

# Full Three-flavor Oscillation Analysis of Atmospheric Neutrino Data Observed in Super-Kamiokande

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## 1. Introduction

Aim of the full three-flavor oscillation analysis is to measure or constrain  $\Delta m_{32}^2$ ,  $\sin^2\theta_{23}$ ,  $\sin^2\theta_{13}$ ,  $\delta_{CP}$  and mass hierarchy.

$\nu_e$  oscillation due to matter effect, solar term and CP term are considered in full three-flavor analysis. All oscillation parameters:  $\Delta m_{21}^2$ ,  $\Delta m_{32}^2$ , three mixing angles  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ , and CP phase parameter  $\delta_{CP}$  are included at the same time.

Change in  $\nu_e$  events due to oscillation can be expressed as:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m_{21}^2) + \Delta_3(\theta_{13}, \Delta m_{21}^2, \delta)$$

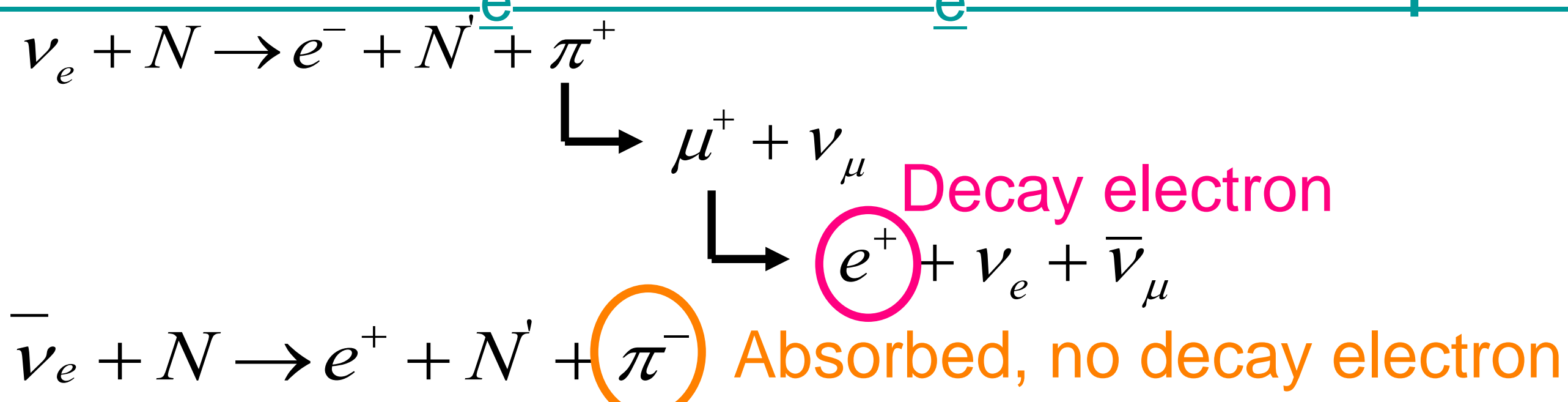
$\nu_e$  oscillation due to matter effect  
Solar term analysis  
CP term

Full three-flavor analysis

The octant of  $\theta_{23}$  can be probed by excess or deficit of Multi-GeV e-like events due to the matter effect. The sensitivity of  $\delta_{CP}$  comes from the CP term.

