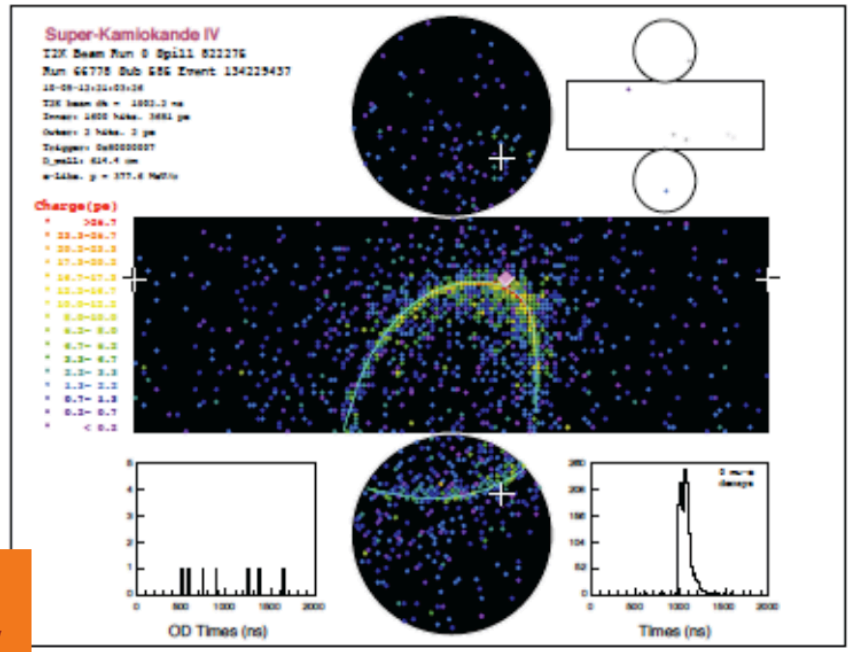
θ_{13} is large: what's next?

My Title Slide in Nufact11, August 5, 2011

If θ_{13} is large, then what ?

Hisakazu Minakata
Tokyo Metropolitan University



(b) electron-like event

The next goal well defined: δ and mass hierarchy

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

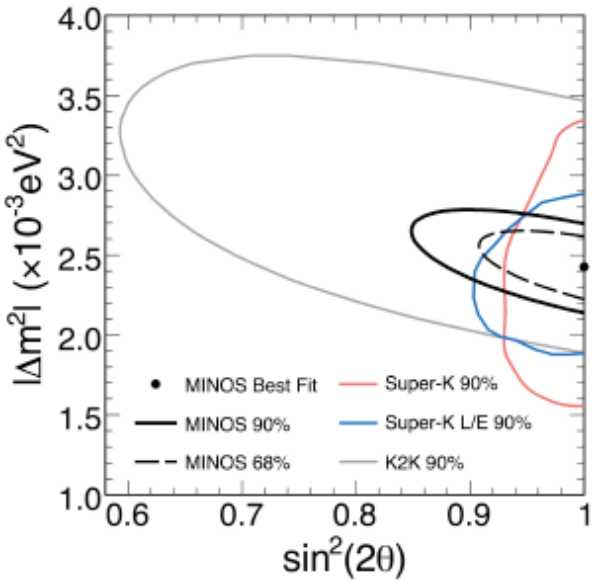
Atm + accel ν =>

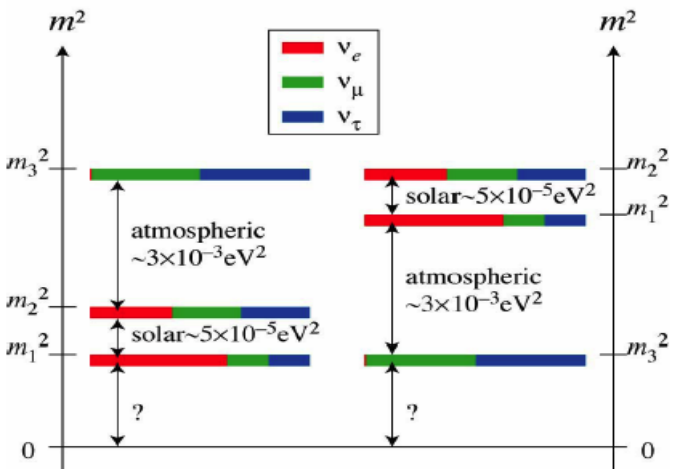
$$U_{MNS} = U_{23}U_{13}U_{12} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

SK-atm+K2K+MINOS

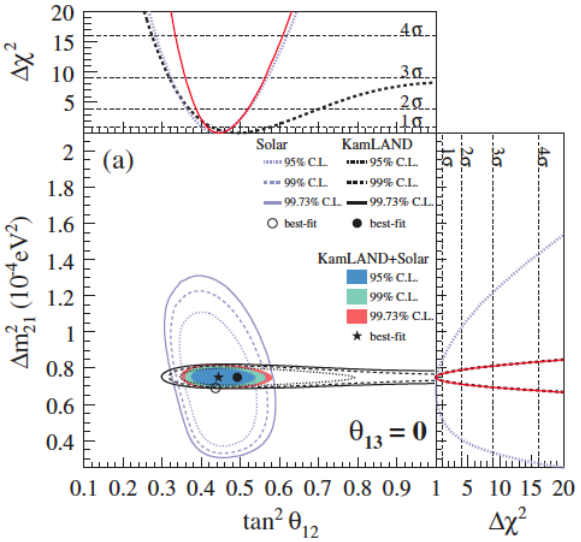
Lepton KM phase

<= solar + reactor ν





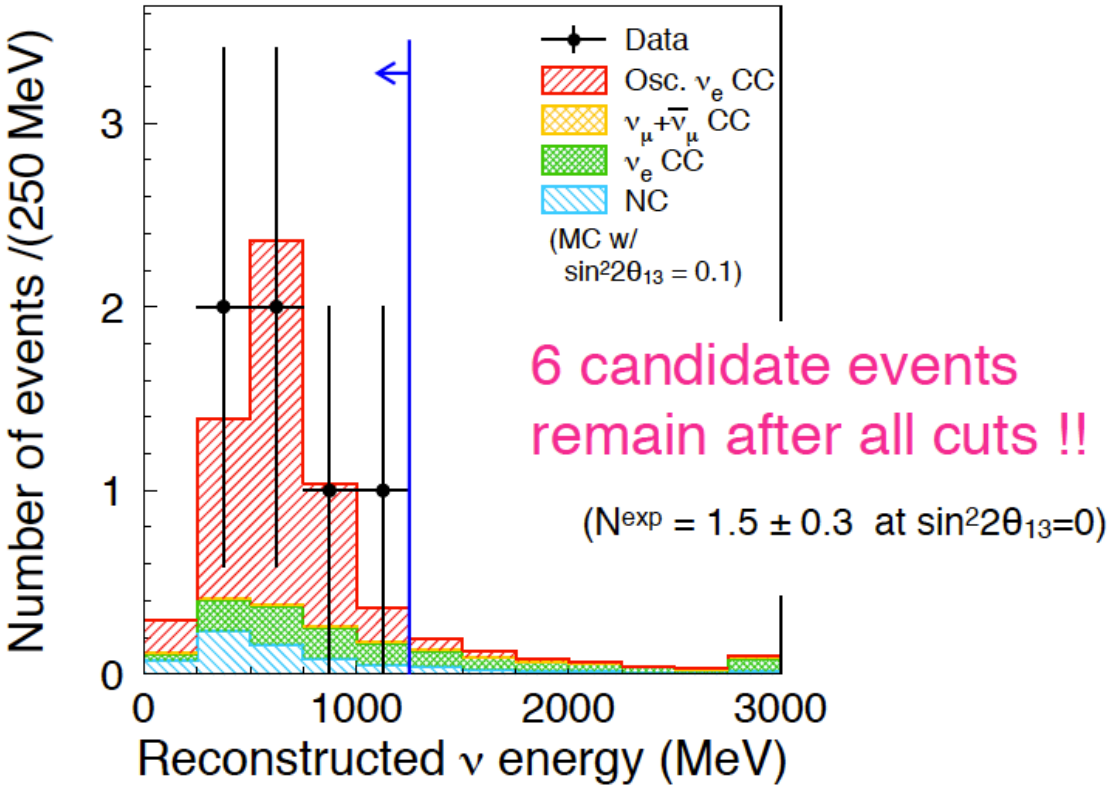
NuTURN@Gran Sasso



solar+KamLAND

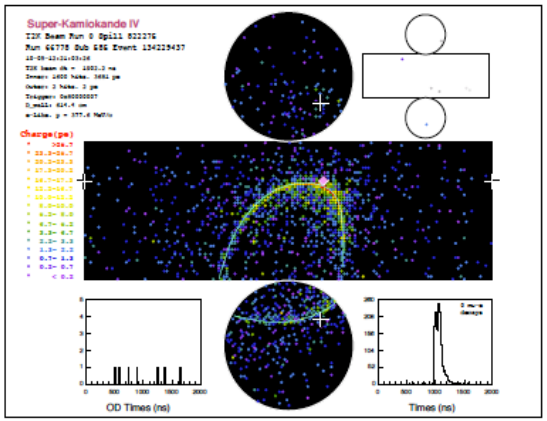
June 2011-Now: Year of θ_{13}

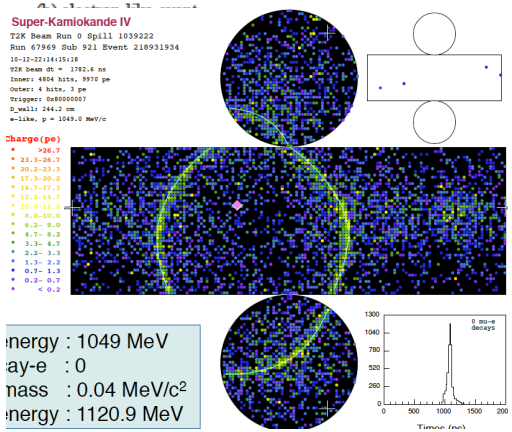
1 year from T2K 6 events: year of θ_{13}



6 candidate events remain after all cuts !!

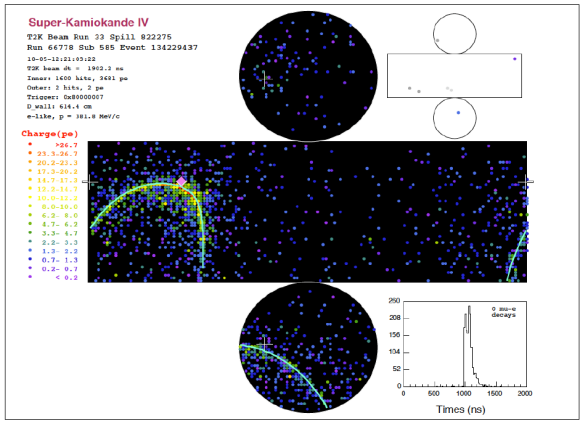
($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)



