Era of accelerator and reactor θ_{13} experiments

Hisakazu Minakata
Tokyo Metropolitan University

Reactor & accelerator θ_{13} experiments blossomed !

A&R順不同

Super-Kamiokande
(ICRR, Univ. Tokyo)

T2K

J-PARC Main Ring
(KEK-JAEA, Tokai)

Double Chooz

Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology

rinos

To measure θ_{13} one needs ν_e

- $P(\nu_e \rightarrow \nu_e)$ is the interference between

e->1 -------> 1->e and e->2 -------> 2->e

e->3 -------> 3->

Obviously involve $|U_{e3}|^2 = s^2_{13}$

- $P(\nu_\mu \rightarrow \nu_e)$ is the interference between

μ->1 -------> 1->e and μ->2 -------> 2->e

μ->3 -------> 3->e

Involve $|U_{e3}| = s_{13}$ but in fact s^2_{13}

Reactor and accelerator are equally good probe for θ_{13}

Complementarity is the key word

- Reactor measurement depends only on θ_{13}
- Clean measurement of θ_{13}
- Relatively inexpensive, but single purpose exp.

- Accelerator measurement can enjoy richness of the world, θ_{13} and δ, the last parameter in the νSM (except for Majorana phases)
- Expensive but extendable to CP measurement

The most important feature for me is that we can enjoy redundancy of these two methods!

I participated the era by proposing reactor θ_{13} experiment, a good time

Reactor Measurement of θ_{13} and Its Complementarity to Long-Baseline Experiments

H. Minakata,* H. Sugiyama,† and O. Yasuda‡

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

K. Inoue§ and F. Suekane¶

Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, 980-8578, Japan

(Dated: March 17, 2011)

Abstract

A possibility to measure $\sin^2 2\theta_{13}$ using reactor neutrinos is examined in detail. It is shown that the sensitivity $\sin^2 2\theta_{13} > 0.02$ can be reached with 20 ton-year data by placing identical CHOOZ-like detectors at near and far distances from a giant nuclear power plant whose total thermal energy is 24.3 GW_{th}. It is emphasized that this measurement is free from the parameter degeneracies which occur in accelerator appearance experiments, and therefore the reactor measurement plays a role complementary to accelerator experiments. It is also shown that the reactor measurement may be able to resolve the degeneracy in θ_{23} if $\sin^2 2\theta_{13}$ and $\cos^2 2\theta_{23}$ are relatively large.

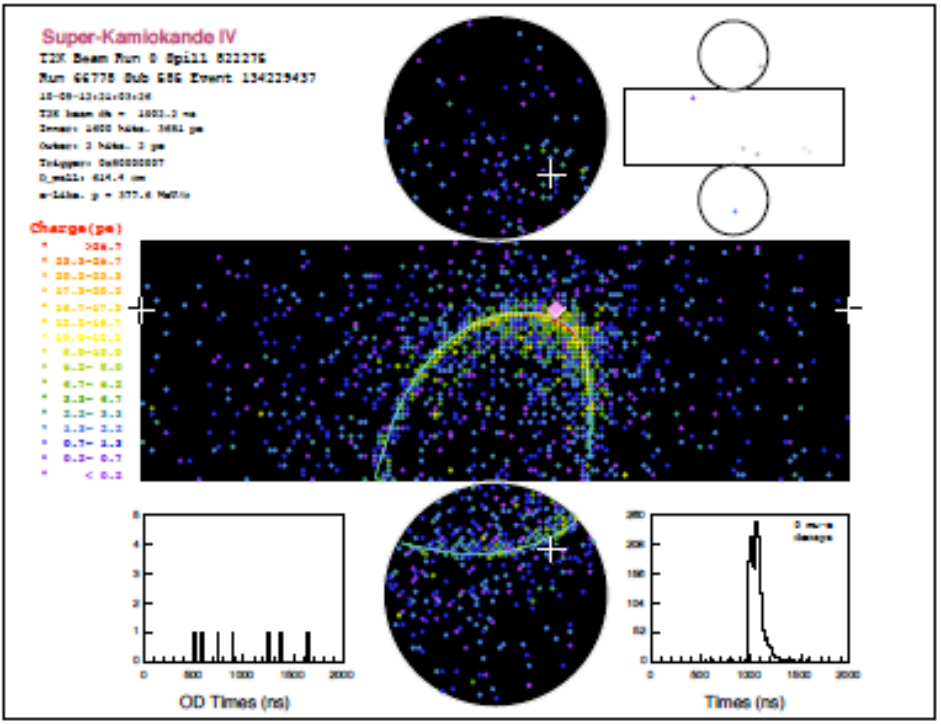
PACS numbers: 14.60.Pq,25.30.Pt,28.41.-i

T2K surprised us in June 2011

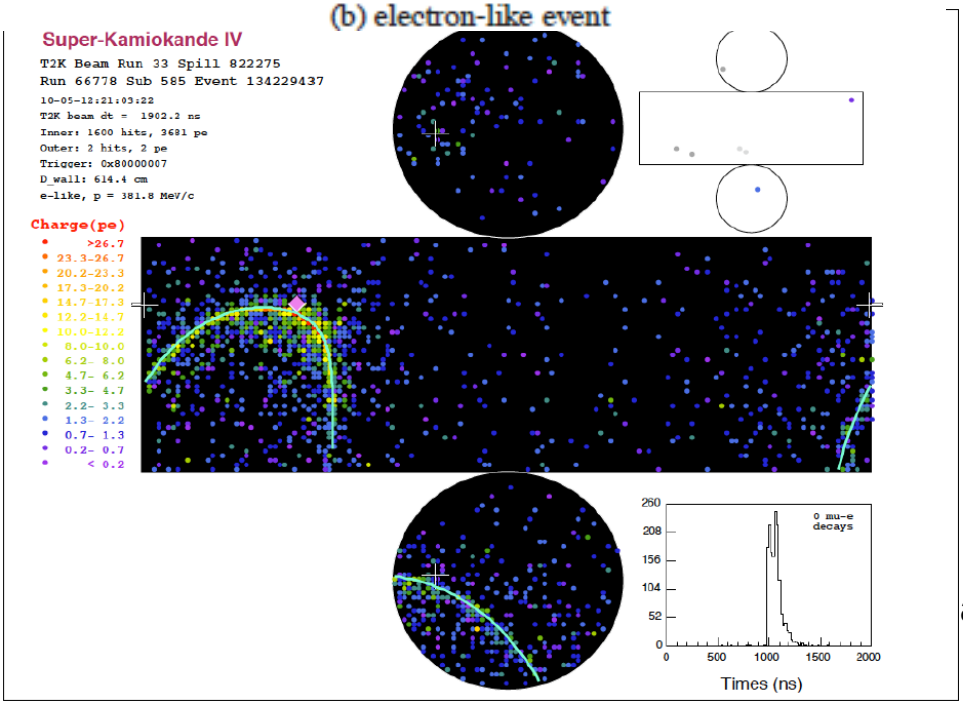
1st indication of nonzero θ_{13}

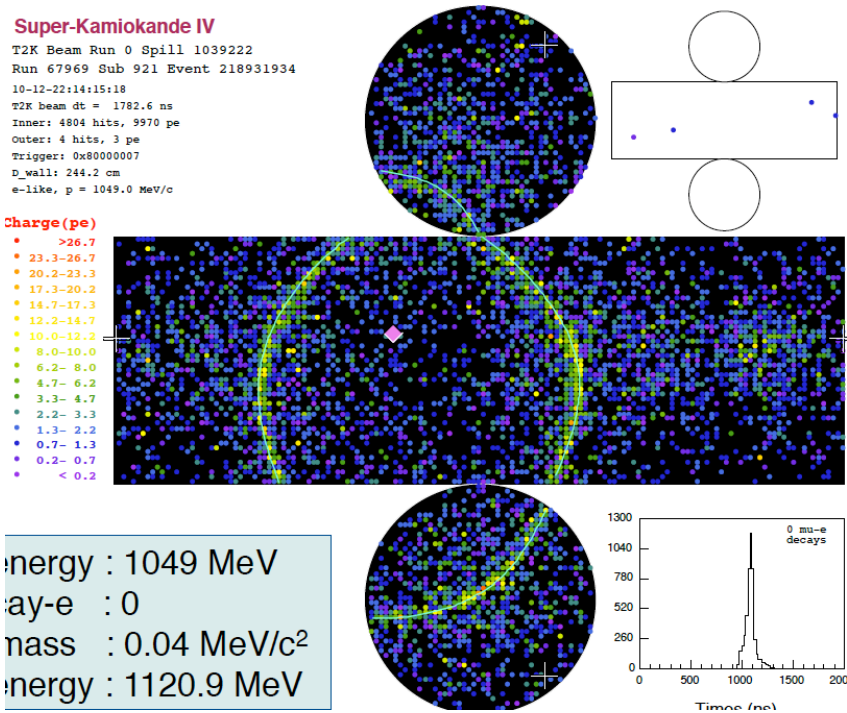
6 events at T2K !

