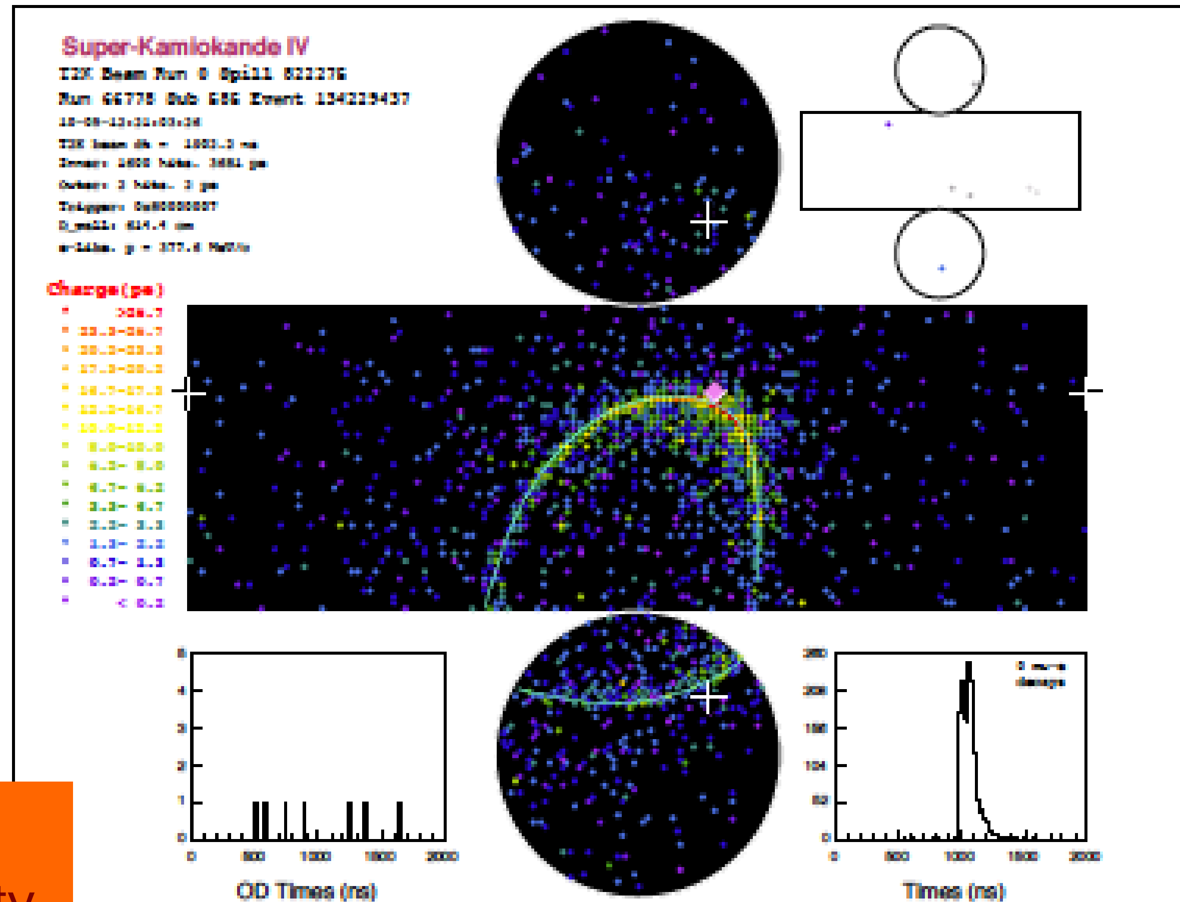
If θ_{13} is large, then what ?



(b) electron-like event

Hisakazu Minakata
Tokyo Metropolitan University

Title too timely? Yes, but meant to be a speculative one when proposed

差出人: Hisakazu Minakata <minakata@tmu.ac.jp>

日時: 2011年5月10日 21:45:38:JST

宛先: Thomas Schwetz-Mangold <schwetz@mpi-hd.mpg.de>

Cc: Hisakazu Minakata <minakata@tmu.ac.jp>
件名: Re: Nufact 11

Dear Thomas,

Thank you for your quick reply.

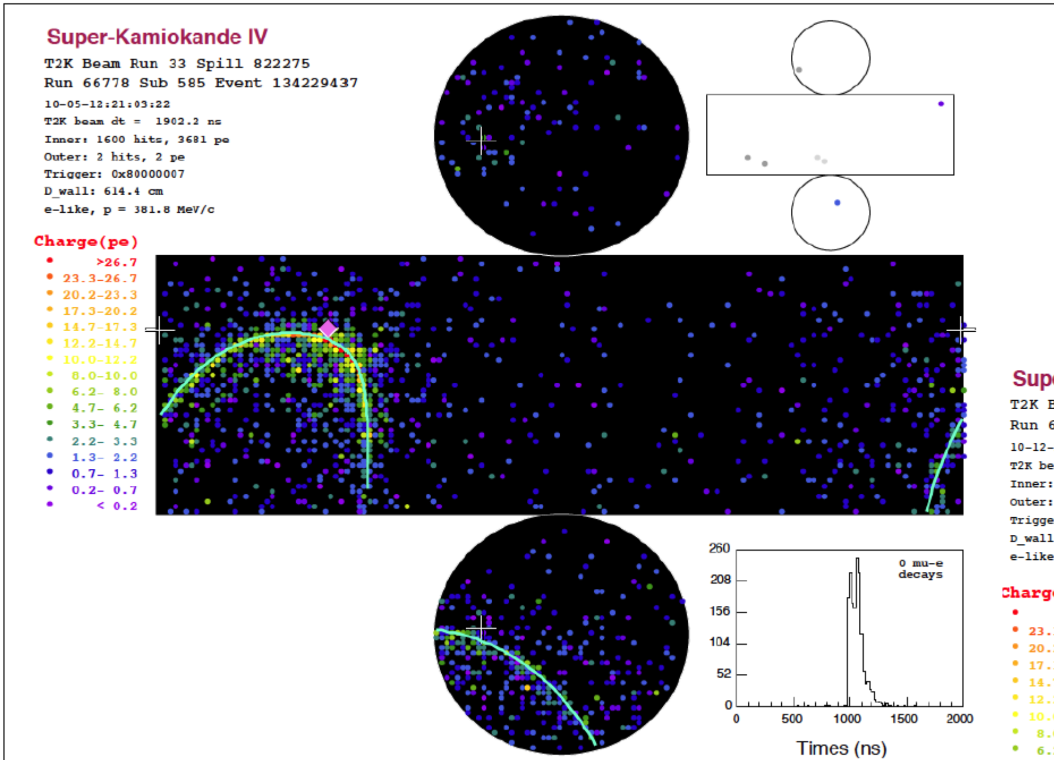
A possible tentative title would be:
``If theta_13 is large, then ?"

It is not the one whose content is clearly defined, but the one I want to think about.
At the bottom line I want to cover my recent paper arXiv:1103.4387
(with my student) but I will try this part relatively minor.
I do not know how far I can go.

It would be nice if you have any suggestions on the content, or
some counter arguments.