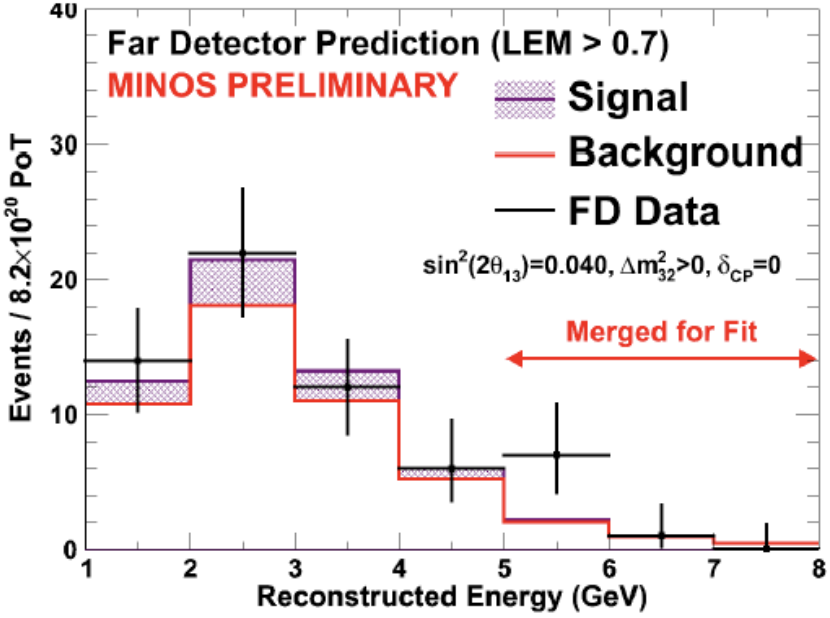


Auror @Saint Petersburg

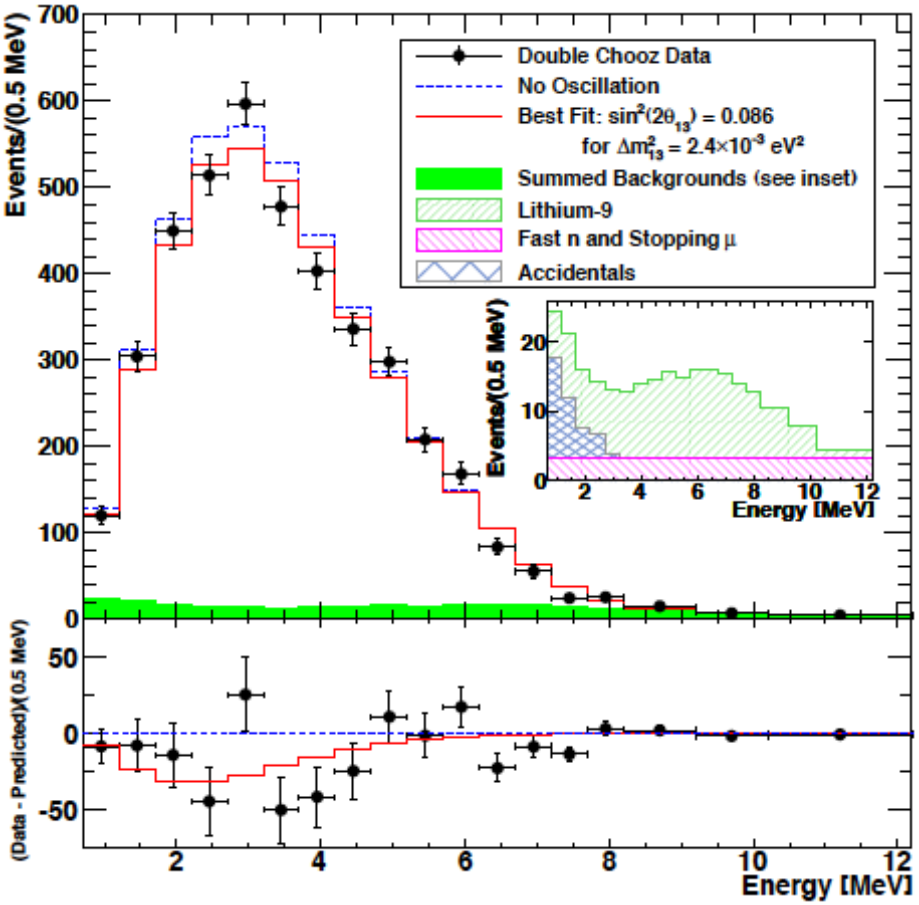
NuTURN@Gran Sasso



Followed by MINOS and Double Chooz: year of θ_{13}



MINOS

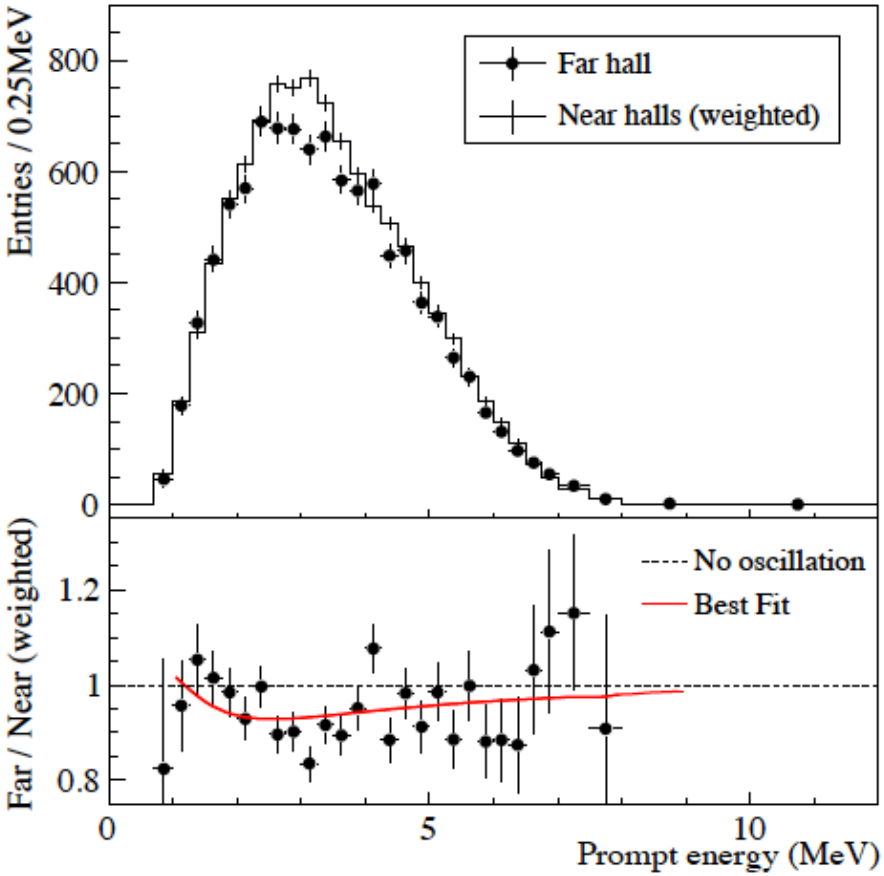


Double Chooz

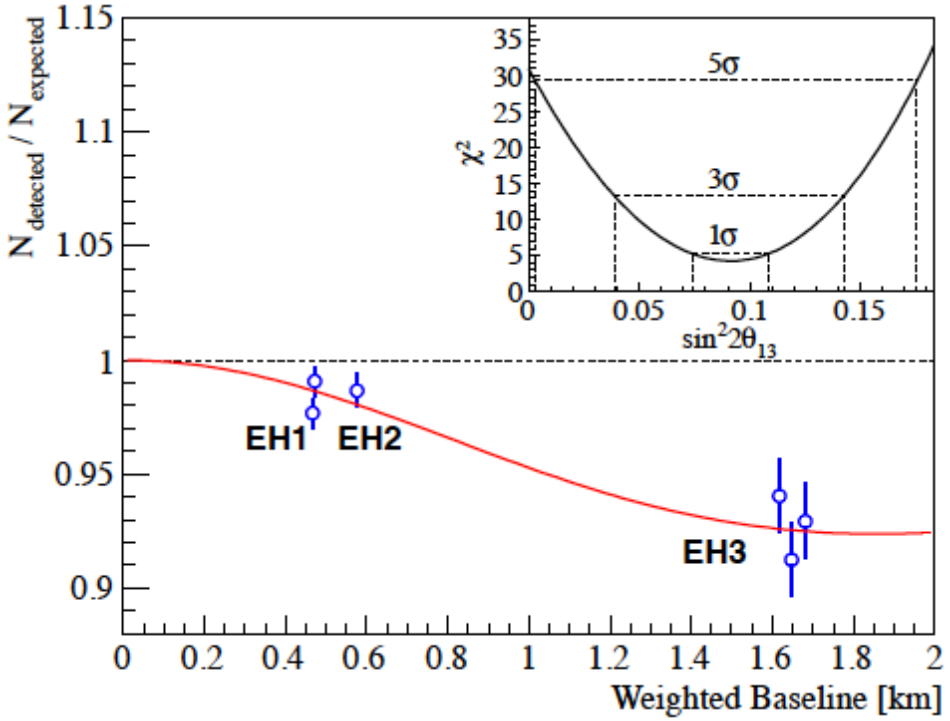
55 days at Daya Bay

@義和団事変
(Boxer's Uprising)

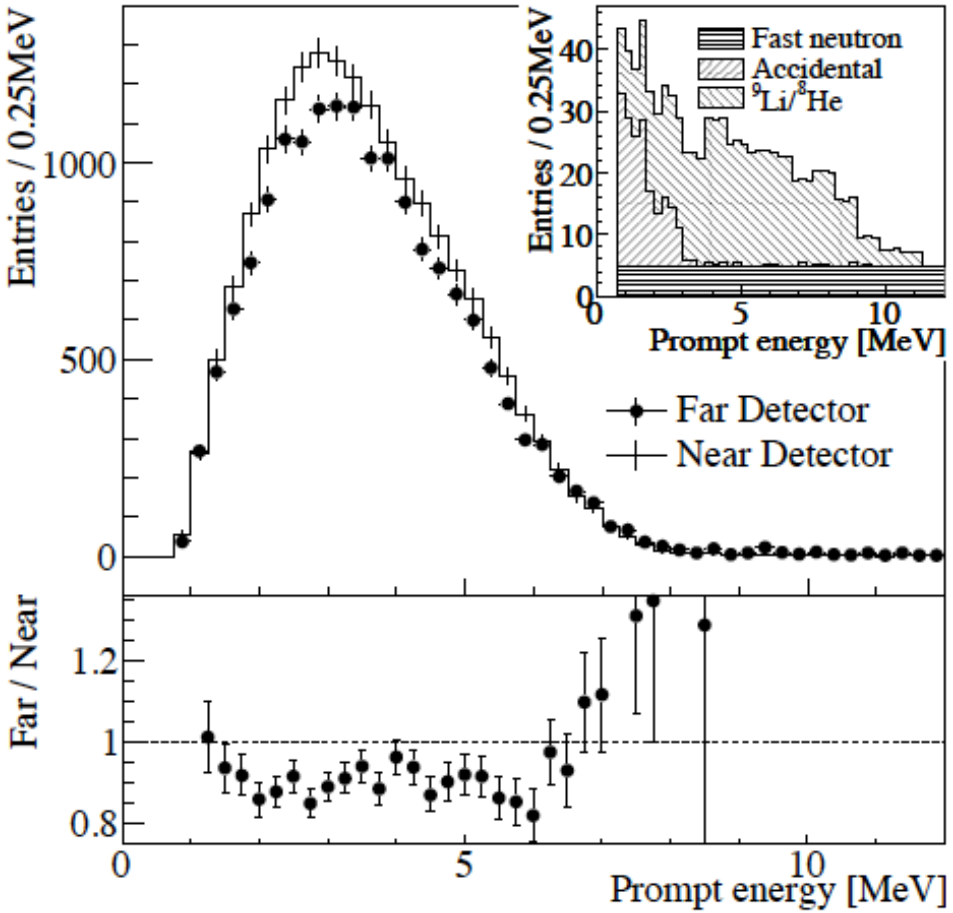
55 days measurement at Daya Bay

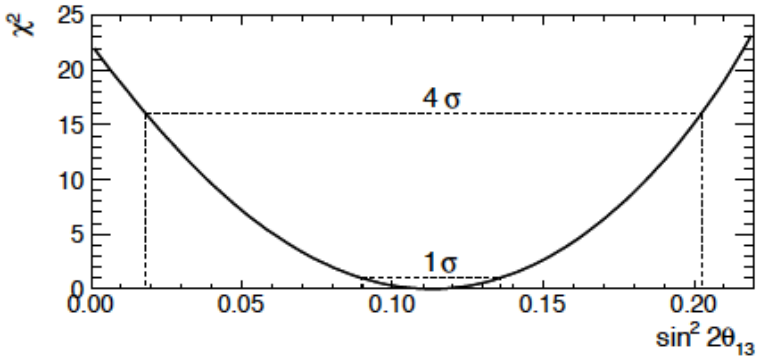


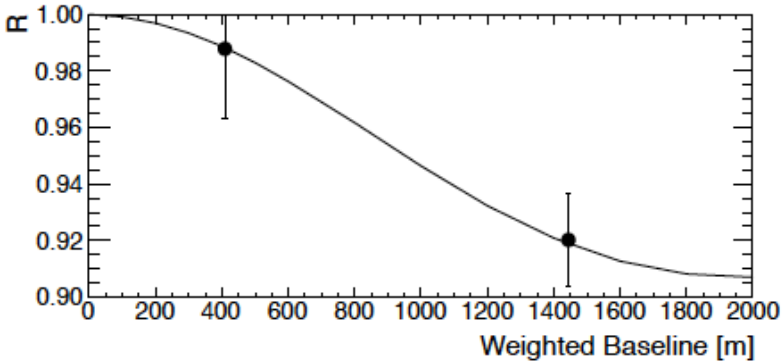
5.2 σ evidence for nonzero θ_{13}!



Then, RENO

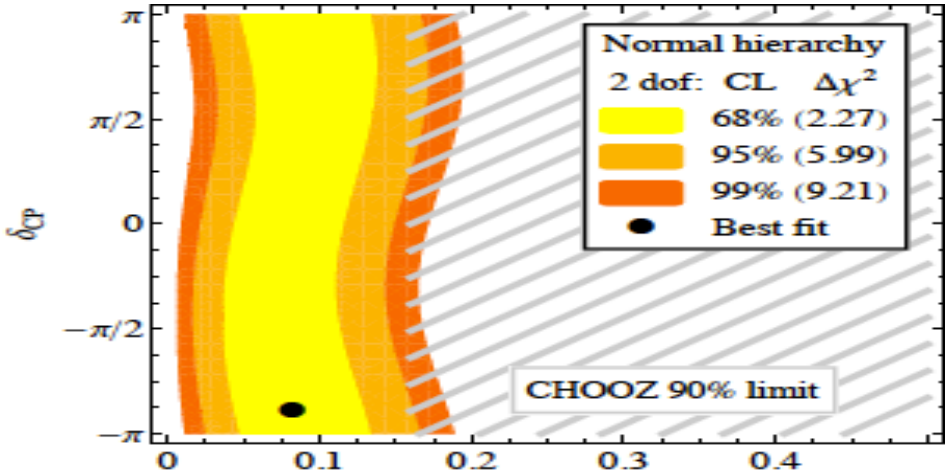




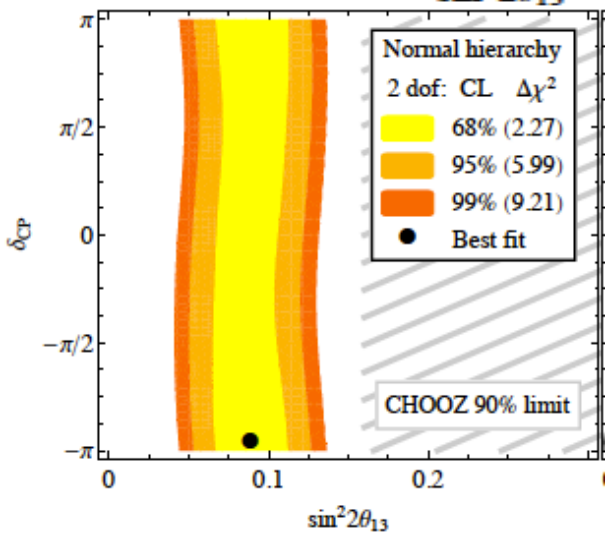


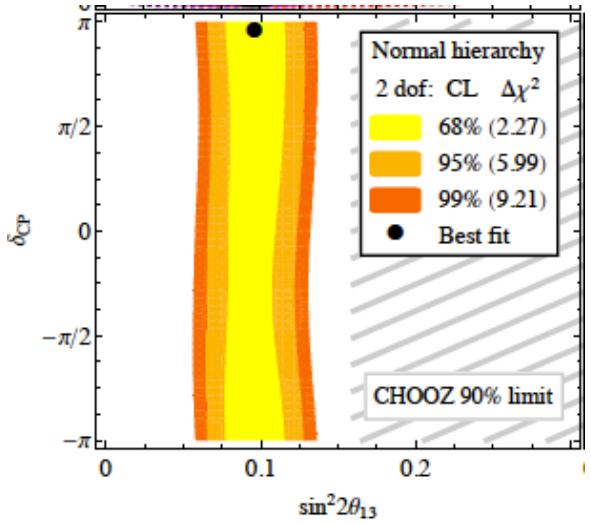
4.9 σ evidence for nonzero θ_{13}!

We were busy in updating: allowed region varied a lot!



