



The **H**yper-**K**amiokande Experiment

-Neutrino Physics Potentials-

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Hiroyuki Sekiya

ICRR, University of Tokyo
for the Hyper-K Working Group

Let's answer remaining questions!

PMNS framework $\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} = U \begin{pmatrix} \nu_1(t) \\ \nu_2(t) \\ \nu_3(t) \end{pmatrix}$ Majorana phase $\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} \\ 0 & 1 & 0 \\ -\sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

octant of θ_{23} Dirac CP phase δ mass hierarchy

$$i \frac{d}{dt} \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} = \left(\frac{UM^2U^\dagger}{2E} + V \right) \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} \quad M^2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} \quad \text{matter potential } V = \begin{pmatrix} \frac{a}{2E} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Through the oscillation

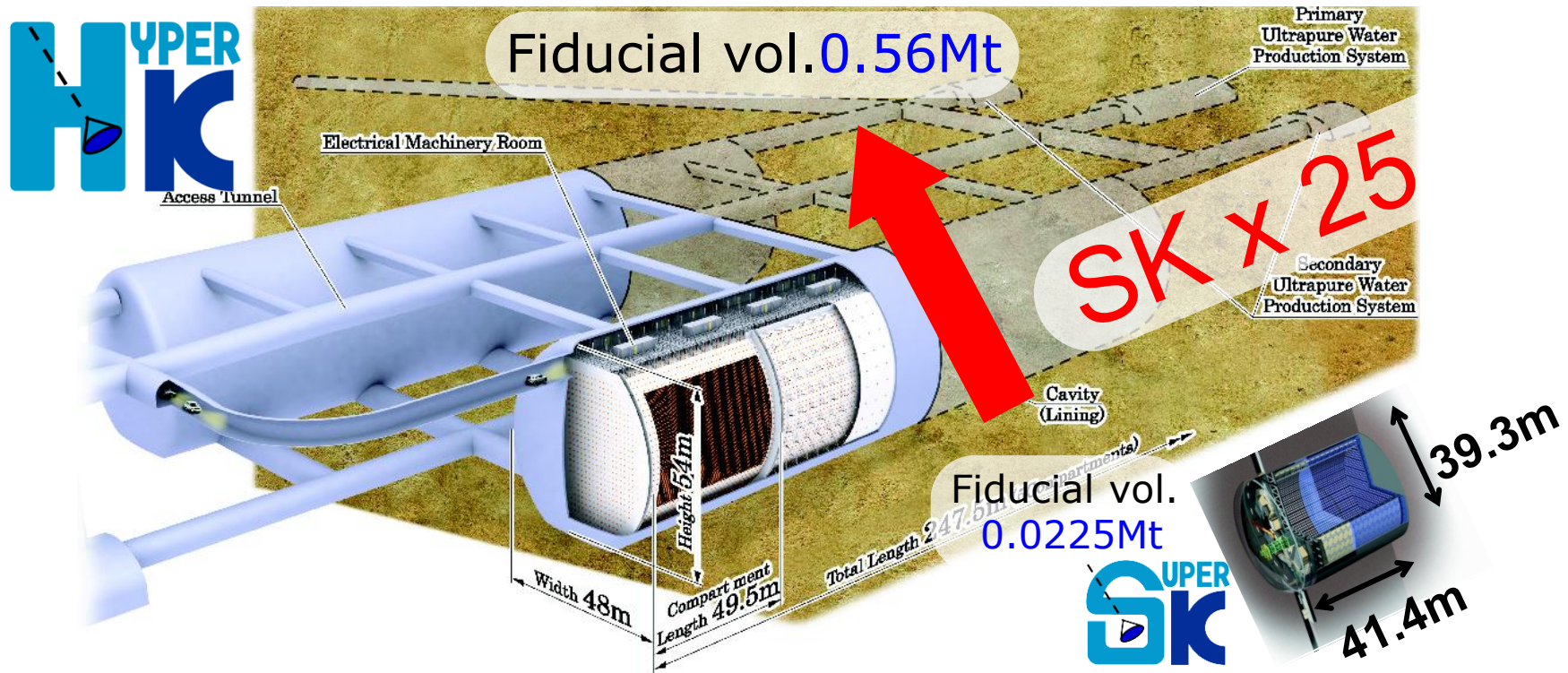
$$a = 2\sqrt{2}G_F n_e E$$

$$7.56 \times 10^{-5} \times \rho[\text{g/cm}^3] \times E_\nu[\text{GeV}]$$