Released in June 15@KEK



(b) electron-like event

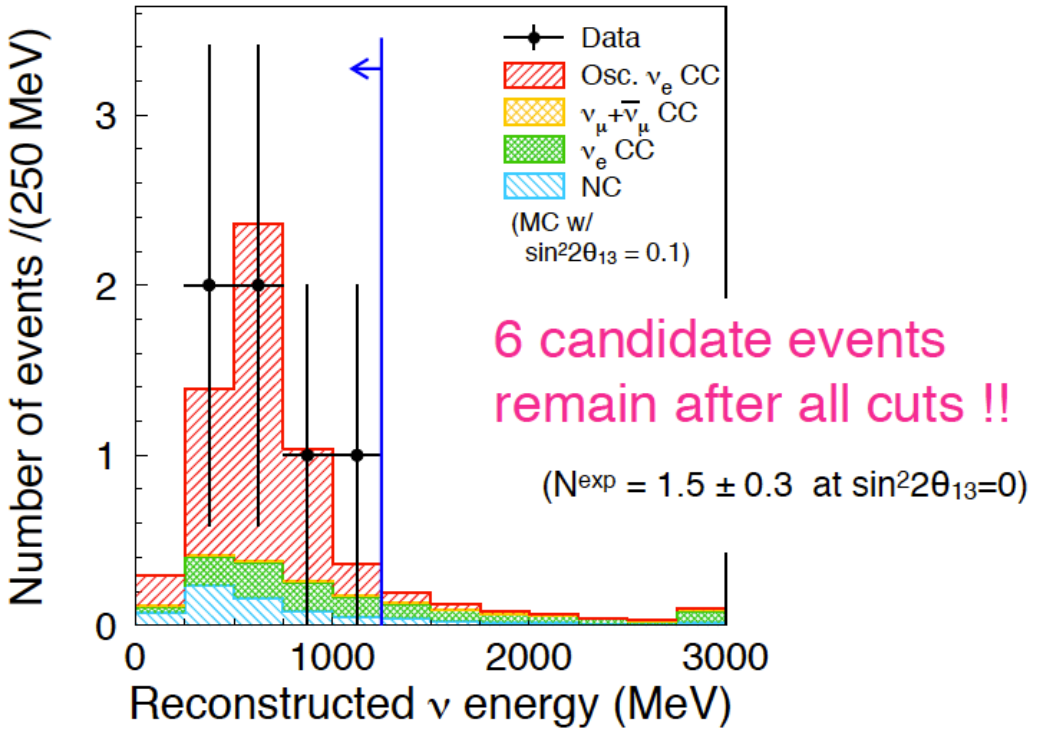


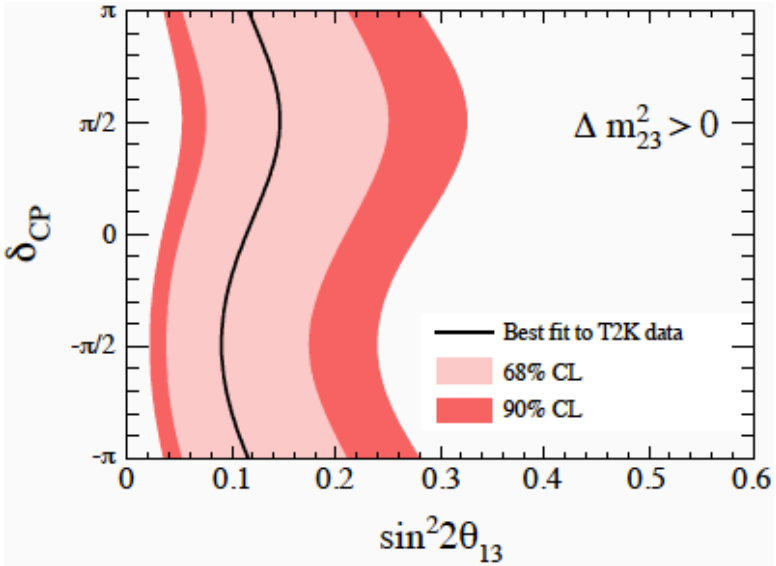


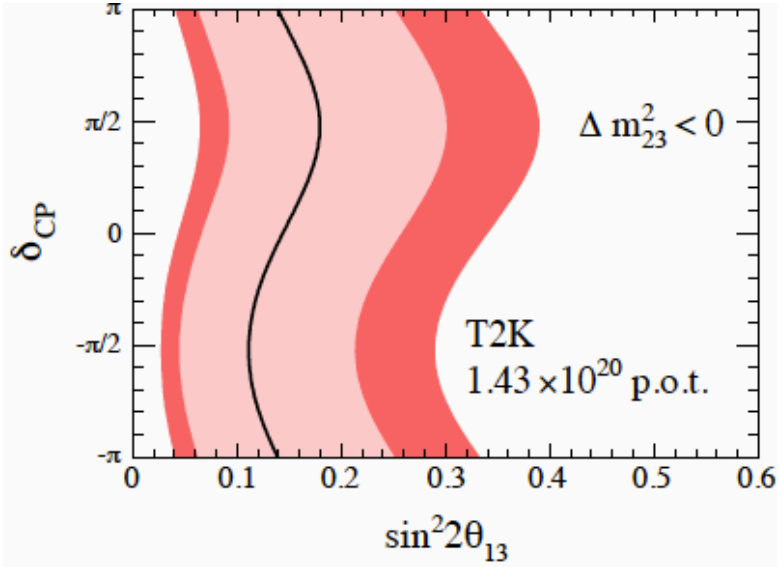
ay and

nergy : 1049 MeV
ay-e : 0
nass : 0.04 MeV/c²
nergy : 1120.9 MeV

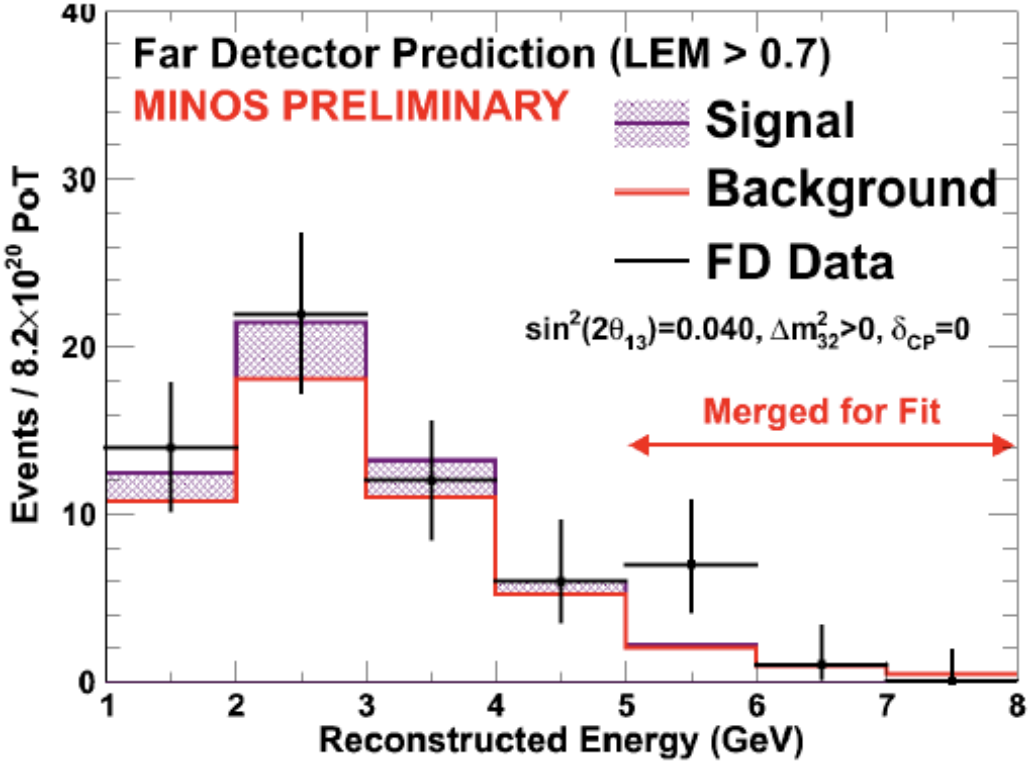
T2K appearance event distribution

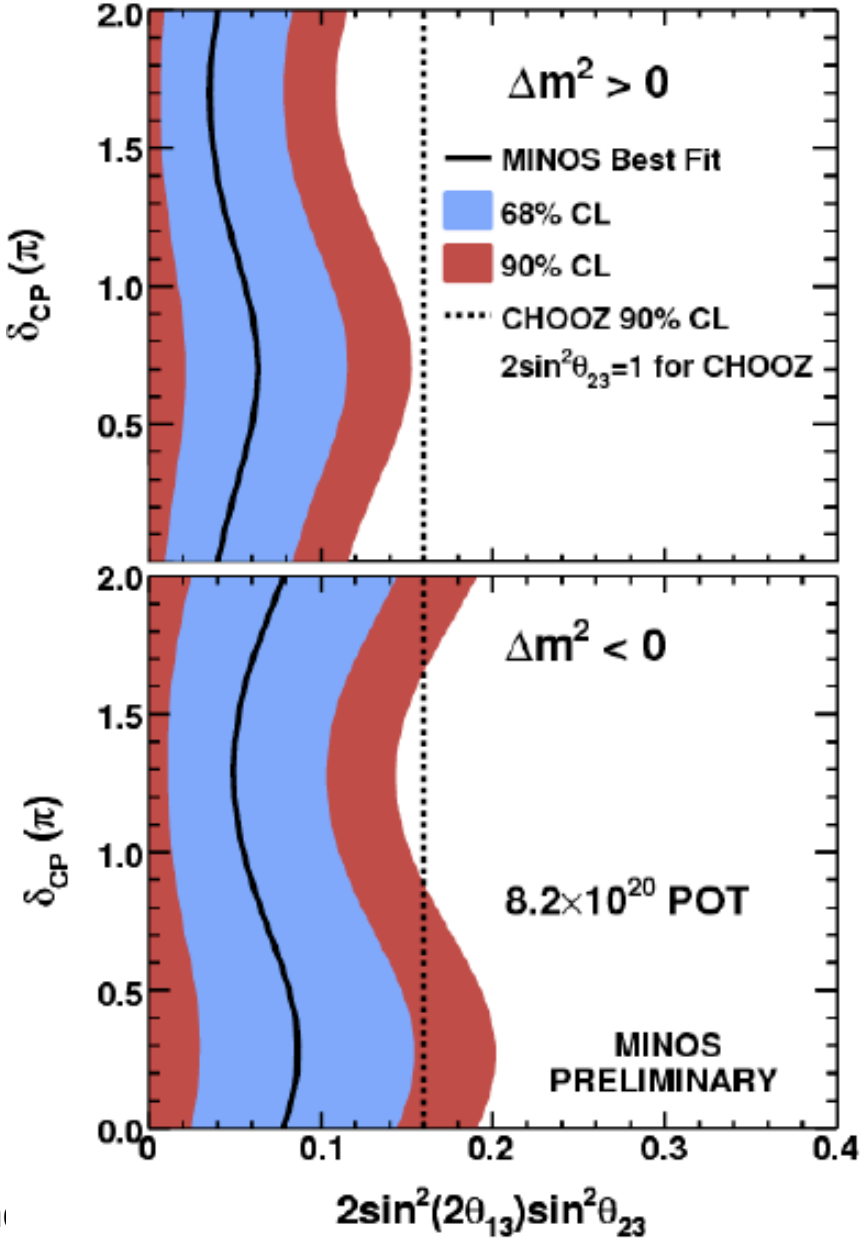






MINOS also saw excess

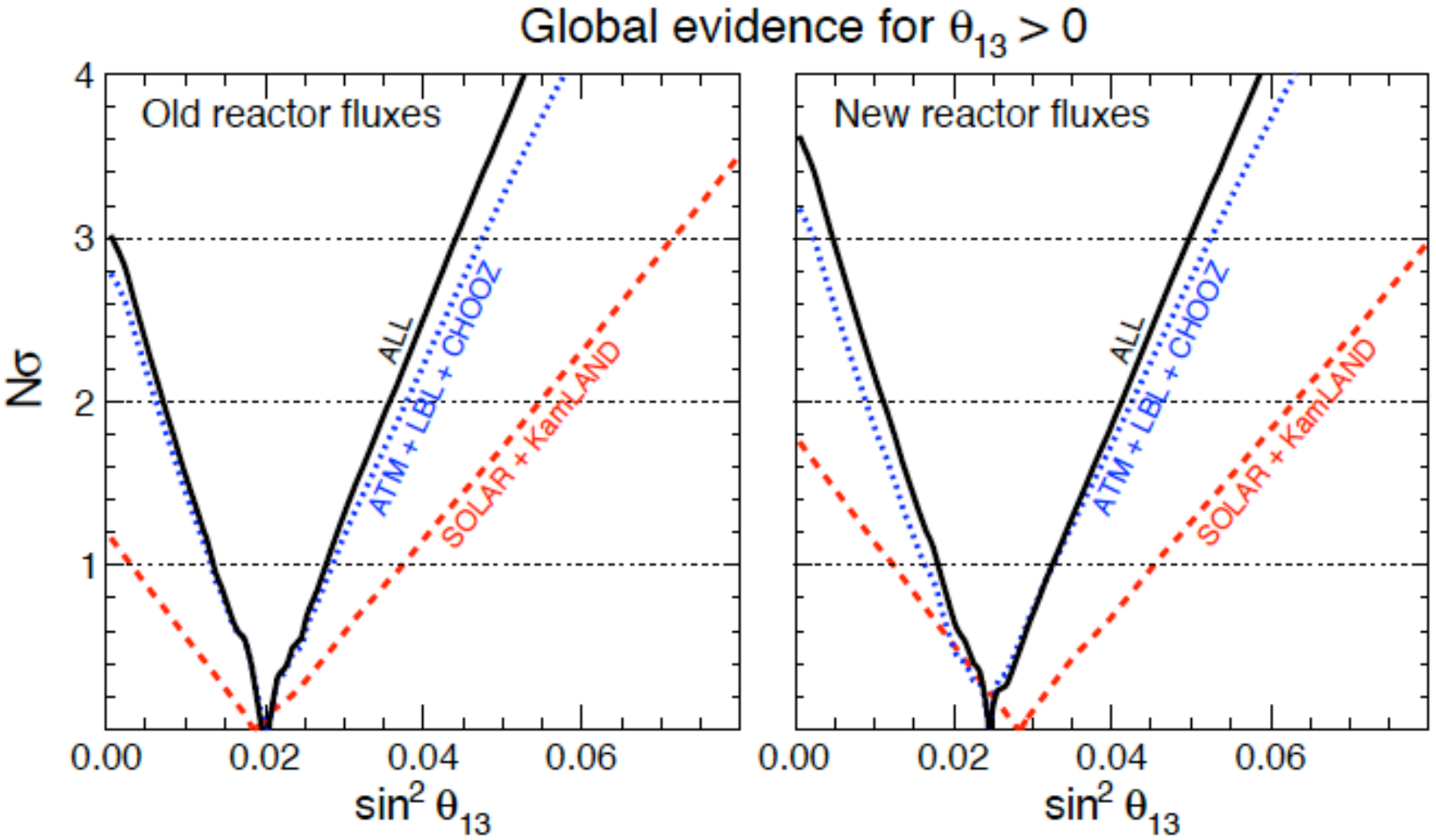




Global analysis

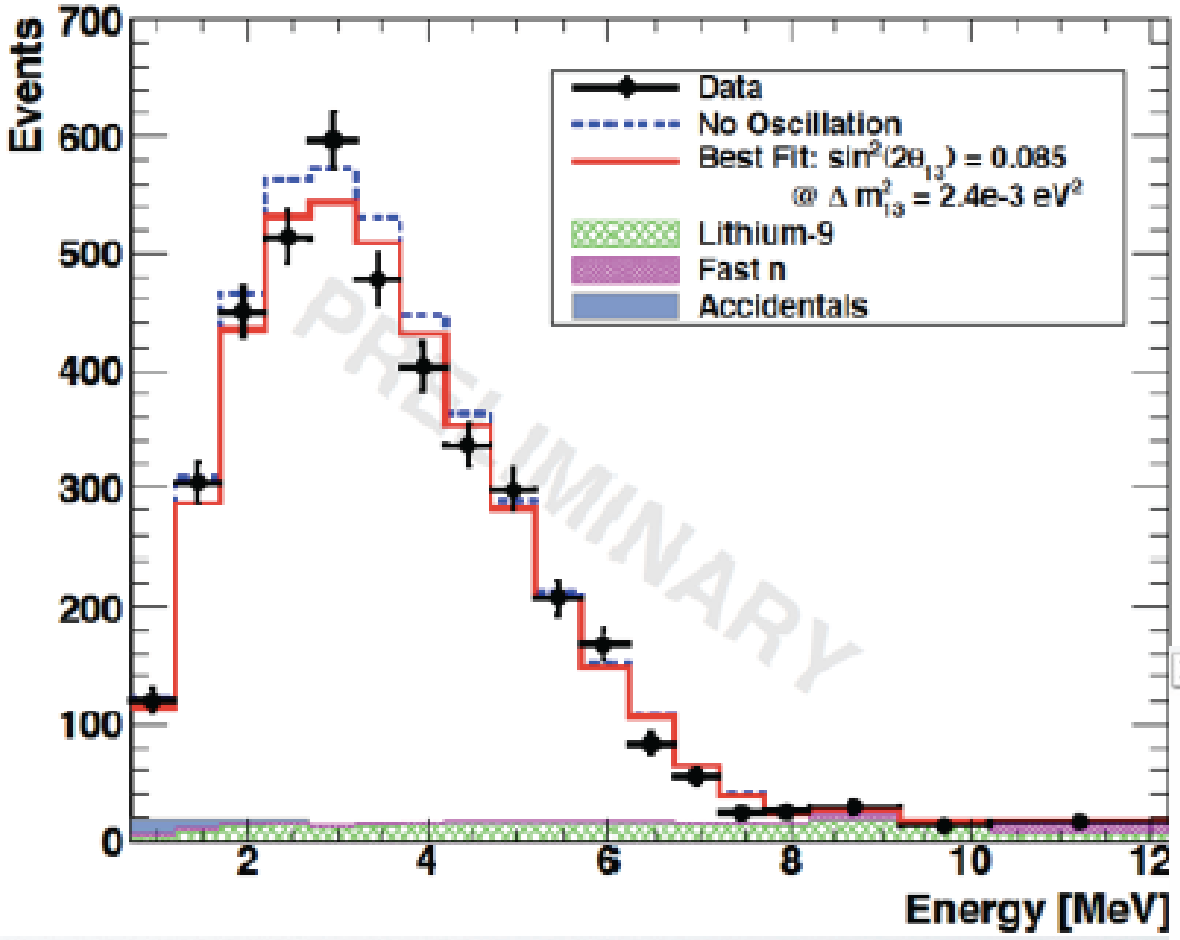