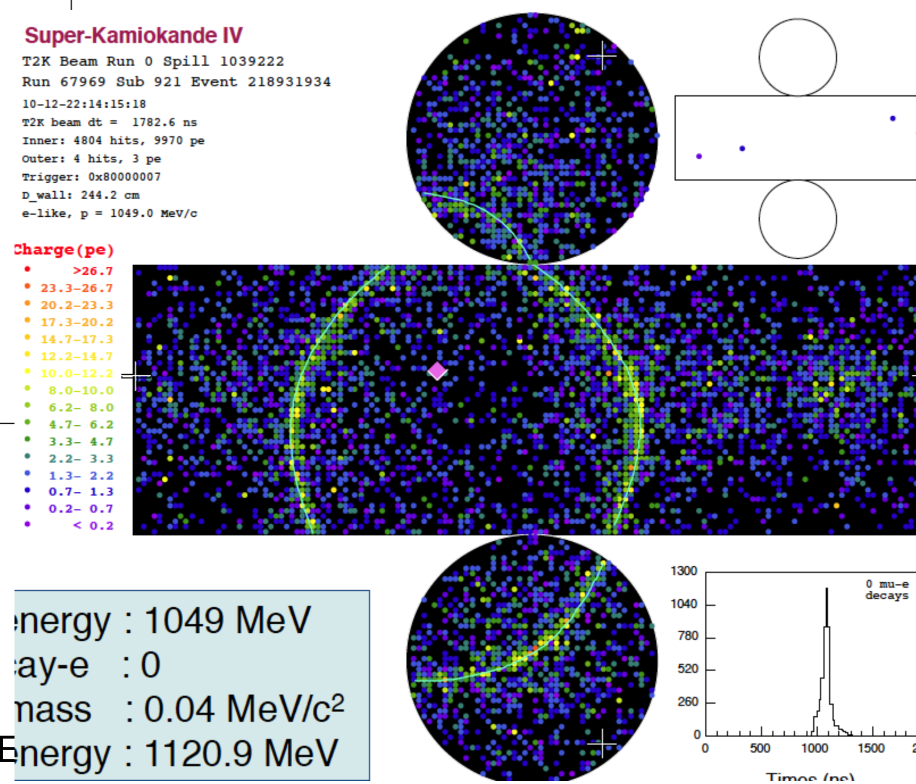
Best,
Hisakazu

Apparently θ_{13} is large

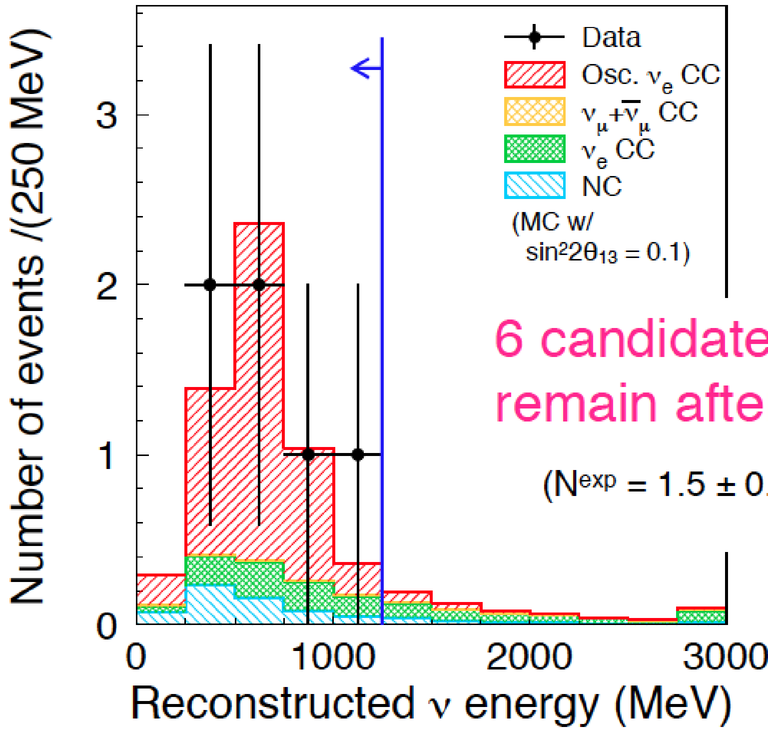


6 events at T2K !