can reach all of them
Using both accelerator and atmospheric vs

Kamioka 3rd Generation 1Mt Water Cherenkov Detector



- 2 cylindrical tanks lying side-by-side (48m x 54m x 250m each)
- 5 compartments in each tank w/ photo-sensitive separation walls
- Each compartment is “twice the size of Super-Kamiokande II”
 - ✓ ID 20% photo-coverage with 99,000 20” PMTs
 - ✓ OD 2m layer with 25,000 8” PMTs

The channel $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}} \text{ Leading } \sin^2 2\theta_{13} \text{ CPC} \\
 & \boxed{+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21}} \text{ CPV} \\
 & \boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21}} \text{ CPV} \\
 & \boxed{+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21}} \text{ Solar} \\
 & \boxed{-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31}} \text{ matter} \\
 & \boxed{+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31}} \text{ matter}
 \end{aligned}$$

Oscillation term

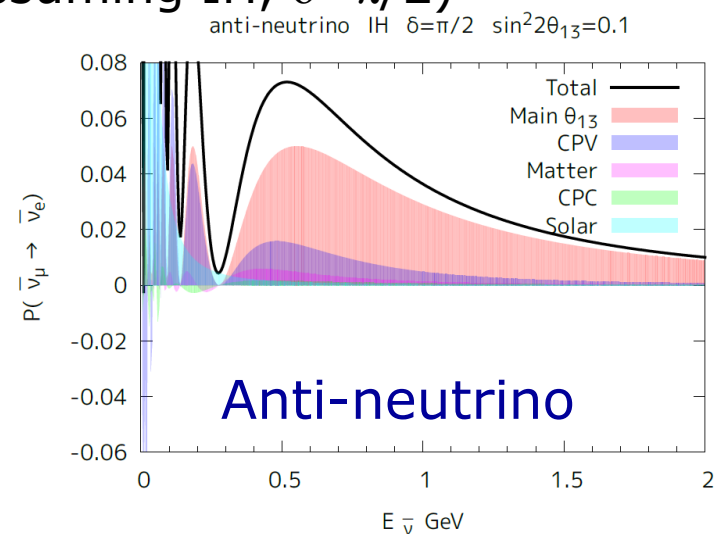
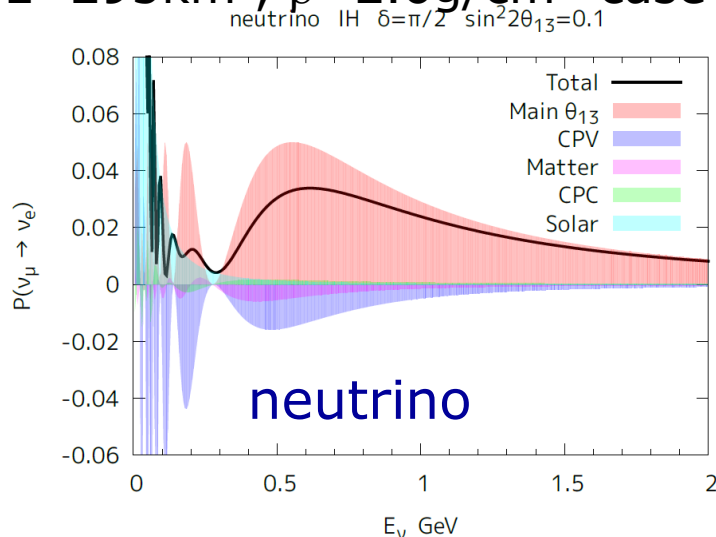
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