- All ν experiments coherently support $\theta_{13} \sim 8$ degree

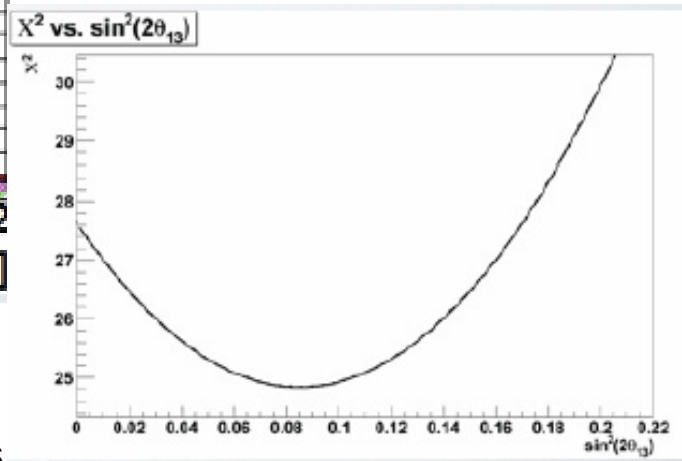
Fogli et al. June 29



Double Chooz reminded us that there is a complementary way for θ_{13}

Double Chooz Reactor data just released at Low-Nu11 in Seoul, Korea!





Rate + Shape Analysis:

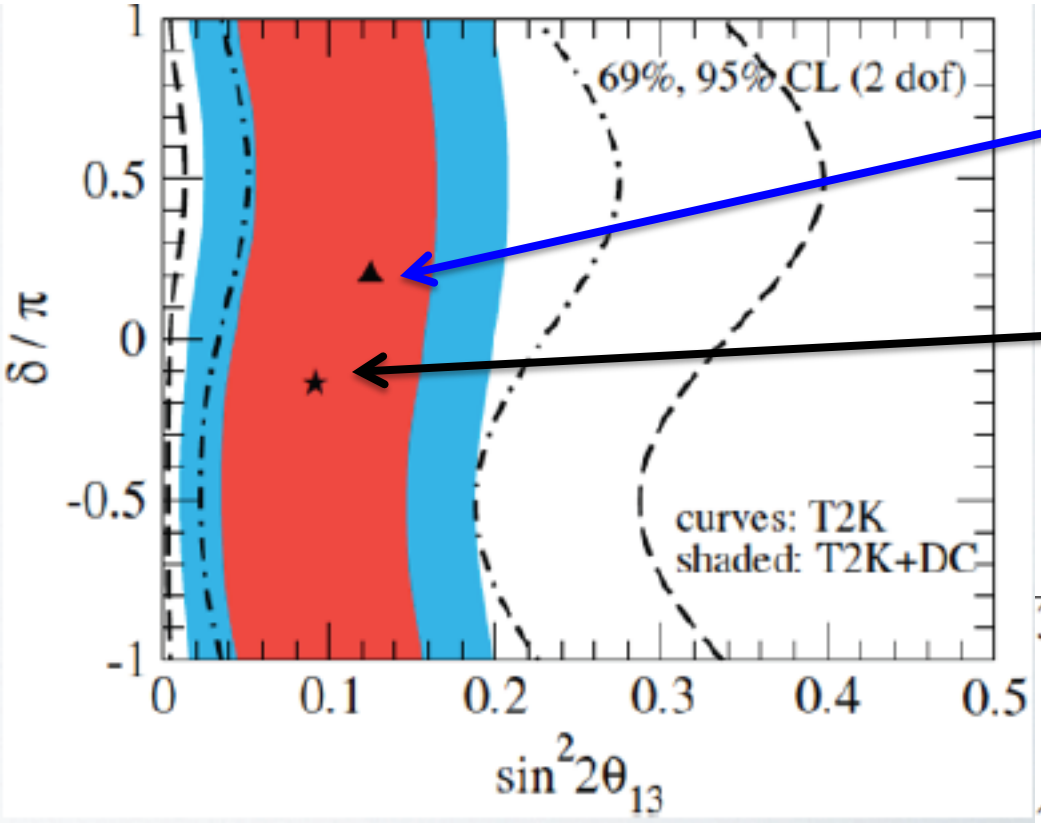
$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

Rate Only:

$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$

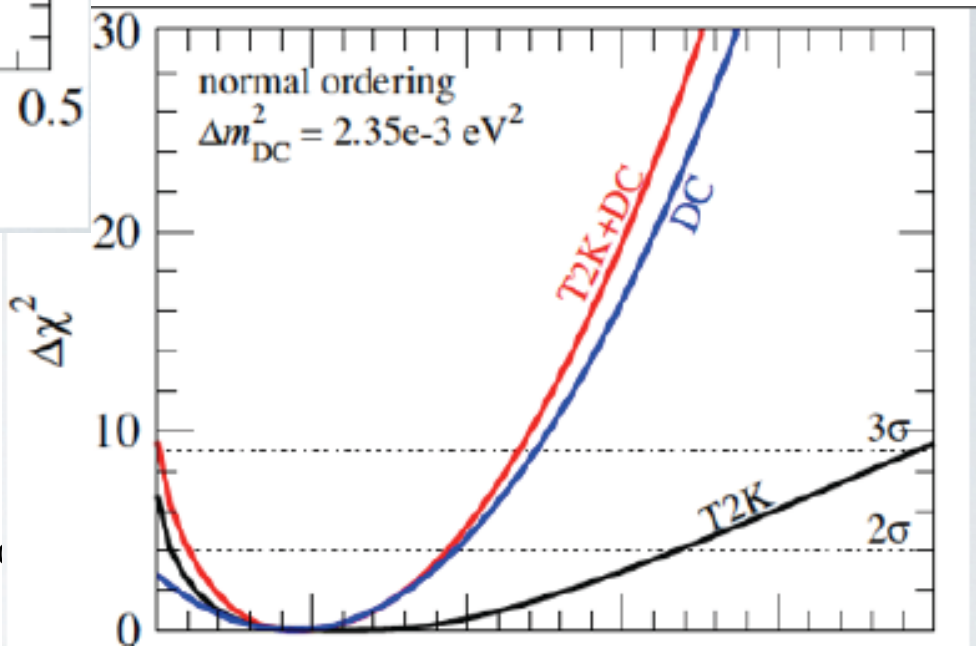
trinos

> 3 σ evidence for nonzero θ_{13}!



