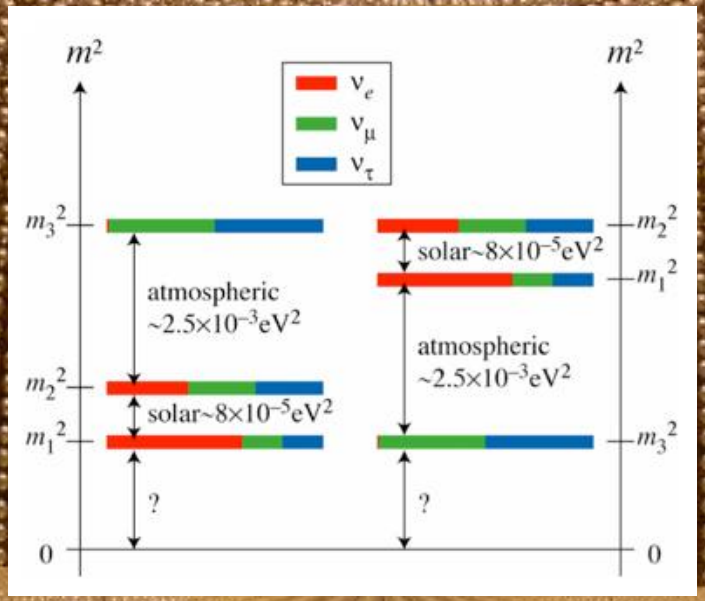
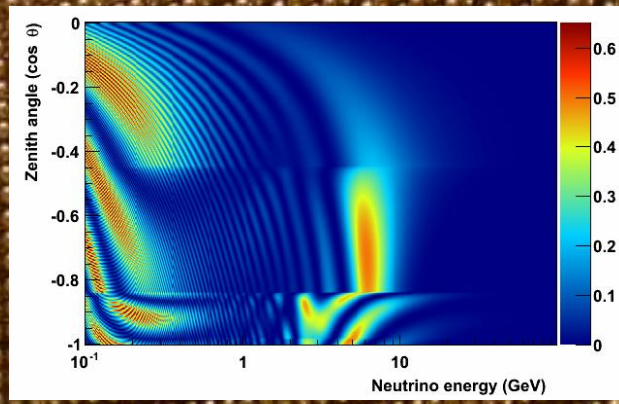
Atmospheric neutrino oscillation and mass hierarchy determination in Super-Kamiokande





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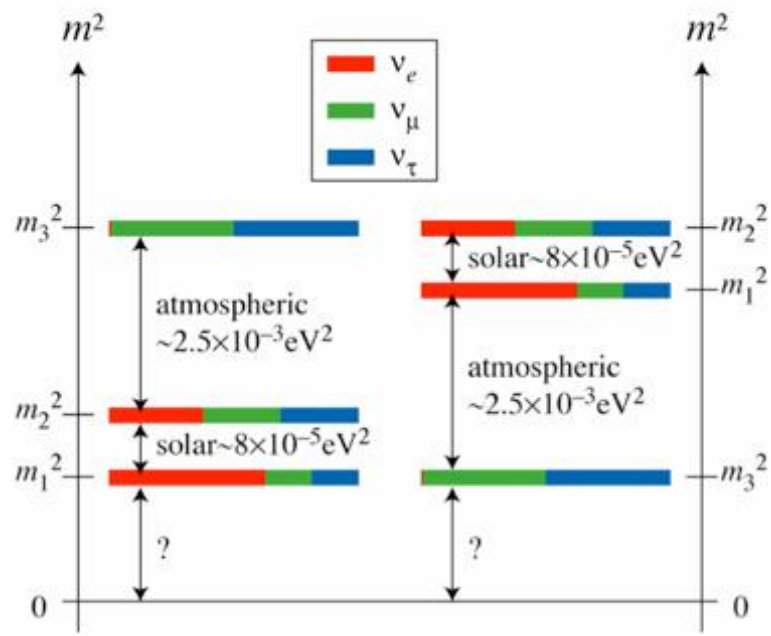
TAUP 2013 Conference

Introduction

- Mass hierarchy (MH) is one of the important parameters to be measured along with CP violation phase in future

- Several experiments aims at detecting MH:
  - Medium-baseline reactor (ex. Juno, RENO-50)
  - Double-beta decay
  - $\nu_\mu \rightarrow \nu_e$ measurement by accelerator neutrino
    - longer baseline needed (~1000km)
  - Atmospheric neutrino
    - L= O(10) ~ 13000 km



Normal Inverted

$\nu_\mu \rightarrow \nu_e$ oscillation in atm. ν

ν_e oscillation due to non-zero θ_{13} provides atm. nu. observation to investigate mass hierarch effect

$\nu_\mu \rightarrow \nu_e$ osc. probability in matter:

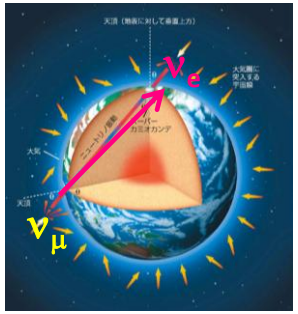
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left(\frac{1.27\Delta m_{31,M}^2 L}{E}\right)$$