Measured angles

$$\begin{aligned}
 S_{23}^2 &\sim 0.5 & S_{12}^2 &\sim 0.3 \\
 S_{13}^2 &\sim 0.03
 \end{aligned}$$

$$\begin{aligned}
 P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) & \quad a \rightarrow -a \\
 & \quad \delta \rightarrow -\delta
 \end{aligned}$$

- $L=295\text{km}$, $\rho=2.6\text{g/cm}^3$ case (assuming IH, $\delta=\pi/2$)

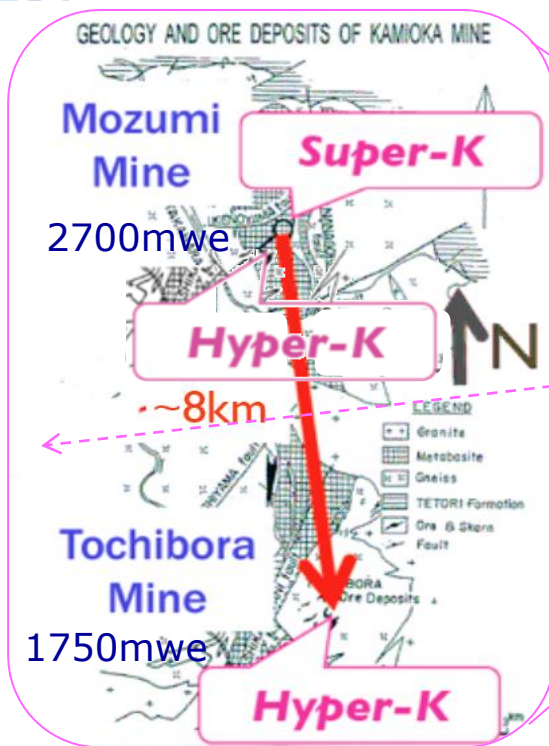


Accelerator ν from J-PARC

- 2.5° off-axis high intensity ν beam



site candidates in Kamioka



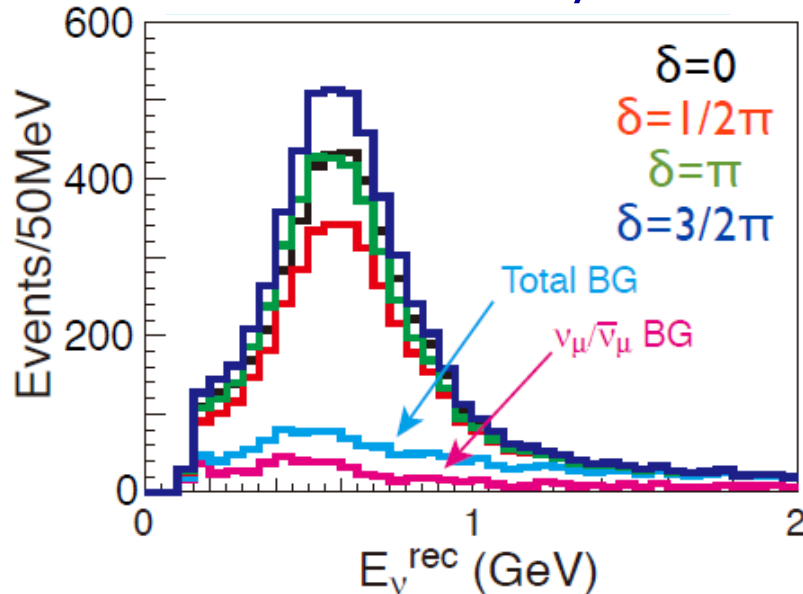
- J-PARC 30GeV proton beam power will be upgrade to 0.75MW

Expected spectrum (δ dependence)