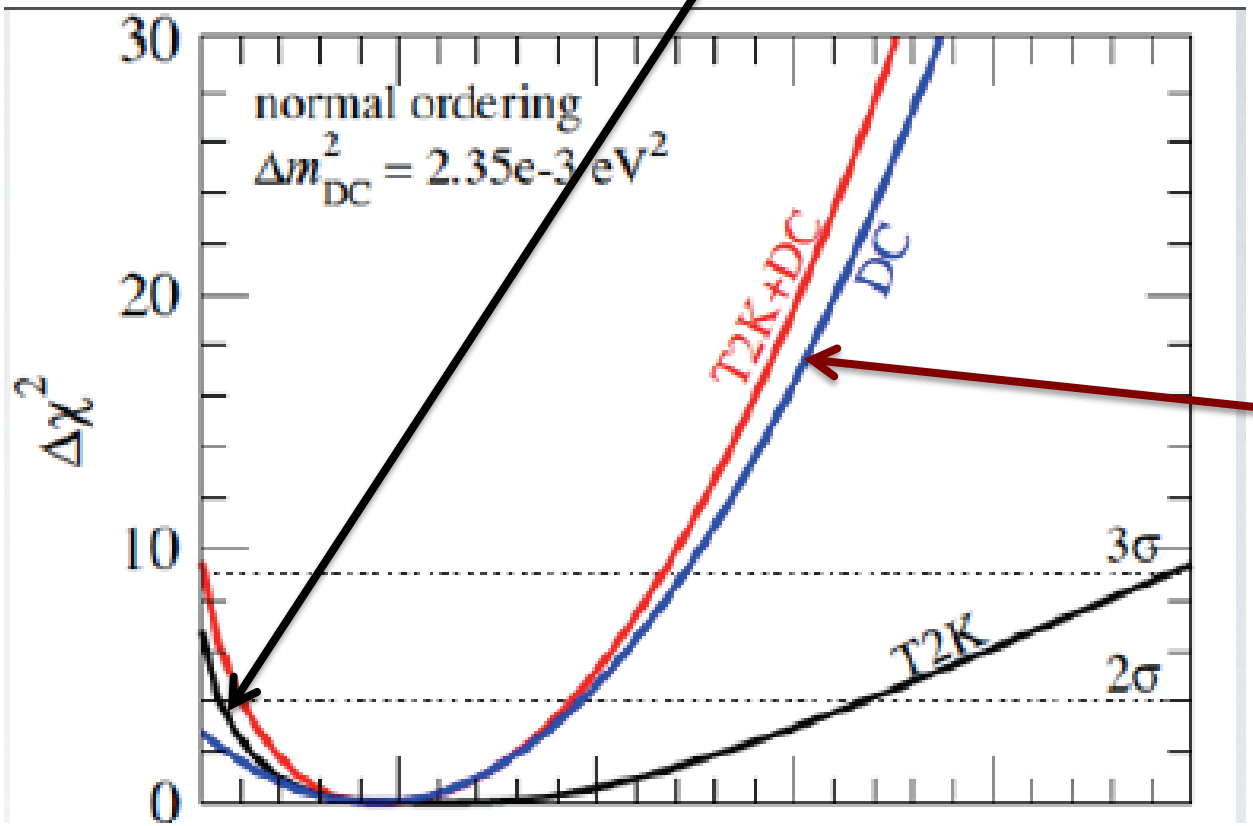
T2K best fit

DC+T2K best fit



Another A-R complementarity ?

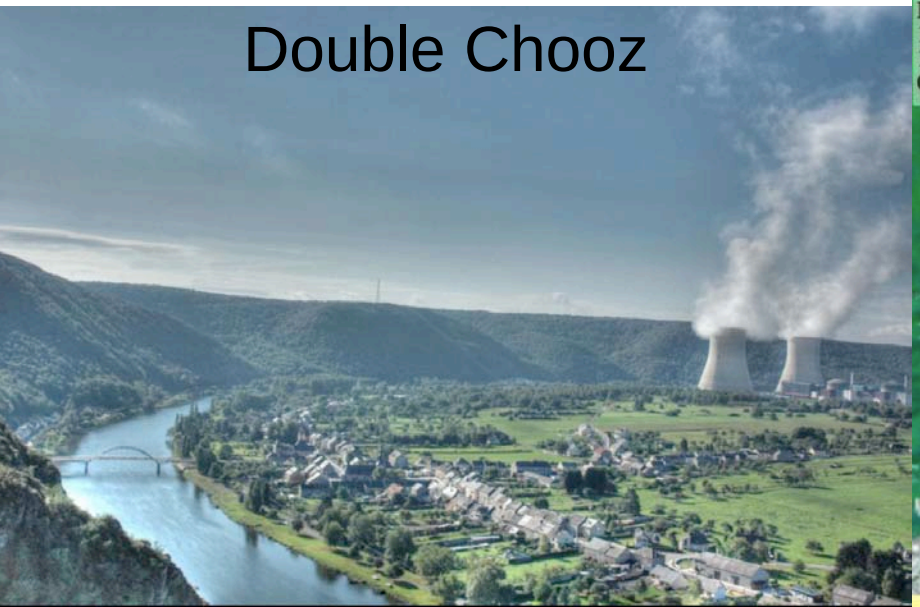
At small θ_{13} the major player is T2K

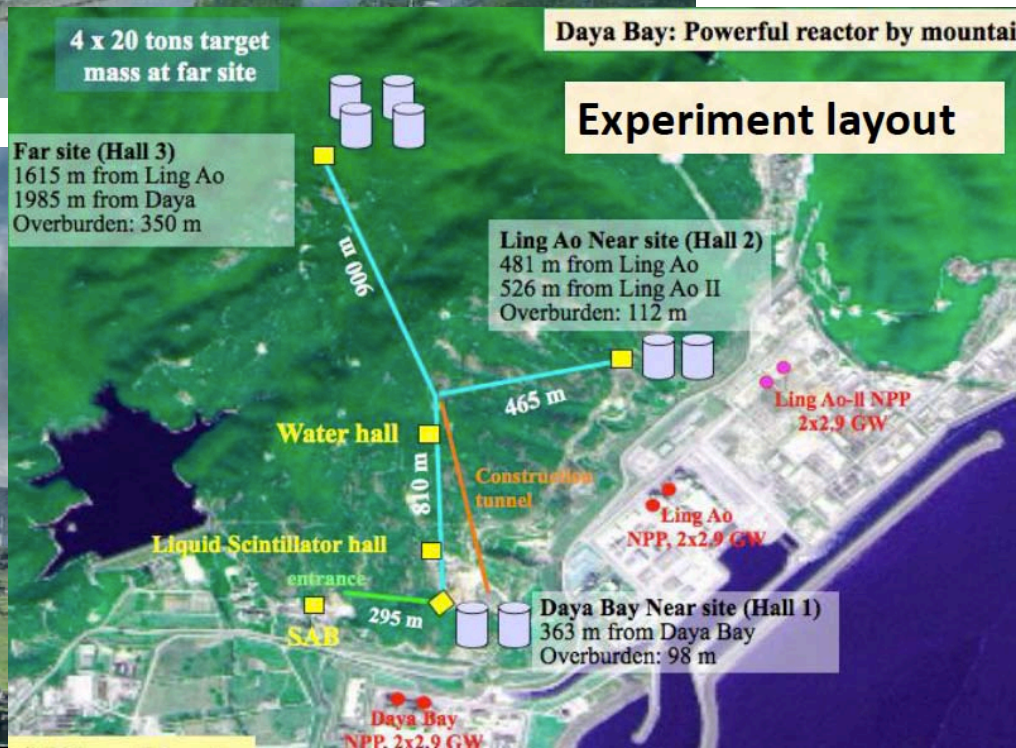


At large θ_{13} the major player is Double Chooz

More reactor θ_{13} data are coming

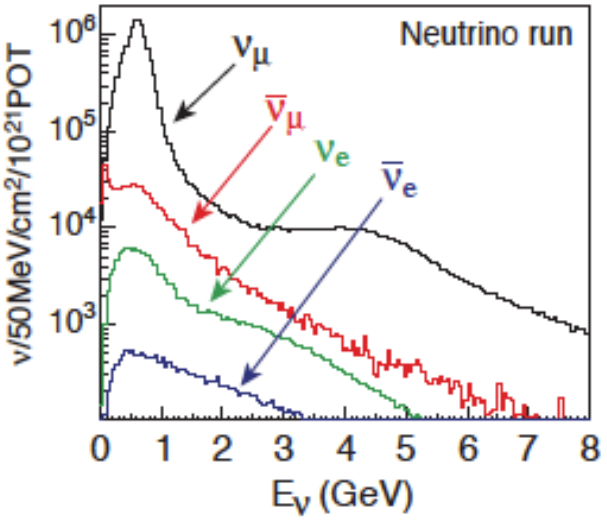
Double Chooz

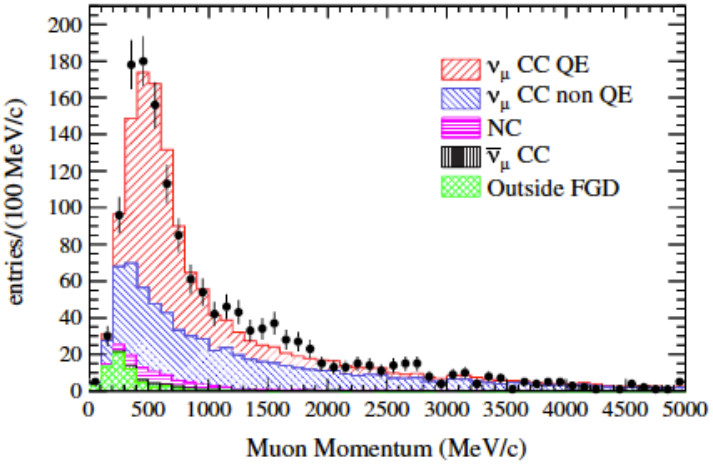




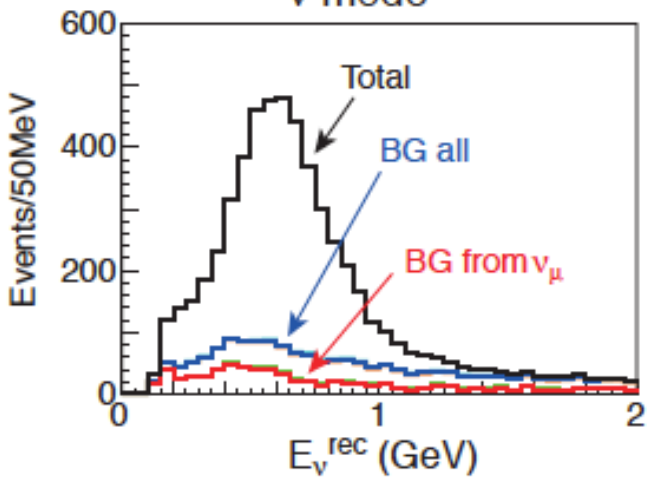
New era for ν phenomenology

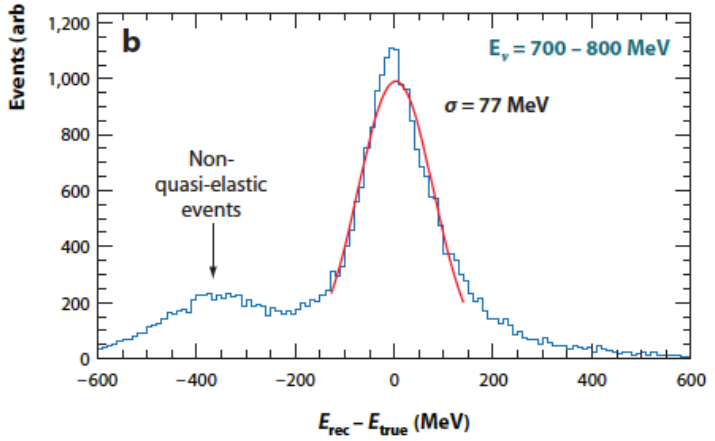
We attempted an independent analysis using T2K paper, HK-LOI, etc.