Released in June 15@KEK

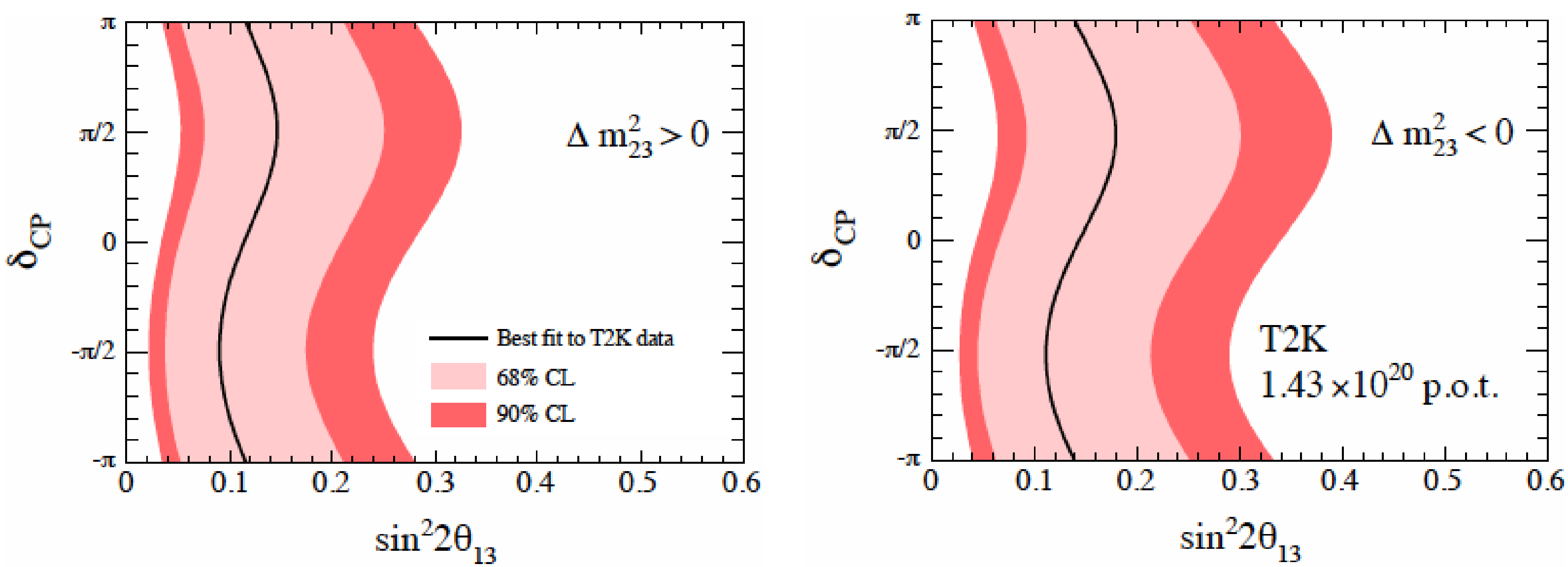


T2K appearance event distribution

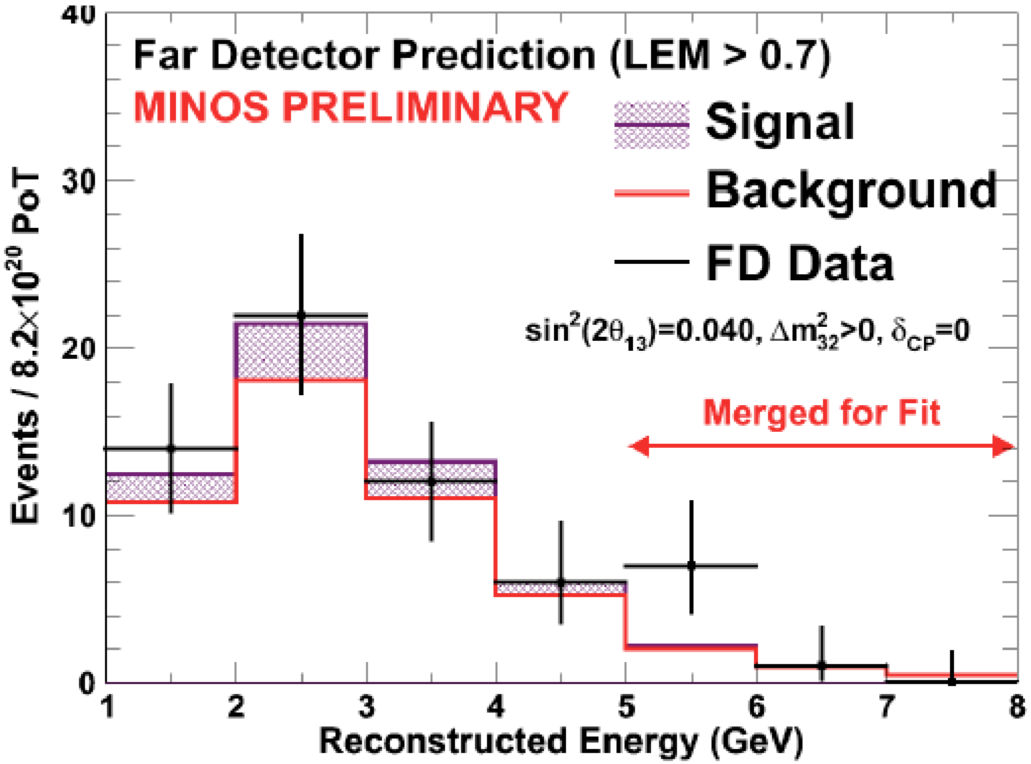


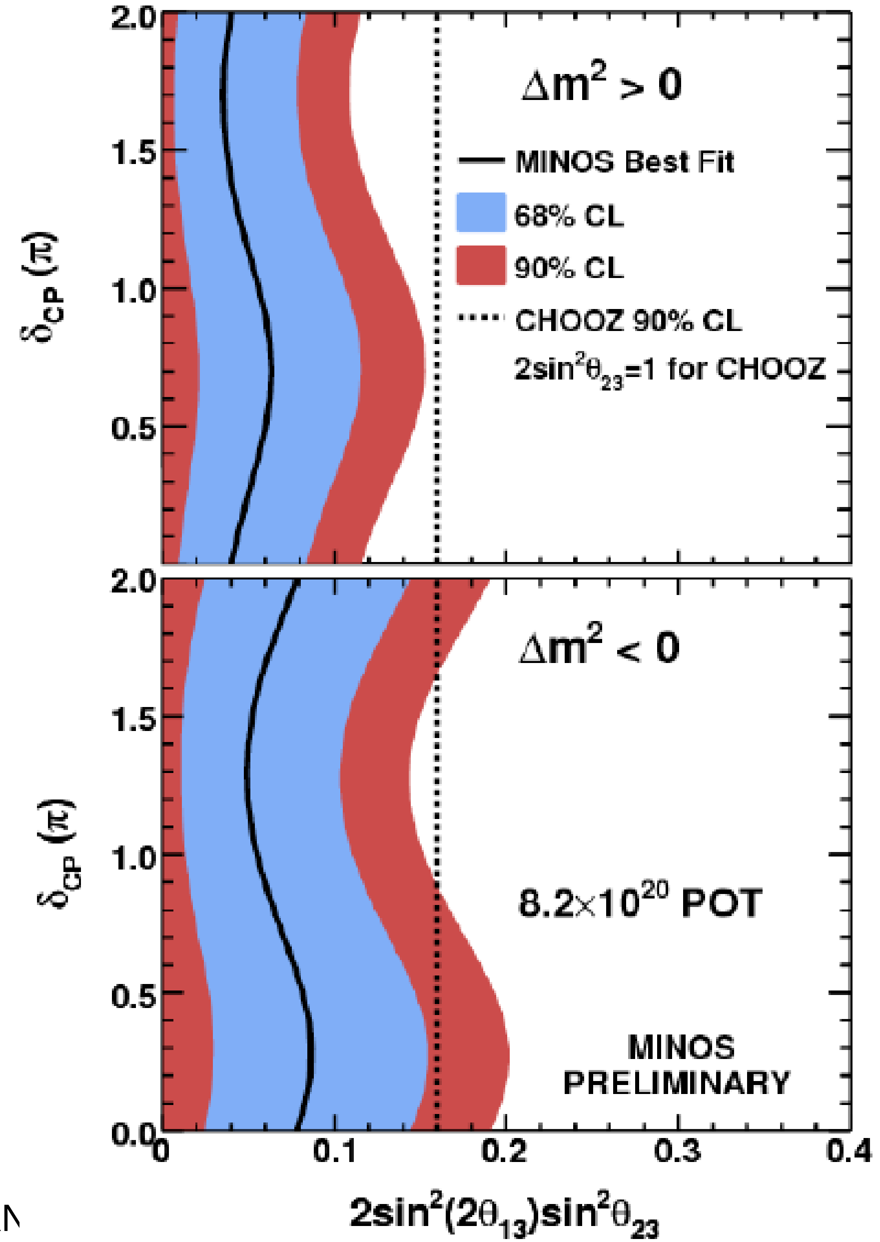
6 candidate events remain after all cuts !!

($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)



MINOS also saw excess

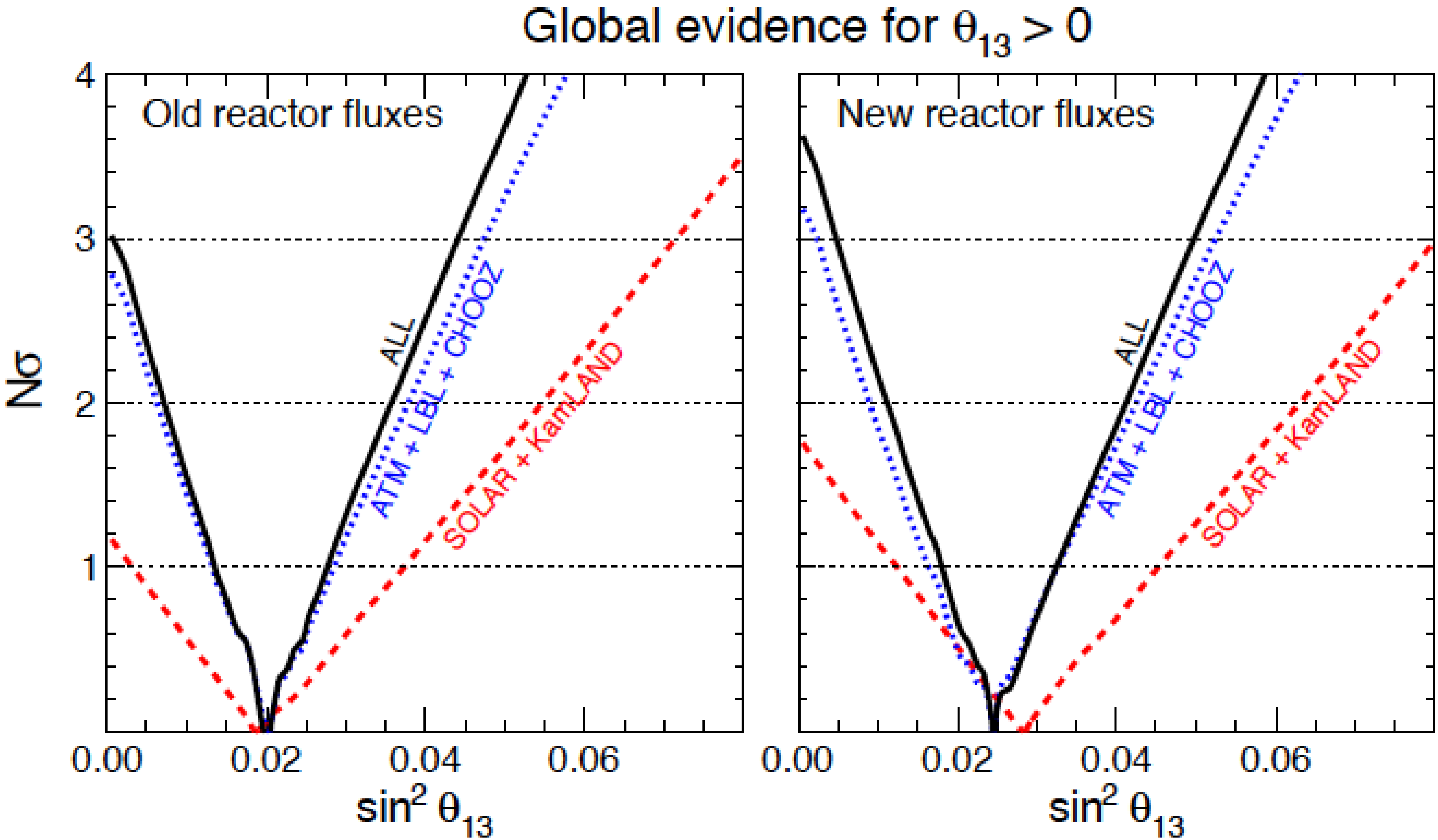




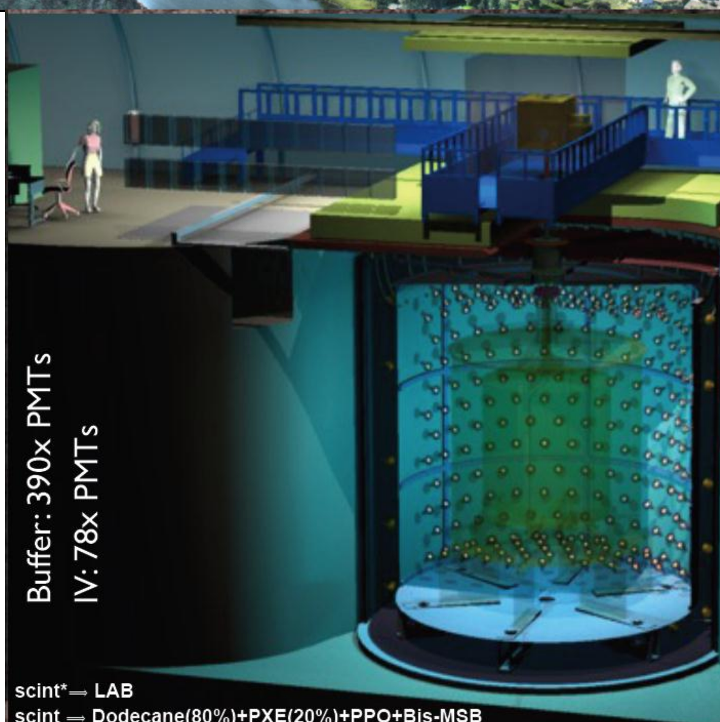
Global analysis

- All ν experiments coherently support $\theta_{13} \sim 8$ degree

Fogli et al. June 29



We will soon hear more about this from reactors!



There are two issues (at least)

Two issues of large θ_{13}

- What is the influence of large θ_{13} on strategies of future ν oscillation experiments ?

