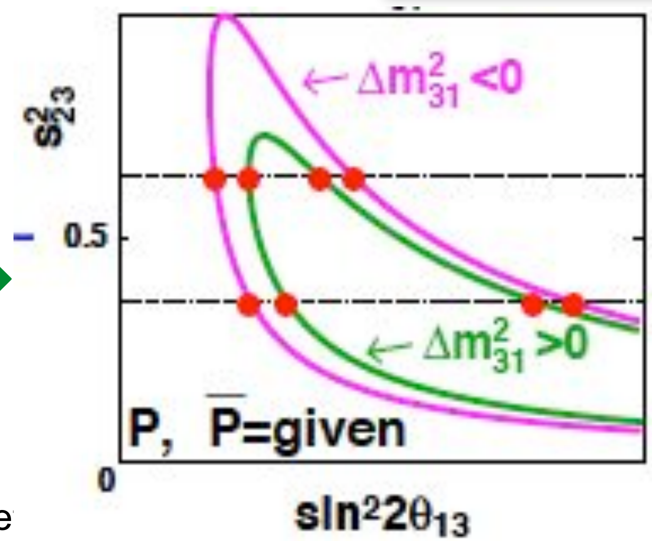


OY Nufact03

$P\mu e= \sin^2 2\theta_{13}\ \times s^2_{23}$

Solar Δm^2 on

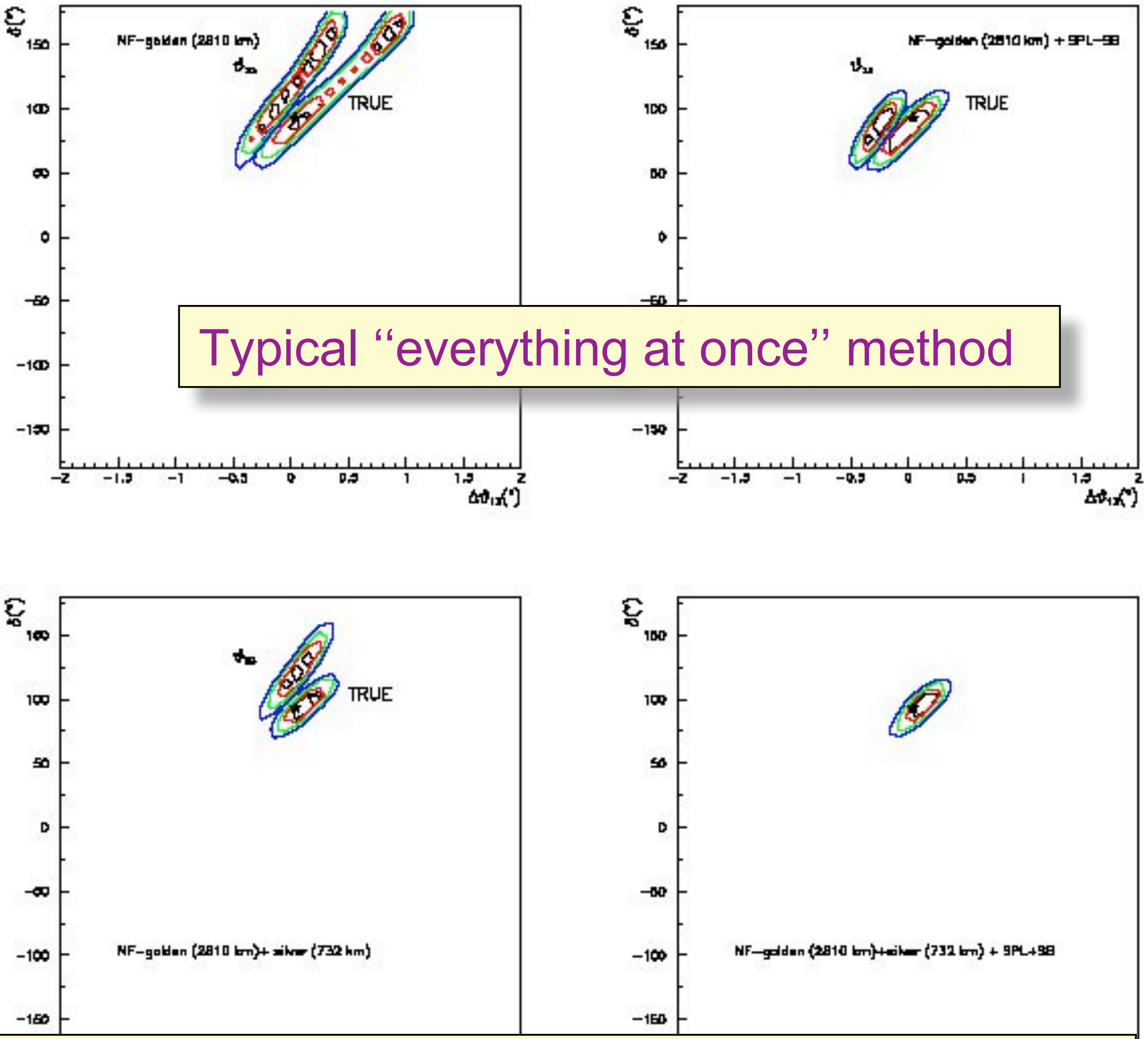
Matter effect on



Altogether, 2 x 2 x 2 = 8-fold degeneracy

ν factory as ultimate degeneracy solver

- 40 Kton MID
- 4 Kton ECC
- 400 Kton WC



Typical "everything at once" method

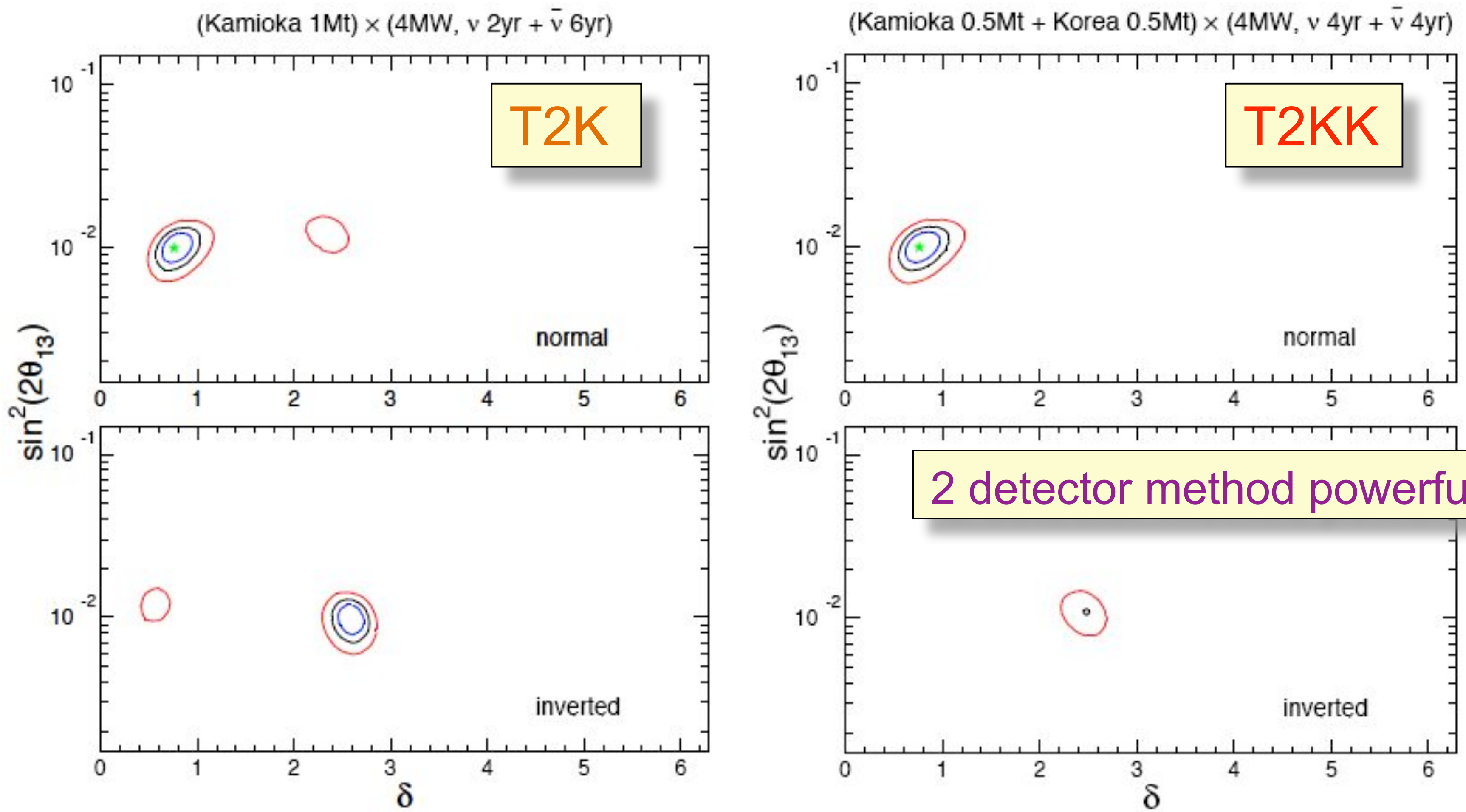
- By combining at 3 detectors at 130, 730, and 2810 km, it was claimed that neutrino factory can resolve all the 8-fold degeneracy if $\theta_{13} > 1°$ (Donini, NuFACT03)