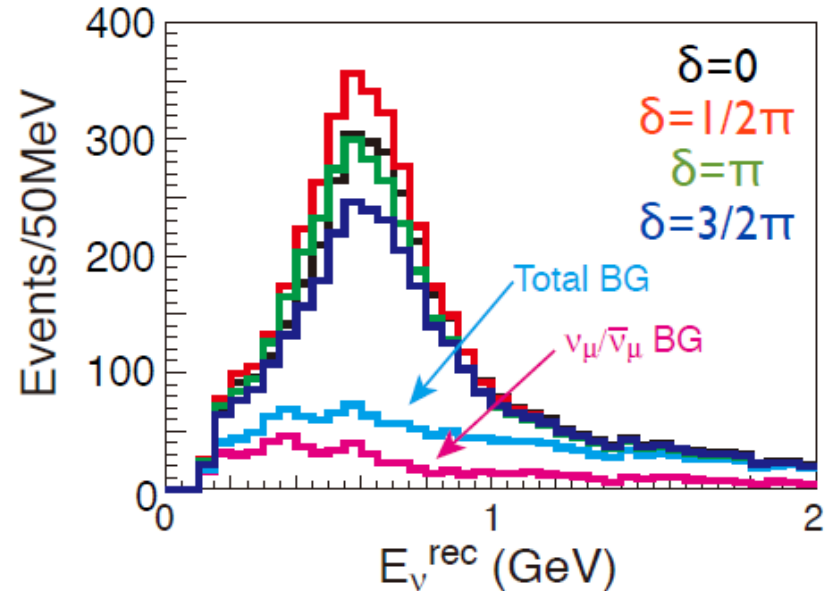
- Full MC (beam, ν interaction, detector, reconstruction)

NH, $\sin^2 2\theta_{13} = 0.1$

ν mode 3.0 years



$\bar{\nu}$ mode 7.0 years



Signal efficiency is 64%

ν_μ CC BG rejection $> 99.9\%$, NC π^0 rejection $> 95\%$

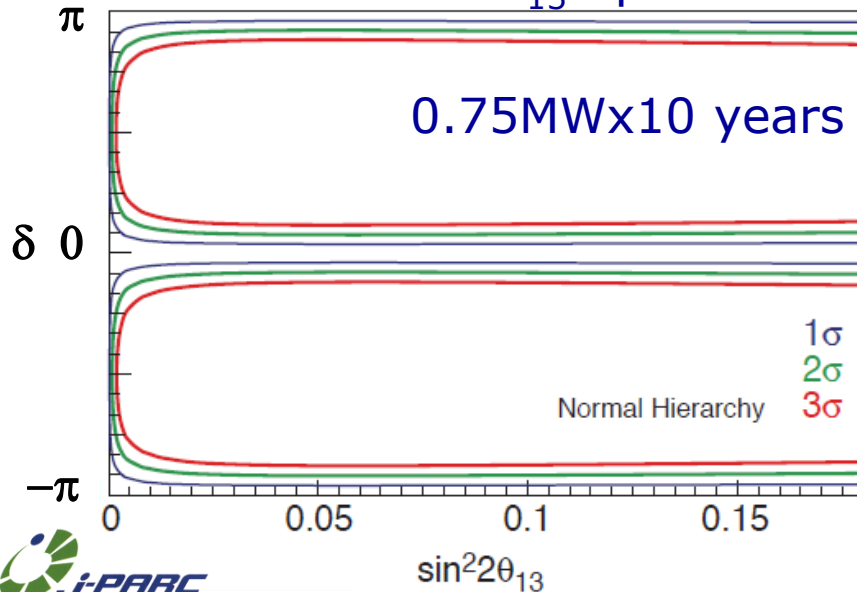
Sensitivity to CP violation

| | $\sin^2 2\theta_{13}=0.1$ |
|------------------------|---------------------------|
| Flux+Xsec in T2K fit | 5.7% |
| Xsec (from other exp.) | 7.5% |
| SK + FSI | 3.9% |
| Total | 10.3% |