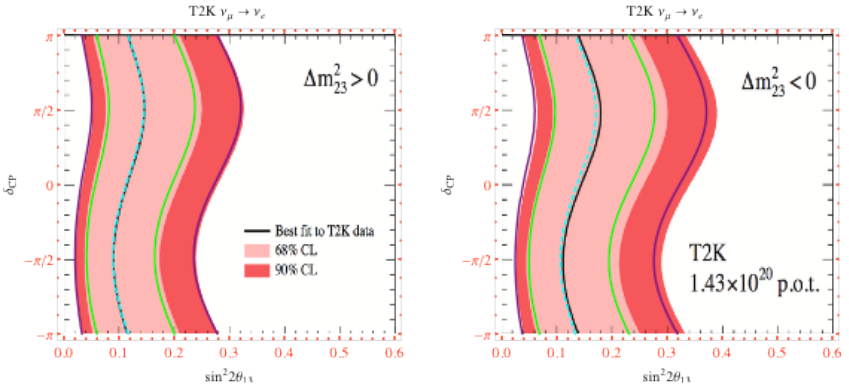
Lindroos-Mezetto 2010

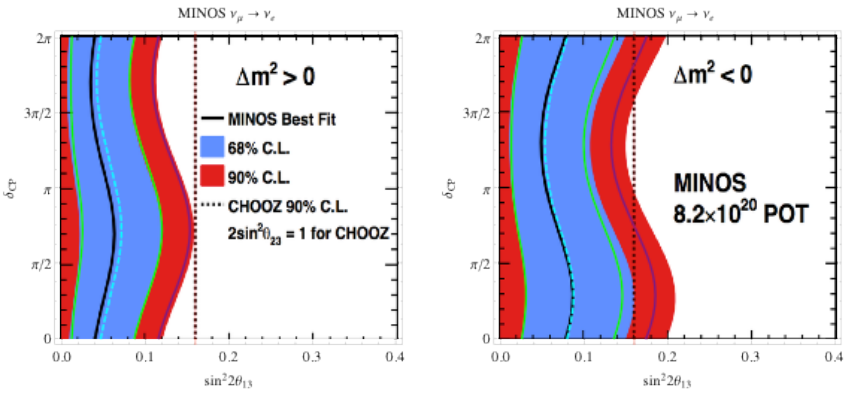


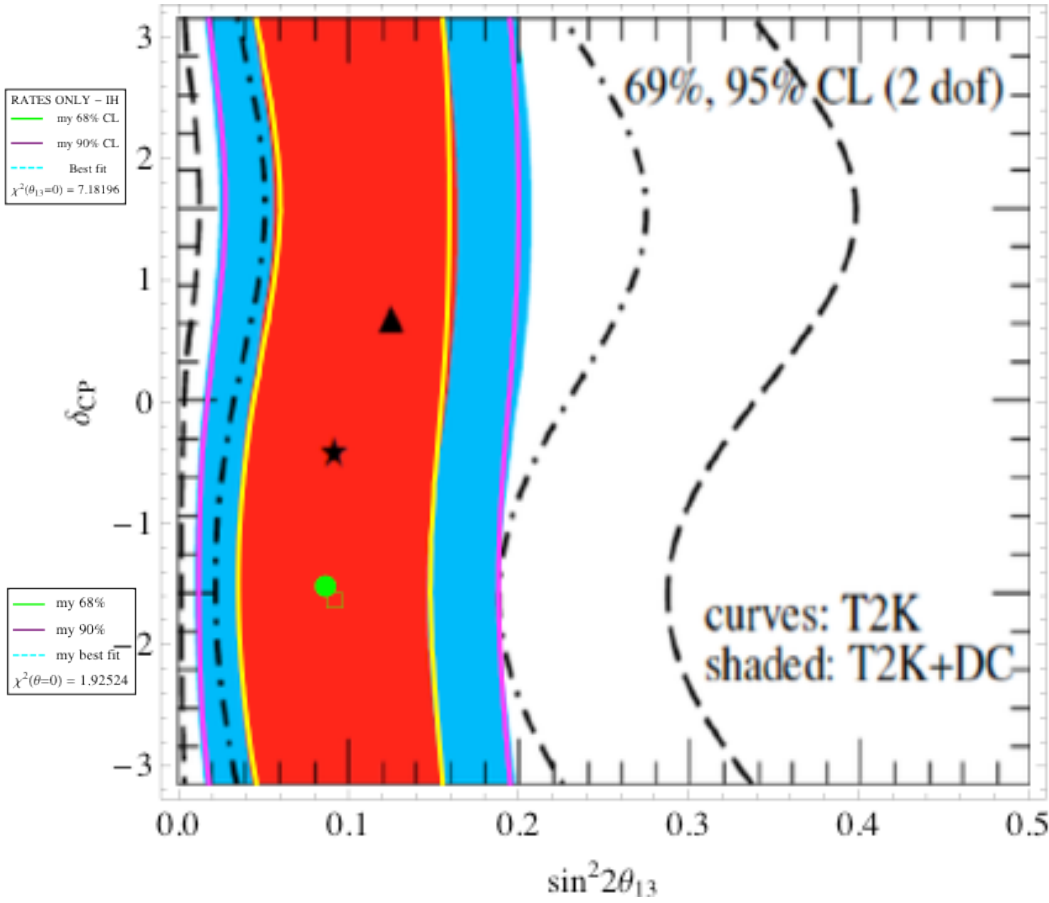


P.A.N.Machado, HM, H.Nunokawa, R.Zukanovich Funchal, to appear

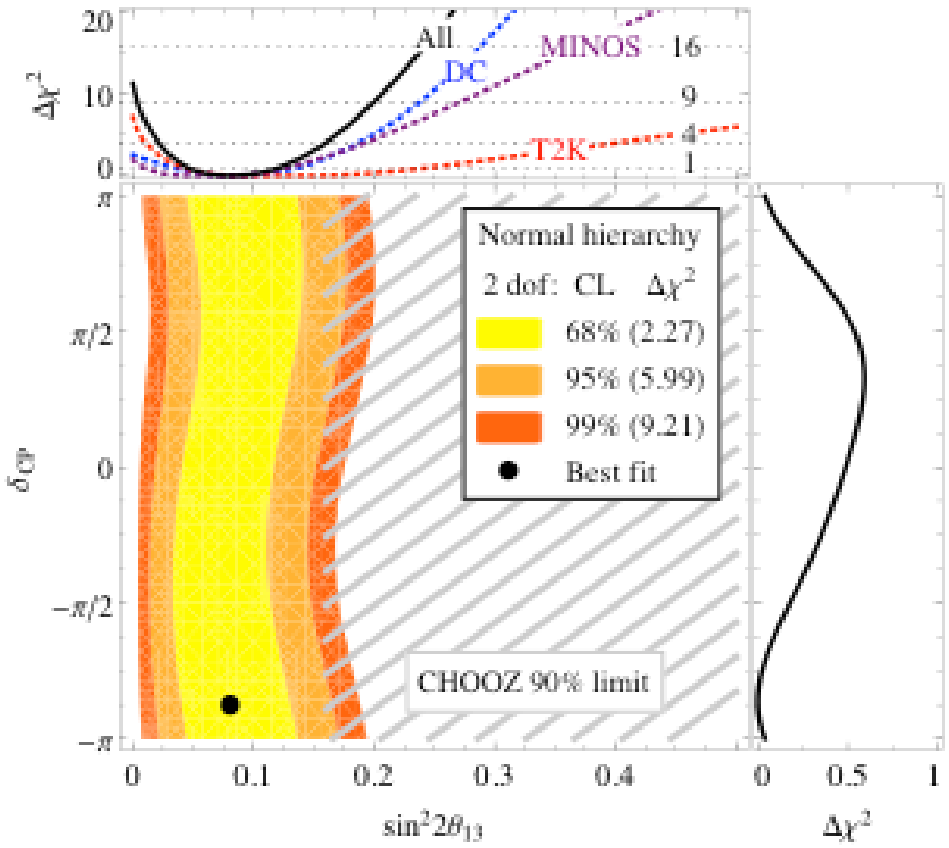
We reproduced T2K, MINOS and T2K+DC contours

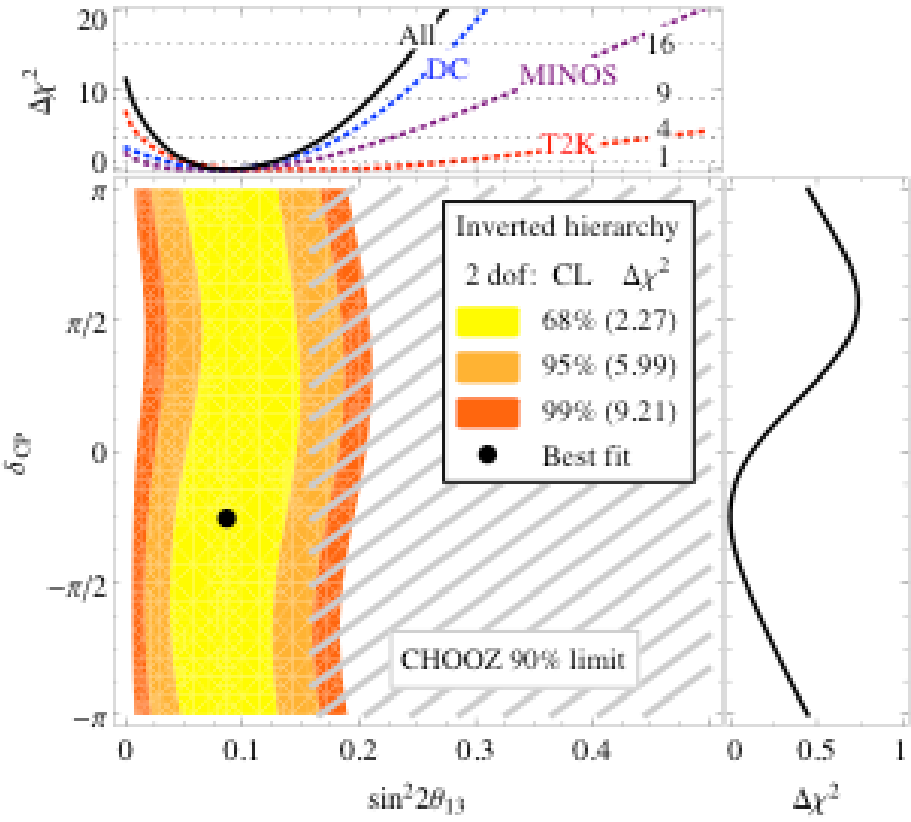






T2K+DC+MINOS: normal vs. inverted hierarchies





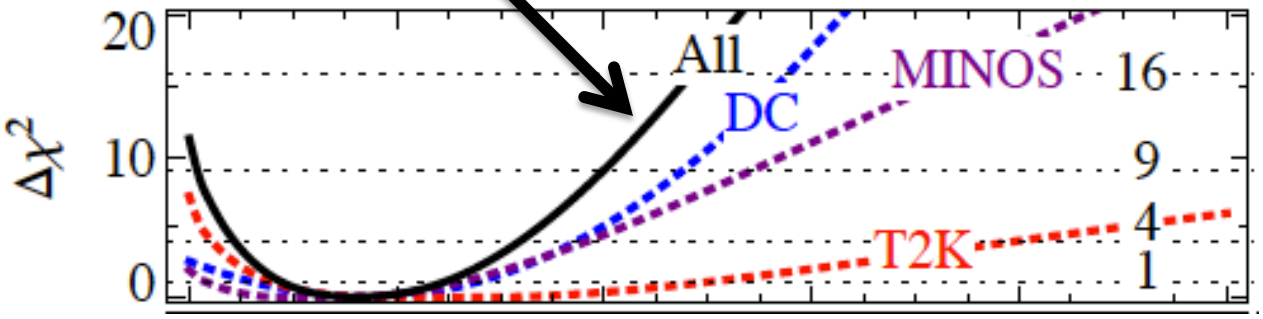
P.A.N.Machado, HM, H.Nunokawa, R.Zukanovich Funchal, to appear in ArXiv today