Powerful, but expensive! ~1000 Million Euro/degeneracy

Let us resolve degeneracy one by one

Spectral information solves intrinsic degeneracy

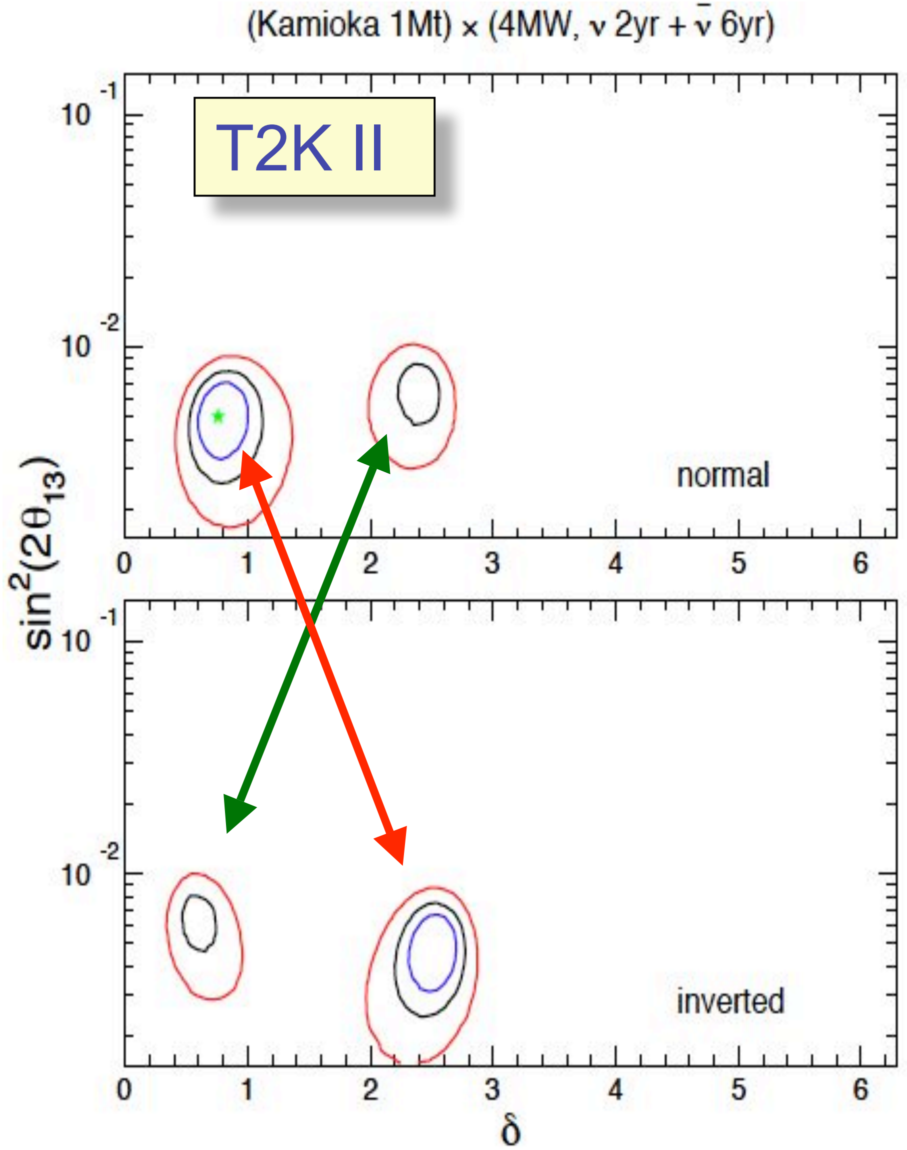
from 1000 page Ishitsuka file



2 detector method powerful!

SK momentum resolution ~30 MeV at 1 GeV

Structure of intrinsic & sign-Δm^2 degeneracy in (matter) perturbative regime



- Intrinsic degeneracy; $\delta_2 = \pi - \delta_1$
- sign(Δm^2)-δ degeneracy arises because P is approx. invariant under:
- $\Delta m^2 \longrightarrow -\Delta m^2$
- $\delta \longrightarrow \pi - \delta$