- What the large θ_{13} means? → Physics behind the large θ_{13}

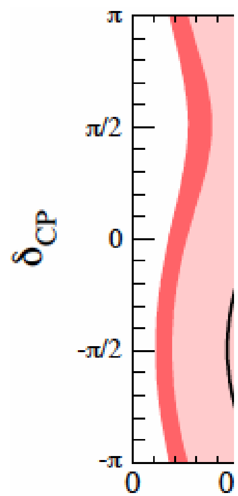
Smirnov's talk
Mohapatra's talk …

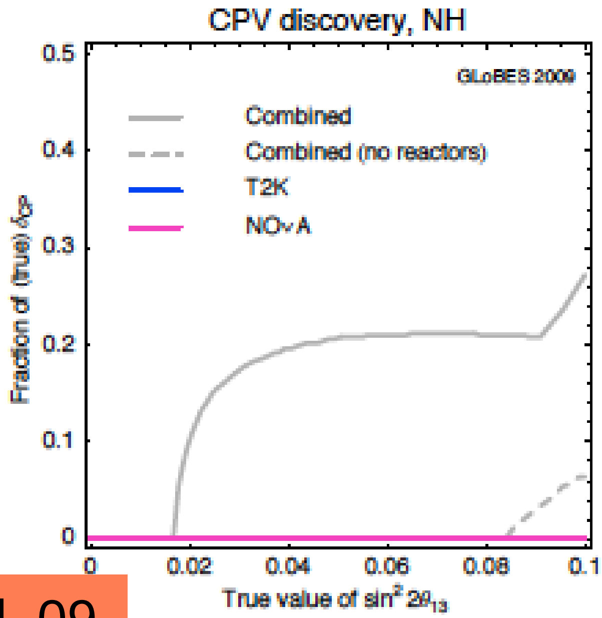
Wide possibilities are now open for CP

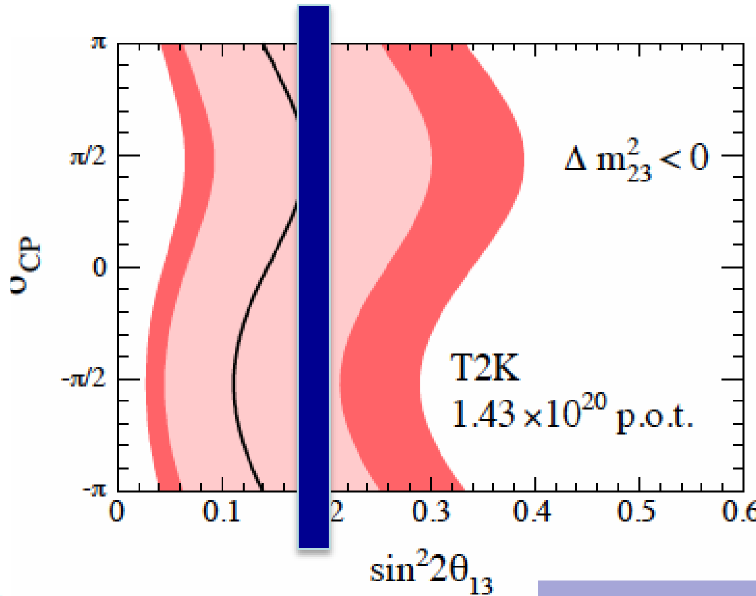
- Conventional ν_μ superbeam can do a much better job for CP (and possibly for mass hierarchy) than it was thought
- This means that we should reconsider about strategy for CP
- I believe megaton-scale water Cherenkov / 100 kt liquid Ar is still needed for robust discovery of CPV
- Yet, the paths to go there could have more variety → "guerrilla type" approaches possible