Breakdown of χ^2 : θ_{13}

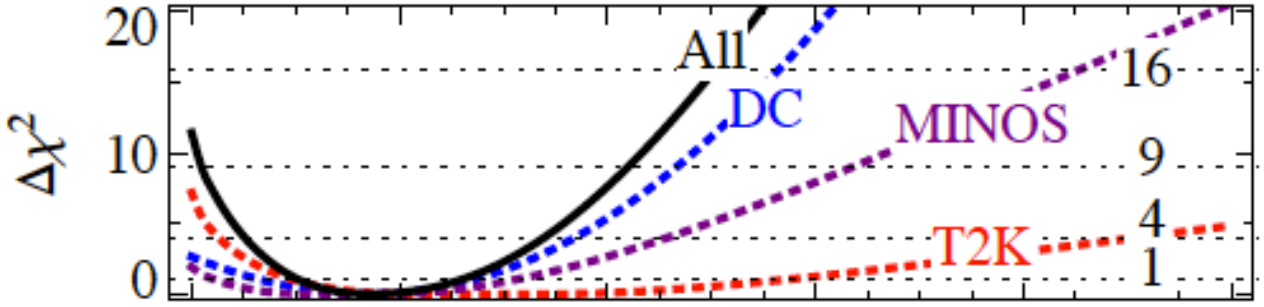
All combined

Best fit: $\sin^2 2\theta_{13}$=0.081 (normal)
0.087 (inverted)

3.36 σ evidence for nonzero θ_{13} !



Normal hierarchy



Inverted hierarchy

At small θ_{13} the major player is T2K
At large θ_{13} the major player is DC and MINOS

Predicting (boldly) June and December 2012

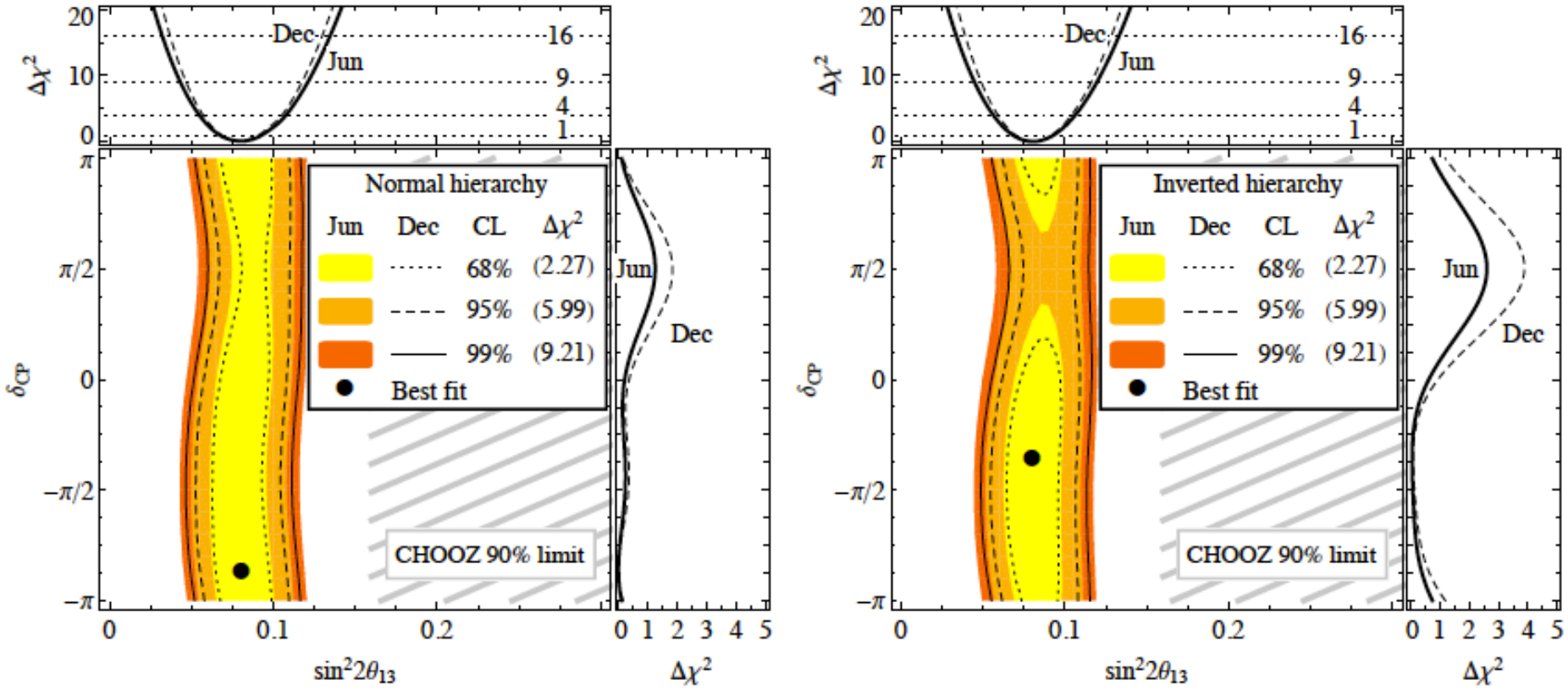


FIG. 3: Predicted allowed region in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for T2K, MINOS, DC and RENO combined at 68%, 95 % and 99% CL for 2 dof at the middle and end of 2012, assuming normal (left panel) or inverted (right panel) mass hierarchy and as input the normal hierarchy best fit point of our current analysis.

In June and December 2012; RENO is powerful

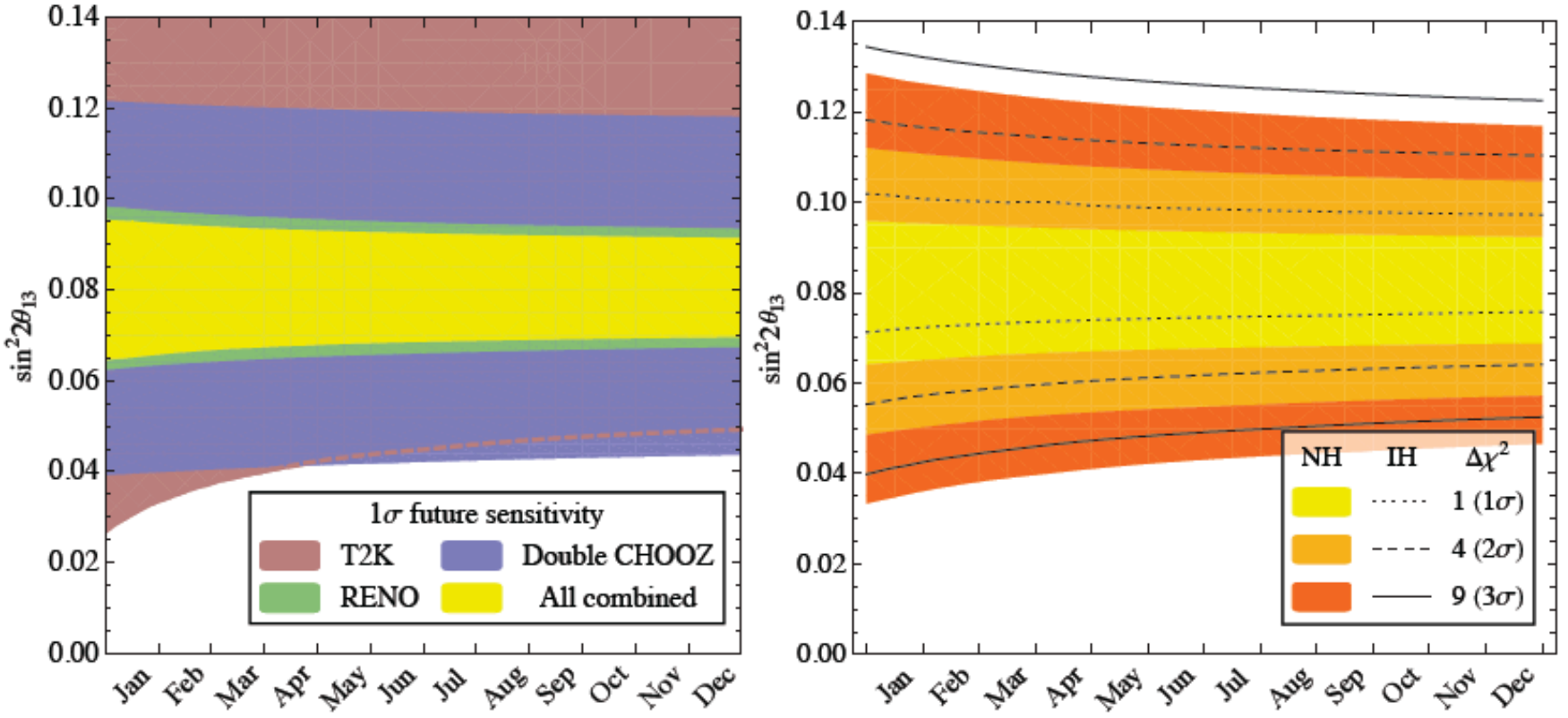


FIG. 2: In the left panel, we show the expected 1 σ uncertainty on $\sin^2 2\theta_{13}$ for the case where the true value of $\sin^2 2\theta_{13} = 0.08$ (current best fit for the normal hierarchy) as a function of the months in 2012 for Double Chooz, RENO, T2K as well as the combined case. In the right panel, we show the expected 1-3 σ uncertainties on $\sin^2 2\theta_{13}$ as a function of time for our current normal (by color shaded regions) and inverted (by solid, dotted and dashed curves) hierarchy best fit points. In fitting, the hierarchy is assumed to be unknown.

Apparently θ_{13} is large !