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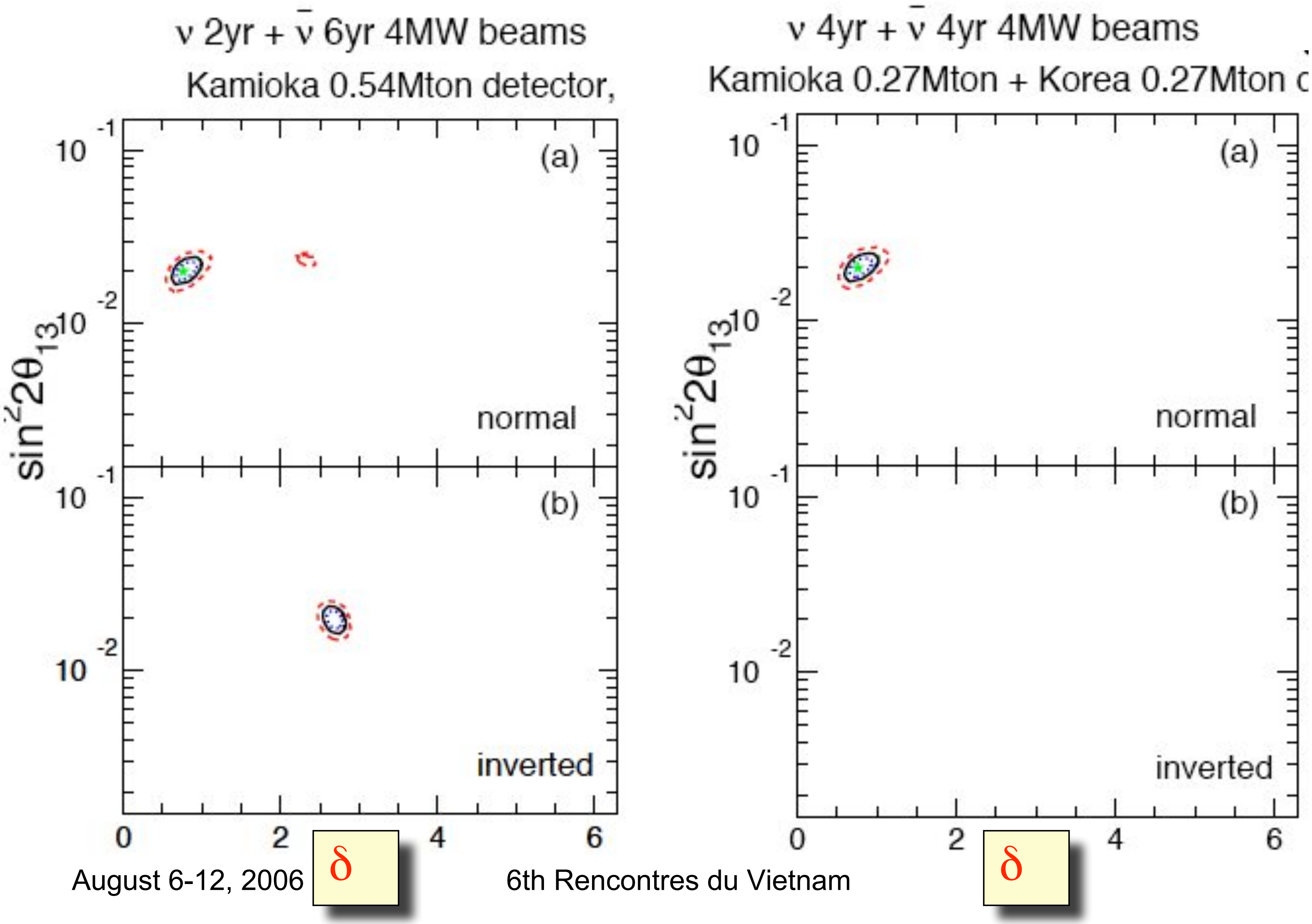
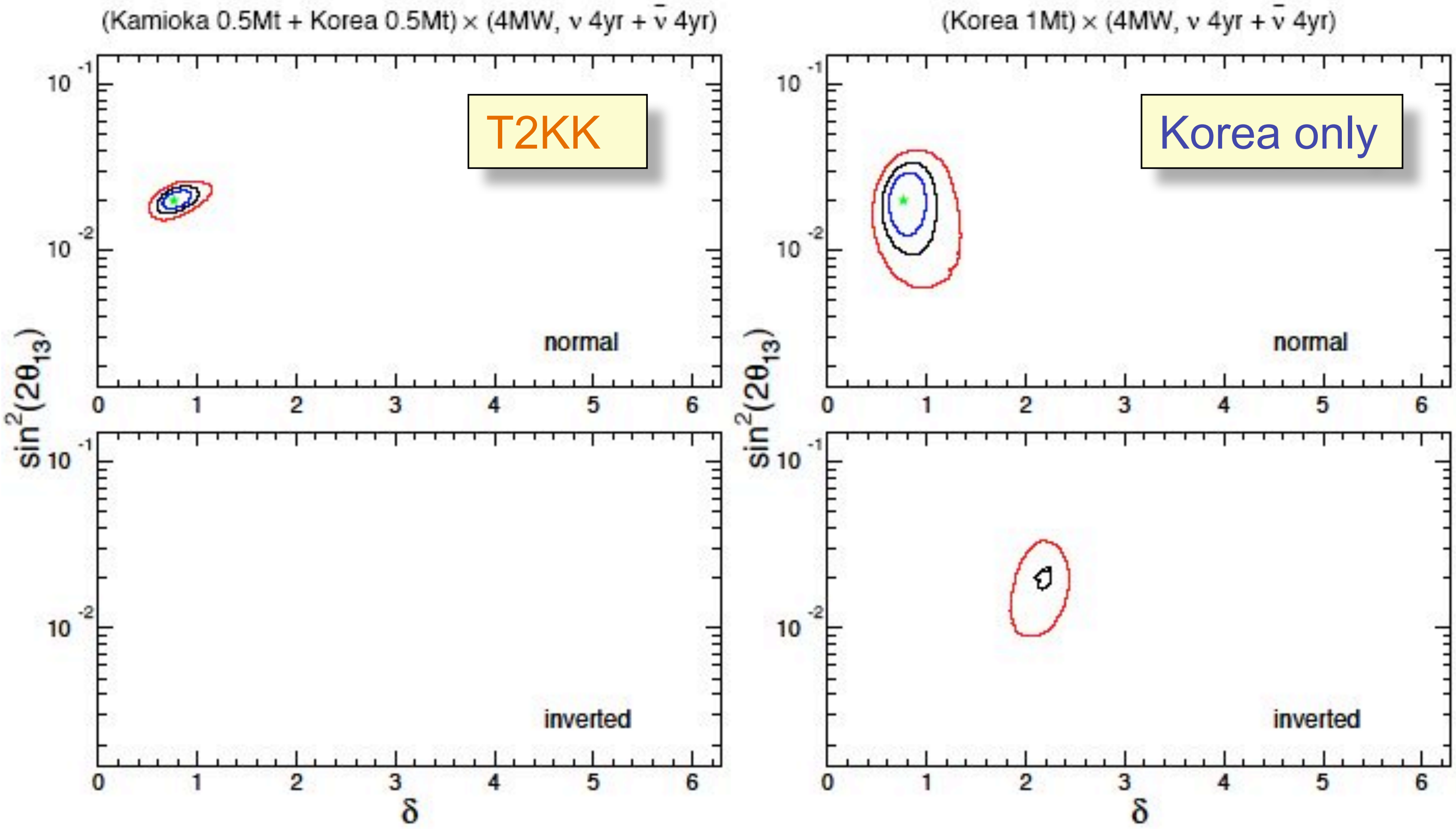
du Vietnam

T2K(0.54 Mt) vs. T2KK(0.27+0.27 Mt)