Various options become possible for CP

Reactor accelerator combination

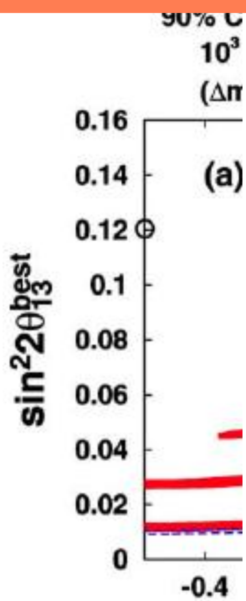


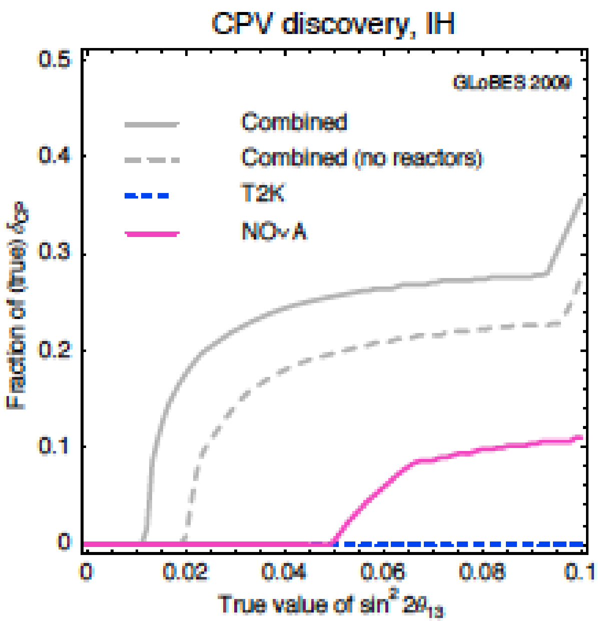


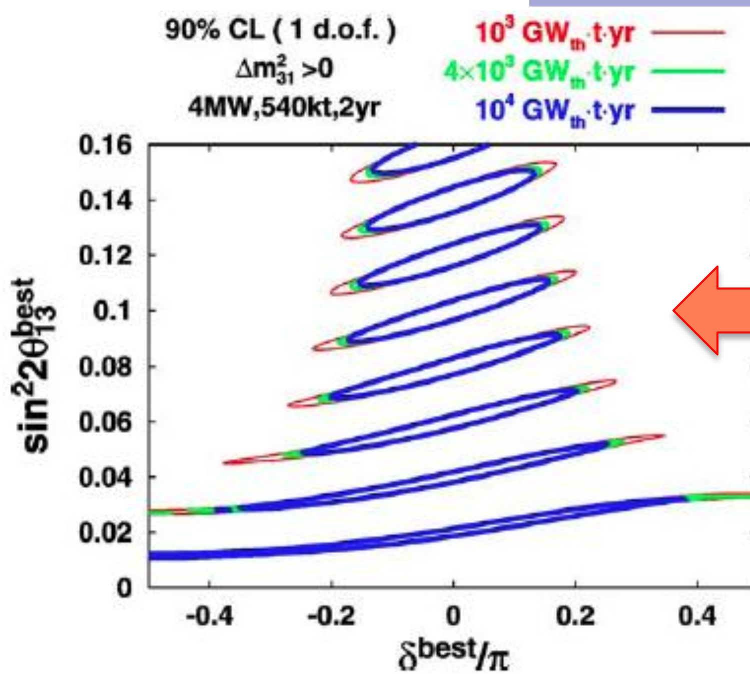


Huber et al. 09

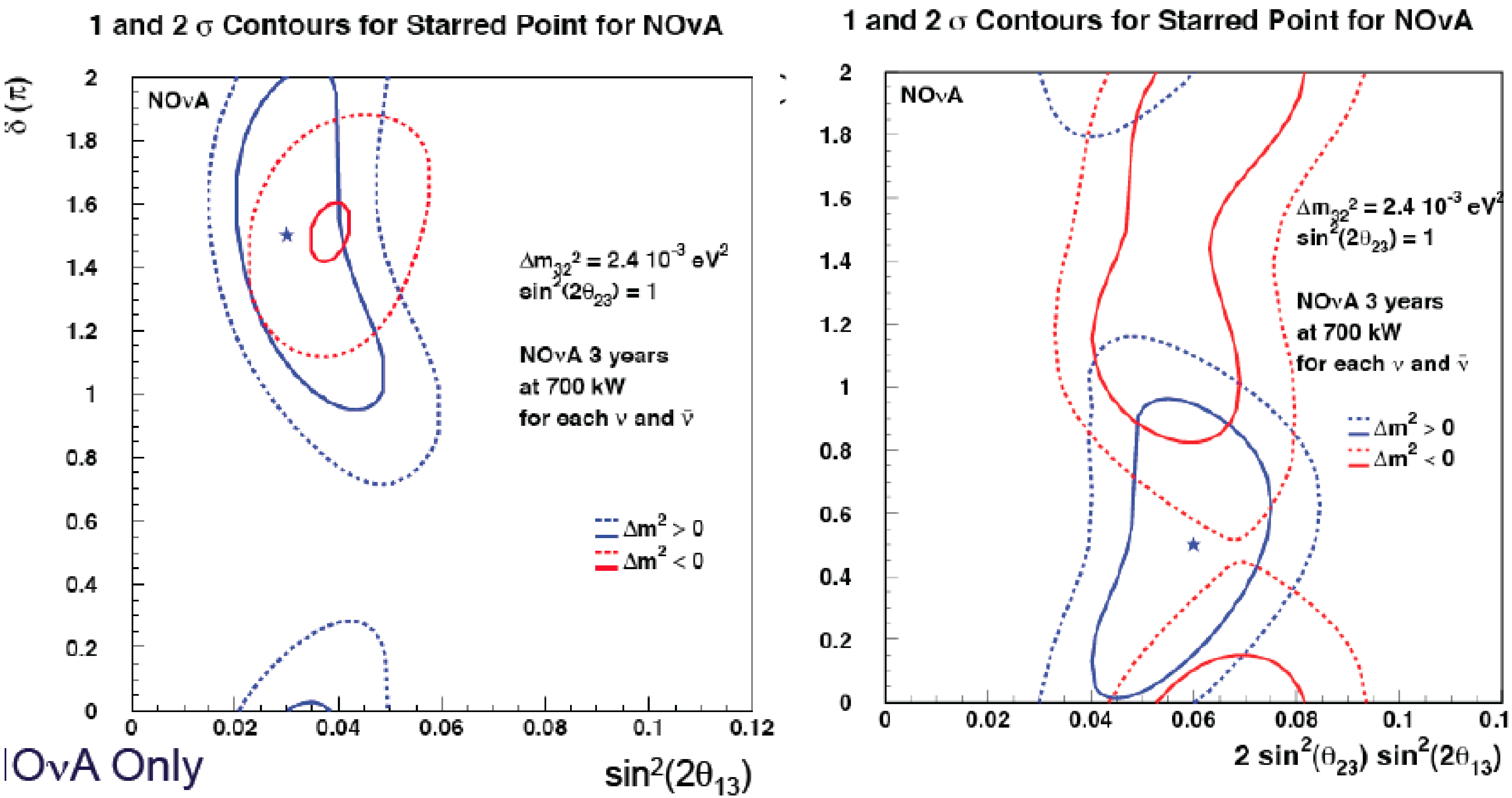
HM-Sugiyama 04







ν + ν-bar combination in NOνA / T2K

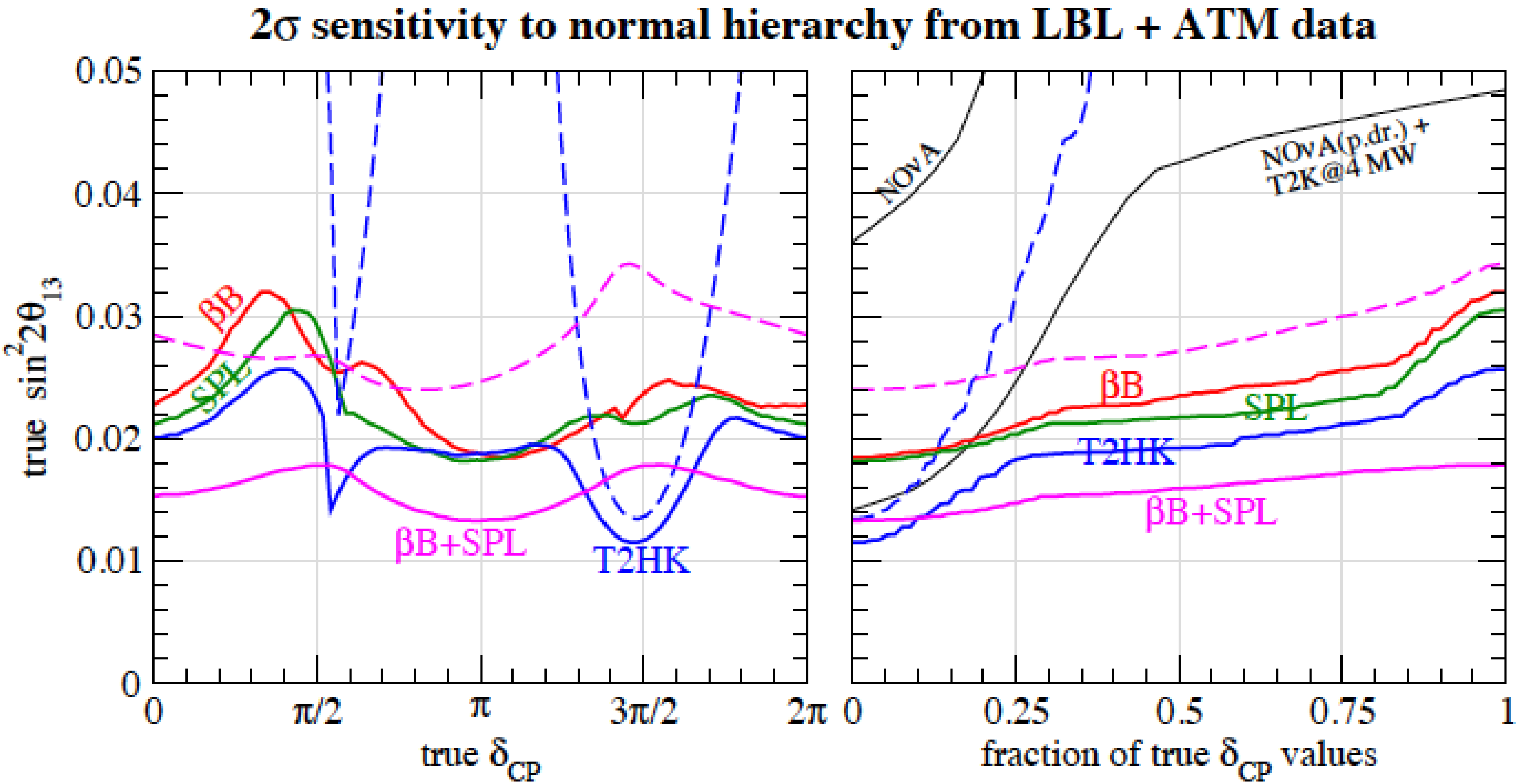


NOVA@wine&cheese June17

Reactor-accelerator & ν+ν-bar methods

- Apparently the methods works, but unlikely to cover all the δ space
- Quantitative estimation of CP sensitivity required → very interesting !!
- Results of CP sensitivity studies indicate the importance of mass hierarchy resolution

Various options possible…



MEMPHYS: Dashed line = combining SPL + beta

Campagne et al. 07

What do you propose?

Opening the possibility of "all in one"

- With large θ_{13} ~ Chooz limit a megaton scale water Cherenkov can do many
- With intense ν and ν-bar beam it can measure δ
- With gigantic atmospheric ν events it could determine mass hierarchy

Kakuno-san's talk

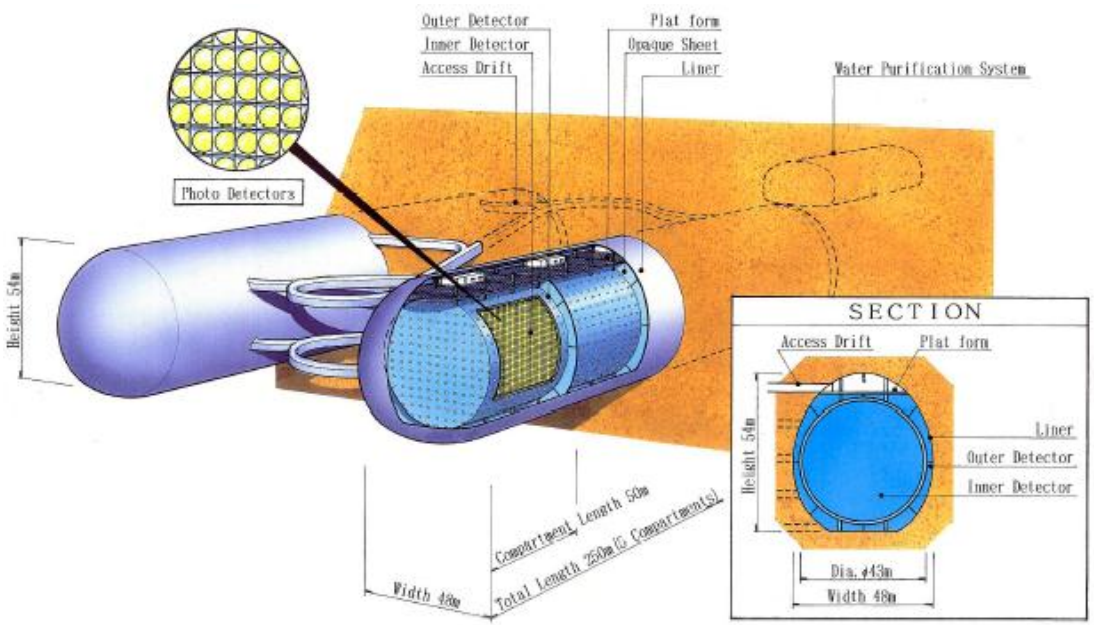
→ in situ measurement of everything in a single detector