Machado et al.v1-2: T2K +MINOS+DC





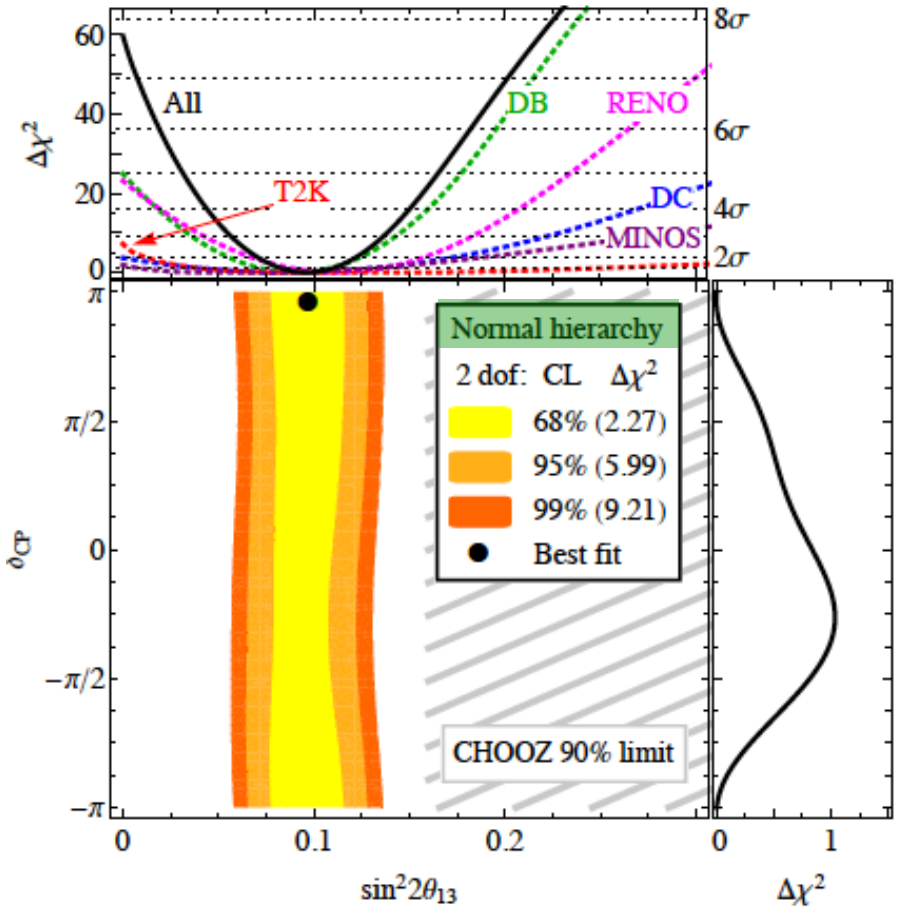
v3: +Daya Bay

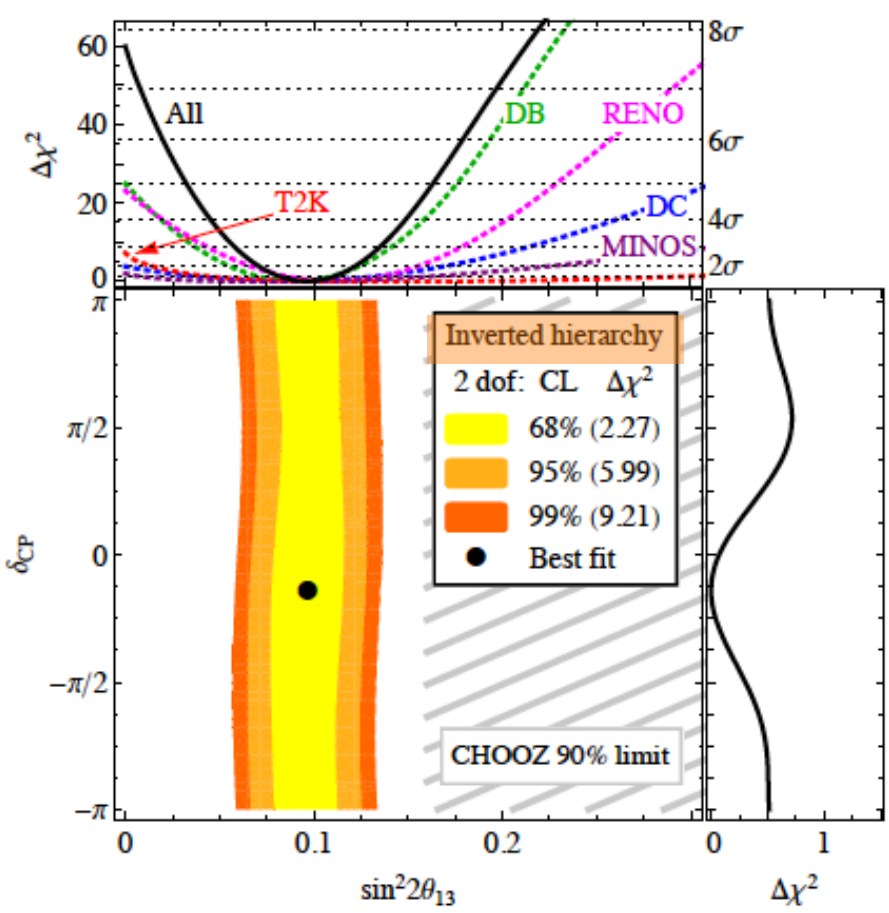
v4: +RENO

T2K+DC+MINOS+DB+RENO:

normal vs. inverted hierarchies

7.7 σ evidence for nonzero θ_{13}!



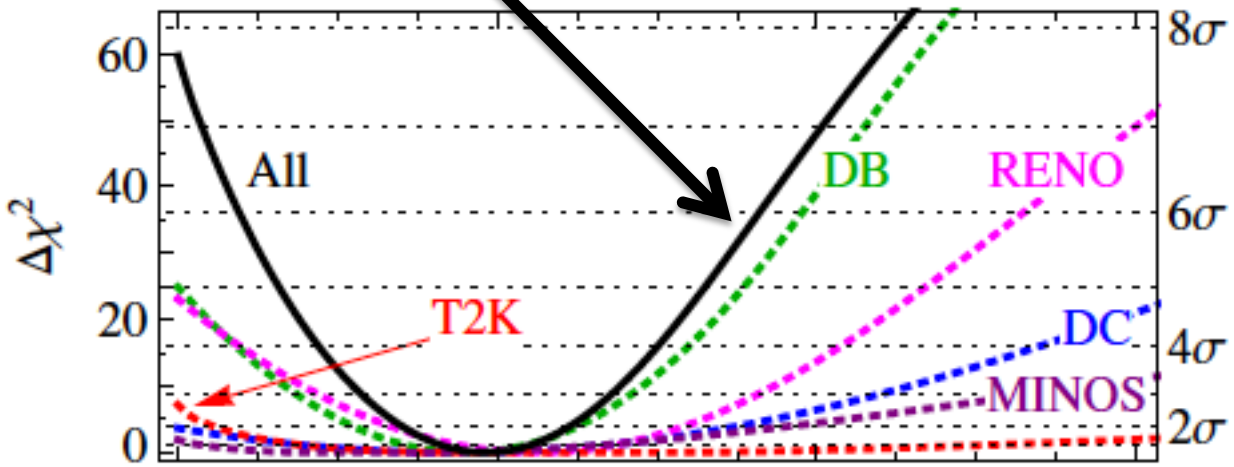


P.A.N.Machado, HM, H.Nunokawa, R.Zukanovich Funchal, ArXiv **1111.3330 ->JHEP**

Breakdown of χ^2 : θ_{13}

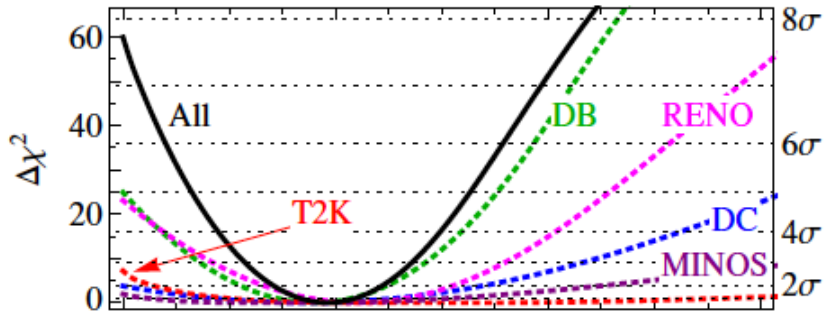
All combined

Best fit: $\sin^2 2\theta_{13}=0.096$
$0.07 < \sin^2 2\theta_{13} < 0.122$ (1σ)
(both normal & inverted)



7.7 σ evidence for nonzero θ_{13} !

Normal hierarchy

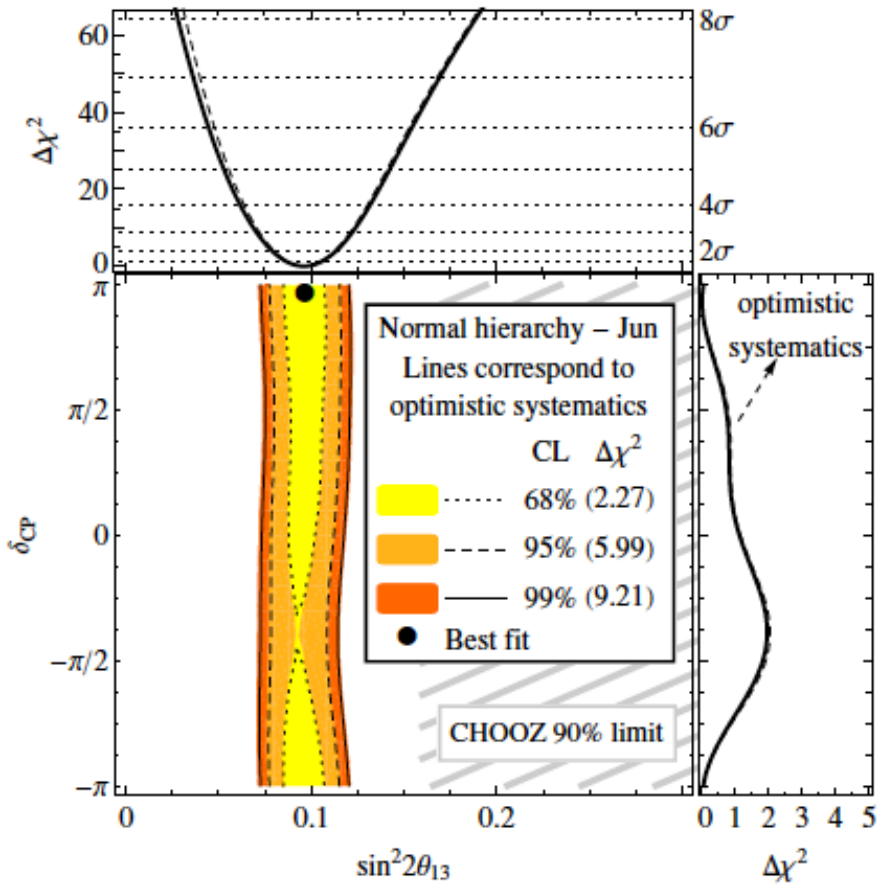


Inverted hierarchy

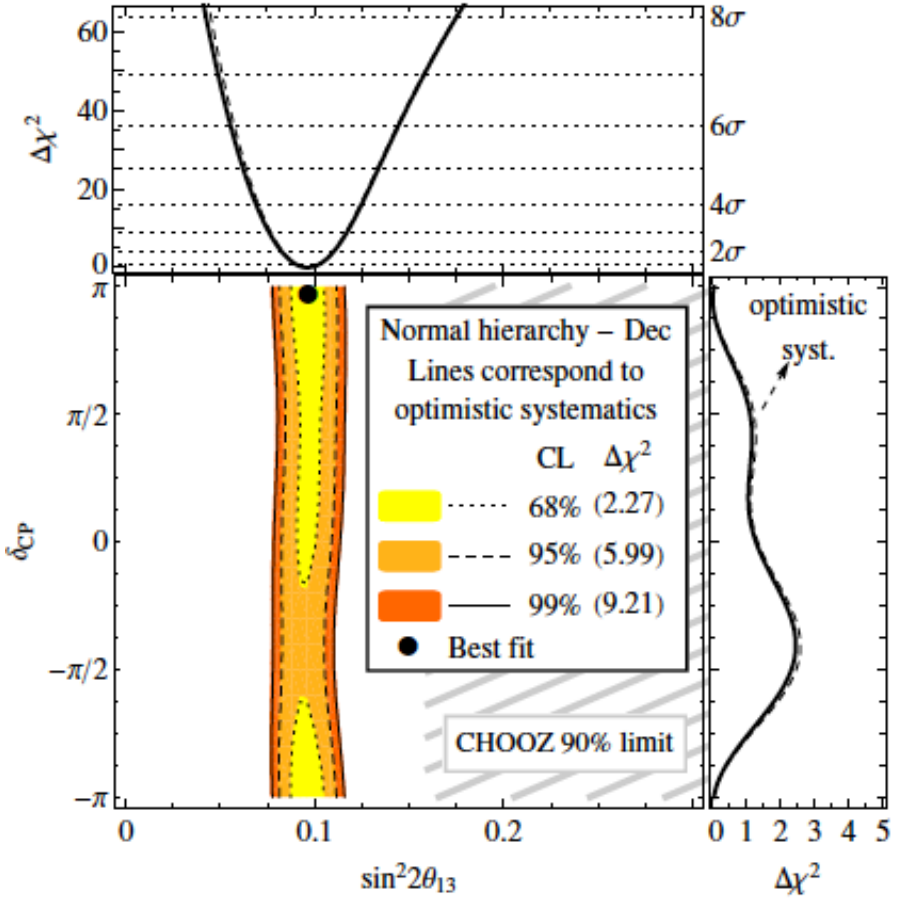
At small θ_{13} the major players are Daya Bay and RENO
At large θ_{13} the major player is Daya Bay

Predicting (boldly) June and December 2012

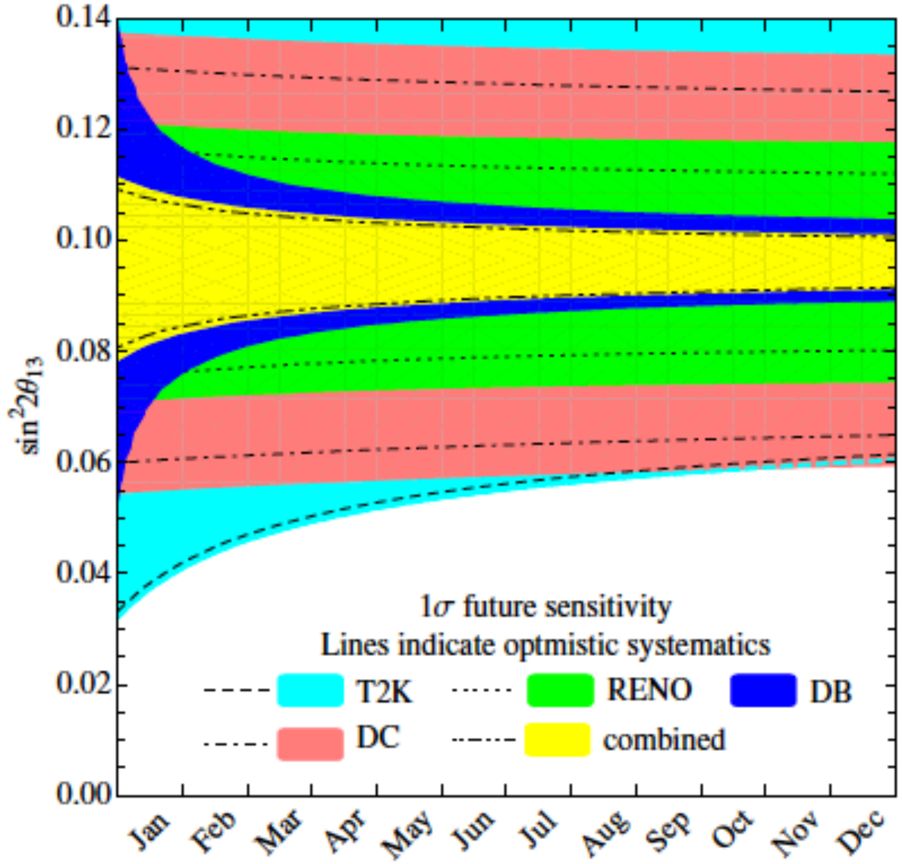
June 2012 — 11 σ

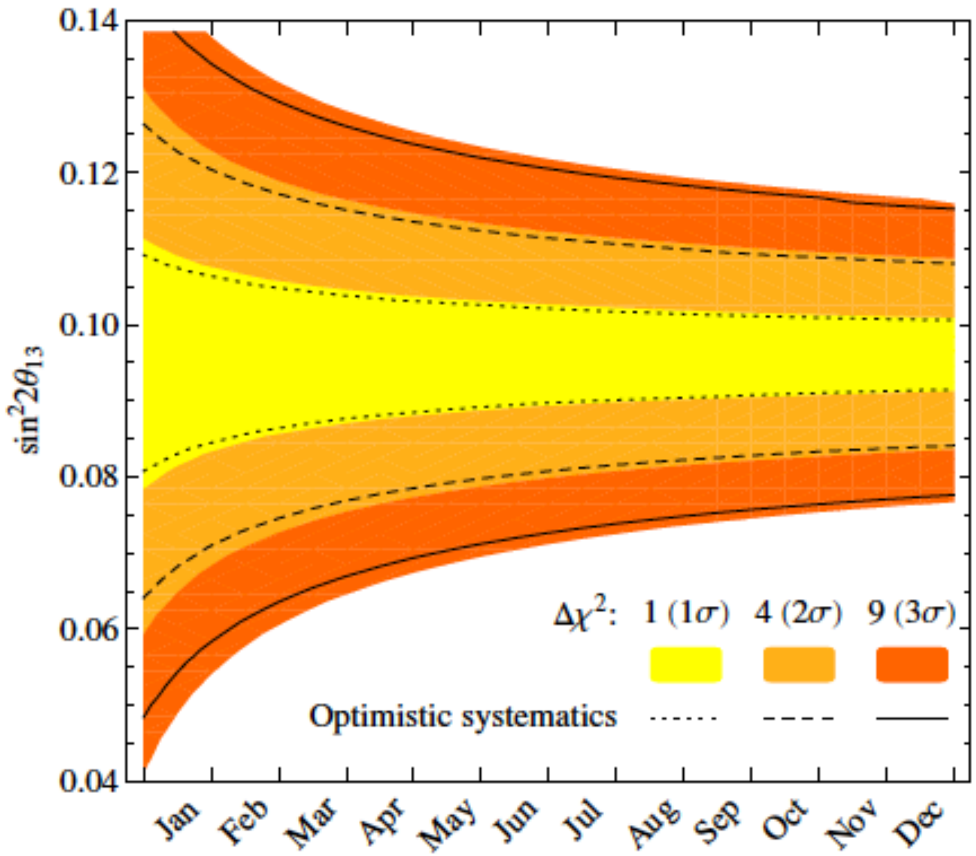


December 2012 — 14 σ



In June and December 2012; reactors will be powerful !