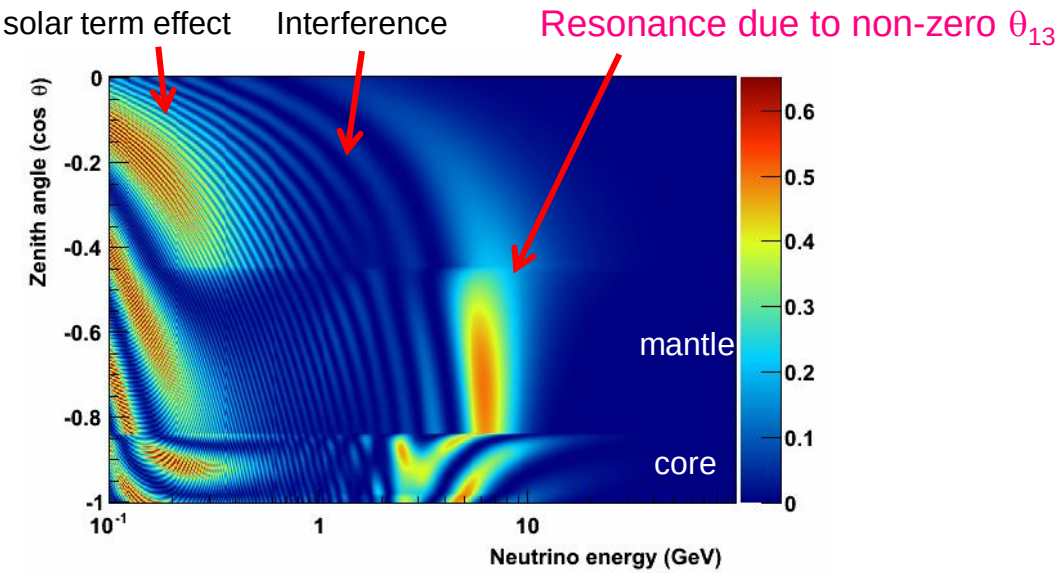
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m_{31}^2\right)^2 + \sin^2 2\theta_{13}}$$

$\sin^2\theta_{13,M}$ has resonance feature when $A_{CC} \sim \Delta m_{31}^2 \cos 2\theta_{13}$ $\quad (A_{CC} = 2\sqrt{2}G_F N_e E)$

$\nu_\mu \rightarrow \nu_e$ resonance in multi-GeV region

$P(\nu_\mu \rightarrow \nu_e)$ of earth-throughgoing ν :





Occurrence of resonance feature depends on neutrino type and mass hierarchy:

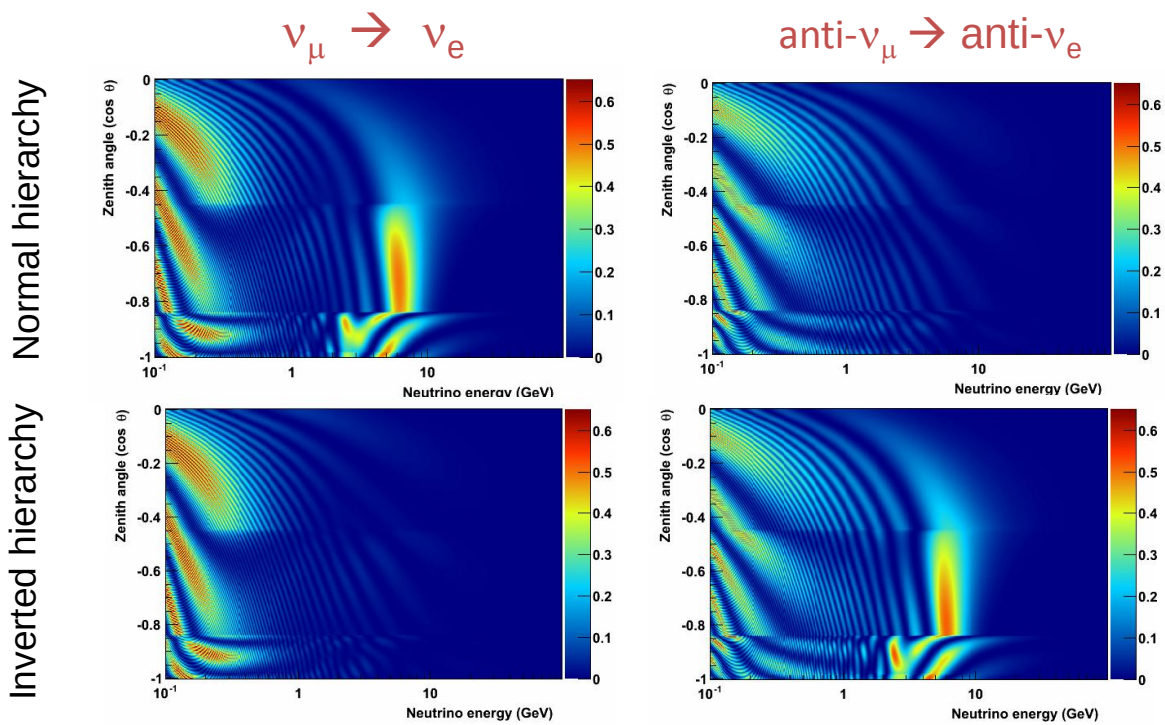
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m_{31}^2\right)^2 + \sin^2 2\theta_{13}}$$

In case of Inverted hierarchy:

$$\Delta m^2 \rightarrow -\Delta m^2$$

In case of anti neutrino :