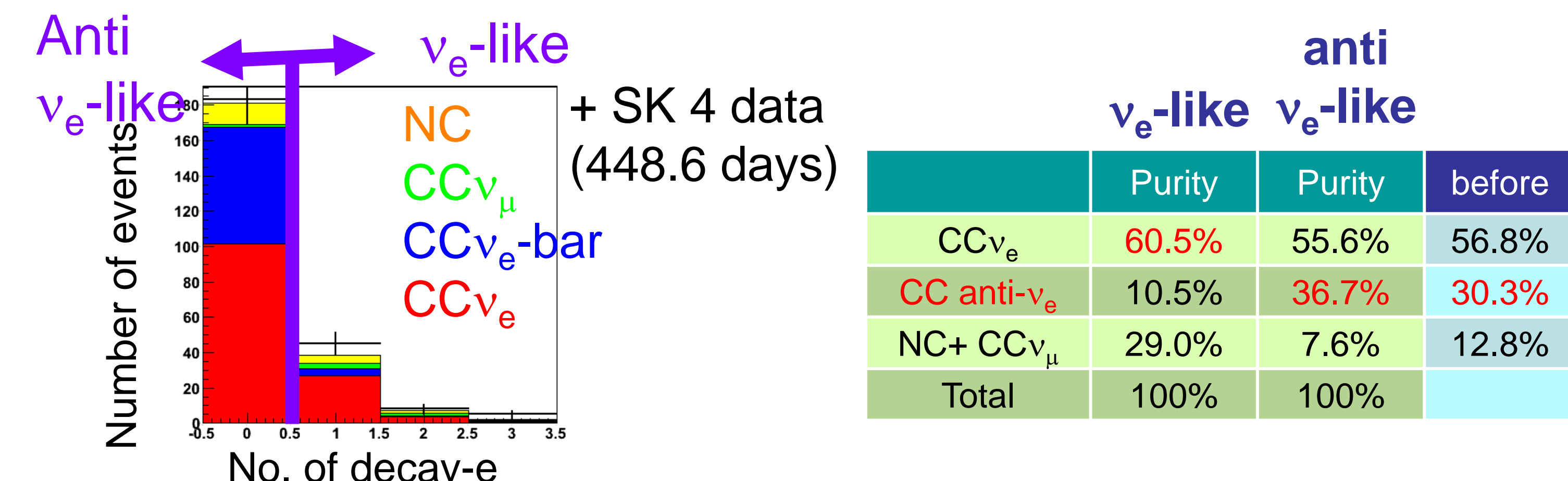
In case of normal hierarchy (inverted hierarchy),  $\nu_e$  (anti- $\nu_e$ ) is enhanced, therefore the sensitivity can be enhanced by introducing  $\nu_e$  and anti- $\nu_e$  enriched samples with new likelihoods.

## 2. Separation of $\nu_e$ and anti- $\nu_e$ event samples

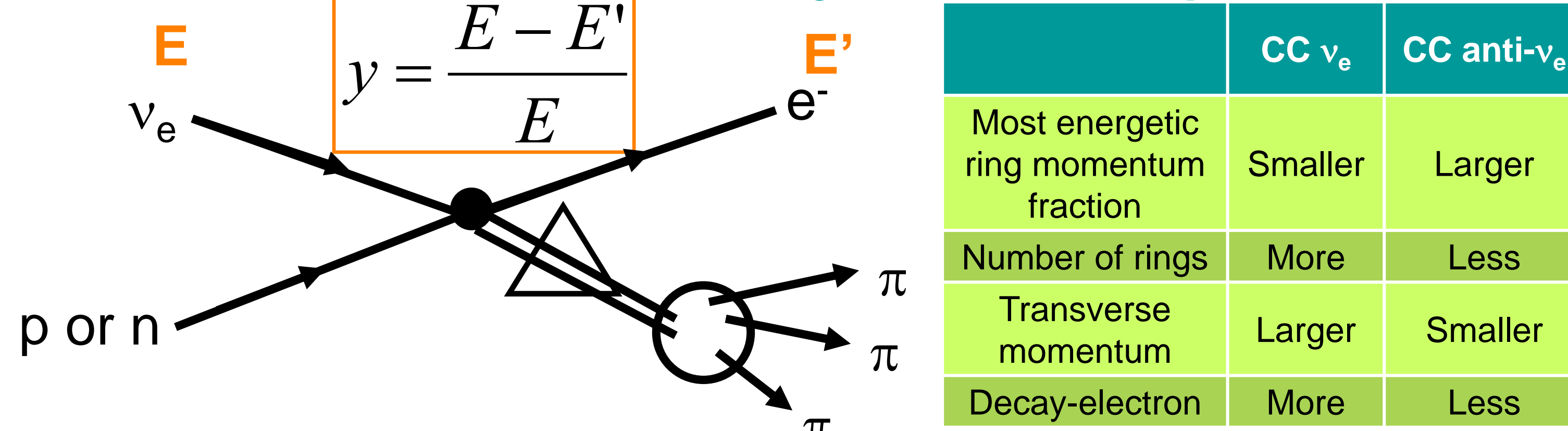


Multi-GeV e-like samples are divided into  $\nu_e$  and anti- $\nu_e$  samples by considering the difference in physical properties of  $\nu_e$  and anti- $\nu_e$ .