$\Delta(\sin^2 2\theta_{13})$ at 1σ: +/-0.013 → +/-0.005

We are experiencing a very rapid change in this year!

Large θ_{13} natural

Large θ_{13} natural if there is no symmetry to enforce it small

Large θ_{13}?

- Let me emphasize the possibility that θ_{13} may be large
- Because MNS matrix is $S^{+}(l)S(\nu)$, and 2 angles (θ_{12} , θ_{23}) are large, it is hard to believe that 3rd angle is extremely small (unless there is a symmetry)
- It is important to pursue large θ_{13} possibility
- Let me focus on ``near future'' options

May 25-30, 2008 Nu2008@Christchurch

Large θ_{13} in QLC context

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

"bimaximal minus CKM mixing."

Bi-maximal mixing from neutrinos

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

$$U_{\rm MNS} = V^{\rm CKM\dagger}\Gamma_\delta R_{23}^m R_{12}^m$$
$$= R_{12}^{\rm CKM\dagger} R_{13}^{\rm CKM\dagger} R_{23}^{\rm CKM\dagger}\Gamma_\delta R_{23}^m R_{12}^m$$

$$\Rightarrow \quad \sin\theta_{13} \simeq \frac{1}{\sqrt{2}}\sin\theta_C$$

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

HM-A.Smirnov 04

Predicted value of θ_{13} in this model agrees well with experiments !

What's next?

Given the large θ_{13}, what can be said immediately?

- The role/aim of ongoing experiments may be redefined

  T2K and NOVA
- Can NOVA be optimized as hierarchy determining machine?
- T2K will seek θ_{13} determination by its own way. Then, what is next? Can T2K be optimized as CP determining machine?
- For next generation experiments conventional superbeam would be a natural choice

Mass hierarchy first

Large θ_{13} frees people to speak about various ways to determine the mass hierarchy

百花齐放 or 百花争鳴
or Hundred Flowers Campaign

Mao Zedong

Who determine the mass hierarchy first, say at 3σ?

Lets start from ~existing machines

NOVA as hierarchy determining machine

95% CL Resolution of Mass Hierarchy (Normal Ordering)

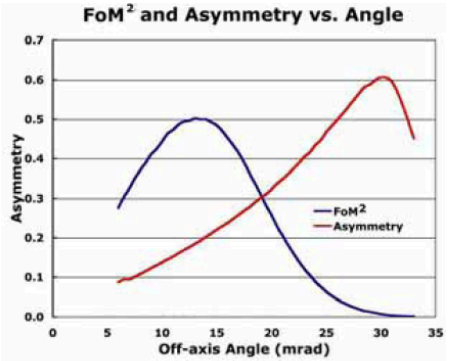
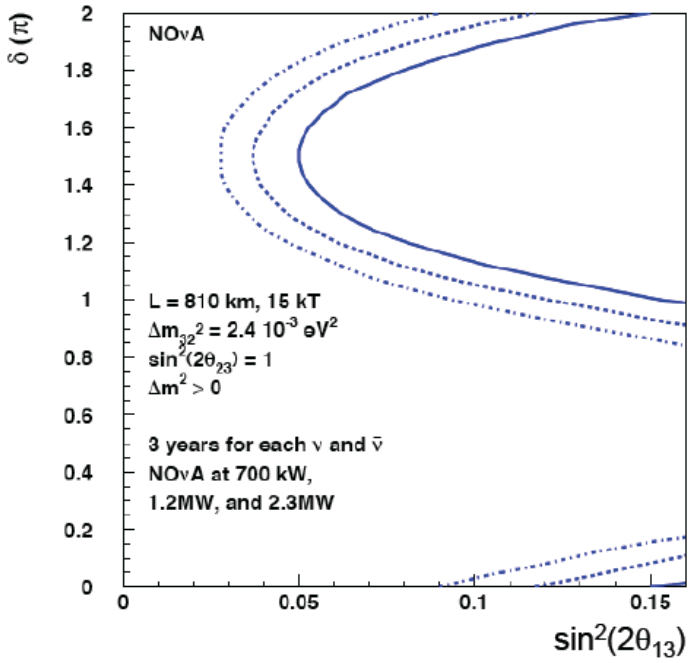
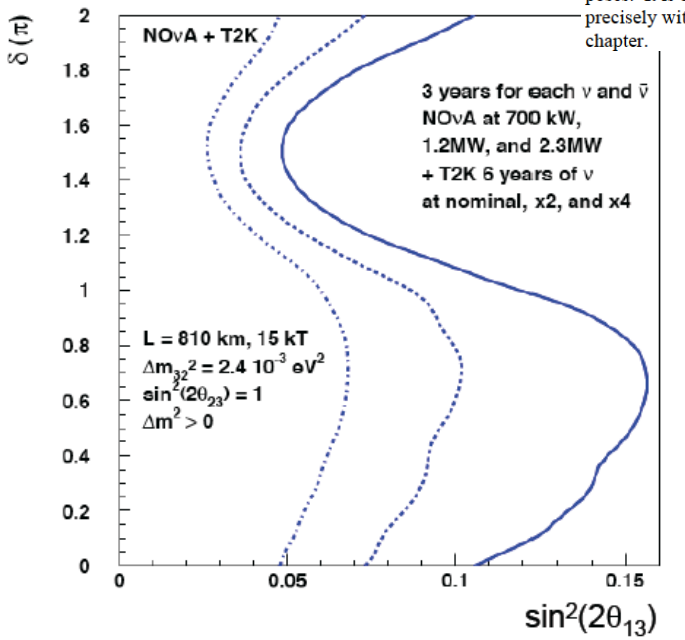


Fig. 13.4: Figure of merit squared (arbitrary units) and neutrino oscillation asymmetry due to the matter effect for $\Delta m^2 = 0.0025$ eV^2 versus off-axis angle. See text for an explanation. This figure is for illustrative purposes. It is based on a toy model and may not agree precisely with the simulation data presented in this chapter.



NOνA Only



NOνA + 6yrs T2K

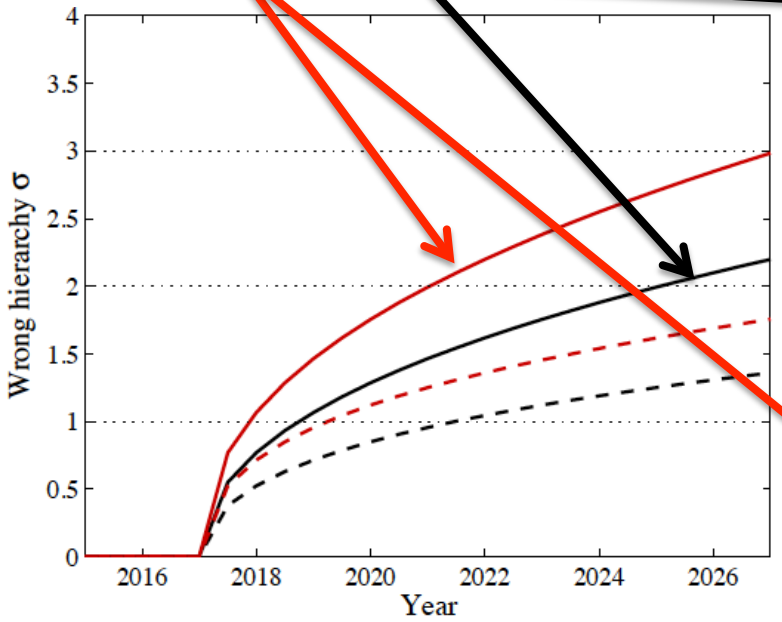
Optimizing MI beam energy to solve hierarchy?