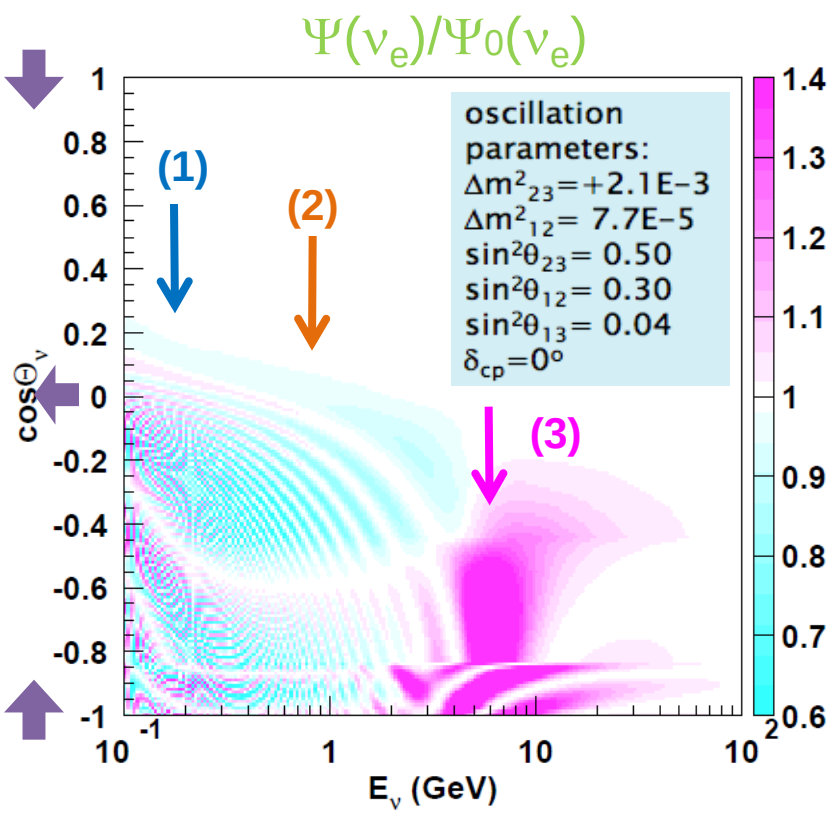
$$A_{CC} \rightarrow -A_{CC}$$



Possible to determine mass hierarchy if we identify in which neutrino (ν_e or anti- ν_e) enhancement is occurring

θ_{23} and δ_{CP} effects

ν_e flux ratio of
$\sin^2\theta_{13}$ =0.04 and θ_{13} =0



Pares and Smirnov
hep-ph/039312

$$\Psi(\nu_e)/\Psi_0(\nu_e) - 1 \cong$$

$$P_2(r\cdot c_{23}^2 - 1) \quad \textbf{(1)}$$

$$-r\cdot\tilde{s}_{13}\cdot\tilde{c}_{13}\cdot\sin 2\theta_{23}(\cos\delta_{CP}\cdot R_2 - \sin\delta_{CP}\cdot I_2) \quad \textbf{(2)}$$

$$+2\cdot\tilde{s}_{13}^2(r\cdot s_{23}^2 - 1) \quad \textbf{(3)}$$

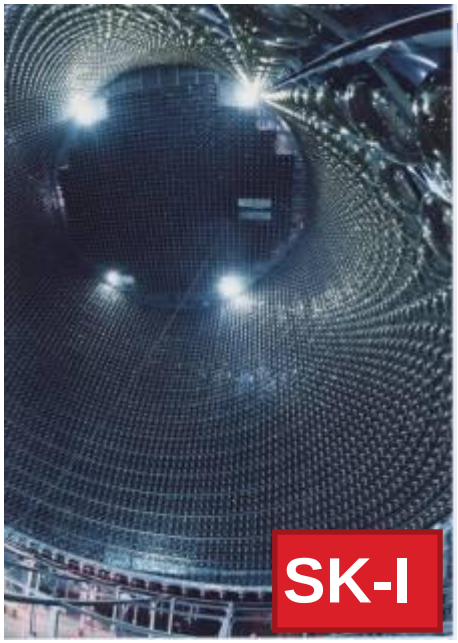
r : $\nu\mu/\nu e$ flux ratio (~2 at low energy)

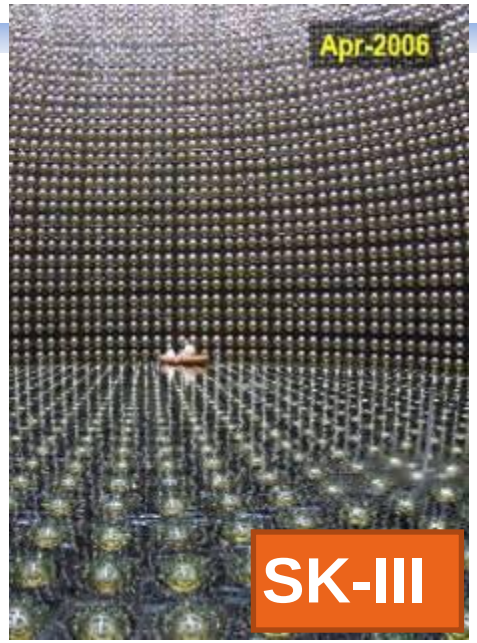
(1) driven by Δm^2_{sol} → sensitive to θ_{23} octant