- It can do proton decay
- It can do many astrophysics too

water Cherenkov vs. liquid Ar vs. TASD debatable

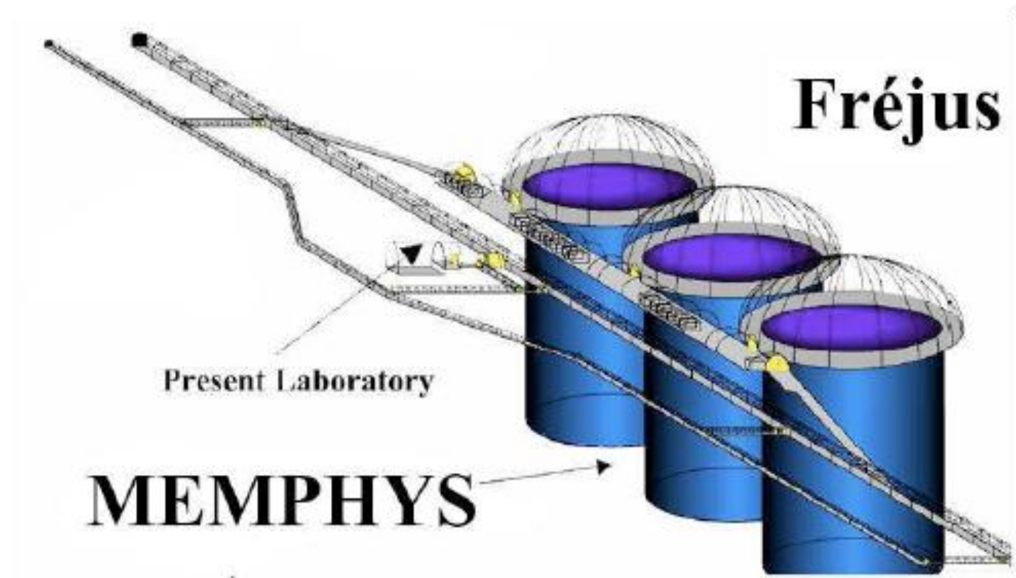
Issues in precision measurement of CP

megaton class detectors (examples)