INO atm+NOVA+T2K

Blennow-Schwetz Mar 12

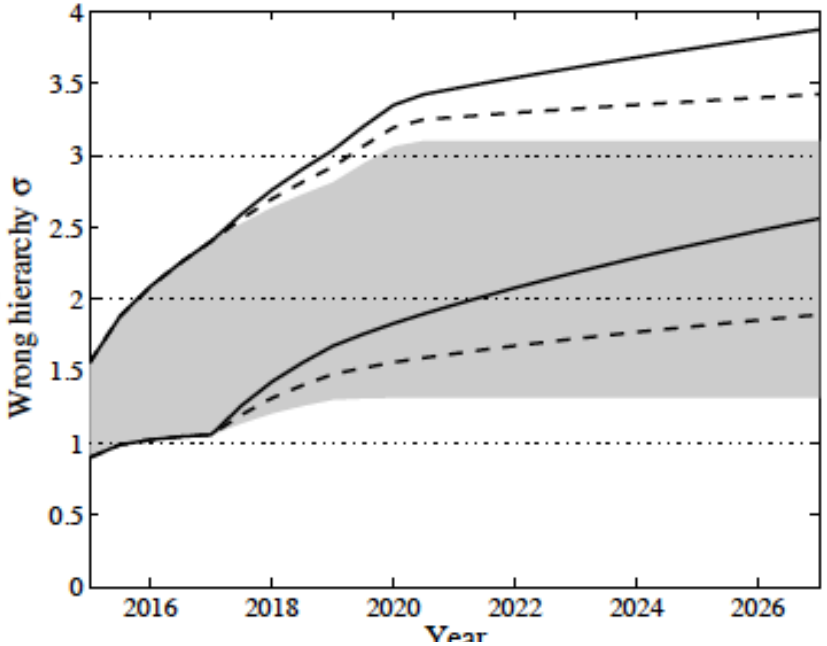
100 kt

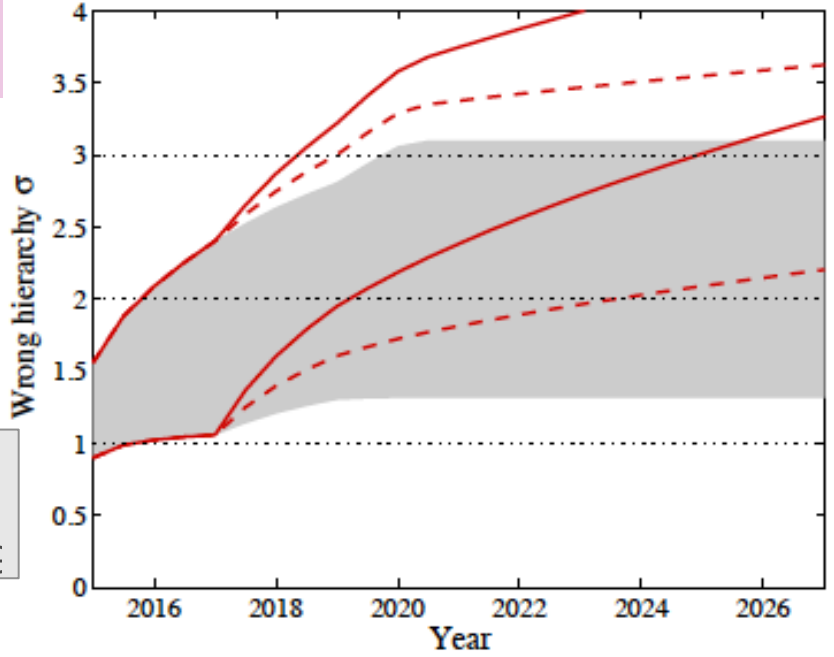
50 kt



10°, 10%

15°, 15%

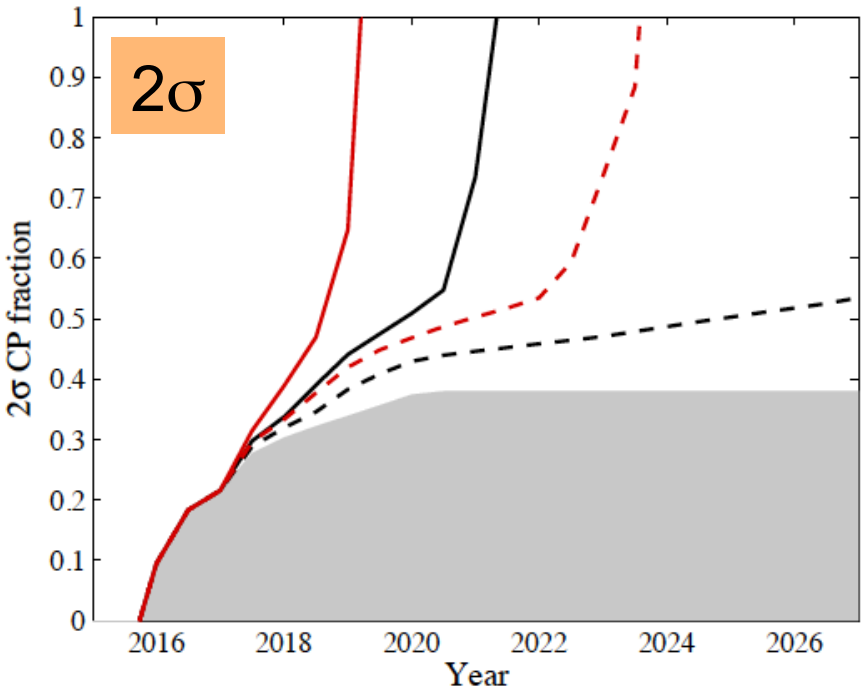


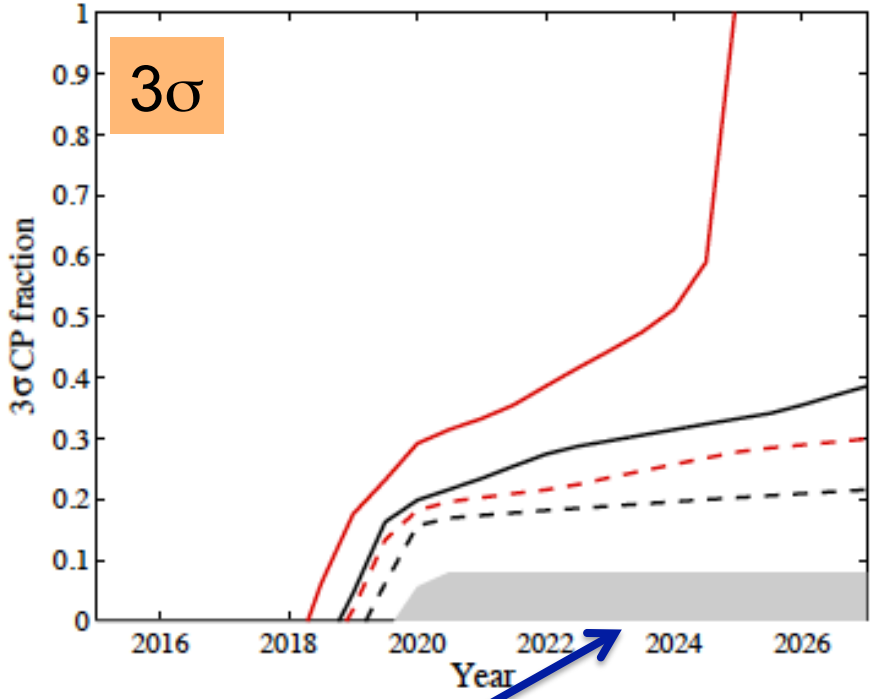


INO-atm only

Shaded region: NOVA+T2K only

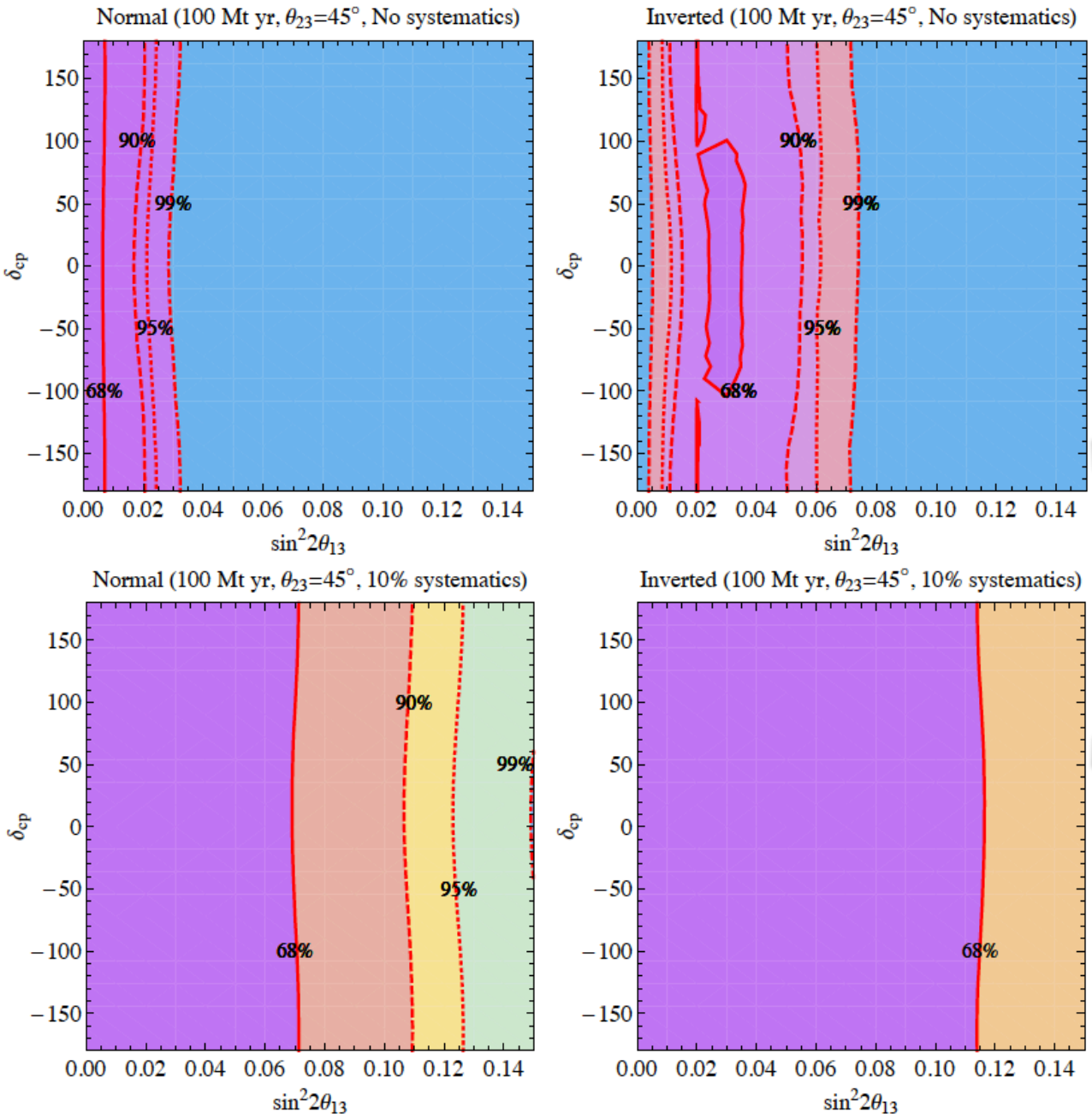
3 σ hierarchy so difficult …





T2K+NOVA alone cannot determine hierarchy at 3σ CL

Atm ν @IceCUBE deep core



2 d.o.f.

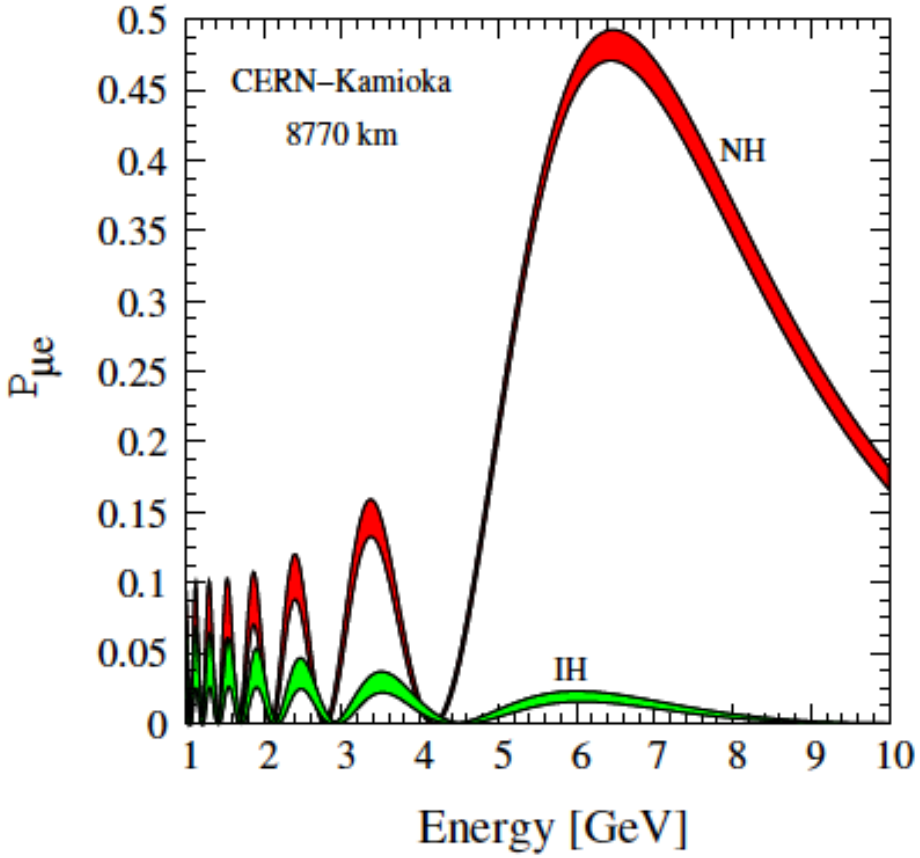
Mena-Mocioiu-Razzaque Mar 08

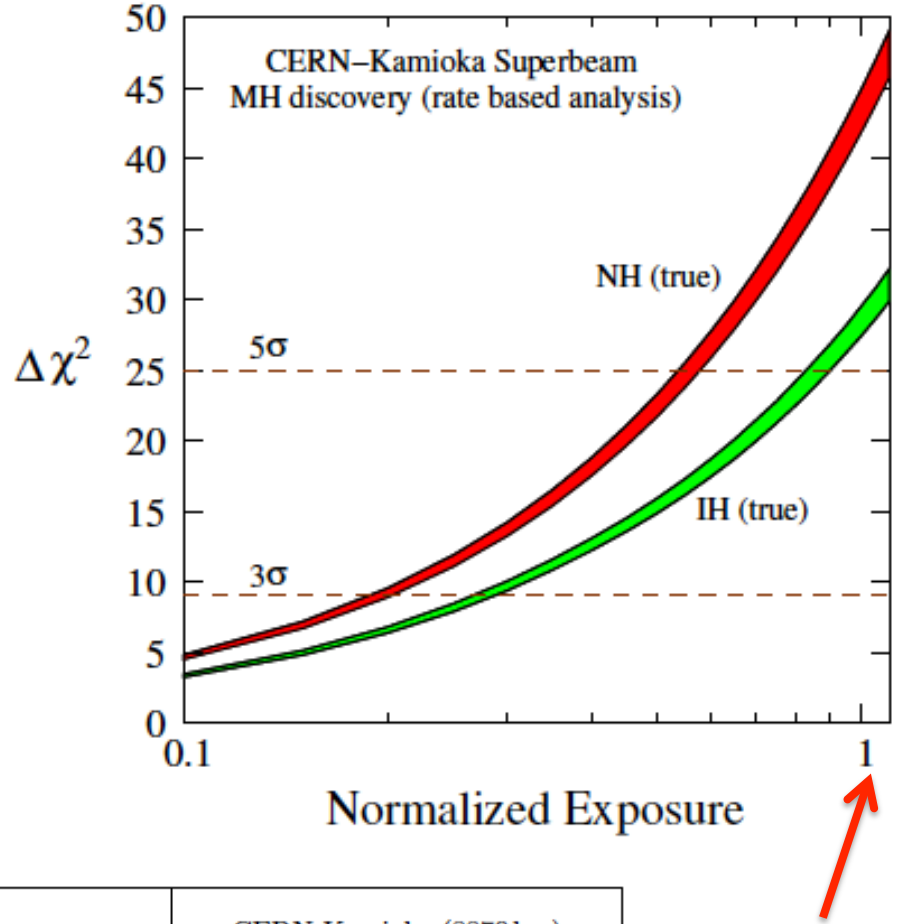
Sensitive to systematics: 0 vs. 10%

PINGU?

CERN-Super-K (8870 km)

Agarwalla-Hernandez April 12





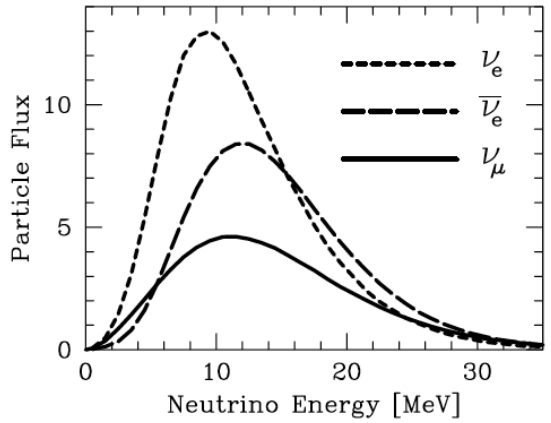
Channel	CERN-Kamioka (8870 km)	
	Signal	Background
	CC-1 ring	Int+Mis-id+NC = Total
$\nu_\mu \to \nu_e$ (NH)	**44**	1+2+16=**19**
$\nu_\mu \to \nu_e$ (IH)	**2**	1+3+16=**20**
$\nu_\mu \to \nu_\mu$ (NH)	**83**	**2**
$\nu_\mu \to \nu_\mu$ (IH)	**91**	**2**

5×10^{21} pot.

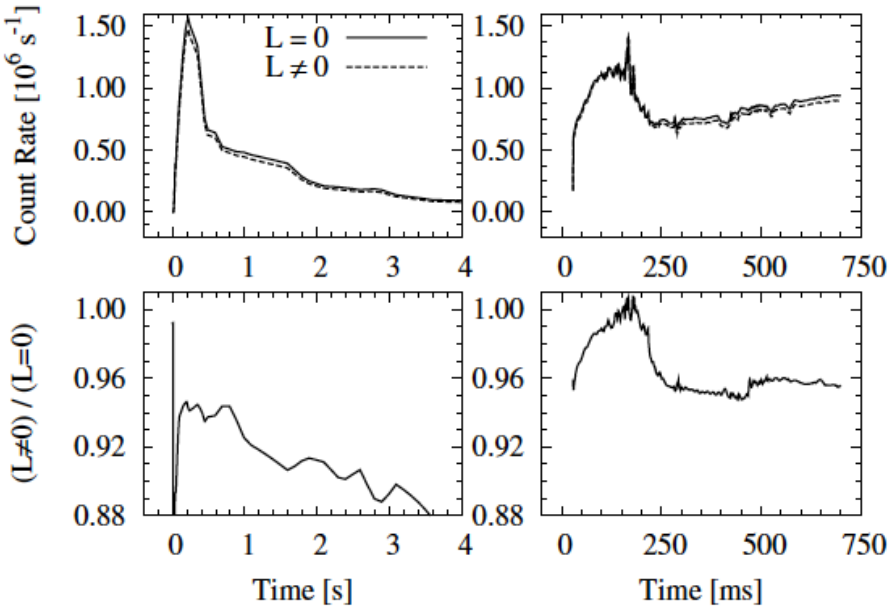
Supernova ν: H-resonance is adiabatic !

old idea: H resonance in ν (normal) and ν–bar (inverted) channels

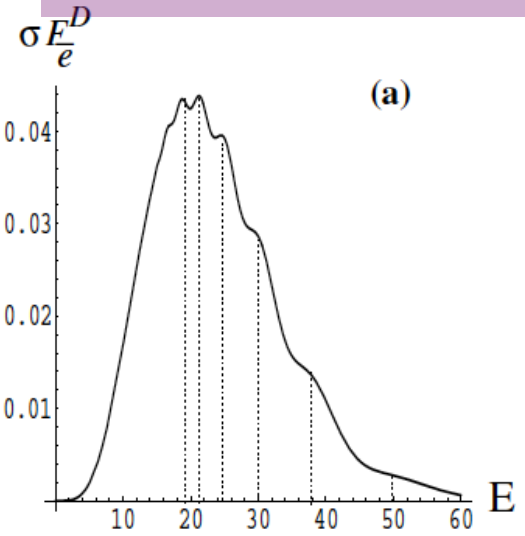
Normal: earth matter effect
Inverted: No earth matter effect



IceCube



Solar-scale oscillation due to earth matter



normal $F_{\bar{e}}^{D1} - F_{\bar{e}}^{D2} \approx (\bar{P}_{1e}^{(1)} - \bar{P}_{1e}^{(2)}) \cdot (1 - 2\bar{P}_L) \cdot (F_{\bar{e}}^0 - F_x^0)$