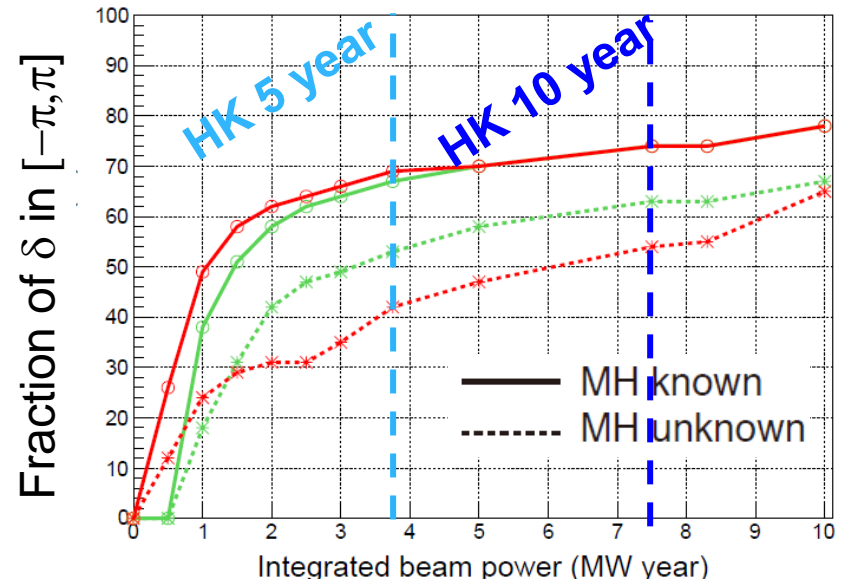
Run time $\nu:\bar{\nu} = 3:7$

5% systematic error is assumed. cf. Systematic error of T2K:10%

$\delta=0$ exclusion (CPV sensitivity)
in true $\delta-\theta_{13}$ space



Chance to observe CP violation
 $>3\sigma$ $\sin^2 2\theta_{13} = 0.1 / 0.03$



10 years operation if MH is known by then
→ 74% chance to observe CPV

Sensitivity to Mass Hierarchy