### (a) Multi-GeV 1-ring $\nu_e$ and anti- $\nu_e$ separation with number of decay-electrons

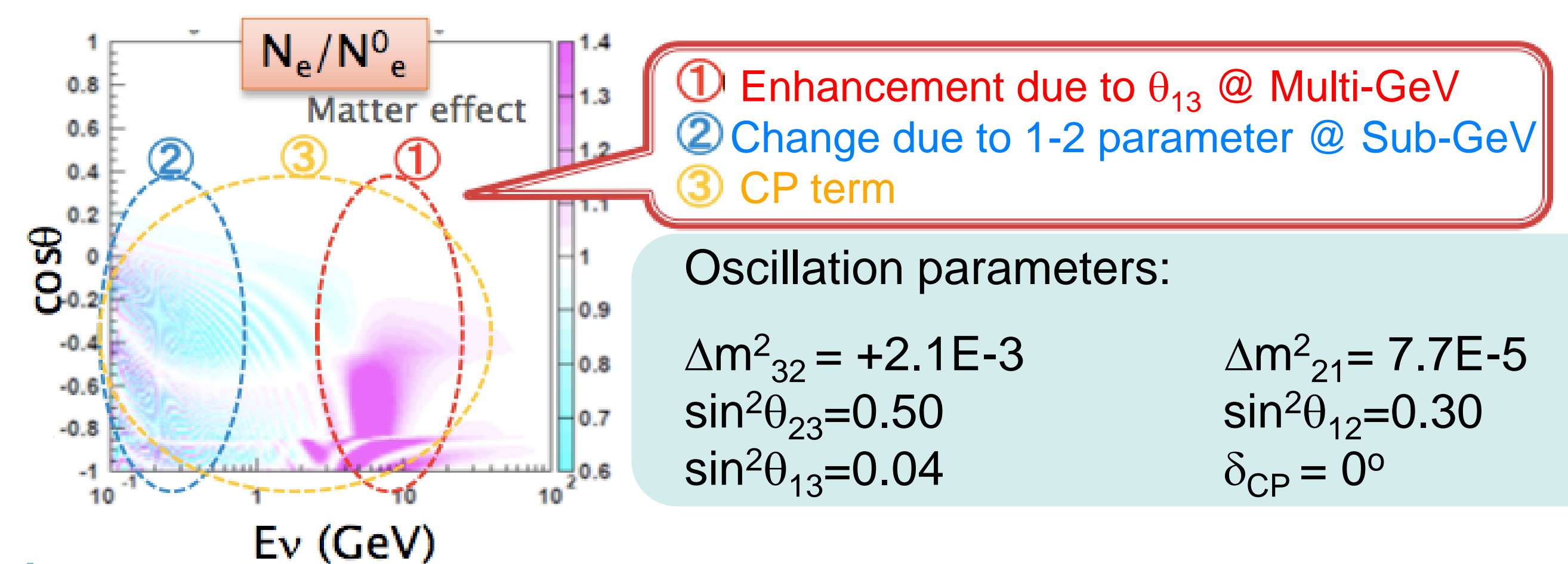
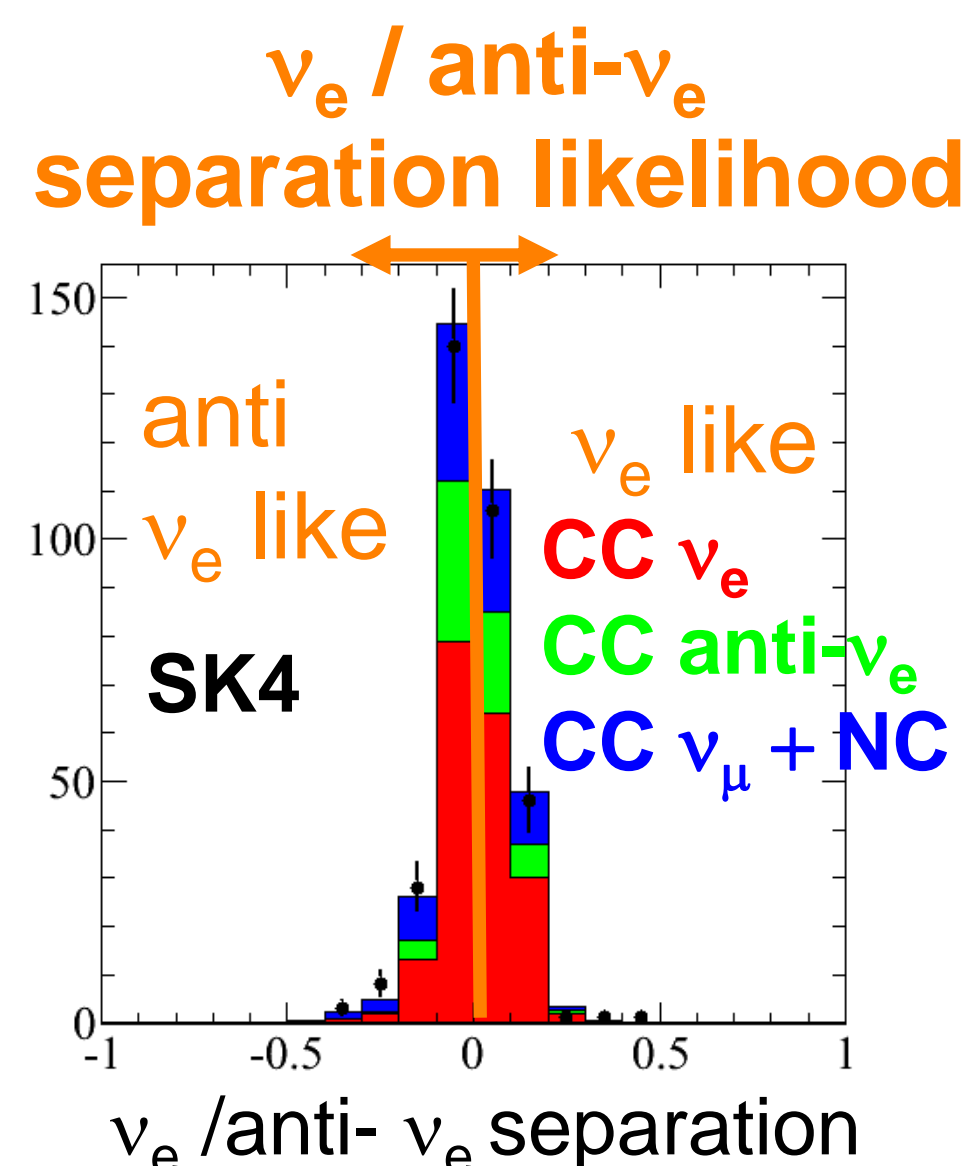