(2) Interference → sensitive to δ_{CP}

(3) θ_{13} resonance → sensitive to θ_{23}, θ_{13}, MH

Super-Kamiokande



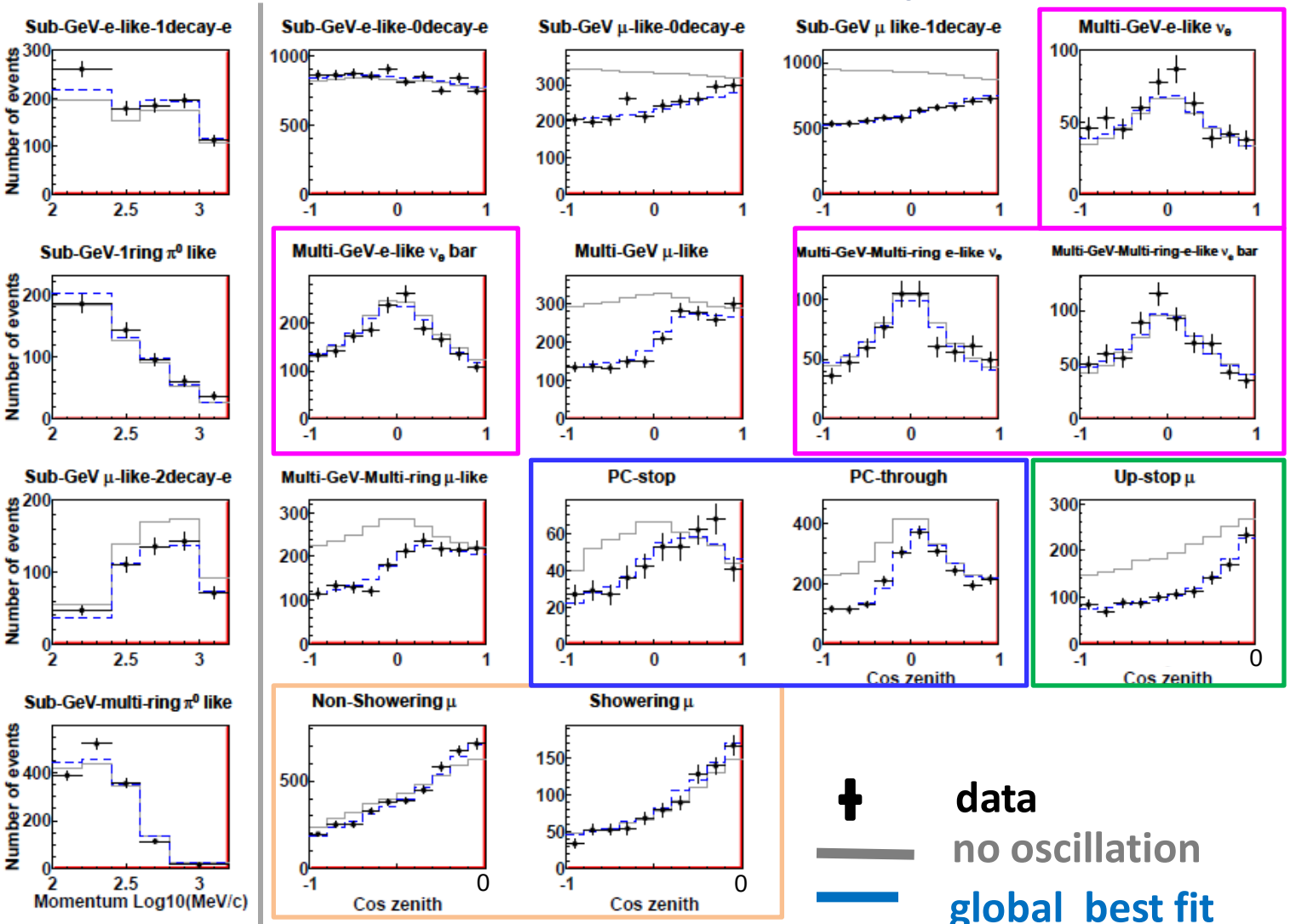


SK-I	SK-II	SK-III	SK-IV
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade

50kt water Cherenkov detector（FV22.5kt）

4223 days livetime for FC/PC, 4527days for UPMU
(~320 days update from Neutrino 2012)

Event distribution (SK1+2+3+4)



Momentum [log10(MeV)]

Zenith angle plot [$\cos\theta_{zen}$] (-1:up 1:down)

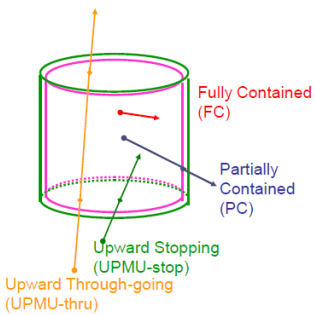
+ data

— no oscillation

— global best fit

Sample classification

Contained or not:



By Particle ID :

- electron-like
- muon-like

By energy :

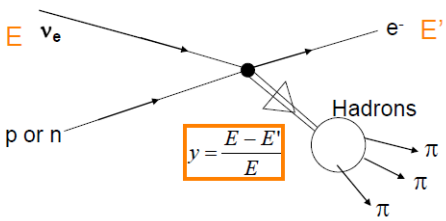
- sub-GeV (Evis<1.33GeV)
- multi-GeV (Evis>1.33GeV)

Others :

- decay electrons
- π^0-like cut
- ν / anti- ν sep.

ν_e / anti-ν_e separation : strategy

- ν / anti-ν identification will increase MH sensitivity, especially for electron sample in multi-GeV energies
- Direct measurement of lepton charge is almost impossible in Super-K
- Statistical separation using kinematical difference and final state of accompanying hadrons is still possible
  - total charge of hadron system is larger for neutrino. therefore π^+ are more produced (π^- are likely to be absorbed in water), and more Cherenkov rings, more decay electrons are observed.