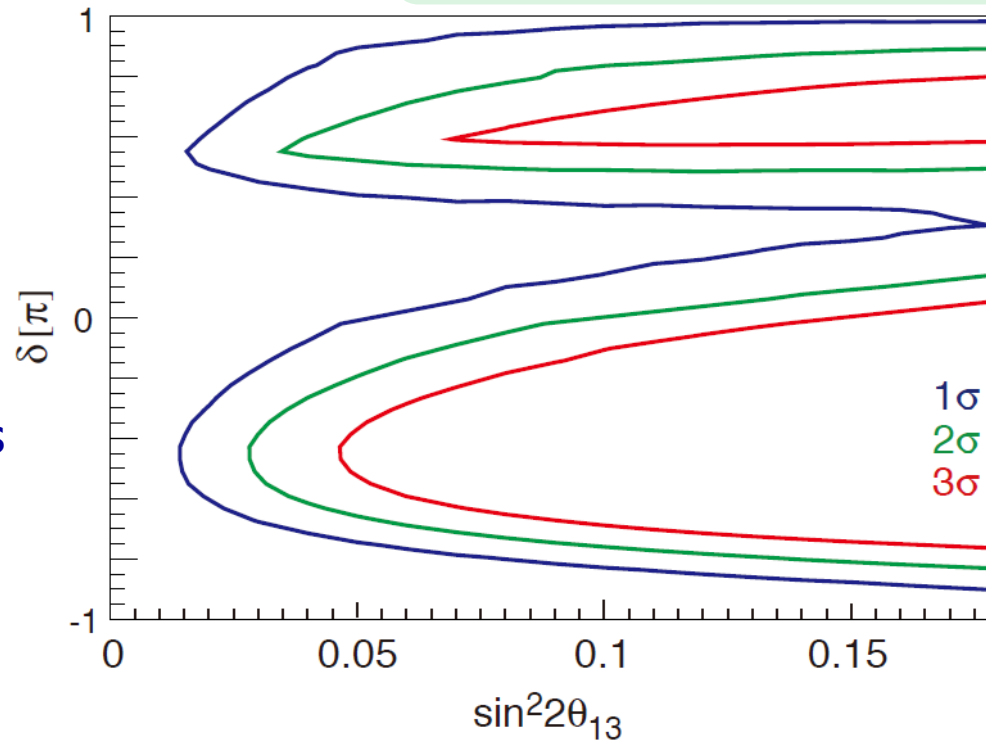
- "J-PARC+Hyper-K" only

Run time $\nu:\bar{\nu} = 3:7$

5% systematic error is assumed.

MH sensitivity
(IH exclusion
for true NH case)
in true δ - θ_{13} space

0.75MWx10 years



10 years operation

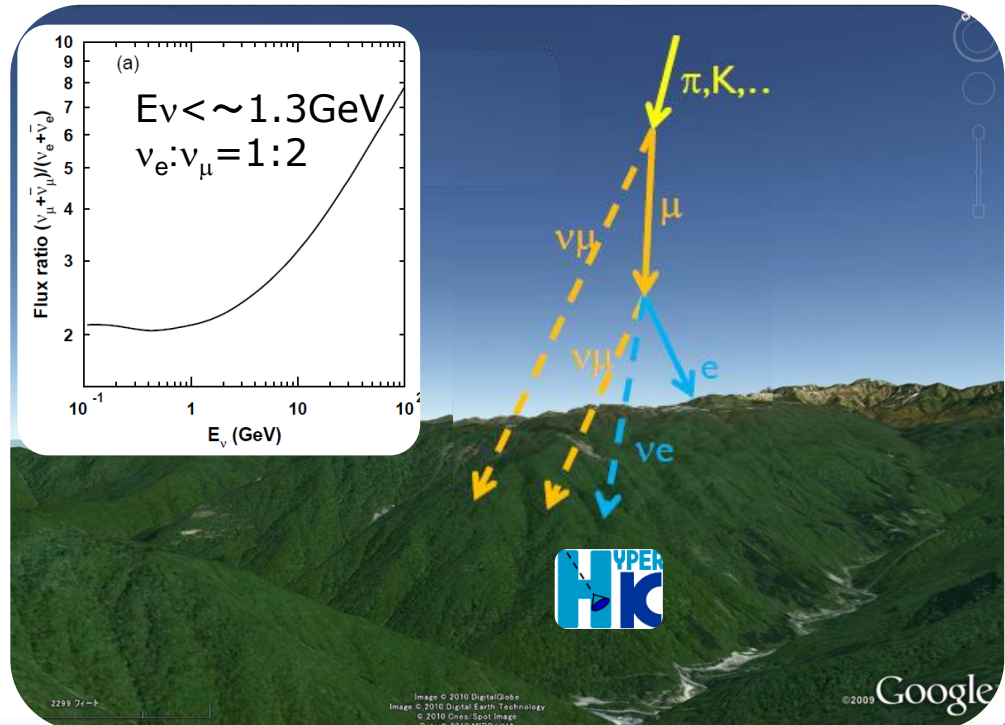
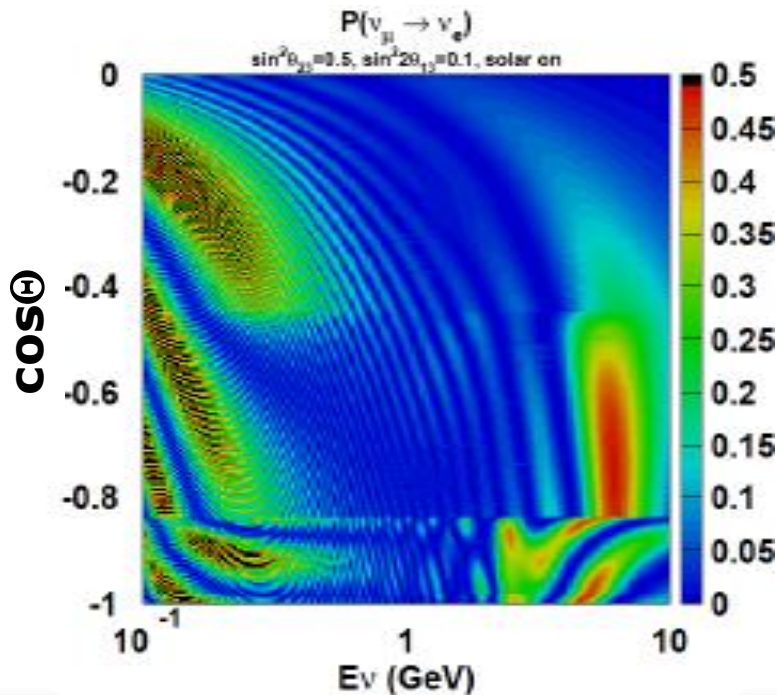
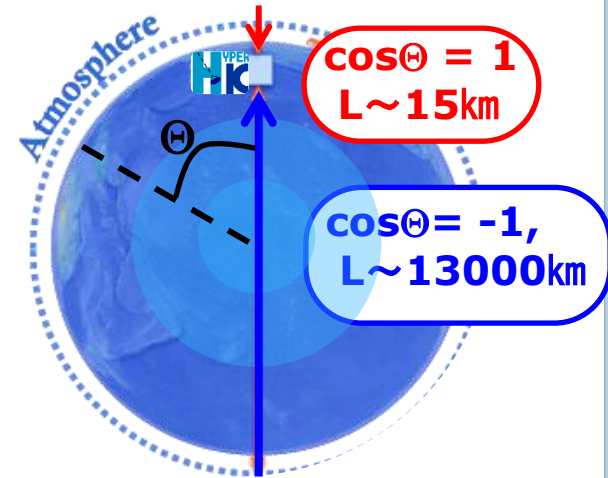
→ 43% chance to determine the MH.