Large θ_{13} : Two issues

- What does large θ_{13} means?; Physics behind the large θ_{13}
- No symmetry hidden for relatively small θ_{13}=0 ?
- natural because $U=V_l^{+}V_\nu$ and two angles are large

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

Wide ranges of possibilities are open for CP and mass hierarchy

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 → Hyper-K LOI
- → in situ measurement of everything in a single detector
- It can do proton decay
- It can do many astrophysics too

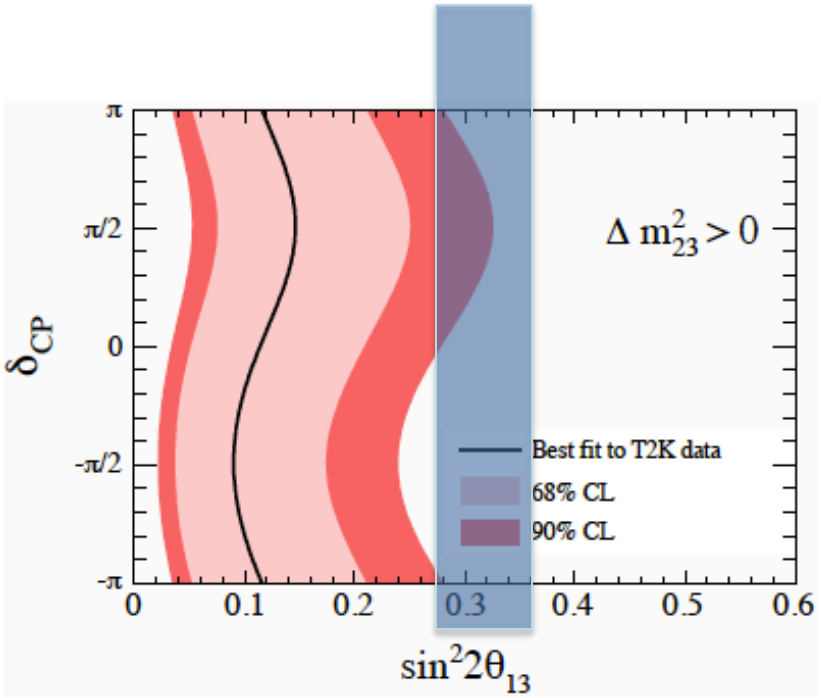
water Cherenkov vs. liquid Ar vs. TASD debatable

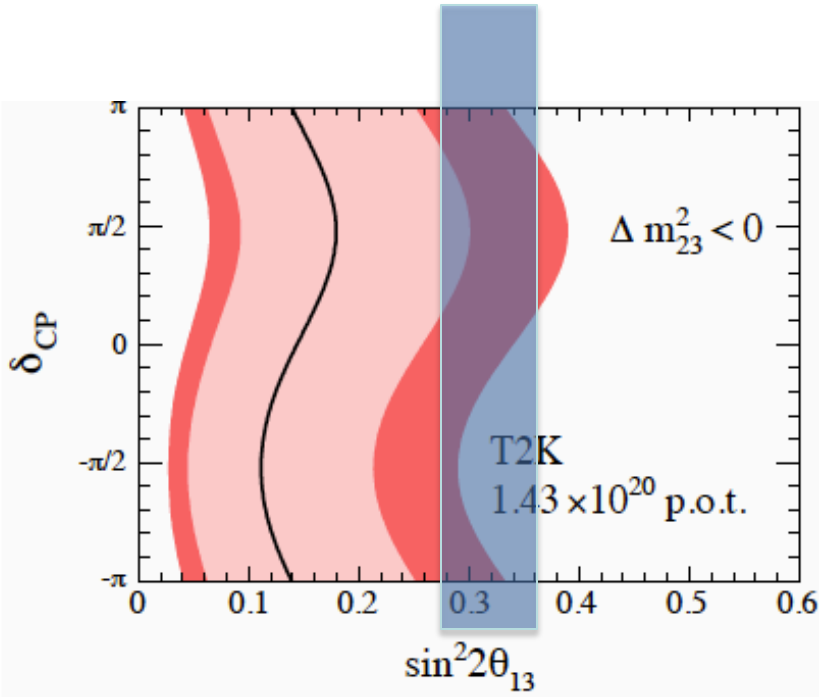
Accelerator-reactor method for CP violation

Accelerator-reactor combined method for CP δ

HM-H.Sugiyama
PLB 04

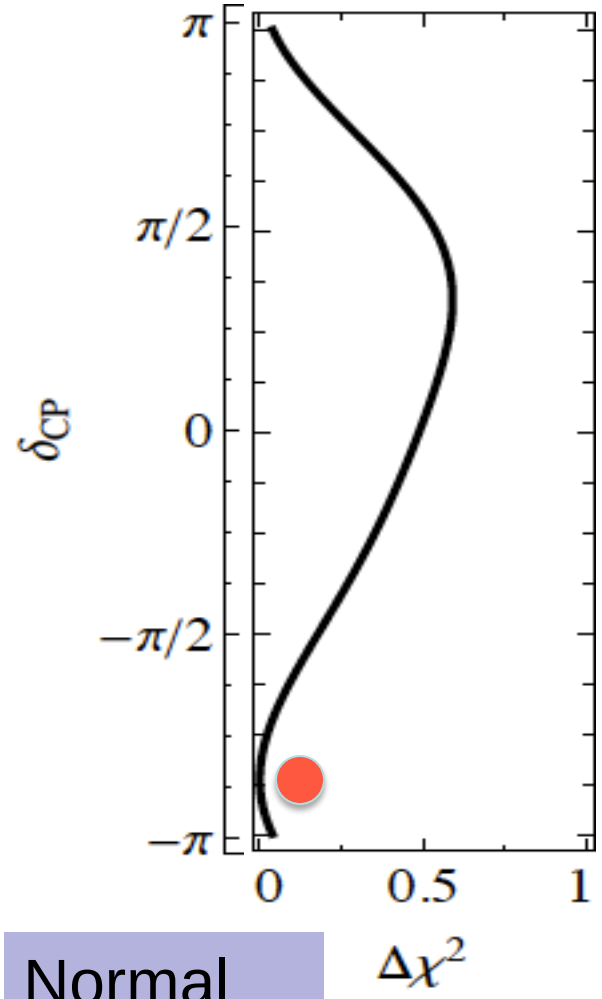
Idea is very simple



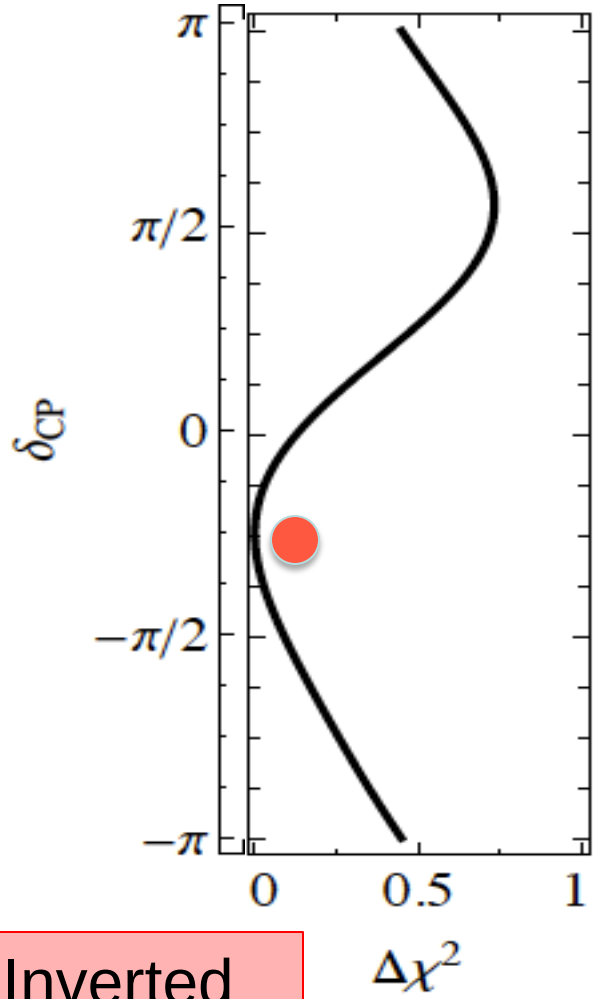


Valid way for determining sign(sin δ), not for precision measurement

Breakdown of χ^2 : δ



Normal hierarchy



Inverted hierarchy

Hint for sign(sinδ) < 0 ?

Similar indication from SK atm (next page)