### (b) Multi-GeV multi-ring $\nu_e$ and anti- $\nu_e$ separation



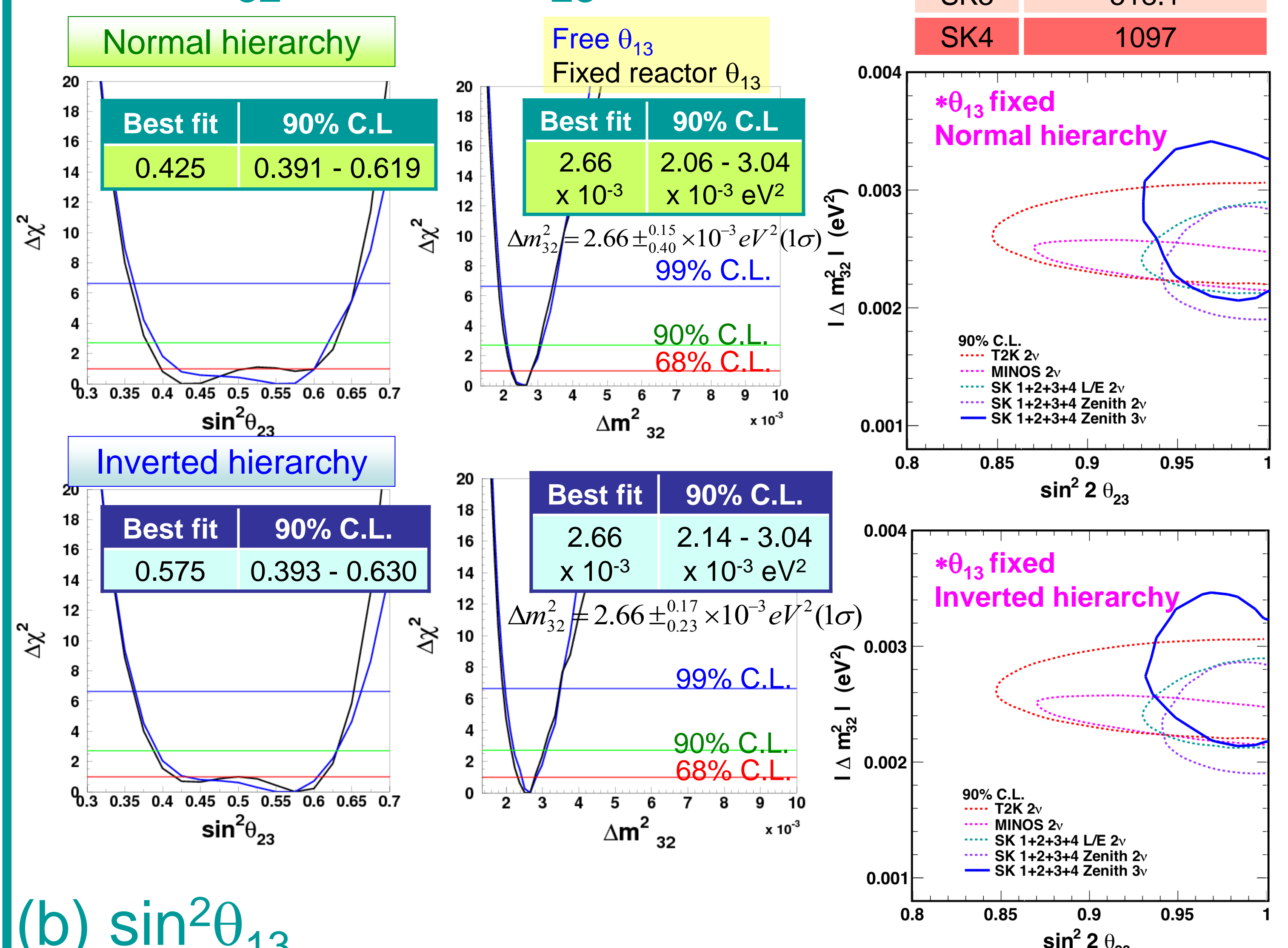
Multi-ring e-like sample is divided by building a likelihood which considers number of rings, transverse momentum and number of decay-electrons.