	CC ν_e	CC anti-ν_e
Energy fraction of lepton	Smaller	Larger
Transverse momentum (P_T)	Larger	Smaller
Number of identified Cherenkov rings	More	Less

Neutrino: total charge

$$\nu_e + p \rightarrow e^- + \boxed{N' + pions} \quad : +2$$

$$\nu_e + n \rightarrow e^- + \boxed{N' + pions} \quad : +1$$

Anti-neutrino:

$$\bar{\nu}_e + p \rightarrow e^+ + \boxed{N' + pions} \quad : +0$$

$$\bar{\nu}_e + n \rightarrow e^+ + \boxed{N' + pions} \quad : -1$$

ν_e / anti-ν_e separation : method

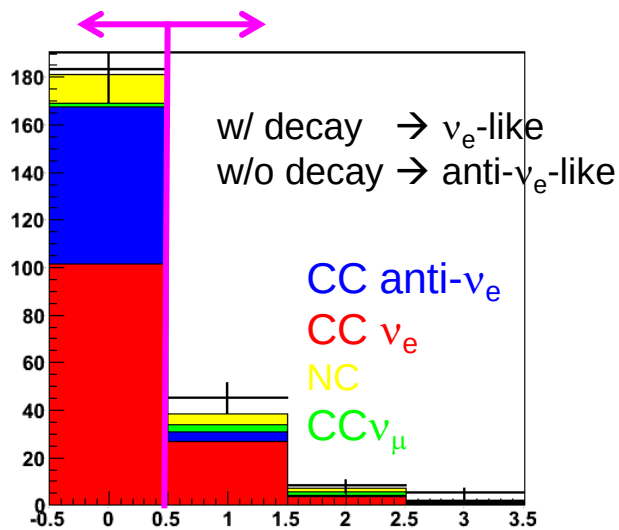
Single-Ring case :

sample divided by N_{dcy}

ex. single-π production:

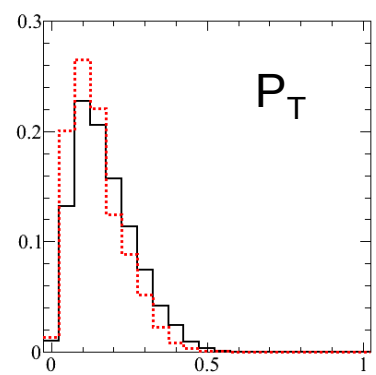
$\nu_e + n \rightarrow e^- + n + \pi^+$: decay

$\bar{\nu}_e + p \rightarrow e^+ + p + \pi^-$: absorbed (no decay)



Multi-Ring case:

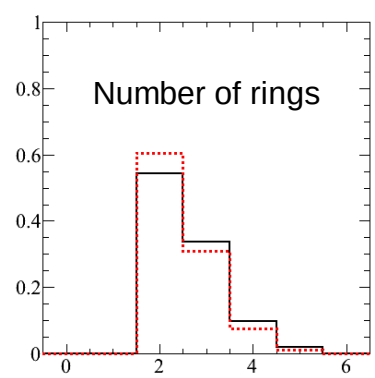
Use Likelihood method with kinematical variables and N_{dcy} :

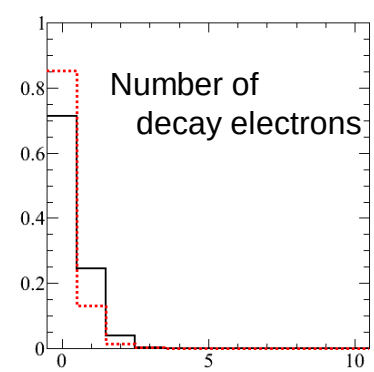


CC ν_e

CC anti-ν_e

(Evis: 2.5~5 GeV)





ν_e / anti-ν_e separation : composition

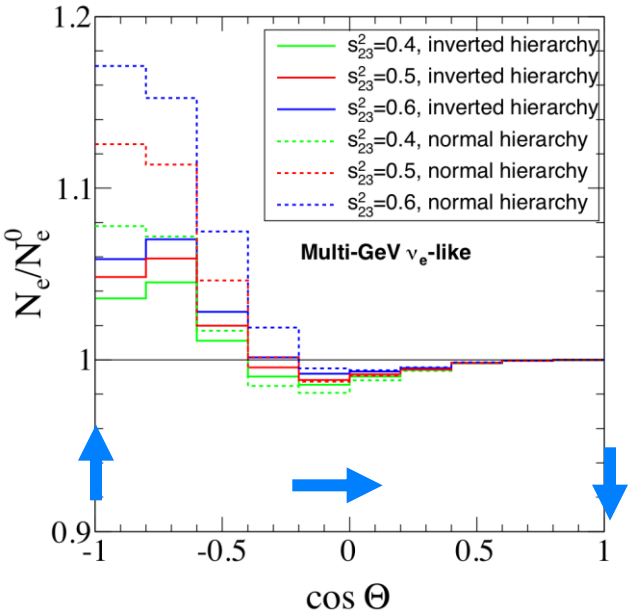
- ν / anti-ν separation is not well separated due to statistical method, but reasonably enriched in each sample
- NC and CC ν_μ backgrounds, which cause hadronic shower events, amounts to ~20%

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

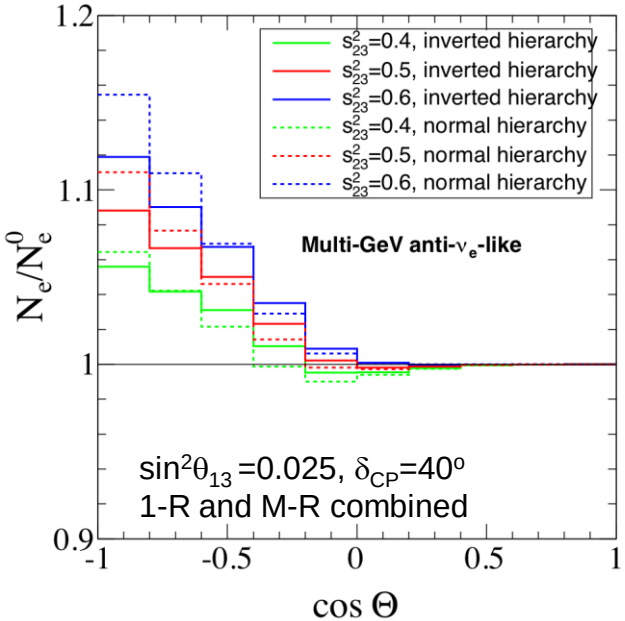
Expected electron enhancement

Ne / Ne(θ_{13}=0)