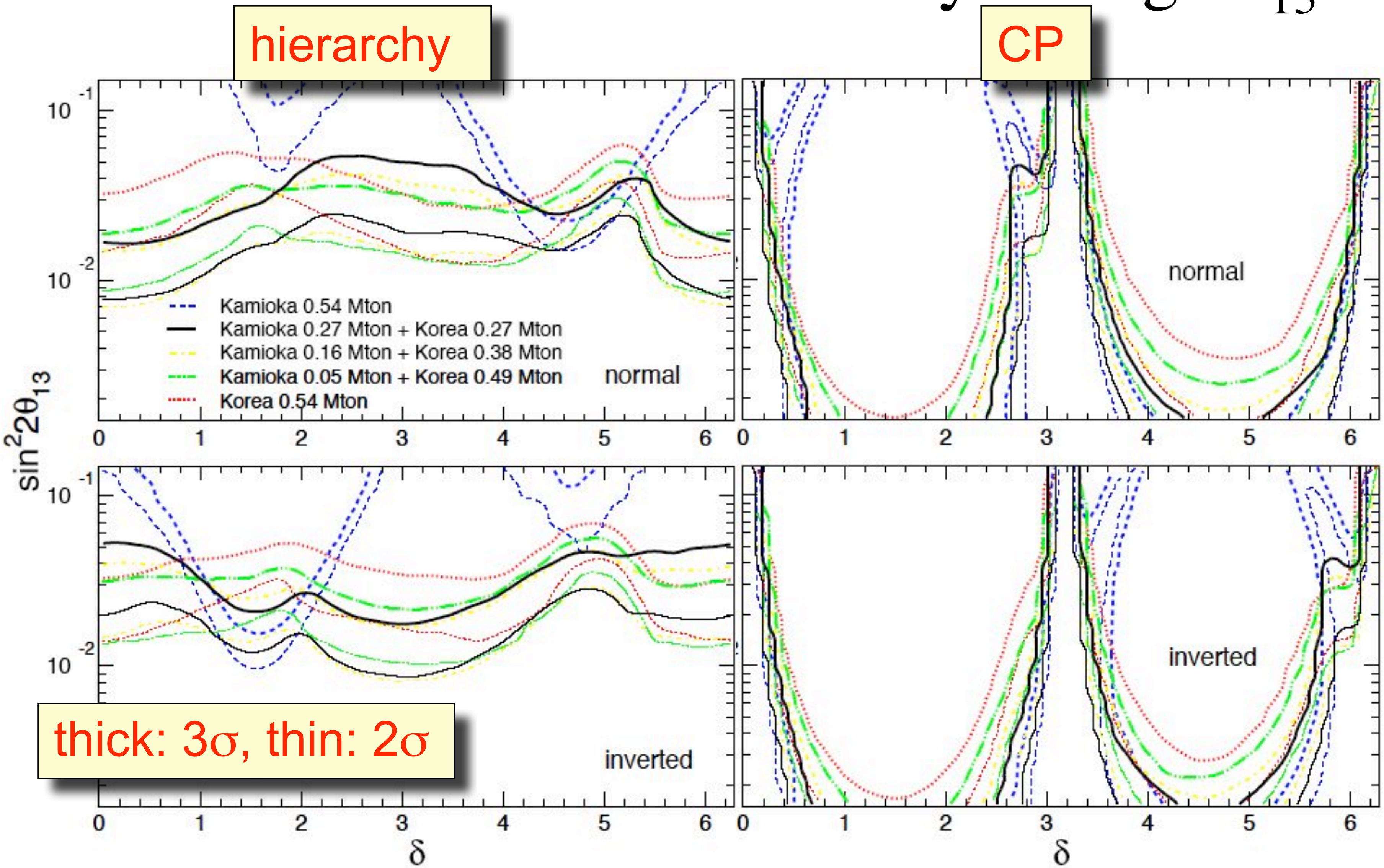
It is not quite only the matter effect



- With the same input parameter and Korean detector of 0.54 Mt the sign-Δm^2 degeneracy is NOT completely resolved

2 identical detector method powerful !

T2KK can resolve ν mass hierarchy with bonus of better CP sensitivity at large θ_{13}



T2KK in situ solves θ_{23} degeneracy!

How to solve θ_{23} octant degeneracy

Strategy: Look for terms which depend on θ_{23} but not through the form $s_{23}^2 \times \sin^2 2\theta_{13}$

- Detect solar Δm^2 term $\sim c_{23}^2$
- Requires very long baseline
- well controlled systematic error plus statistics
- Powerful at small θ_{13}

- Combining reactor measurement of θ_{13}
- Requires great precision in reactor θ_{13} measurement
- Powerful at large θ_{13}

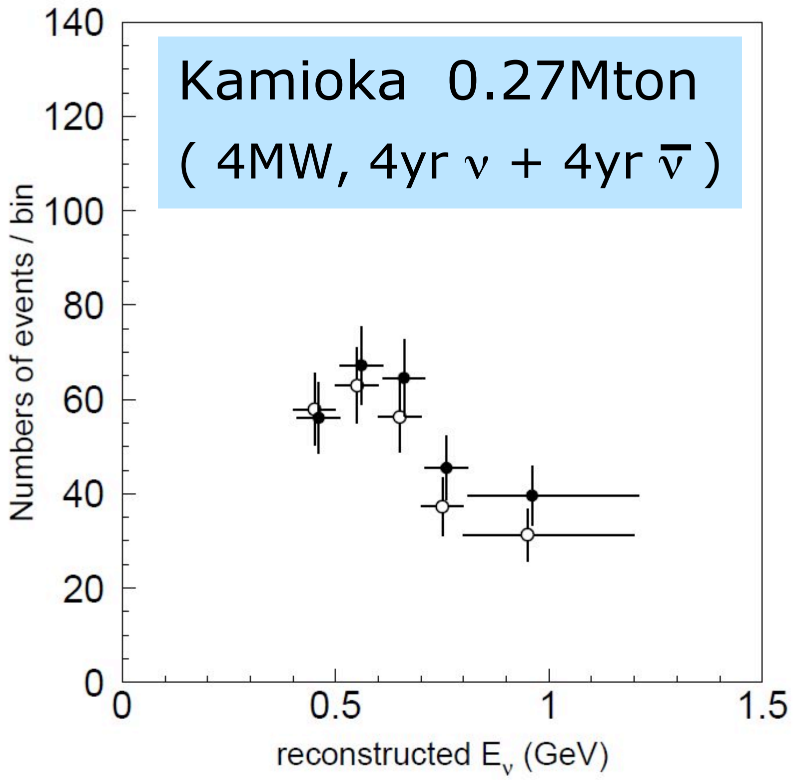
Effect of the solar term

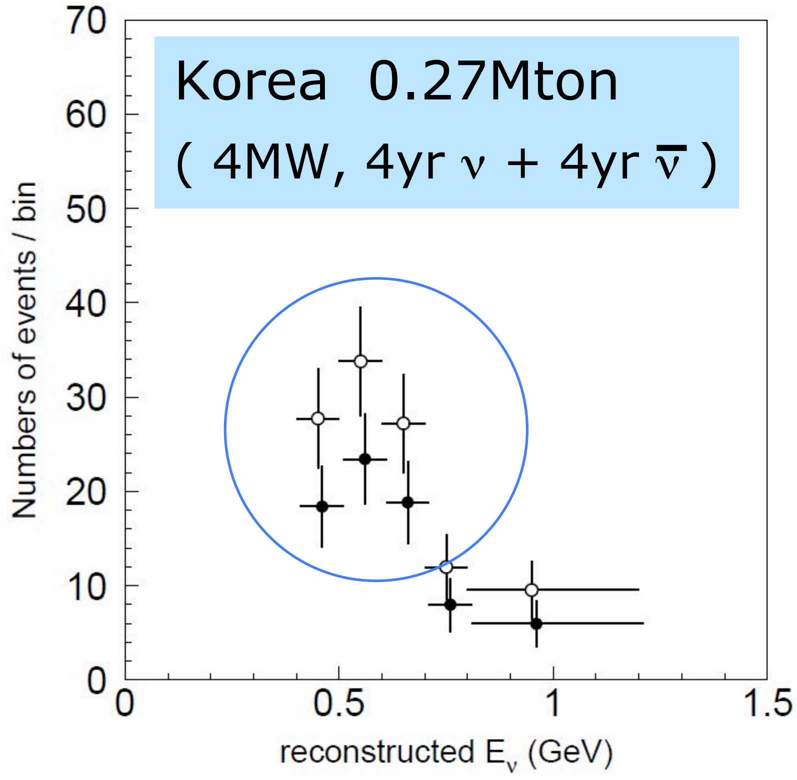
Δm^2_{12}	$= 8.0 \times 10^{-5}$ (eV^2)
Δm^2_{23}	$= 2.5 \times 10^{-3}$ (eV^2)
$\sin^2\theta_{12}$	$= 0.31$
$\sin^2 2\theta_{23}$	$= 0.96$
δ	$= 3/4\,\pi$
normal mass hierarchy	

○ $\sin^2\theta_{23} = 0.4$, $\sin^2 2\theta_{13} = 0.01$

● $\sin^2\theta_{23} = 0.6$, $\sin^2 2\theta_{13} = 0.0067$

Number of signal events
(BG not included)