	$\nu_e$ -like	anti- $\nu_e$ -like	before
CC $\nu_e$	55.1%	53.1%	54.1%
CC anti- $\nu_e$	11.5%	24.7%	18.0%
NC+ CC $\nu_\mu$	33.3%	22.2%	27.9%
Total	100%		



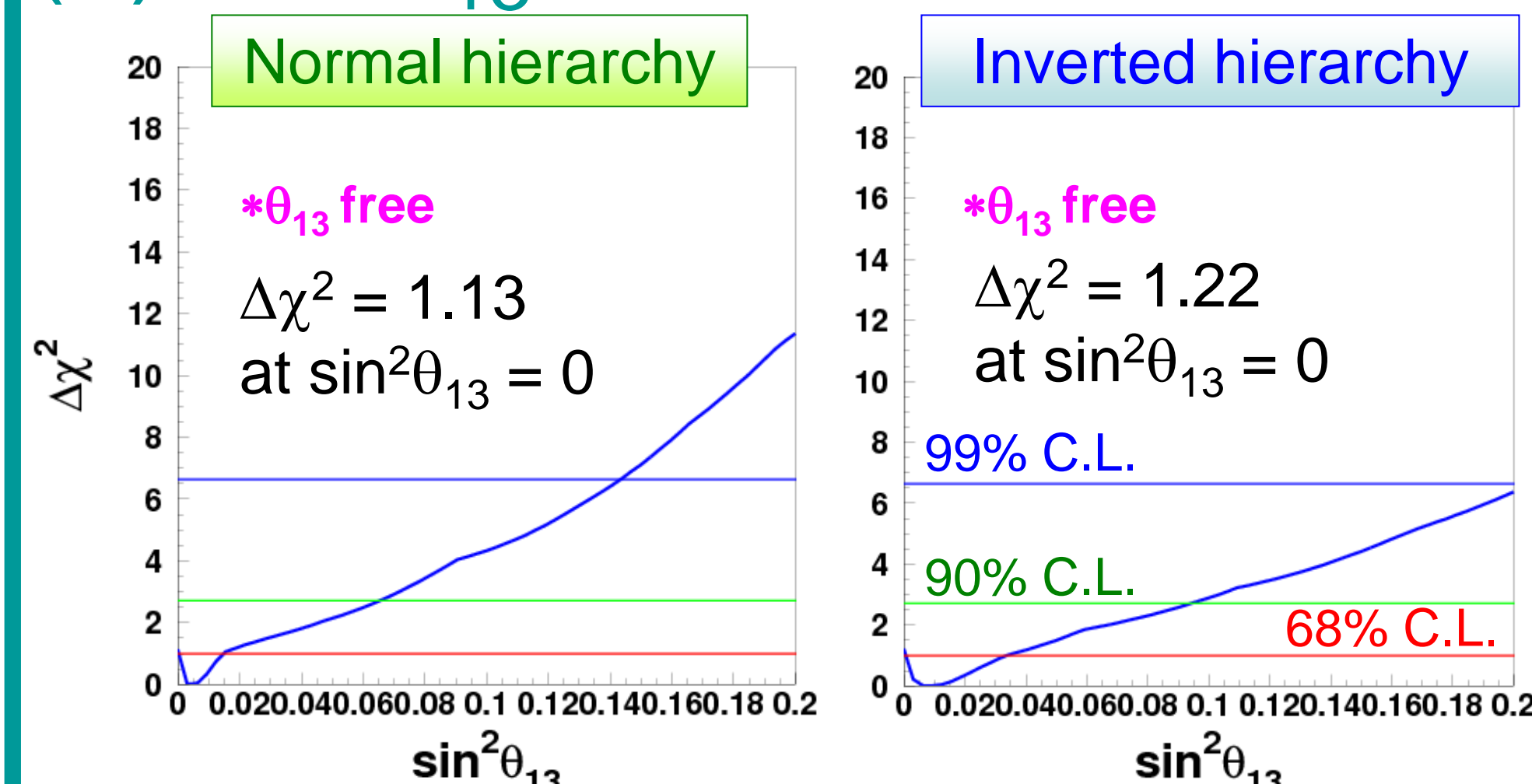
## 4. Results

### (a) $\Delta m_{32}^2$ and $\sin^2\theta_{23}$



	Live time (days)
SK1	1489.2
SK2	798.6
SK3	518.1
SK4	1097

### (b) $\sin^2\theta_{13}$



No significant  $\nu_e$  appearance is observed. The results is consistent with reactor experiment.