Multi-GeV ν_e-like



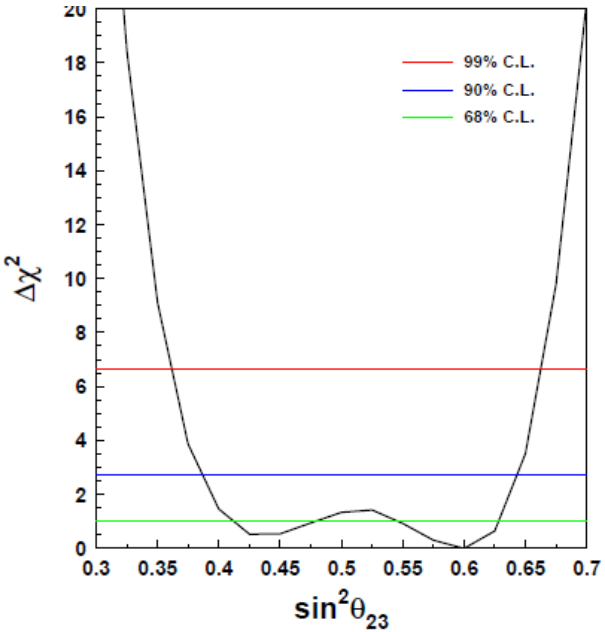
Multi-GeV anti-ν_e-like

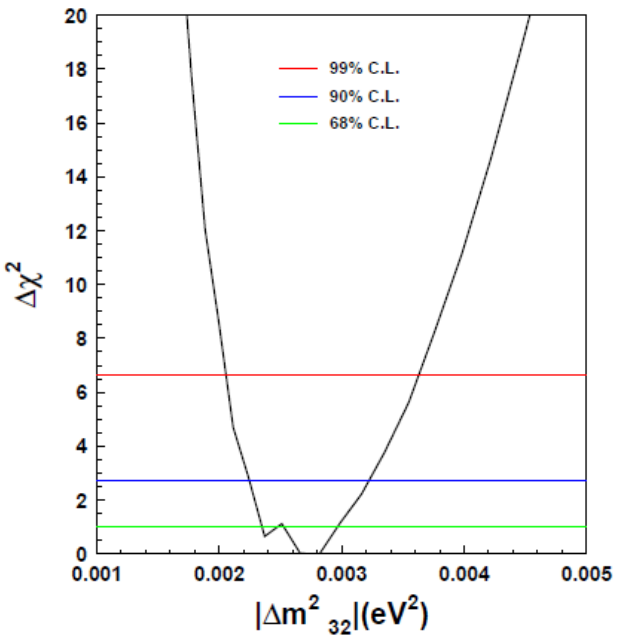


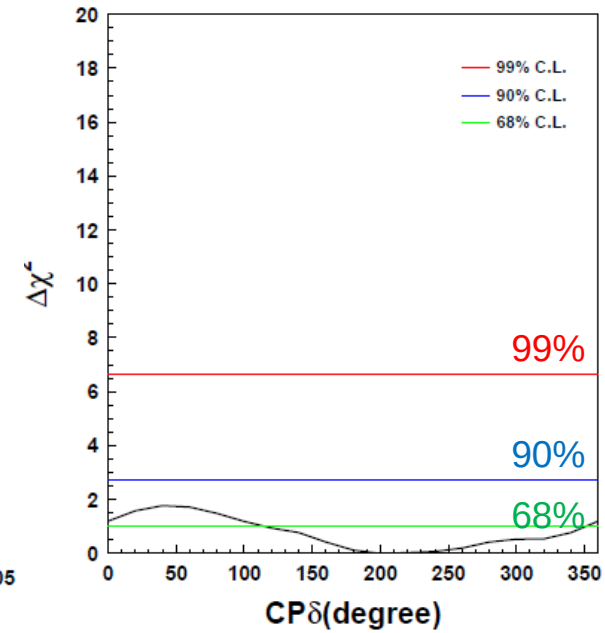
Both sample have increases in upward events compared to θ_{13}=0 case, but amount are different depending on mass hierarchy