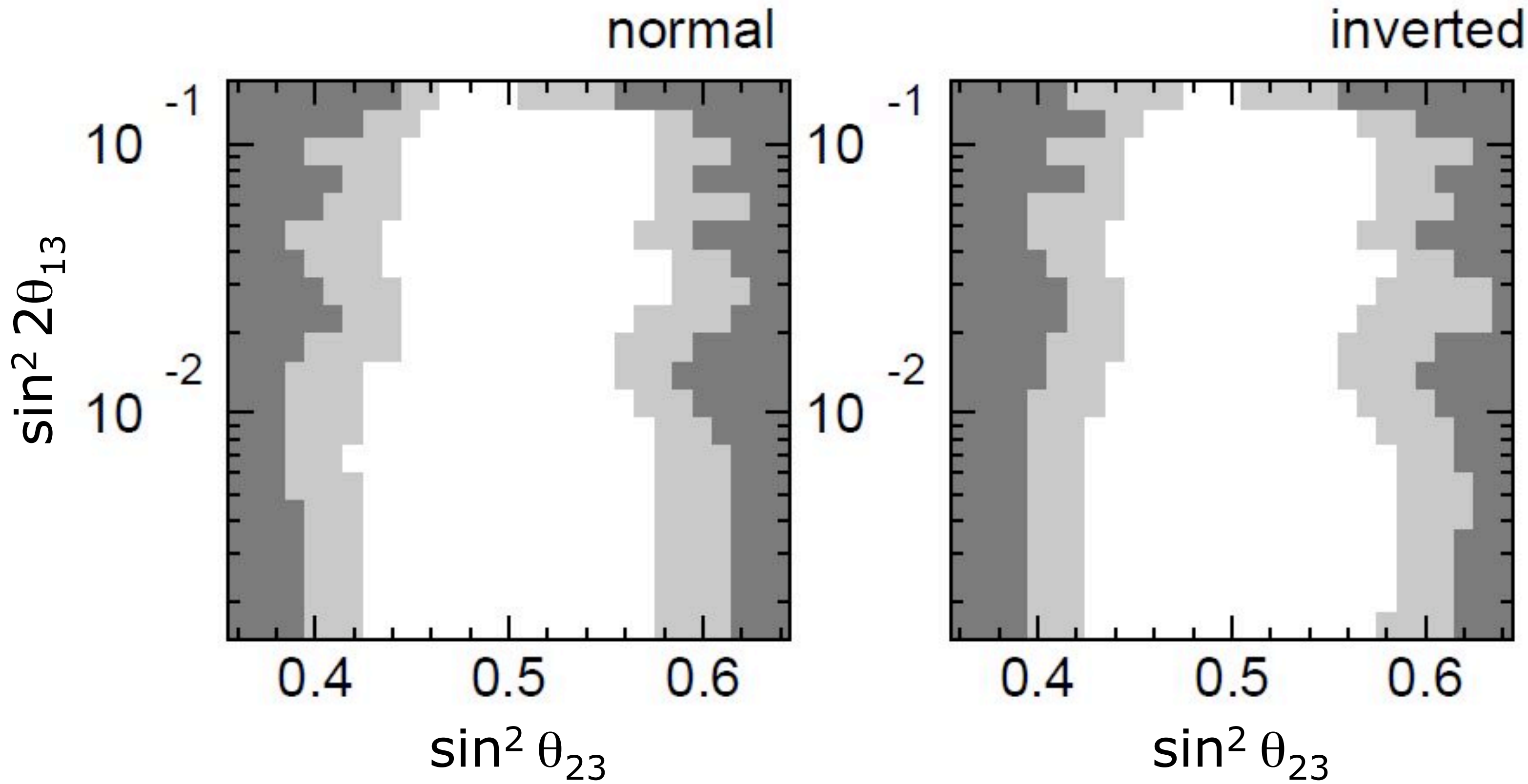




Solar term is negligibly small due to shorter baseline in Kamioka.

Solar term can be seen in low E_ν region in Korea.

Sensitivity to θ_{23} octant (cont'd)



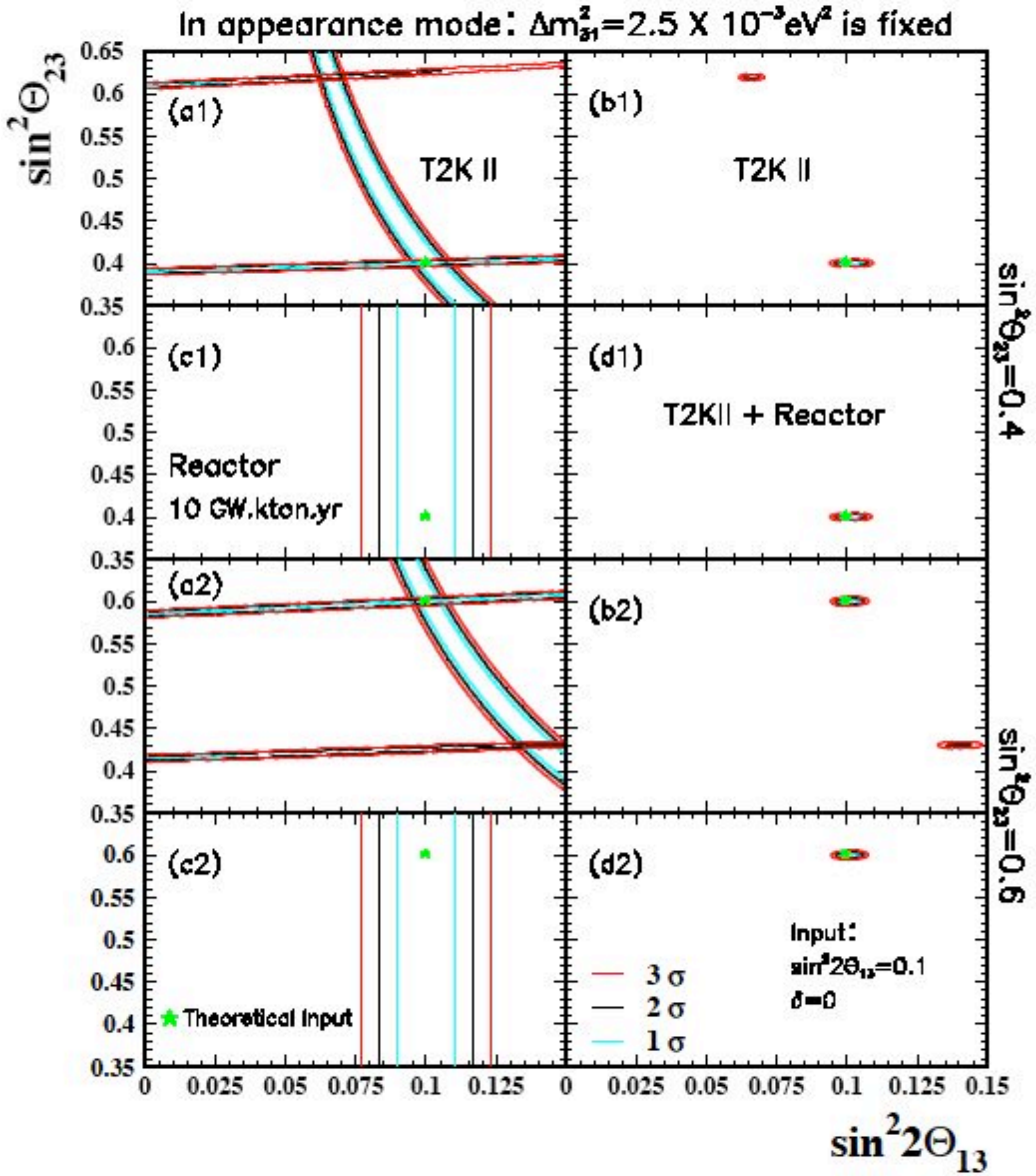
can determine θ_{23} octant for any δ by

> 3σ

$2\sim3\sigma$

If $\sin^2\theta_{23}<0.42$ or >0.58 ($\sin^2 2\theta_{23}= 0.974$), θ_{23} octant can be determined by $>2\sigma$ even at very small $\sin^2 2\theta_{13}$.