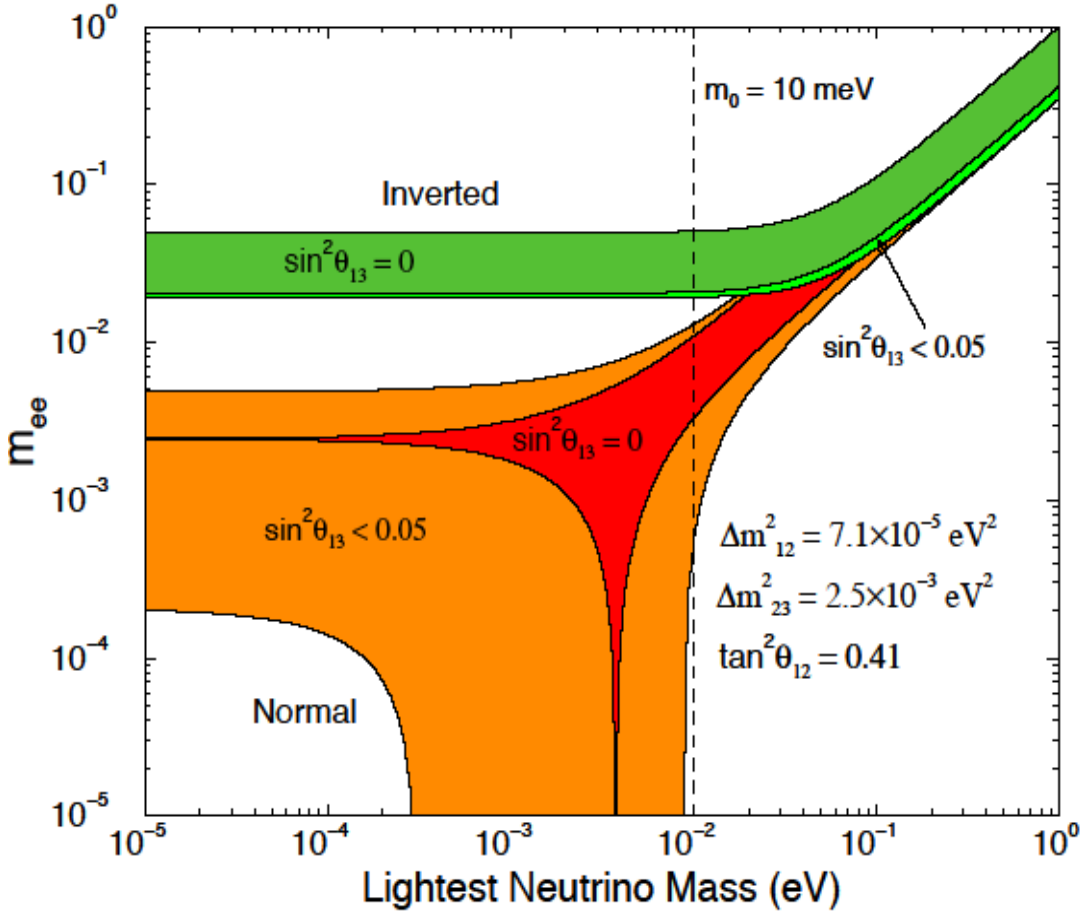
inverted $F_{\bar{e}}^{D1} - F_{\bar{e}}^{D2} \approx \bar{P}_H(\bar{P}_{1e}^{(1)} - \bar{P}_{1e}^{(2)}) \cdot (1 - 2\bar{P}_L) \cdot (F_{\bar{e}}^0 - F_x^0)$

$$F_{\bar{e}}^D = \sin^2\theta_{12} F_{\bar{x}}^0 + \cos^2\theta_{12} F_{\bar{e}}^0 + \Delta F^0 \bar{A}_\oplus \sin^2(\overline{\Delta m^2_\oplus} L y)$$

Double beta do NOT determine the hierarchy

Inverted ⇒ there are events at 50 meV

there are events at 50 meV ⇏ Inverted

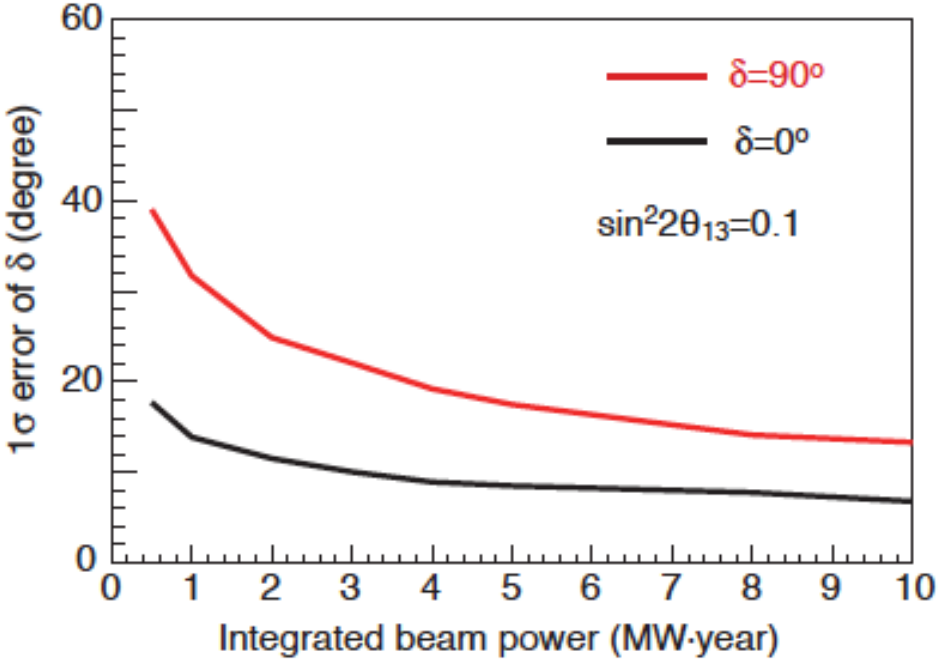


$$< m >_{\beta\beta} \geq c_{13}^2 \left| m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\beta} \right| - m_3 s_{13}^2$$

$$\geq c_{CH}^2 \left| m_1 c_{12}^2 - m_2 s_{12}^2 \right| - m_3 s_{CH}^2$$

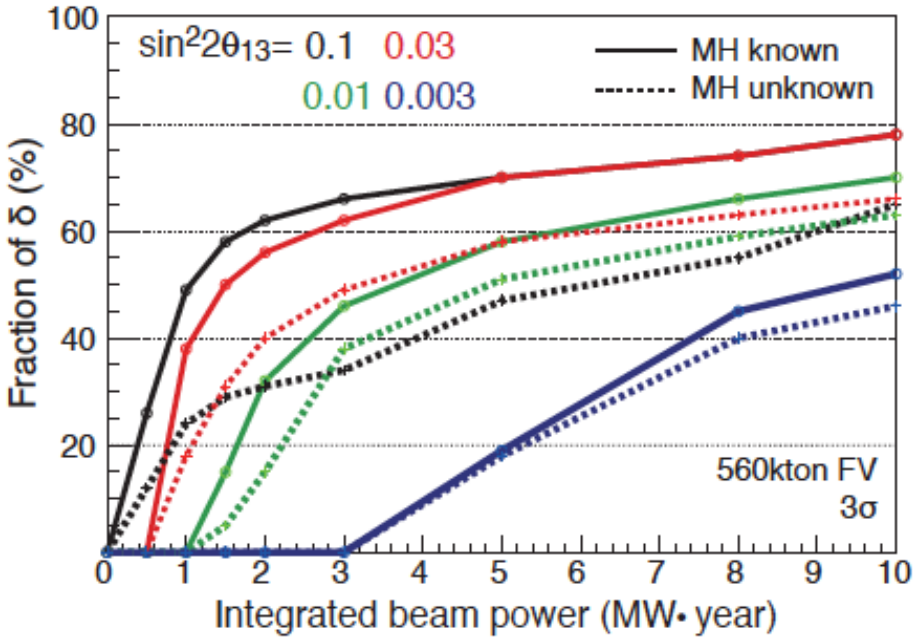
T2K as CP determining machine?

Hints from HK LOI



1σ uncertainty of δ as a function of integrated beam power

1MW yr needed:
~20 years for SK



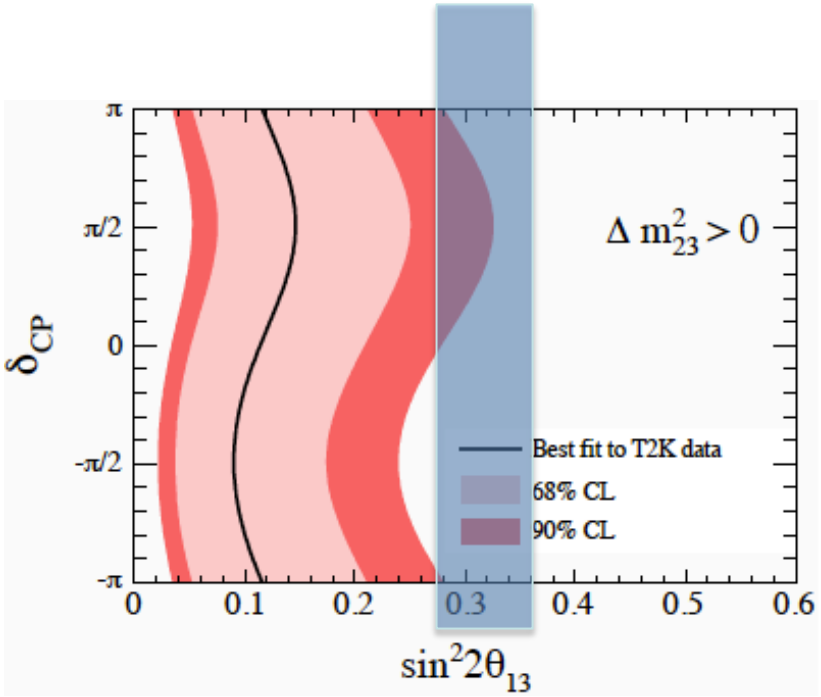
Fraction of δ for which $\sin\delta = 0$ can be excluded with $3\ \sigma$

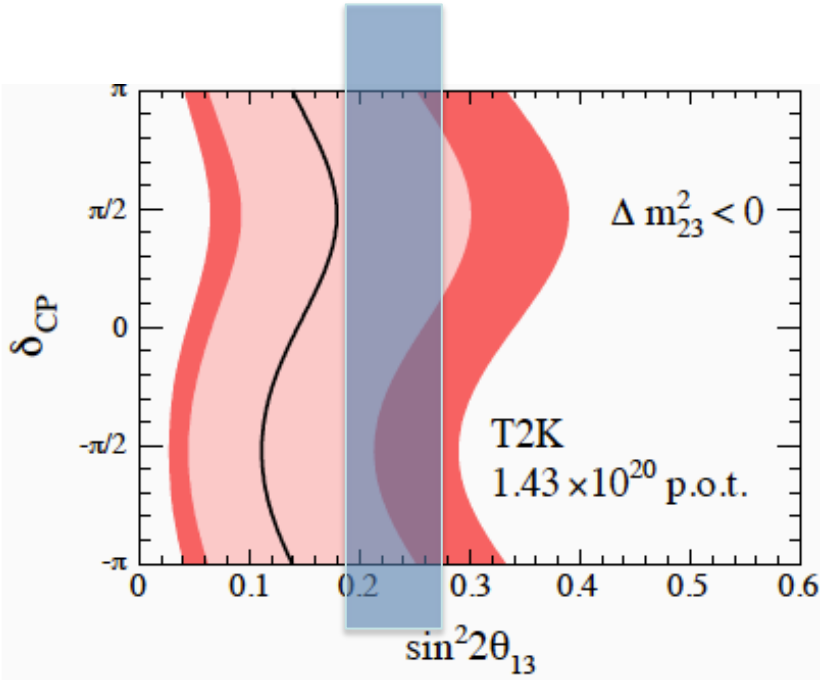
The ratio of neutrino and anti-neutrino mode is fixed to 3:7.

Accelerator-reactor combined method for CP δ

HM-H.Sugiyama PLB 04

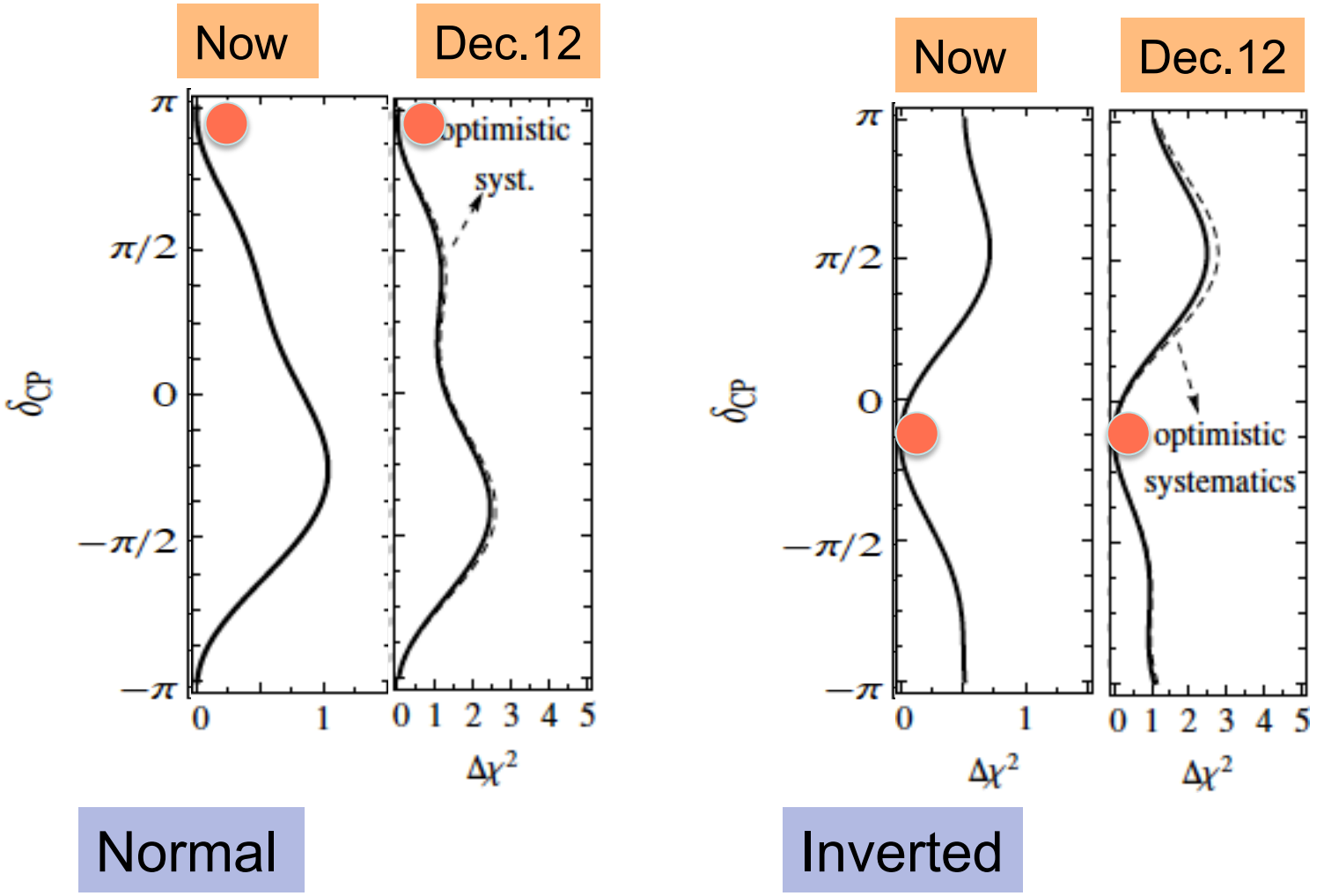
Idea is very simple





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

Breakdown of χ^2 : δ



Normal

Inverted

Slight preference for sinδ > 0 (normal), sinδ < 0 (inverted)?