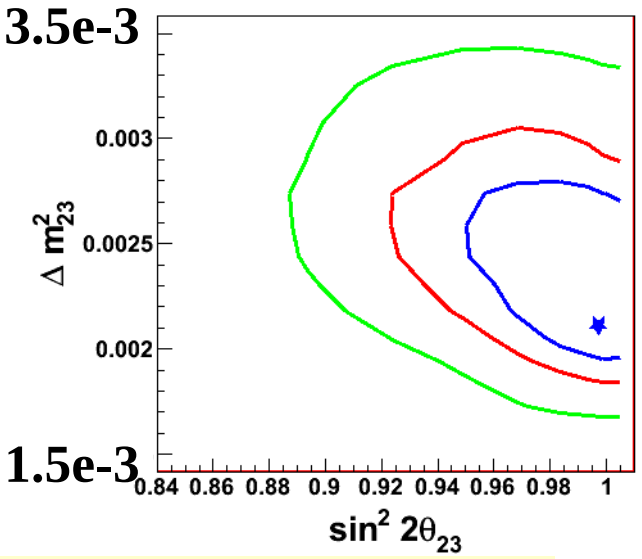
Full 3-flavor oscillation results

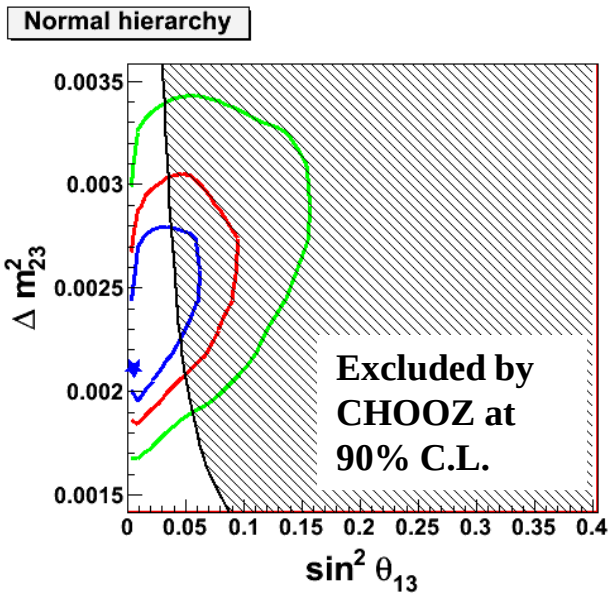
Takeuchi Nu2010

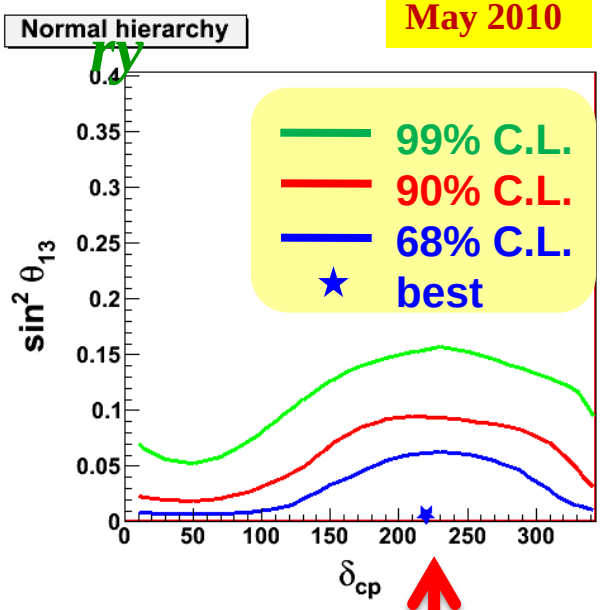
SK-I+II+III *Preliminary*

May 2010

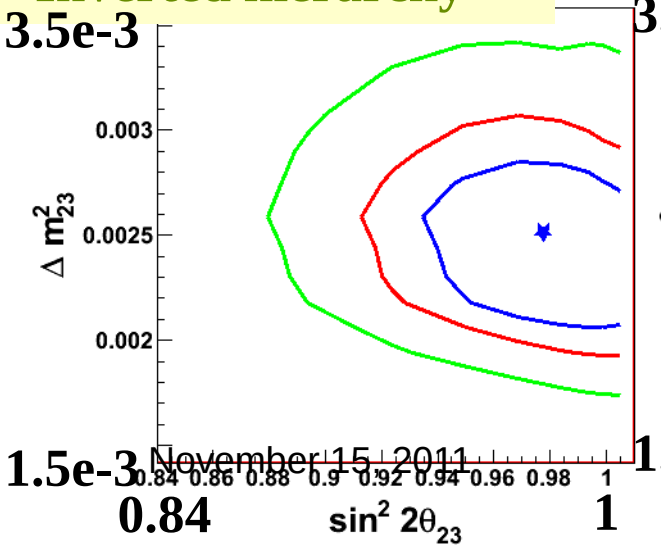
- Normal hierarchy -

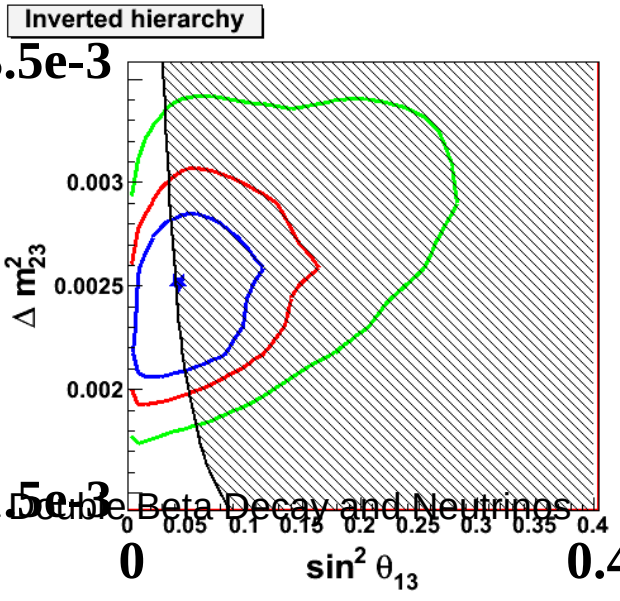


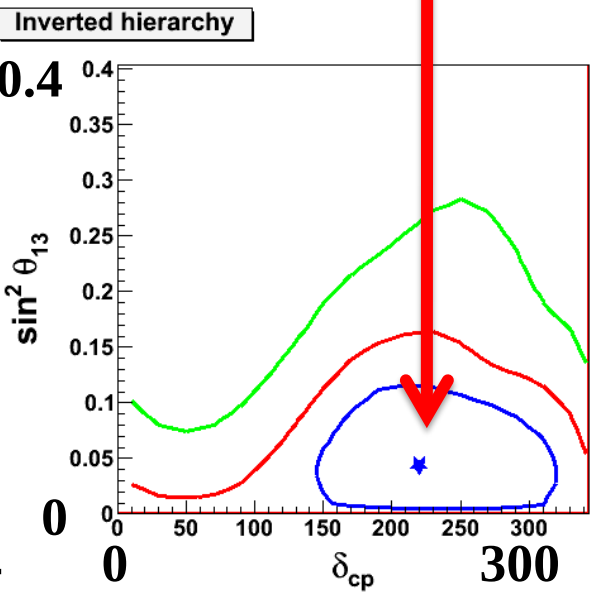




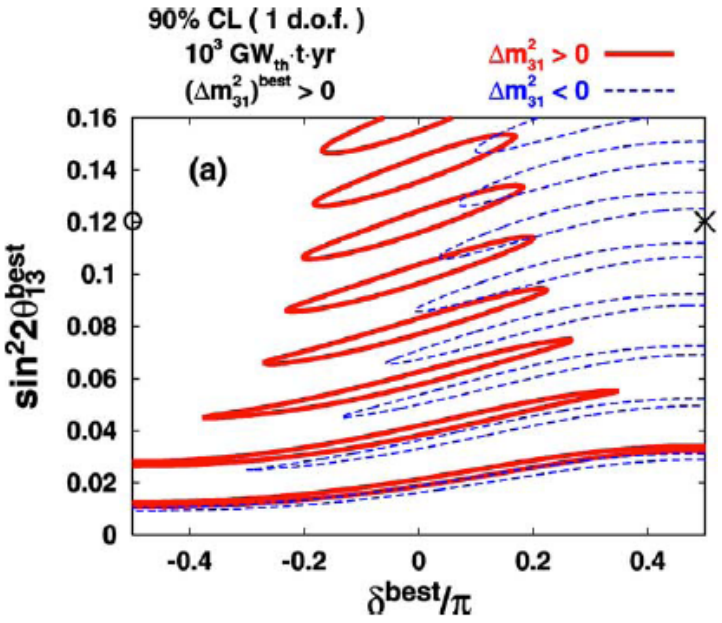
- Inverted hierarchy -





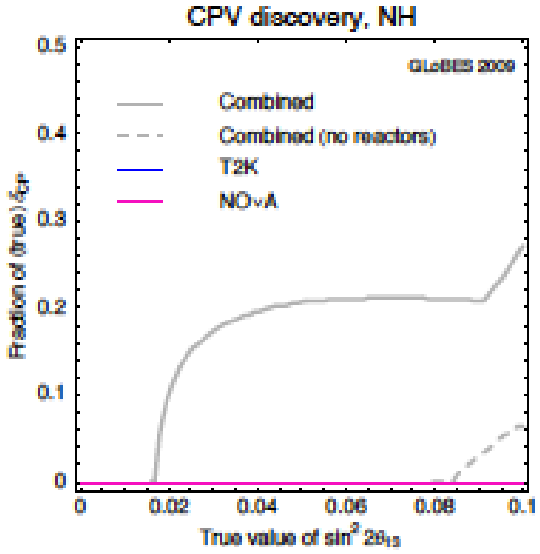


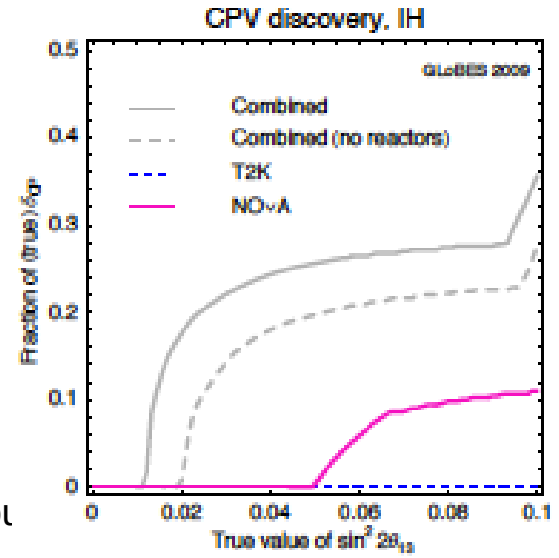
Limitations of accelerator-reactor method



δ determination suffers from sign-Δm^2 degeneracy

HM-Sugiyama 04





CP coverage cannot be great, Huber et al. 09

Dou

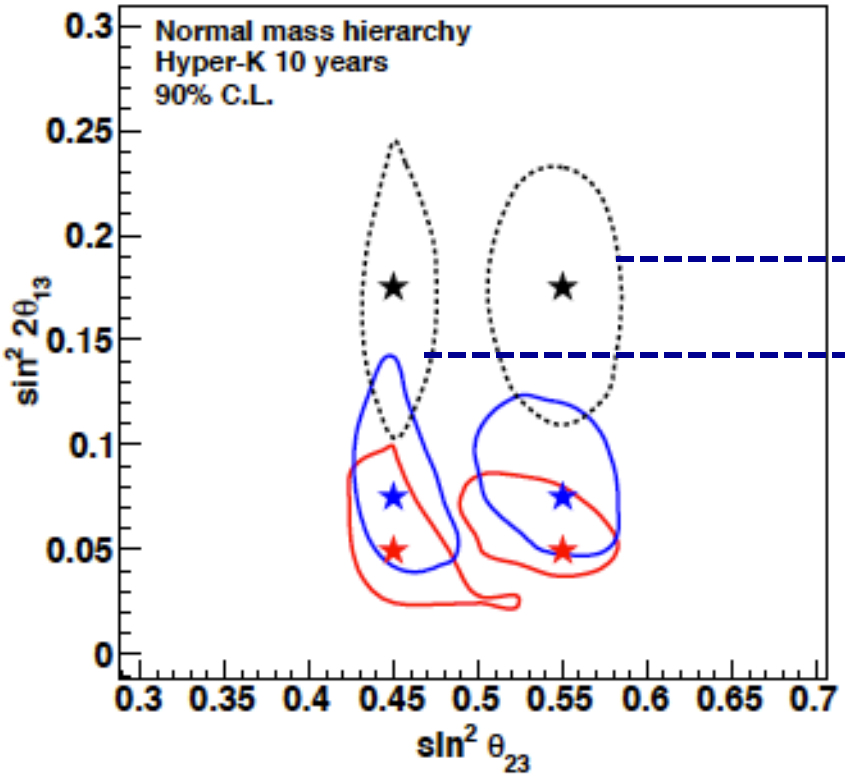
Reactor-accelerator method can compete with HK for θ_{23} degeneracy

Sensitivity comparison: HK atm vs. reactor + JPARC-HK

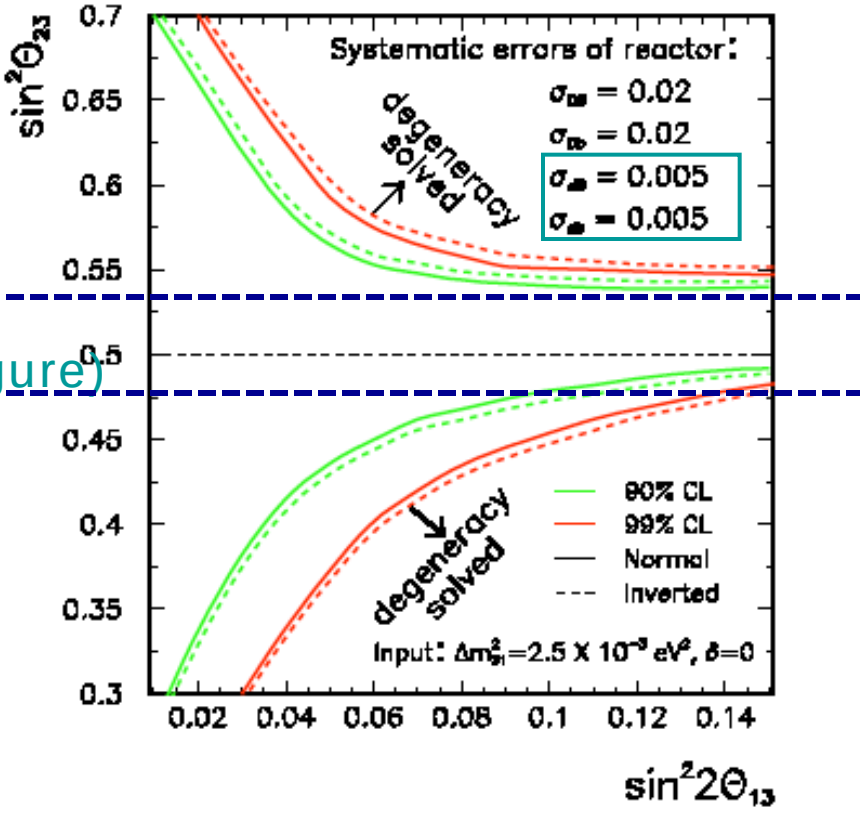
Hiraide et al 06
hep-ph/0601258

HK atm ν (LOI)

JPARC-HK (2+6 yrs)+reactor 10GWktyr



Atm ν
(left figure)



Both methods have comparable sensitivity to θ_{23} octant determination

Conclusion

- Era of accelerator-reactor θ_{13} experiments blossomed
- It appears that θ_{13} is large !
- large θ_{13} opens up wide range of possibilities for hunting CP & mass hierarchy
- large θ_{13} invites "all in one" approach, for example, HK + JPARC beam (with bonus of proton decay)
- Physical meaning of the large θ_{13} has to be understood

Congratulations!

e.g., accelerator-reactor method

Backup slides

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

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

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

Bimaximal mixing
from charged leptons

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

Large θ_{13} prefers bimaximal mixing from ν