Larger excess in ν_e-like (anti-ν_e-like) for normal (inverted) hierarchy

Normal hierarchy : χ^2 distribution



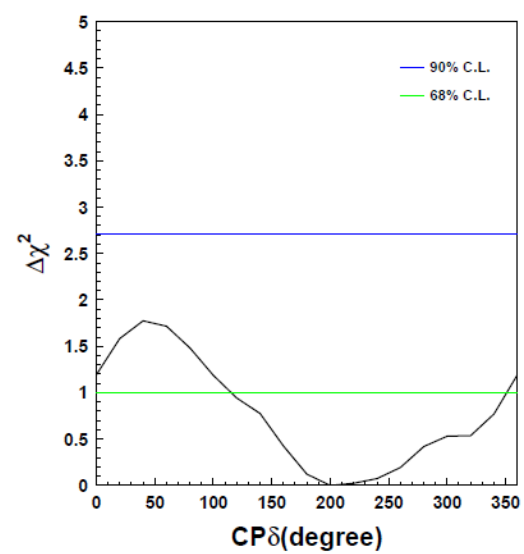




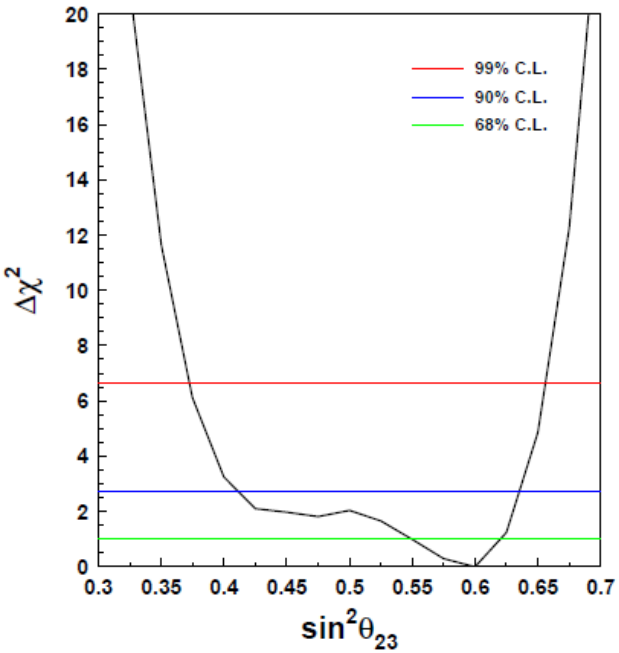
***$\sin^2\theta_{13}$: fixed to be 0.025(reactor experiment)**

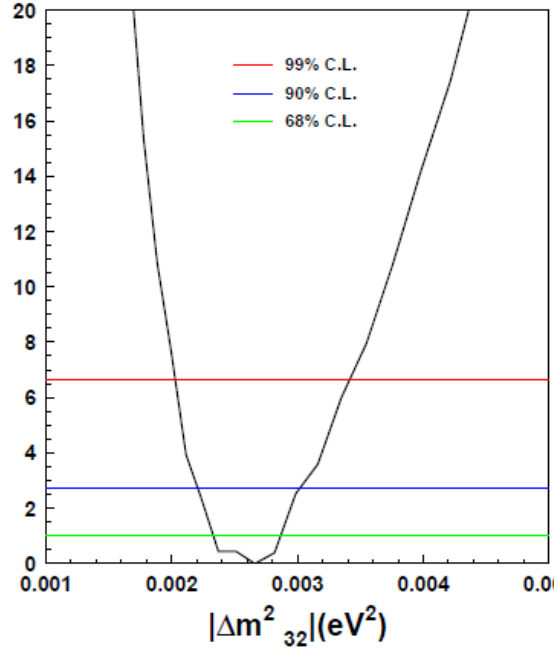
χ^2_{min} = 557.66/477 d.o.f

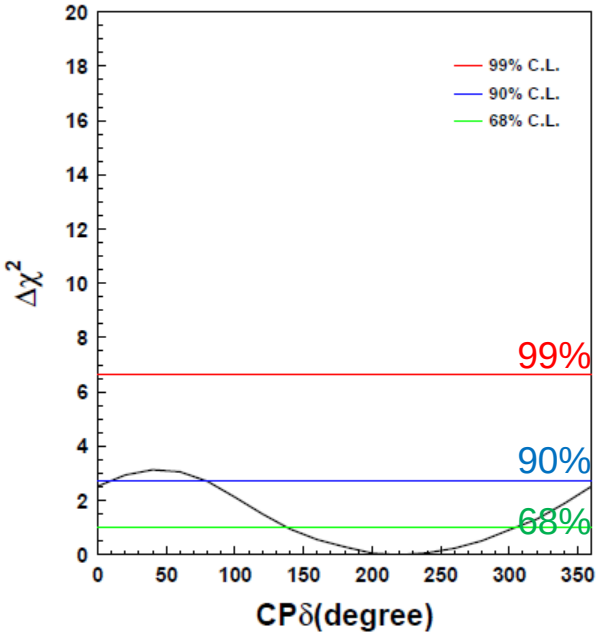
Parameter	Best fit	90% C.L.
$\sin^2\theta_{23}$	0.60	0.39-0.64
Δm^2_{32} ($\times 10^{-3}$ eV^2)	2.82	2.25-3.22
δCP(degree)	200	all allowed