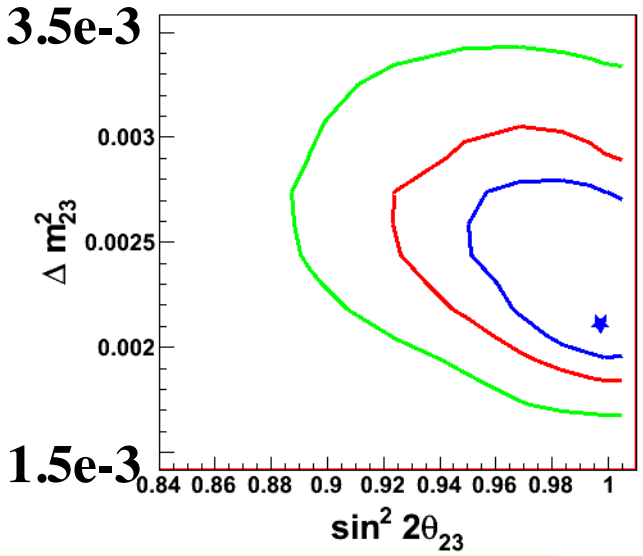
Full 3-flavor oscillation results

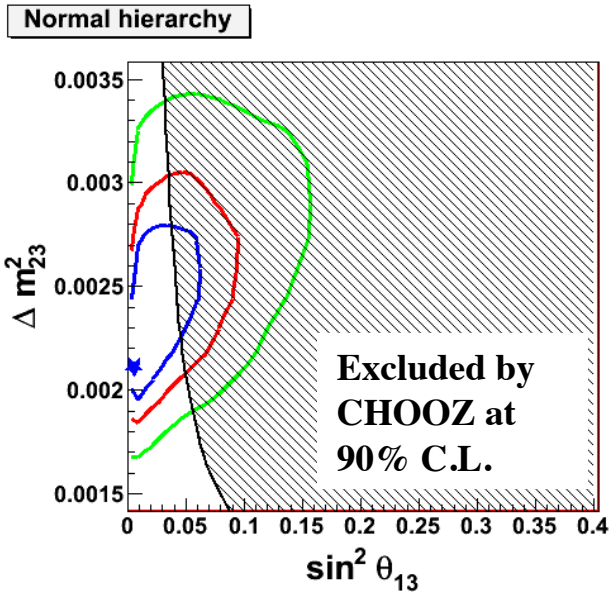
Takeuchi Nu2010

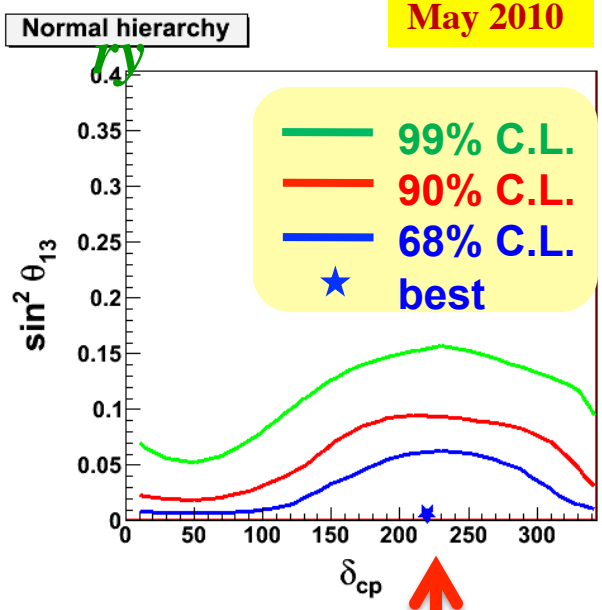
SK-I+II+III *Prelimina ry*

May 2010

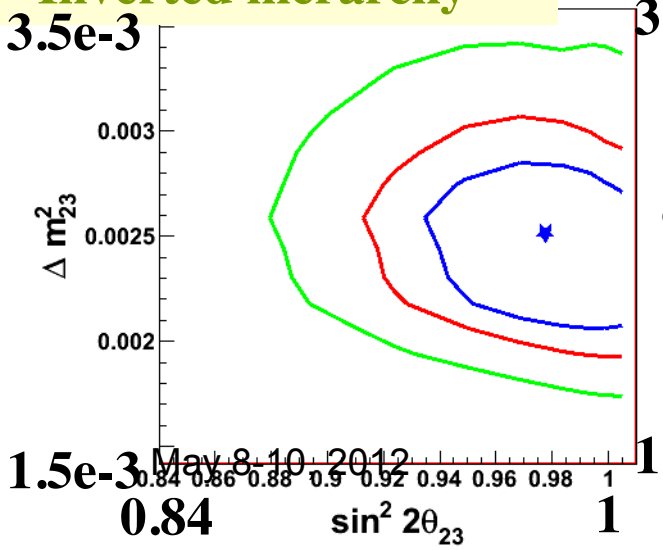
- Normal hierarchy -

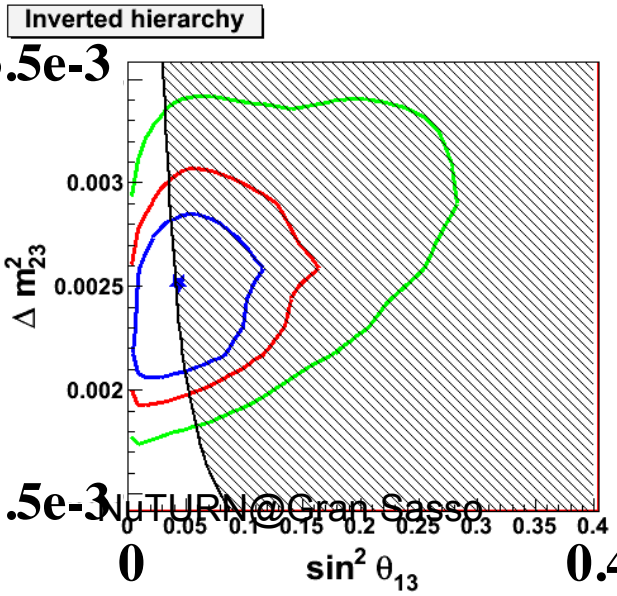


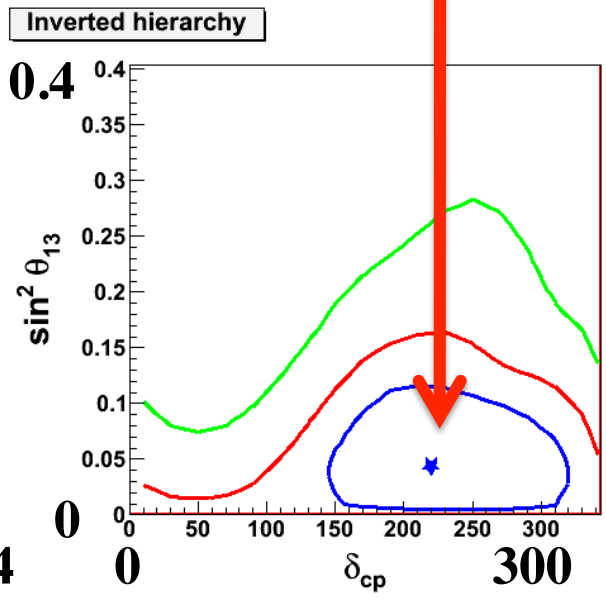




- Inverted hierarchy -



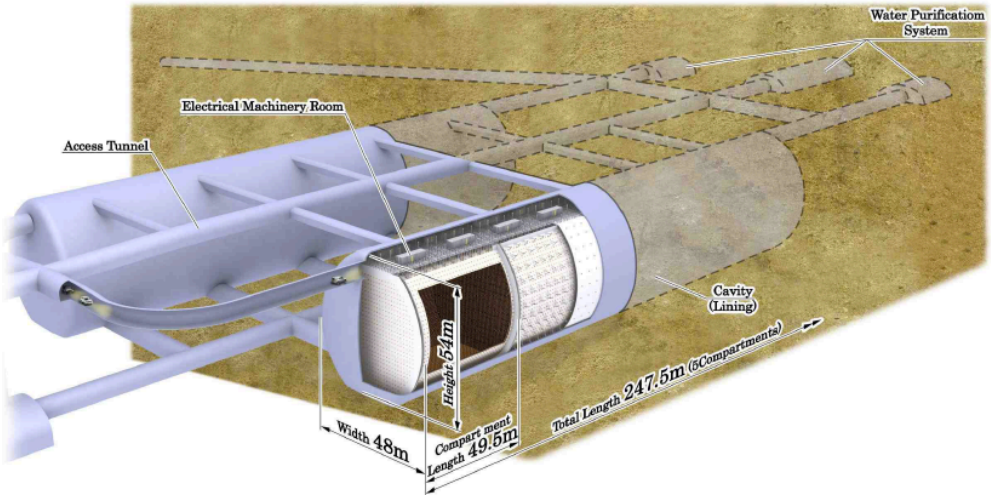




Foreseeing the future

Large θ_{13} opens "all in one" approach

- With large θ_{13} 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 the mass hierarchy ➡ in situ measurement of everything in a single detector
- It can do proton decay, interesting astrophysics ..

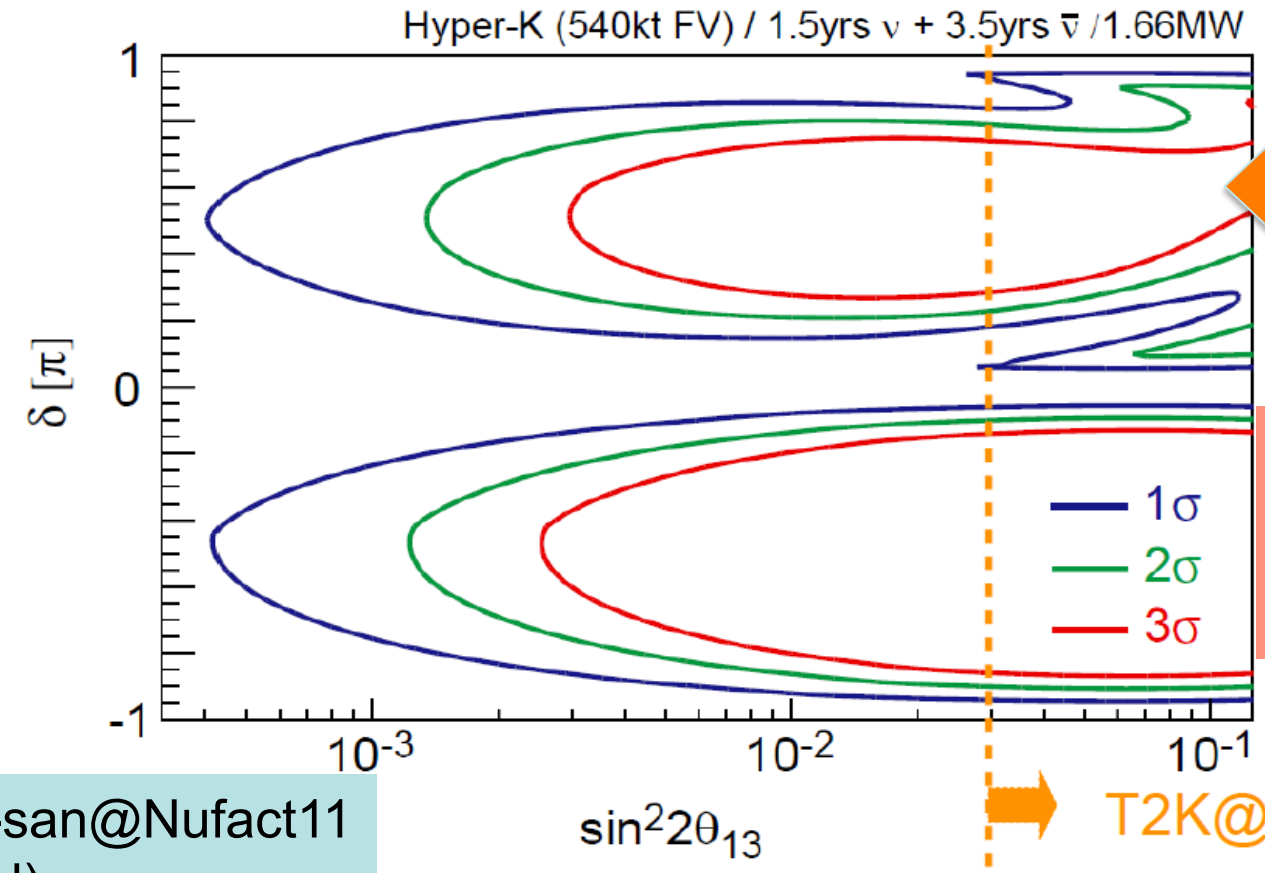


e.g., Hyper-K LOI (2011)

water Cherenkov vs. liquid Ar vs. TASD debatable

Sasso

J-PARC HK CPV sensitivity



Sensitivity is not the best at large θ_{13}

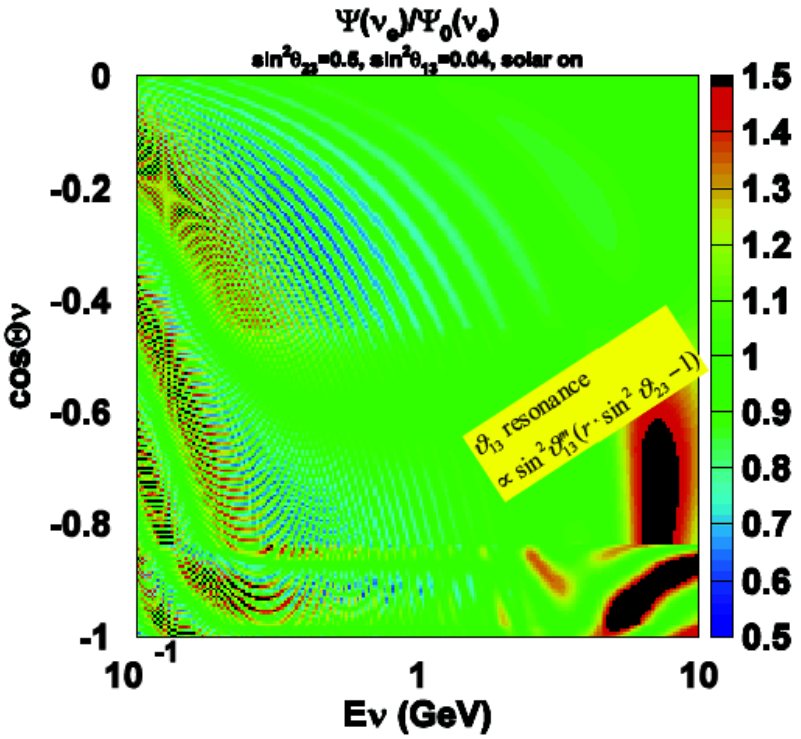
Kakuno-san@Nufact11 (modified)

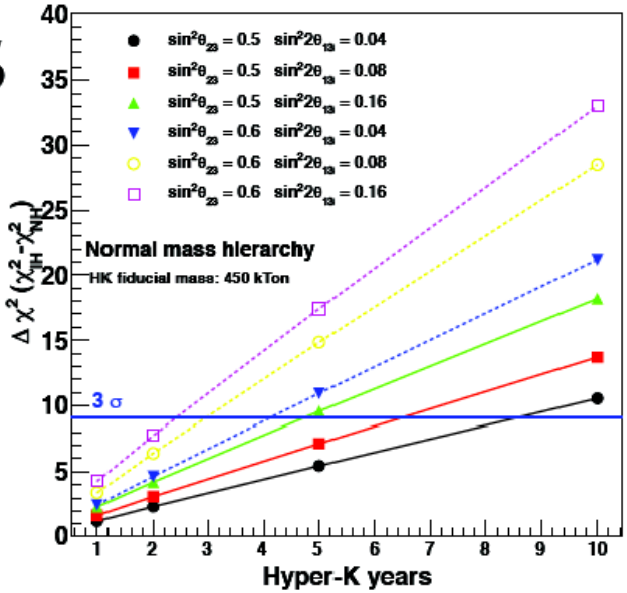
- 5% of systematic uncertainty is assumed
- mass hierarchy is assumed to be ***unknown***

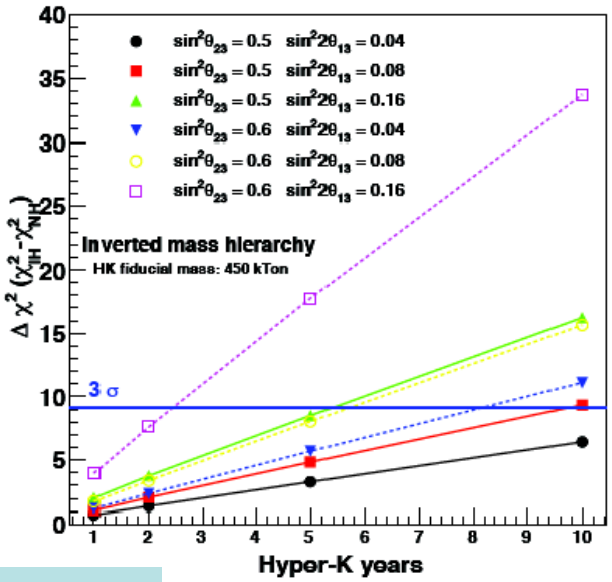
determine together w/ atmospheric ν studies