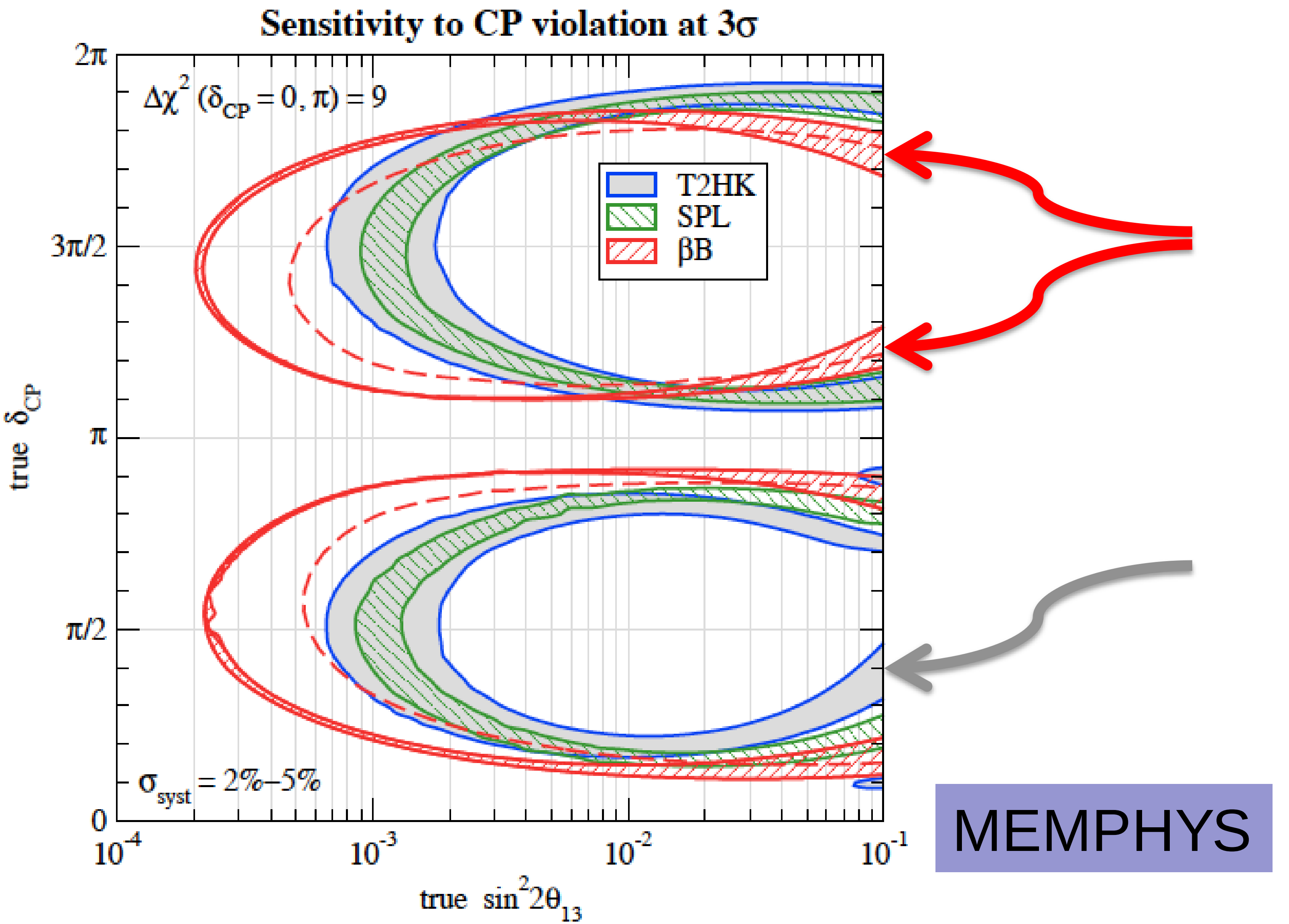
T2K II

MEMPHYS



August 1-6, 2011

CP sensitivity is not maximal at $\sin^2\theta_{13}$=0.1

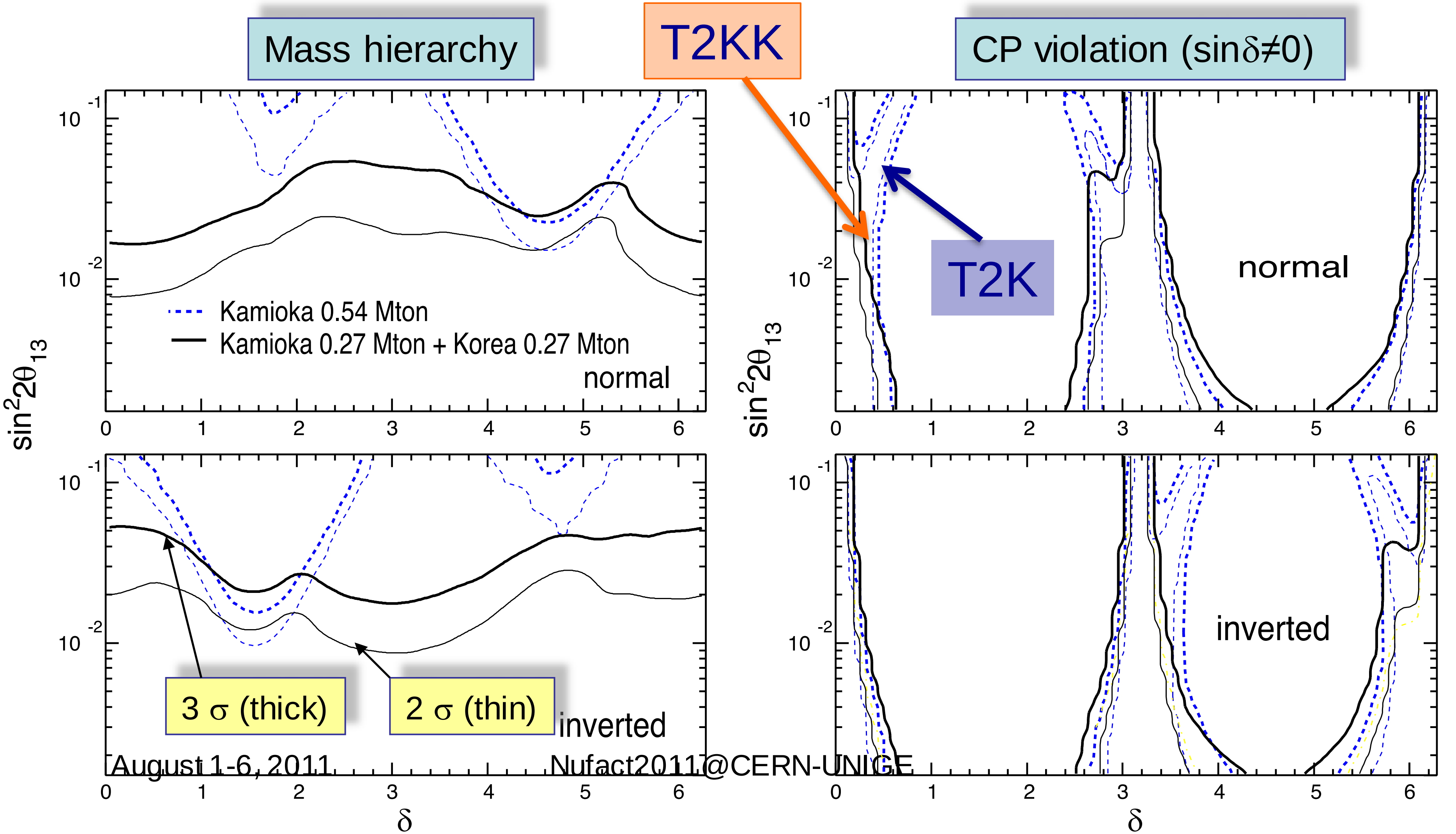


T2KK vs. T2K II Comparison

hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam

4MW!



Precision CP requires …

- T2K-T2KK comparison seems to indicate necessity of mass hierarchy resolution

Supported by analysis in Kakuno-san's talk

➡ importance of lifting sign Δm^2 degeneracy

- Comparison of different error treatments in ν ν-bar shows the relative cross section error affects CP sensitivity

ν cross section measurement crucially important

Does large θ_{13} require new oscillation formula?

Large θ_{13} corrections to Cervera et al. formula

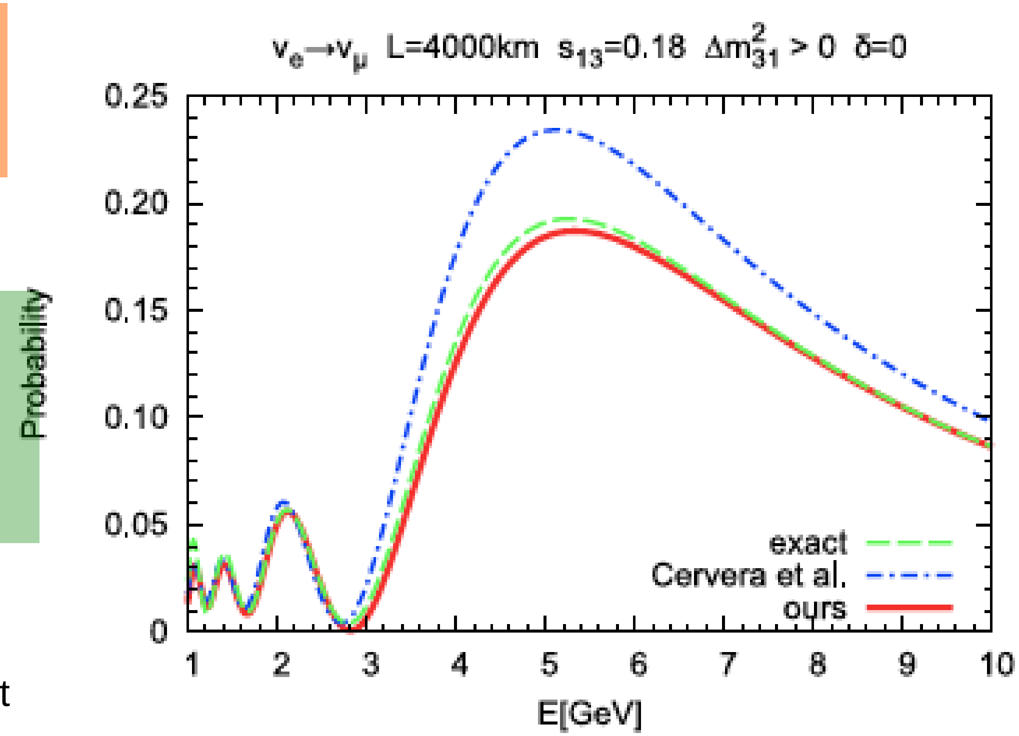
Good perturbative formula for small θ_{13} with $s_{13} \sim \Delta m^2_{21} / \Delta m^2_{31} = \varepsilon$: 2nd order formula

Cervera et al. 00

$$P_{e\mu} - Z = X_{\pm} s_C^2 + Y_{\pm} s_C \left(\cos\delta_C \cos\Delta_{31} \pm \sin\delta_C \sin\Delta_{31} \right),$$
$$\bar{P}_{e\mu} - Z = X_{\mp} s_C^2 - Y_{\mp} s_C \left(\cos\delta_C \cos\Delta_{31} \mp \sin\delta_C \sin\Delta_{31} \right),$$

But, for large $\theta_{13} \sim 10$ deg.
$s_{13} \sim$ \sqrt{ ε }

higher order corrections needed
$P_{NC} \sim s_{13}^4$, or $\sim s_{13}^2\, \varepsilon$



Computed: K. Asano-H.M. JHEP June 7, 2011

Some features of the new formula

$r_\Delta = \Delta m^2_{21} / \Delta m^2_{31}$
$r_A = a / \Delta m^2_{31}$
$\Delta = \Delta m^2_{31} / 2E$

$$P^{(1)}_{e\mu} = 4 s^2_{23} s^2_{13} \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2},$$

$$P^{(3/2)}_{e\mu} = 8 J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2},$$

$$\begin{aligned} P^{(2)}_{e\mu} &= 4 c^2_{23} c^2_{12} s^2_{12} \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2} \\ &-4 s^2_{23} \left[s^4_{13} \frac{(1+r_A)^2}{(1-r_A)^4} - 2 s^2_{12} s^2_{13} \frac{r_\Delta r_A}{(1-r_A)^3} \right] \sin^2 \frac{(1-r_A)\Delta L}{2} \\ &+2 s^2_{23} \left[2 s^4_{13} \frac{r_A}{(1-r_A)^3} - s^2_{12} s^2_{13} \frac{r_\Delta}{(1-r_A)^2} \right] (\Delta L) \sin(1-r_A)\Delta L. \end{aligned}$$

$$\begin{aligned} P^{(5/2)}_{e\mu} &= 8 J_r s^2_{13} \frac{r_\Delta r_A}{(1-r_A)^3} \cos\delta \sin^2 \frac{(1-r_A)\Delta L}{2} \\ &+8 J_r \frac{r_\Delta}{r_A(1-r_A)} \left[-2 s^2_{13} \frac{r_A}{(1-r_A)^2} + (c^2_{12} - s^2_{12}) \frac{r_\Delta}{r_A} + s^2_{12} \frac{r_\Delta r_A}{1-r_A} \right] \\ &\qquad \times \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2} \\ &+8 J_r s^2_{13} \frac{r_\Delta}{(1-r_A)^2} (\Delta L) \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \cos \frac{(1-r_A)\Delta L}{2} \\ &-4 J_r s^2_{12} \frac{r^2_\Delta}{r_A(1-r_A)} (\Delta L) \cos\left(\delta - \frac{r_A \Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \qquad (6.1 \\ &-4 J_r c^2_{12} \frac{r^2_\Delta}{r_A(1-r_A)} (\Delta L) \cos\left(\delta - \frac{(1+r_A)\Delta L}{2}\right) \sin \frac{(1-r_A)\Delta L}{2} \\ &-4 J_r \frac{r_\Delta}{r_A(1-r_A)} \left(s^2_{13} \frac{r_A}{1-r_A} - s^2_{12} r_\Delta \right) (\Delta L) \cos\left(\delta - \frac{(1-r_A)\Delta L}{2}\right) \sin \frac{(1-r_A)\Delta L}{2}. \end{aligned}$$

All the δ dependence is in half-integer power of ε

General theorems!