Reactor + accelerator method



am

MSYIS 02

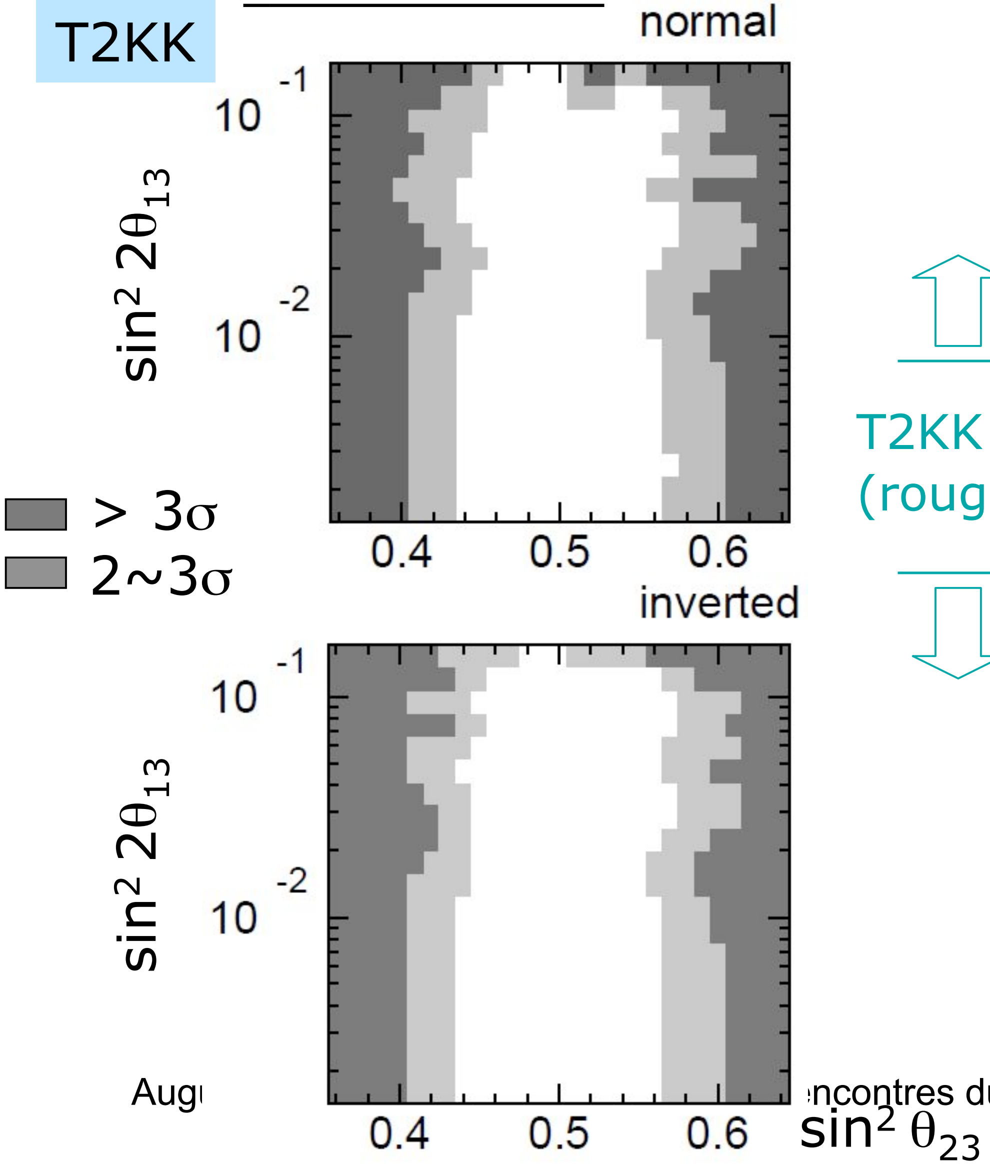
- Acc-disappearance => s^2_{23}=0.4 or 0.6
- Acc-appearance => $s^2_{23}\sin^2 2\theta_{13} = 0.06$
- Reactor => $\sin^2 2\theta_{13} = 0.1$