Inverted hierarchy : χ^2 distribution



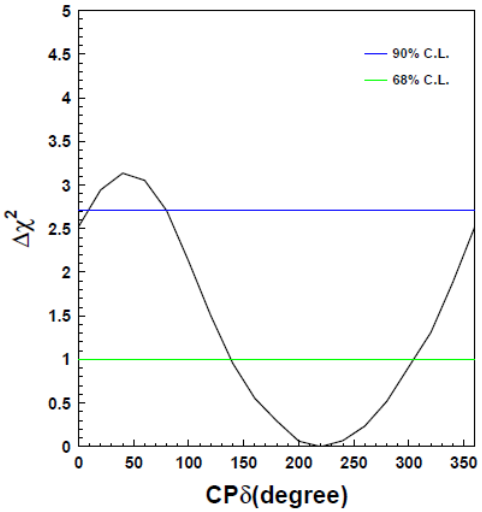




***$\sin^2\theta_{13}$: fixed to be 0.025(reactor experiment)**

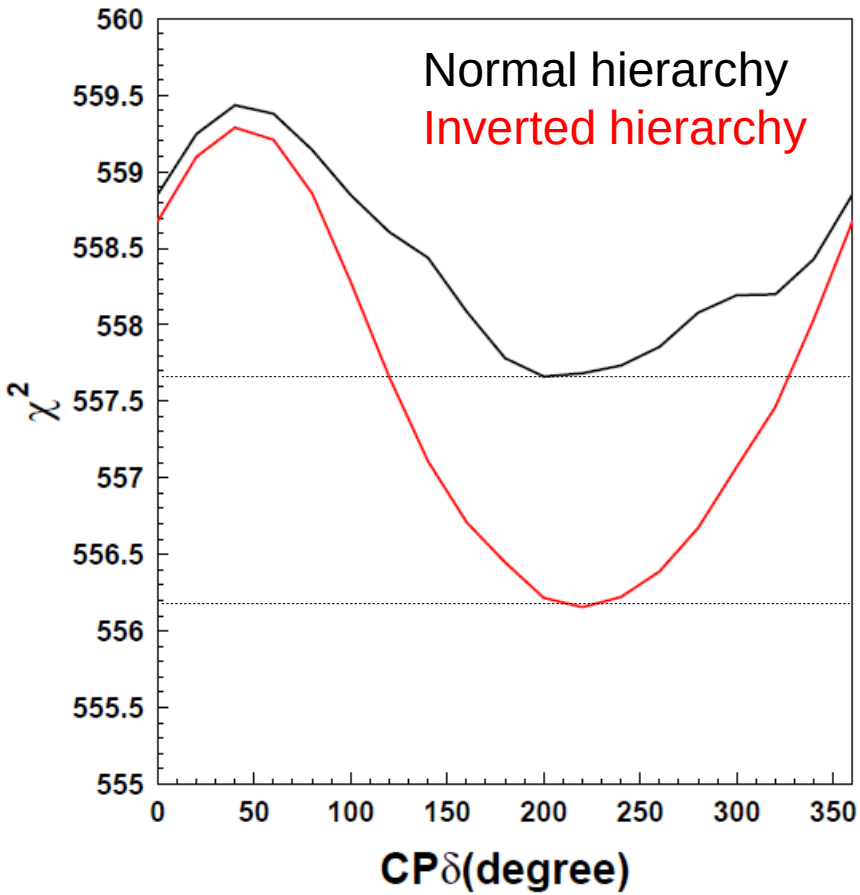
χ^2_{min} = 556.15/477 *d.o.f*

Parameter	Best fit	90% C.L.
$\sin^2\theta_{23}$	0.60	0.41 - 0.64
Δm^2_{32} ($\times 10^{-3}$ eV^2)	2.66	2.21 - 3.02
δCP(degree)	220	0 - 9 , 80 - 360



Normal vs Inverted comparison

***$\sin^2\theta_{13}$: fixed to be 0.025**



Normal hierarchy assumption:
χ^2_{min} = 557.66 / 477 dof

Inverted hierarchy assumption:
χ^2_{min} = 556.15 / 477 dof

$$\chi^2_{\min}(NH) - \chi^2_{\min}(IH) = 1.51$$

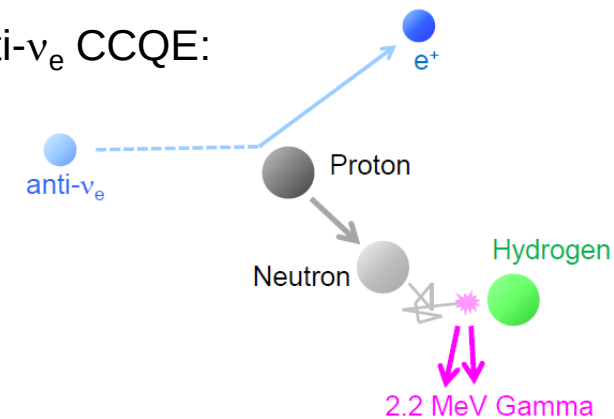
slightly smaller χ^2 for inverted

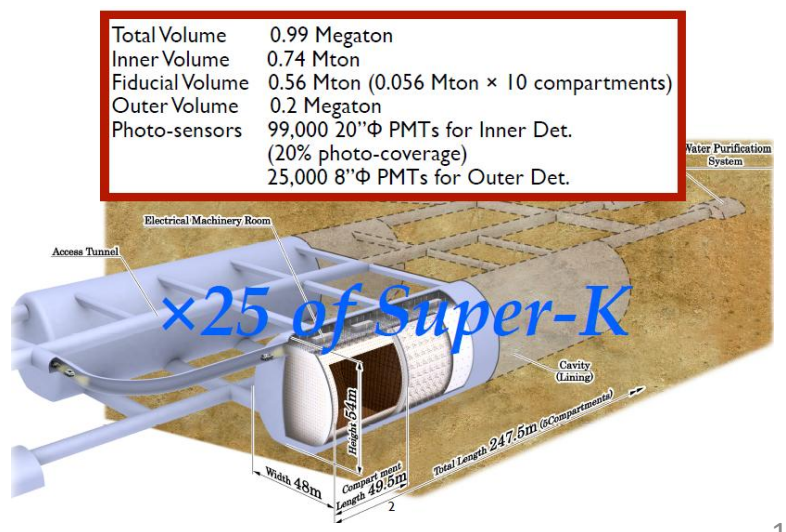
- was $\Delta\chi^2$=1.2 at Neutrino 2012
- $\Delta\chi^2$=2.3 expected by sensitivity study

Future plan and prospect

- Identifying anti-neutrino events by neutron tagging
  - detect 2.2 MeV gamma by n + H → D
- Remove $\nu_\mu \rightarrow \nu_\tau$ background
- Combined analysis with accelerator experiments
- Increase statistics by larger detector (ex. hyper-kamiokande)
  - HK talk: M. Nakahata id:131

ex. anti-ν_e CCQE:





Summary

- $\nu_\mu \rightarrow \nu_e$ oscillation due to non-zero θ_{13} provides us to probe neutrino mass hierarchy by investigating electron enhancement in multi-GeV energies
- Statistical separation of ν / anti-ν was conducted using kinematics and hadron information to increase MH sensitivity
- SK data slightly prefers inverted hierarchy, but marginal. Need analysis improvements, more information from other experiments, and definitely, larger detector !