Correction terms are small

$$P_{e\mu}^{(1)} = 4s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2},$$

$$P_{e\mu}^{(3/2)} = 8J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2},$$

$$P_{e\mu}^{(2)} = 4c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2}$$
$$-4s_{23}^2 \left[s_{13}^4 \frac{(1+r_A)^2}{(1-r_A)^4} - 2s_{12}^2 s_{13}^2 \frac{r_\Delta r_A}{(1-r_A)^3} \right] \sin^2 \frac{(1-r_A)\Delta L}{2}$$
$$+2s_{23}^2 \left[2s_{13}^4 \frac{r_A}{(1-r_A)^3} - s_{12}^2 s_{13}^2 \frac{r_\Delta}{(1-r_A)^2} \right] (\Delta L) \sin(1-r_A)\Delta L.$$

$$P_{e\mu}^{(5/2)} = 8J_r s_{13}^2 \frac{r_\Delta r_A}{(1-r_A)^3} \cos\delta \sin^2 \frac{(1-r_A)\Delta L}{2}$$
$$+8J_r \frac{r_\Delta}{r_A(1-r_A)} \left[-2s_{13}^2 \frac{r_A}{(1-r_A)^2} + (c_{12}^2 - s_{12}^2)\frac{r_\Delta}{r_A} + s_{12}^2 \frac{r_\Delta r_A}{1-r_A} \right]$$
$$\times \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2}$$
$$+8J_r s_{13}^2 \frac{r_\Delta}{(1-r_A)^2} (\Delta L) \cos\left(\delta - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \cos \frac{(1-r_A)\Delta L}{2}$$
$$-4J_r s_{12}^2 \frac{r_\Delta^2}{r_A(1-r_A)} (\Delta L) \cos\left(\delta - \frac{r_A \Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \quad (6.1$$
$$-4J_r c_{12}^2 \frac{r_\Delta^2}{r_A(1-r_A)} (\Delta L) \cos\left(\delta - \frac{(1+r_A)\Delta L}{2}\right) \sin \frac{(1-r_A)\Delta L}{2}$$
$$-4J_r \frac{r_\Delta}{r_A(1-r_A)} \left(s_{13}^2 \frac{r_A}{1-r_A} - s_{12}^2 r_\Delta \right) (\Delta L) \cos\left(\delta - \frac{(1-r_A)\Delta L}{2}\right) \sin \frac{(1-r_A)\Delta L}{2}.$$

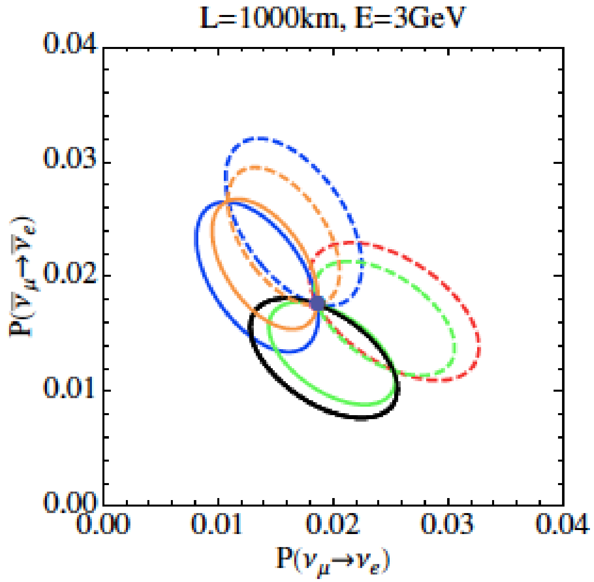
All the correction terms are of order ~ ε^2

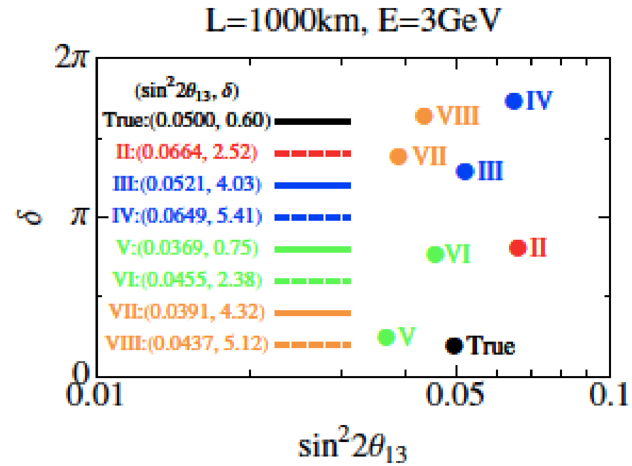
General theorems!

$r_\Delta = \Delta m^2_{21}/\Delta m^2_{31}$
$r_A = a/\Delta m^2_{31}$
$\Delta = \Delta m^2_{31} / 2E$

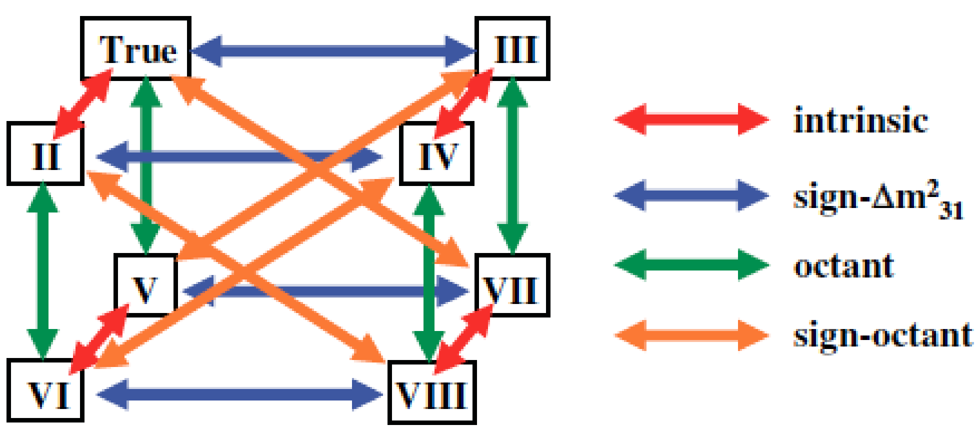
Is parameter degeneracy affected by large θ_{13}?

P degeneracy well understood





$$P_{e\mu} - Z = X_\pm s_C^2 + Y_\pm s_C \left(\cos\delta_C \cos\Delta_{31} \pm \sin\delta_C \sin\Delta_{31}\right),$$
$$\bar{P}_{e\mu} - Z = X_\mp s_C^2 - Y_\mp s_C \left(\cos\delta_C \cos\Delta_{31} \mp \sin\delta_C \sin\Delta_{31}\right),$$



Cervera et al. formula

E

HM-Uchinami JHEP10

Is P degeneracy unchanged for large θ_{13}?

$$P_{e\mu} - Z = X_{\pm} s_C^2 + Y_{\pm} s_C \left(\cos\delta_C \cos\Delta_{31} \pm \sin\delta_C \sin\Delta_{31}\right),$$
$$\bar{P}_{e\mu} - Z = X_{\mp} s_C^2 - Y_{\mp} s_C \left(\cos\delta_C \cos\Delta_{31} \mp \sin\delta_C \sin\Delta_{31}\right),$$

Cervera et al. formula

$$P_{e\mu} - Z = X_{\pm} s_T^2 + Y_{\pm} s_T \left(\cos\delta_T \cos\Delta_{31} \pm \sin\delta_T \sin\Delta_{31}\right) + P_{NC},$$
$$\bar{P}_{e\mu} - Z = X_{\mp} s_T^2 - Y_{\mp} s_T \left(\cos\delta_T \cos\Delta_{31} \mp \sin\delta_T \sin\Delta_{31}\right) + \bar{P}_{NC},$$

$P_{NC} \sim s_{13}^4$, or $\sim s_{13}^2\, \Delta m^2_{21} / \Delta m^2_{31}$

- One can show on general ground that P_{NC} must be order $(\Delta m^2_{21} / \Delta m^2_{31})^2 \sim 0.001$
- Difference between Cervera sol. and our solutions is tiny (apart from a particular region)

Asano-HM JHEP11

What large θ_{13} means?

What large θ_{13} means?

- Large θ_{13} is natural because in $U=V_l^+V_\nu$ two angles are large, and hence extremely small θ_{13} is not expected,
- Anarchy ?
- The above argument assumes no symmetry is hidden → symmetries which enforce $\theta_{13}=0$ somewhat discouraged (?) unless you have good reasons

Large θ_{13} in QLC context

QLC based on observation: $\theta_{12} + \theta_C = \pi/4$

"bimaximal minus CKM mixing."

Raidal 04,
HM-A.Smirnov 04

Bimaximal mixing from neutrinos

$$U_\nu = R_{23}^m R_{12}^m, \qquad U_l = V^{\rm CKM}. \qquad U_{\rm MNS} = V^{\rm CKM\dagger}\Gamma_\delta R_{23}^m R_{12}^m$$

$$\sin^2\theta_{13} = 0.026 \pm 0.008$$

Bimaximal mixing
from charged leptons

$$|U_{e3}|^2 \simeq 5 \times 10^{-4}$$

Large θ_{13} prefers bimaximal mixing from ν

Conclusion

- large θ_{13} opens up wide range of possibilities for hunting CP & mass hierarchy
- While guerrilla type approach is possible, a charming case would be to determine all at once by a megaton-scale detector (+proton decay) → Hyper-K
- Yet, precision measurement would require resolution of sign-Δm^2 degeneracy
- Physical meaning of the large θ_{13} has to be understood