- Solves θ_{23} degeneracy

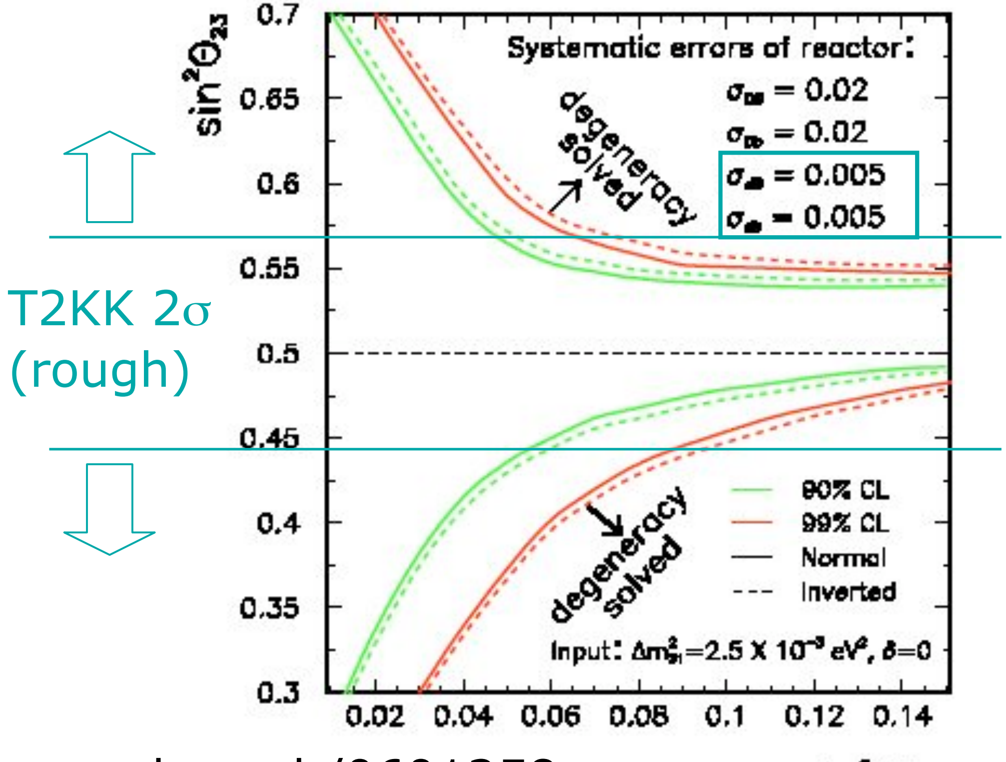
Sensitivity comparison with T2K+Reactor

T2KK

$\delta=0$ assumed



T2K-II + phase II reactor

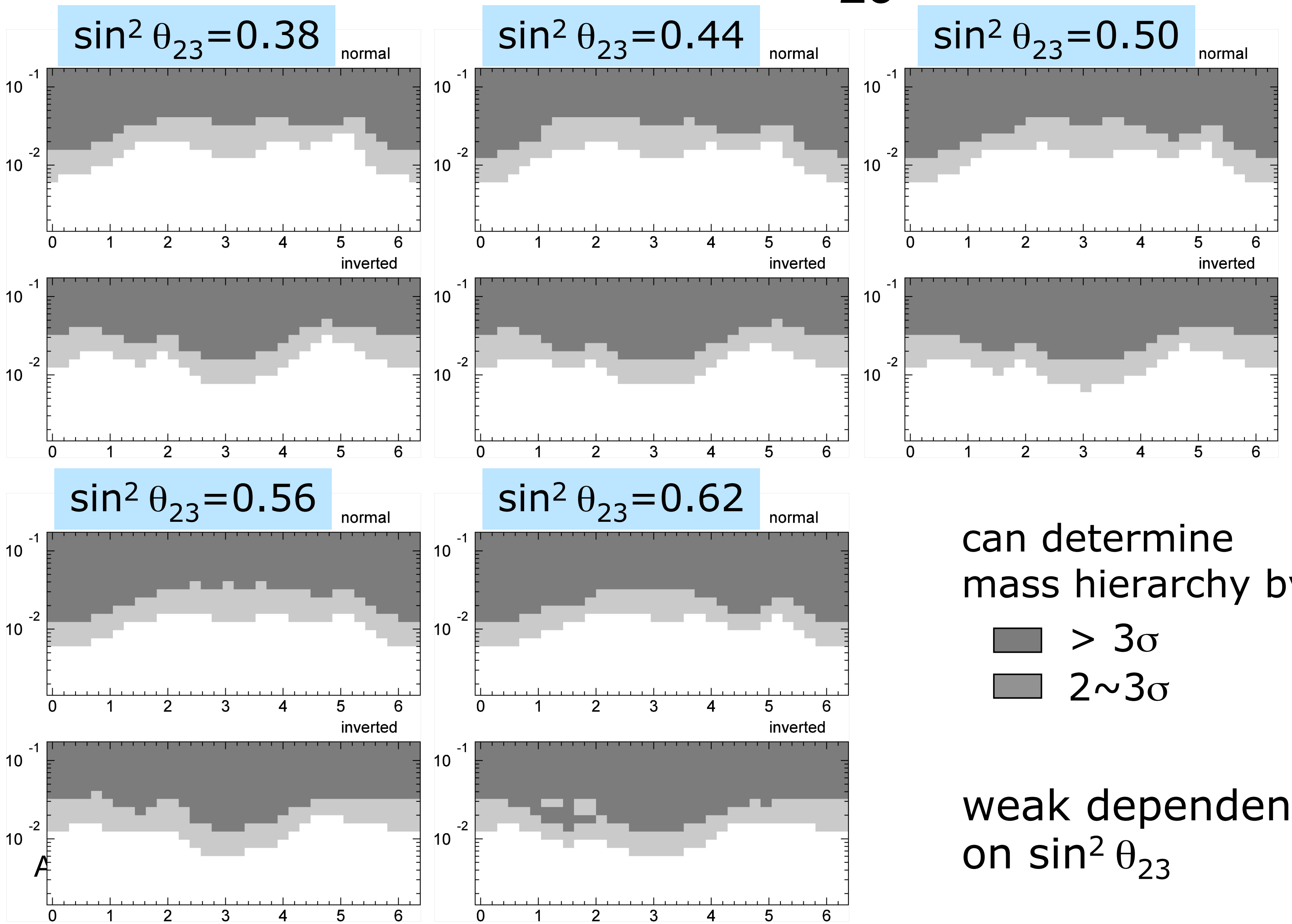


hep-ph/0601258

T2KK has better sensitivity at $\sin^2 2\theta_{13} < 0.06\sim0.07$.

Sign-Δm^2 degeneracy and CP violation revisited

Sensitivity to mass hierarchy (for various θ_{23})

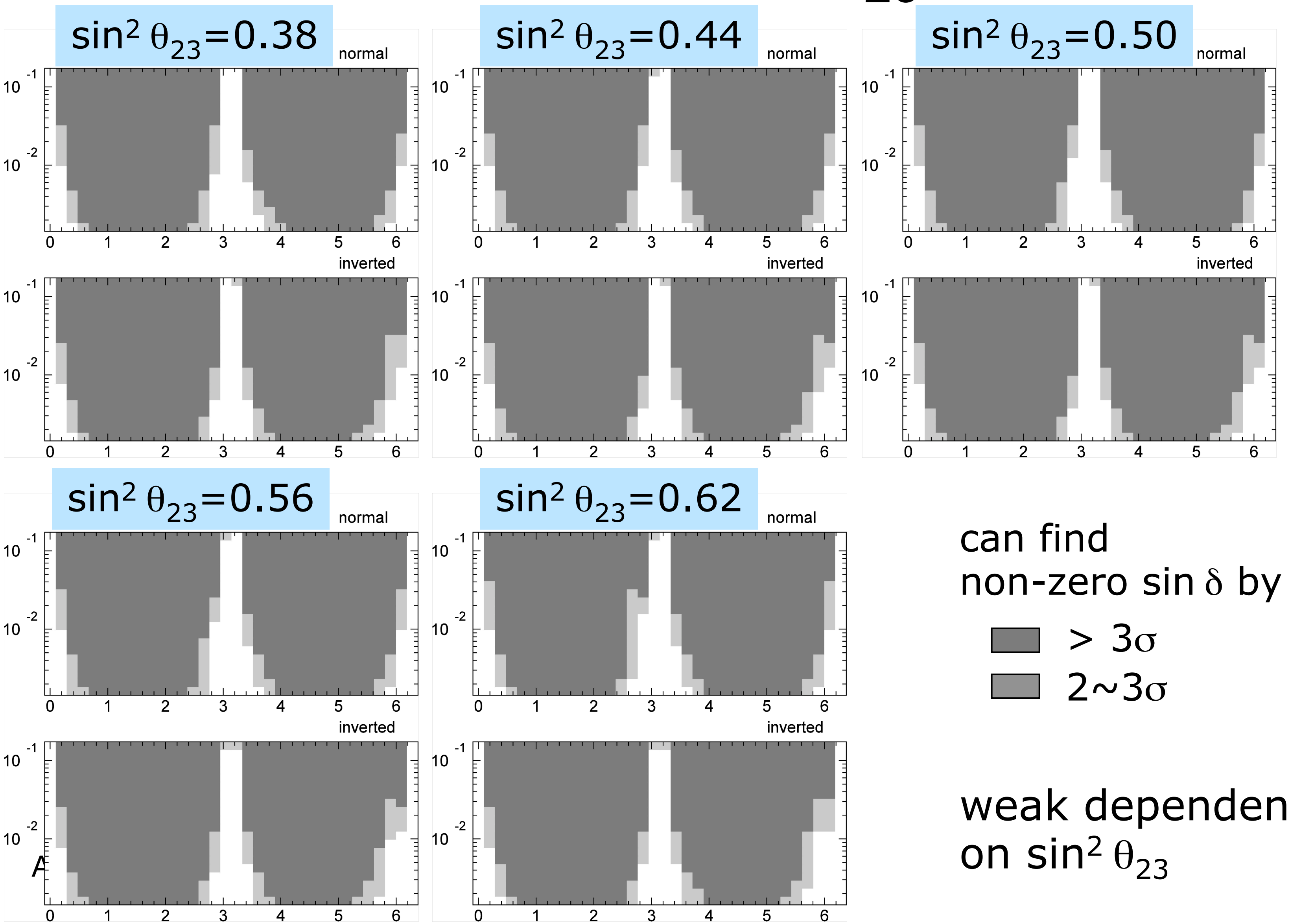


can determine mass hierarchy by

- $> 3\sigma$
- $2\sim3\sigma$

weak dependence on $\sin^2\theta_{23}$

Sensitivity to leptonic CP violation (for various θ_{23})



can find non-zero $\sin\delta$ by

- $> 3\sigma$
- $2\sim3\sigma$

weak dependence on $\sin^2\theta_{23}$

Decoupling between degeneracies

- Suppose that you succeeded to solve the particular degeneracy, by forgetting about the remaining ones
- It does NOT necessarily mean that the problem is solved
- You have to verify that your treatment of degeneracy A is valid irrespective of the presence of degeneracy B
- One solution: decoupling between the degeneracies

θ_{23} and sign-Δm^2 degeneracy decouple

- For example, one can show, to first order in matter effect, the followings:
- ΔP(octant) = P(1st octant) - P(2nd) is invariant under the interchange of two sign-Δm^2 degenerate pair
- ΔP(hierarchy) = P(Δm^2 +) - P(Δm^2 -) is invariant under the interchange of two θ_{23} octant degenerate pair
- in T2K or T2KK setting, the intrinsic degeneracy is resolved by spectrum analysis → decouple from the game

In a nutshell, 8 fold degeneracy can be resolved by T2KK because ..