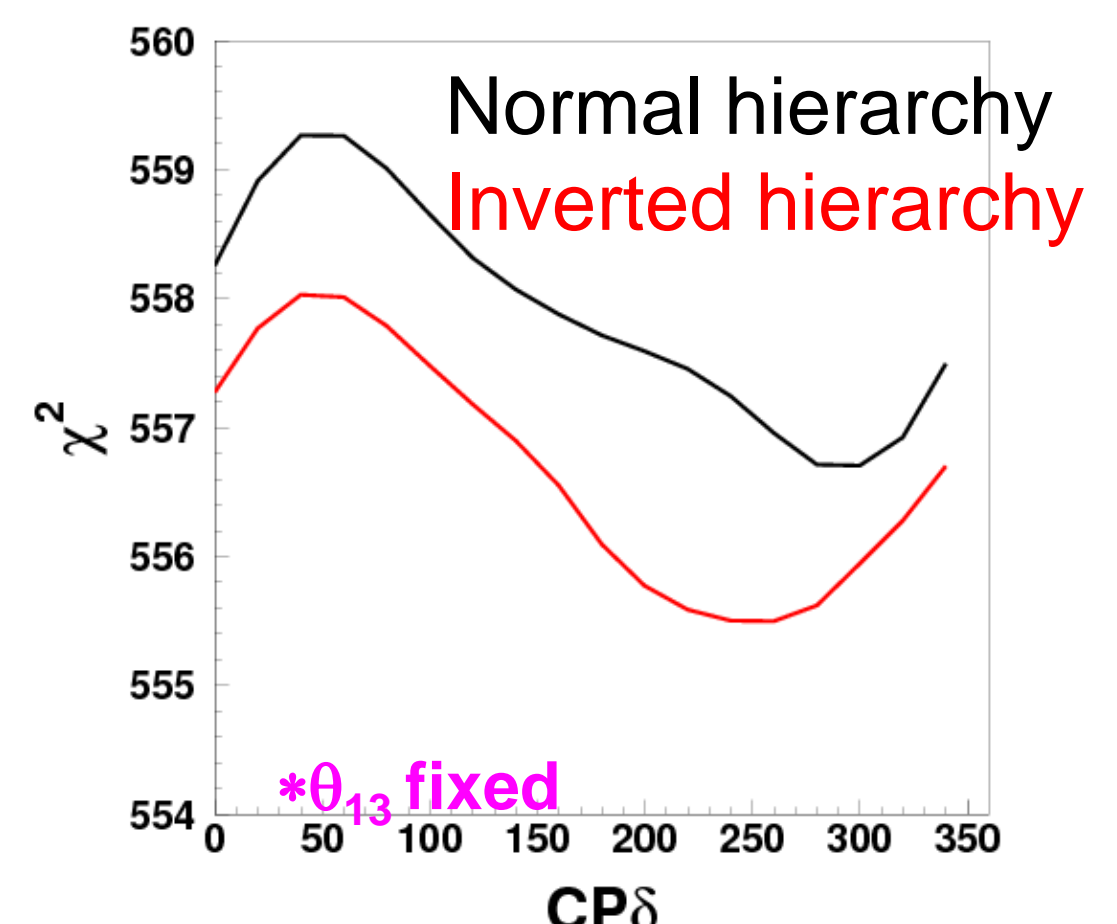
### (c) Mass hierarchy

Normal hierarchy  $\chi^2_{\min} = 556.7 / 477$  dof

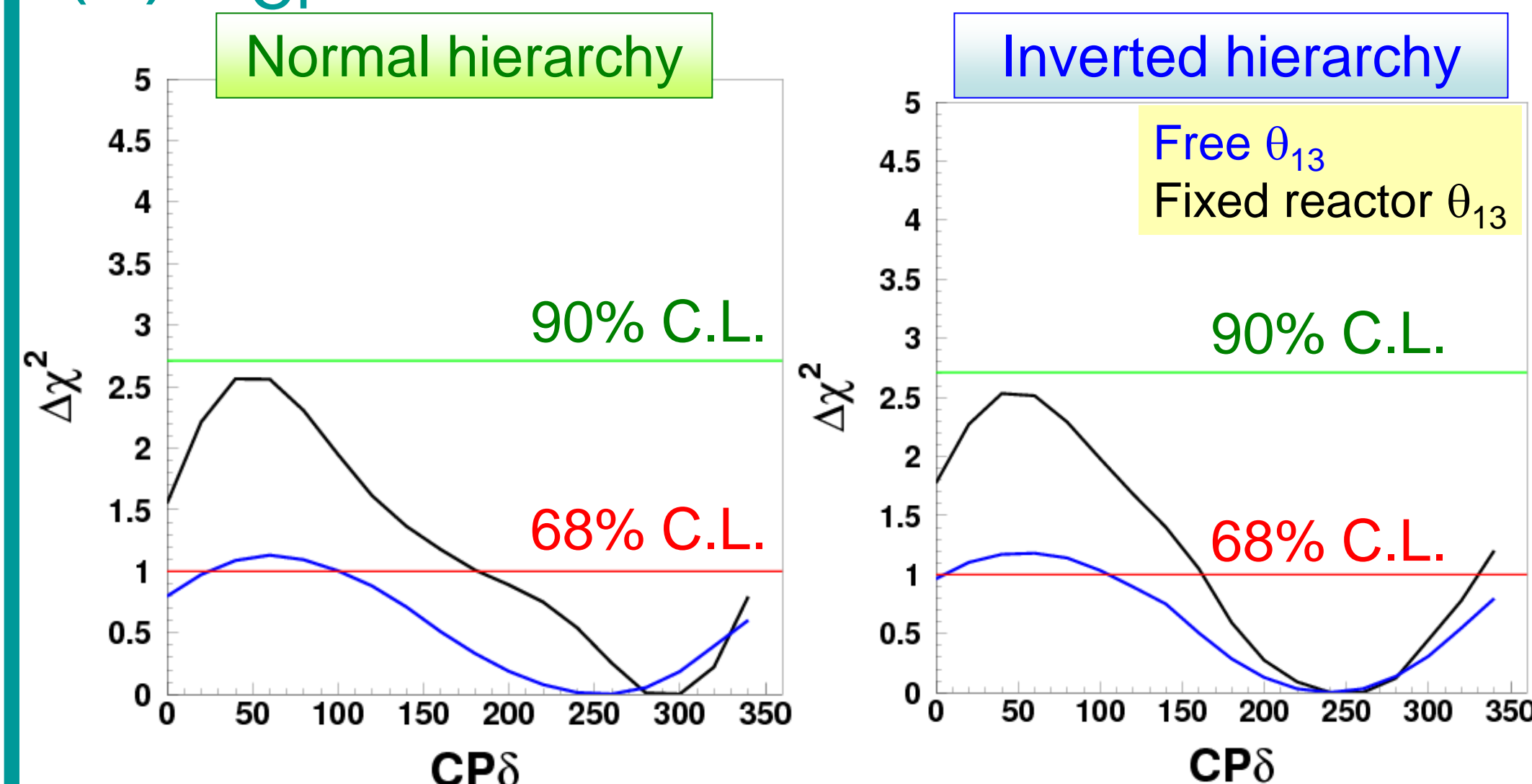
Inverted hierarchy  $\chi^2_{\min} = 555.5 / 477$  dof

$$\chi^2_{\min}(NH) - \chi^2_{\min}(IH) = 1.2$$

Smaller  $\chi^2$  for inverted hierarchy



### (d) $\delta_{CP}$



At 90% C.L., all values of  $\delta_{CP}$  are allowed.

In summary,  $\sin^2\theta_{23}$  and  $\Delta m_{32}^2$  are measured. As for  $\theta_{13} > 0$ , SK alone has  $\Delta\chi^2 \sim 1$ , due to non-significant  $\nu_e$  appearance. No strong conclusion can be drawn for mass hierarchy and  $\delta_{CP}$ .

In future, improve the sensitivity of determination of mass hierarchy by carrying out global fit with using result of other experiments.

## 3. Expected zenith angle distribution