Hyper-K LOI

Atmospheric ν studies (mass hierarchy)





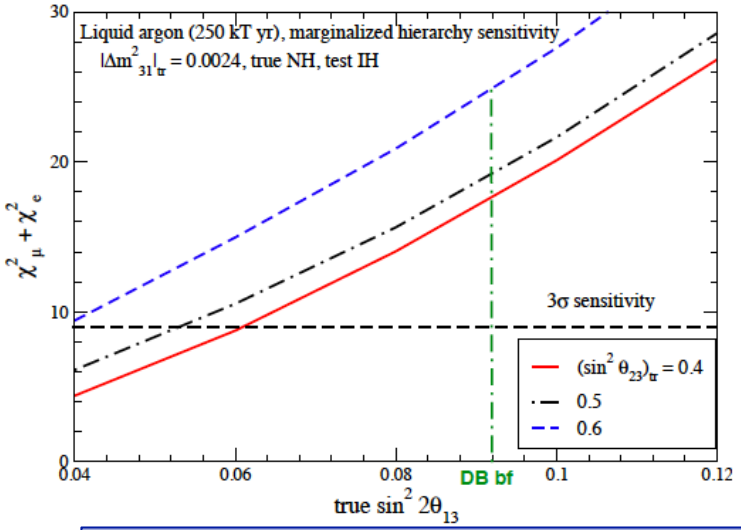


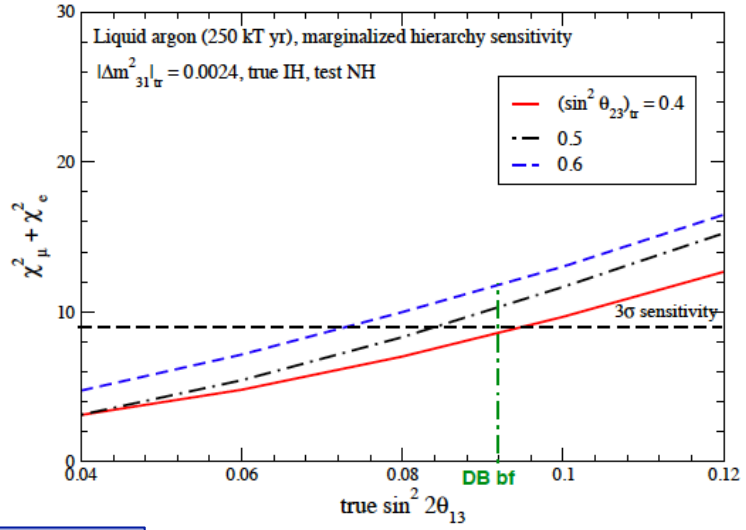
- Normal mass hierarchy → resonance in ν_e appearance
- Inverted mass hierarchy → resonance in anti-ν_e

Good chance if θ_{23} and θ_{13} are large

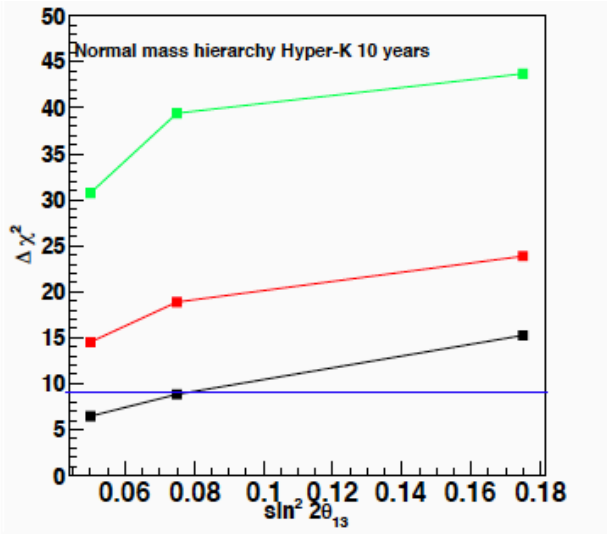
Hyper-K LOI

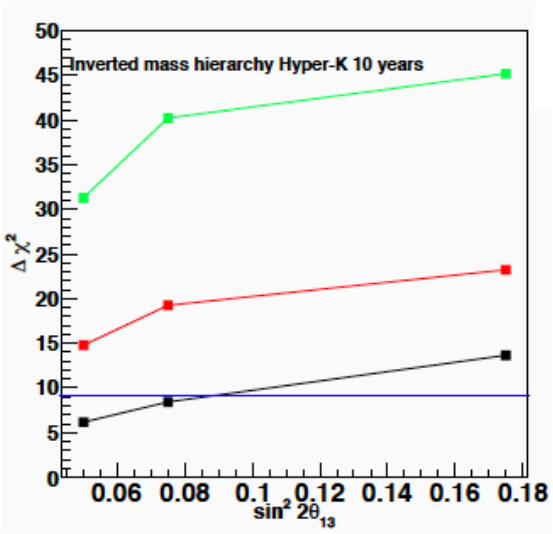
Liquid Ar can do a better/comparable job but with optimistic errors





250 kton yr: Barger et al. Mar 12





$$\sigma_{E_e} = \sigma_{E_\mu} = 0.01\,,$$
$$\sigma_{E_{had}} = \sqrt{(0.15)^2/E_{had} + (0.03)^2}\,,$$
$$\sigma_{\theta_e} = 0.03 \text{ radians} = 1.72^\circ,$$
$$\sigma_{\theta_\mu} = \sigma_{\theta_{had}} = 0.04 \text{ radians} = 2.29^\circ$$

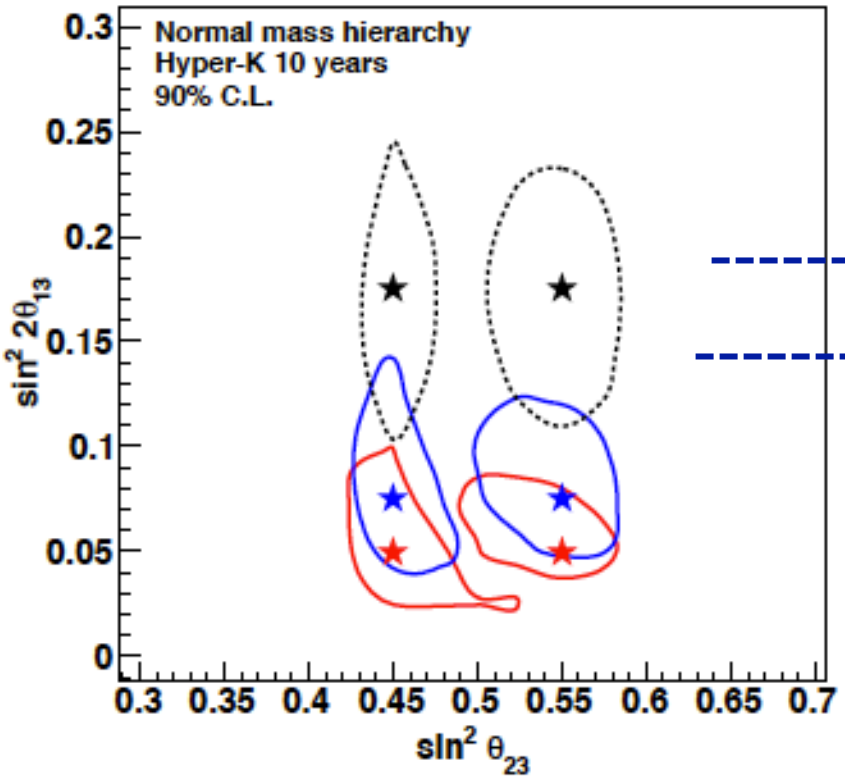
Hyper-K LOI

23 degeneracy: HK atm vs. reactor + JPARC-HK

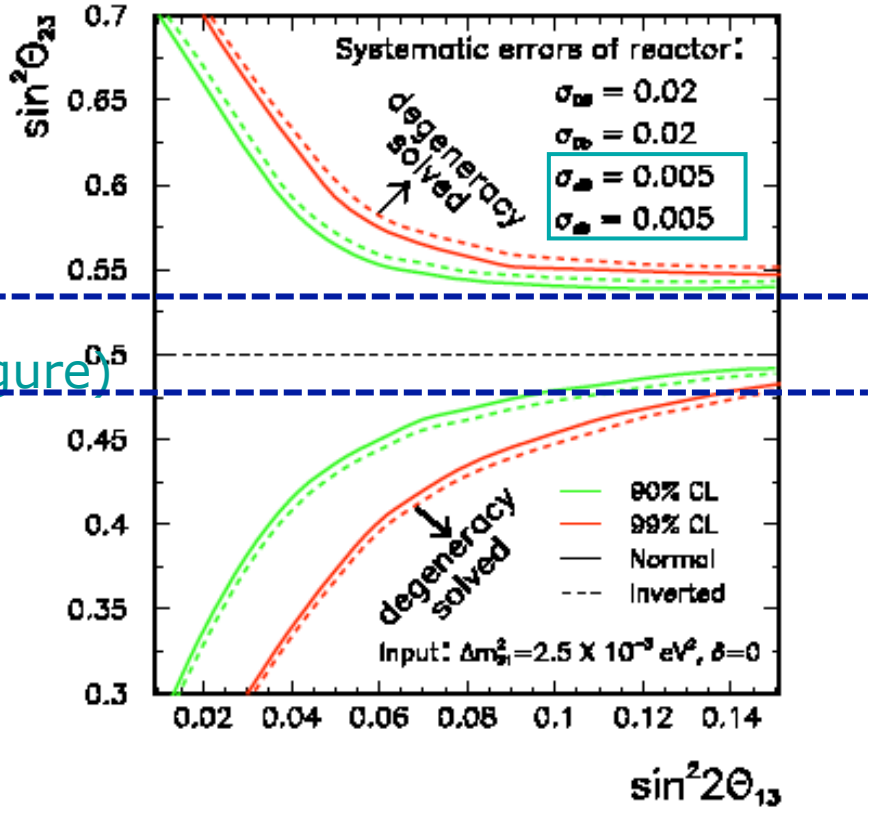
Hiraide et al 06
hep-ph/0601258

HK atm ν (LOI)

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

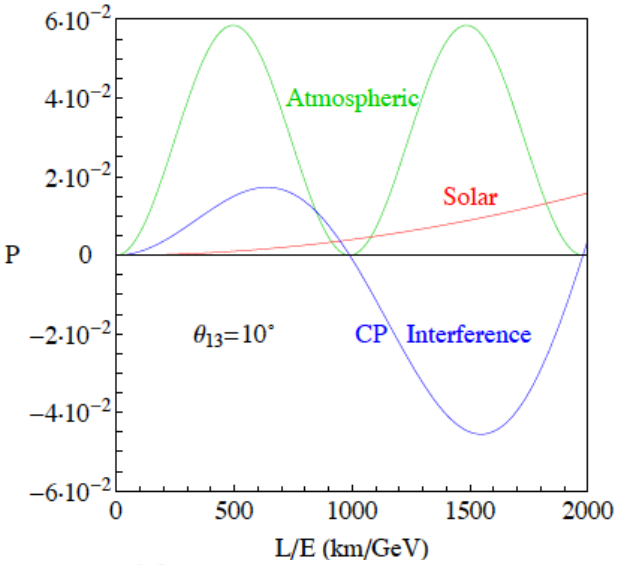


Atm ν
(left figure)



Both methods have comparable sensitivity to θ_{23} octant determination (Liquid Ar too)

Use of 2nd oscillation maximum



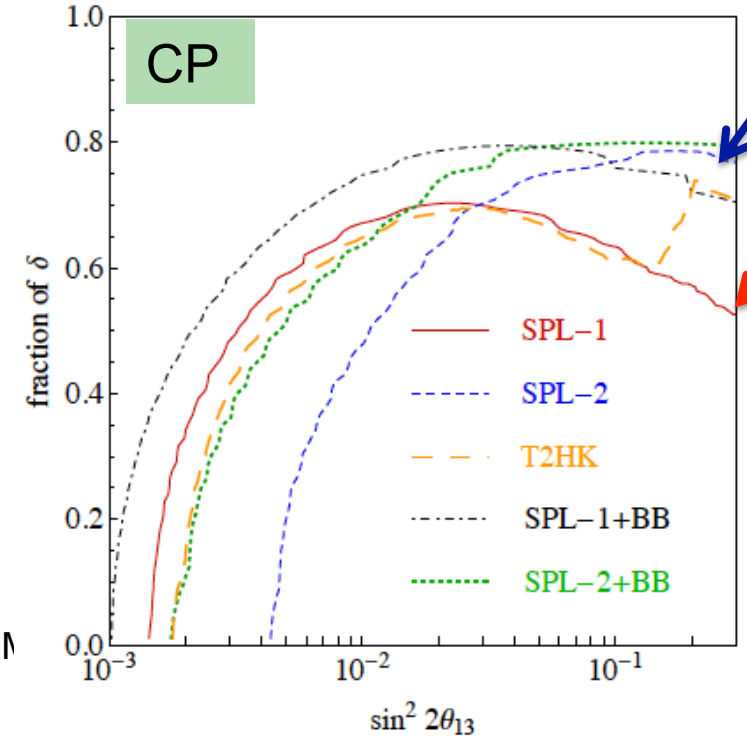
Coloma-Fernandez-Matinez Nov 11

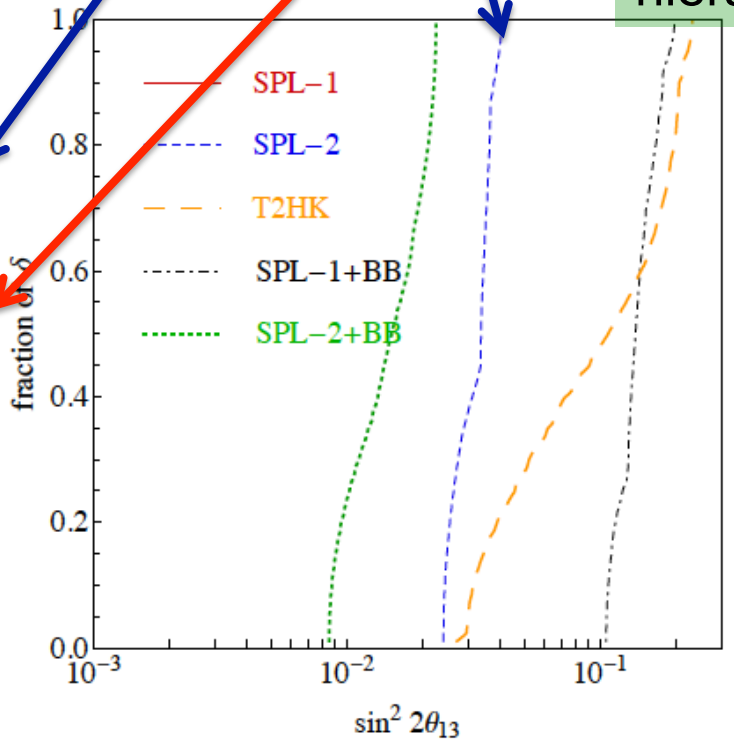
650 km

130 km

hierarchy

CP





Concluding remarks

Conclusion

- I started by reviewing the current situation of θ_{13} : Within this year θ_{13} will be determined very precisely
- Large θ_{13} triggers "hundred flowers" situation with many ideas for mass hierarchy: Who determine it 1st ? (2nd Daya Bay hidden?)
- Strategy for CP is not transparent (for me) unless dedicated machine is build
- "All in one" approach possible with large θ_{13} : decisive machine for CP and hierarchy