- intrinsic degeneracy is resolved by spectrum information
- sign-Δm^2 degeneracy is solved with matter effect + 2 identical detector comparison
- θ_{23} octant degeneracy is solved by identifying the solar oscillation effect in T2KK

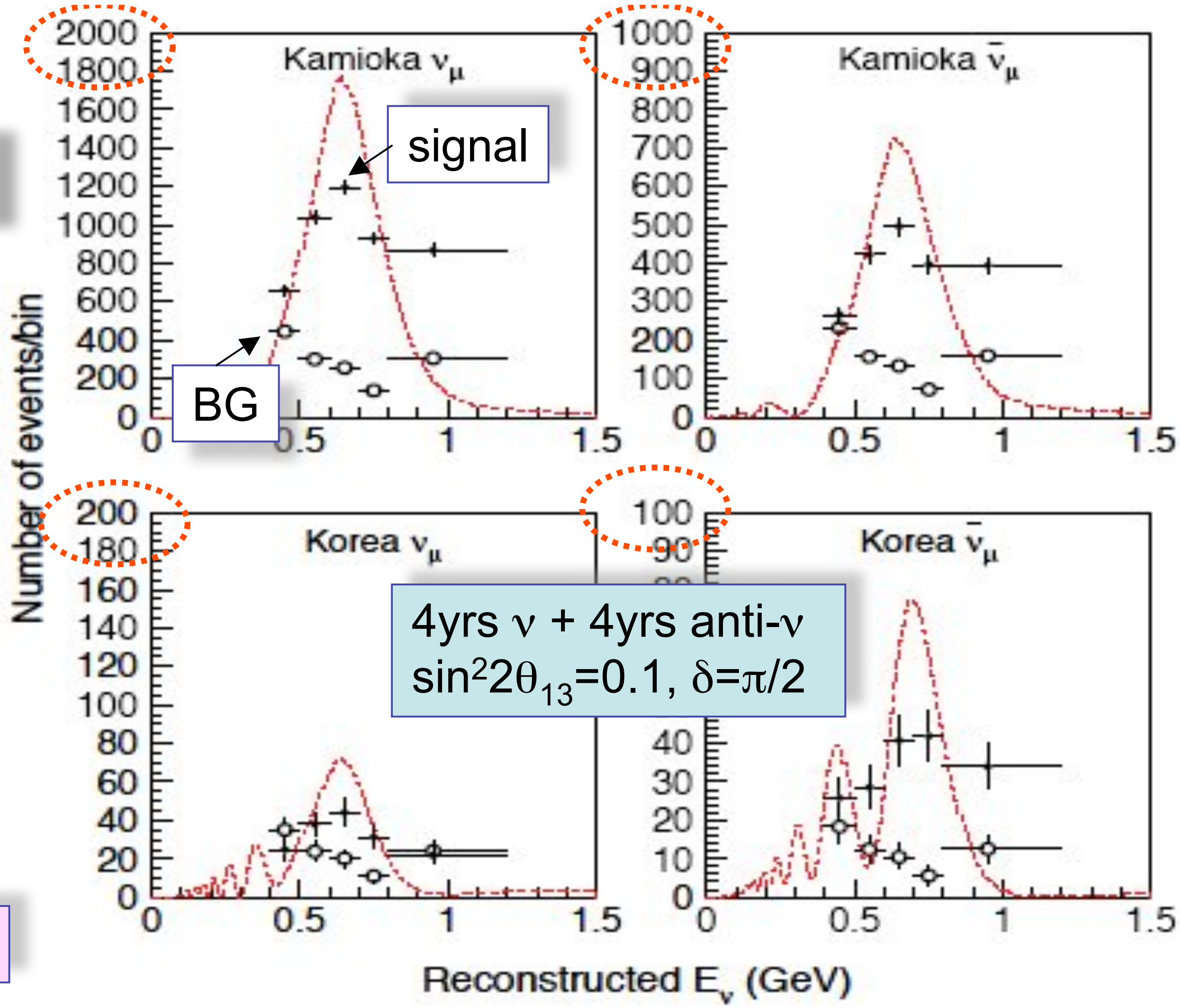
Conclusion

- With T2KK setting, we have formulated a concrete strategy for resolving 8 fold parameter degeneracy *in situ* with consistency maintained by "decoupling"

conventional ν superbeam can do it !

Kajita in NOVE2006

Expected signal, BG and χ^2



ν and anti-ν × Kamioka and Korea

5 energy bins

$$\chi^2 = \sum_{k=1}^{4}\left(\sum_{i=1}^{5}\frac{\left(N(e)_i^{\text{obs}} - N(e)_i^{\text{exp}}\right)^2}{\sigma_i^2}\right) + \sum_{j=1}^{3}\left(\frac{\epsilon_j}{\tilde{\sigma}_j}\right)^2$$

$$N(e)_i^{\text{exp}} = N_i^{\text{BG}}\cdot\left(1+\sum_{j=1}^{2} f_j^i\cdot\epsilon_j\right) + N_i^{\text{signal}}\cdot\left(1+f_3^i\cdot\epsilon_3\right) \quad .$$

syst. Errors:

5% BG (overall)
5% BG (energy dep.) 5% signal efficiency

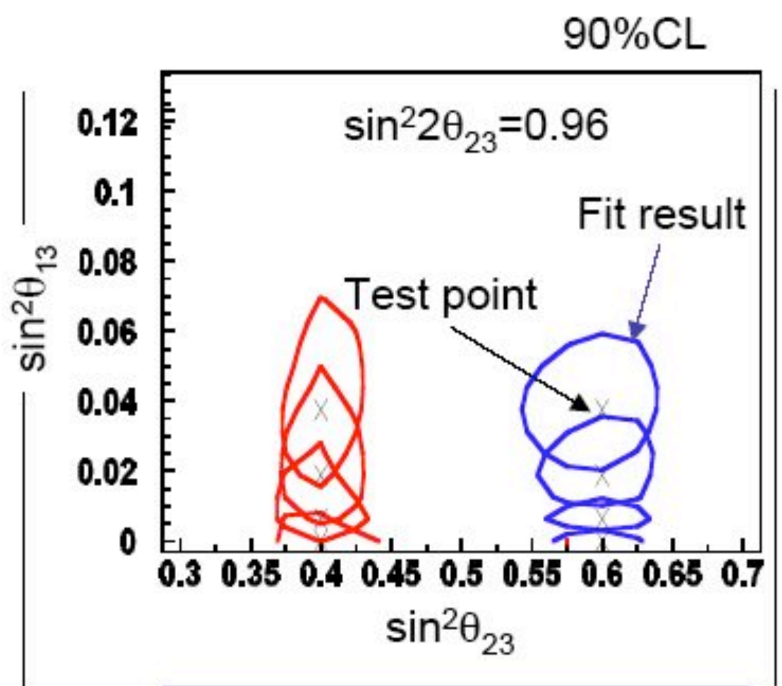
Atm ν; powerful way for octant degene.

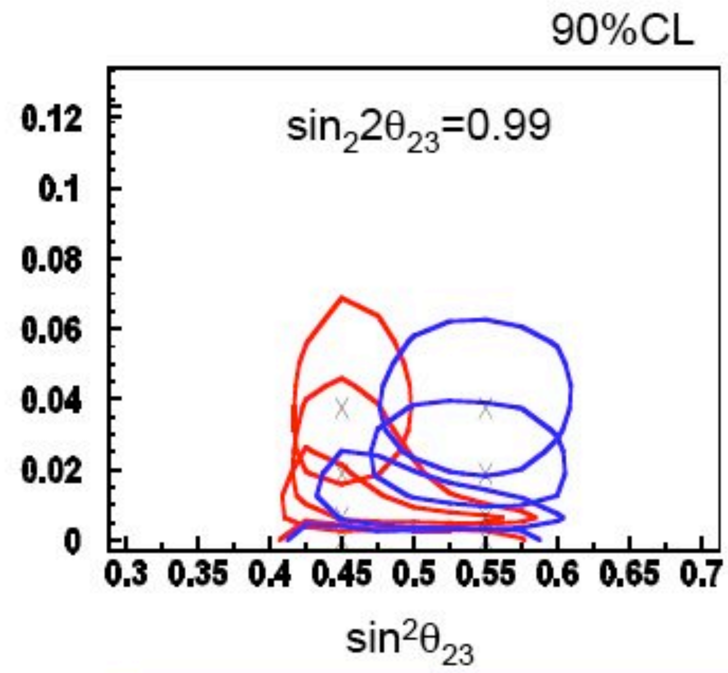
T.Kajita@NNN05

Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ with the (12) and (13) terms

$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
δcp=45°

1.8Mtonyr = 3.3 yrs HK





Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is possible for all θ_{13}.

Discrimination between $\theta_{23} > \pi/4$ and $< \pi/4$ is marginally possible only for $\theta_{13} > 0.04$.