N.B. Do not multiply 43% bf 74%!

Atmospheric ν

- Free neutrino source
- Very long base line (in matter)
- Wide energy range

Region of interest is
Multi-GeV, upward($\Theta < 0$)

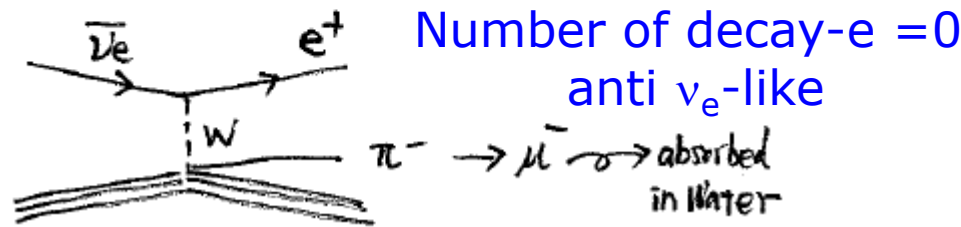
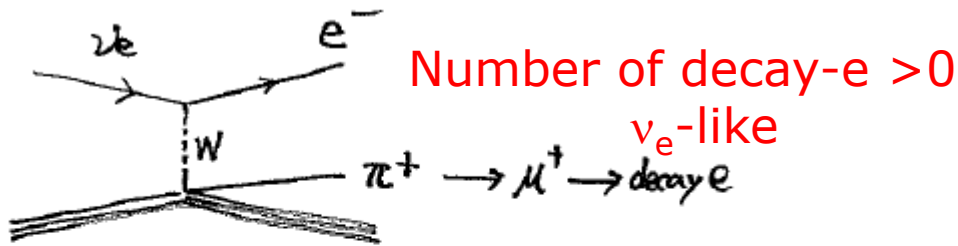


Statistical PID

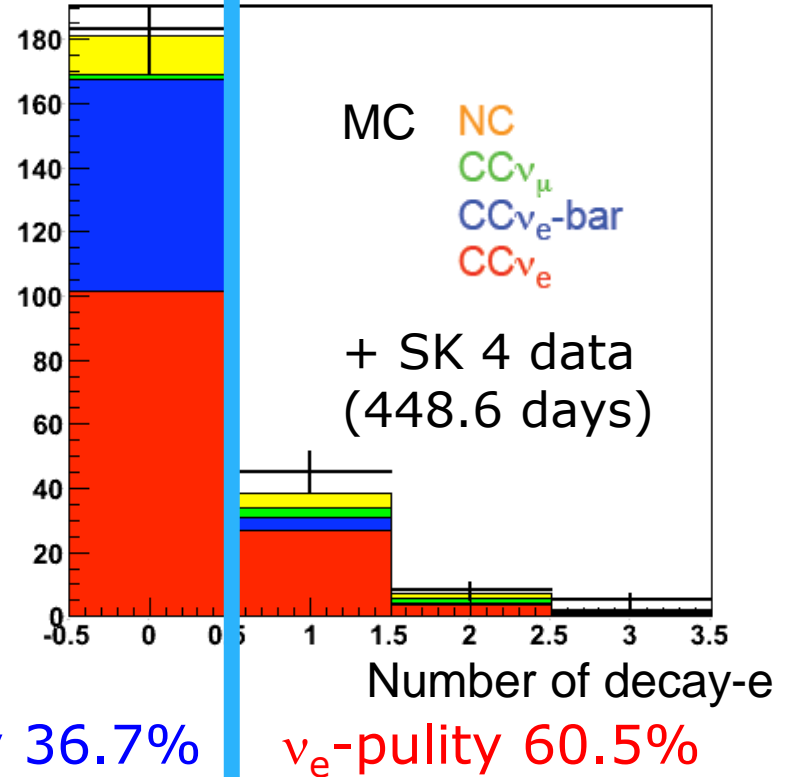
- Water Cherenkov detector can separate $\bar{\nu}_e$ from ν_e statistically.

ex)

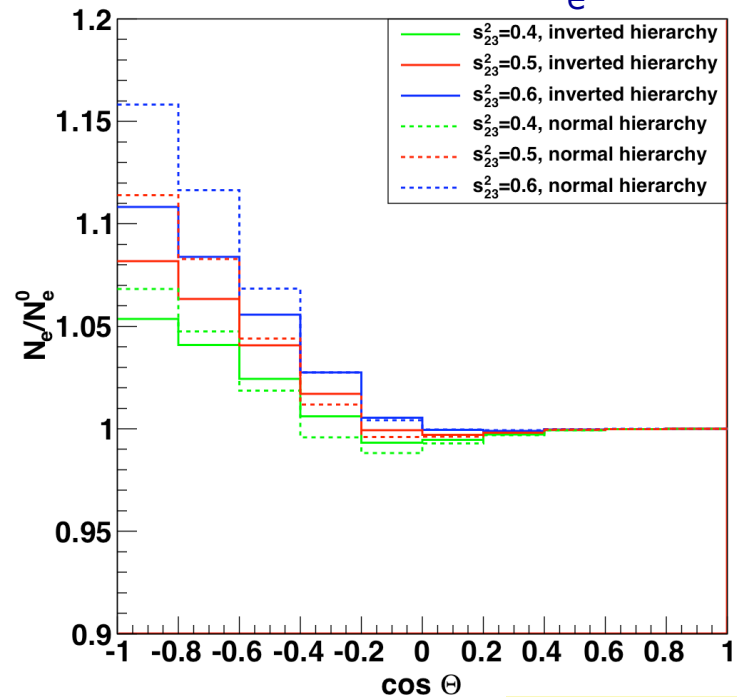
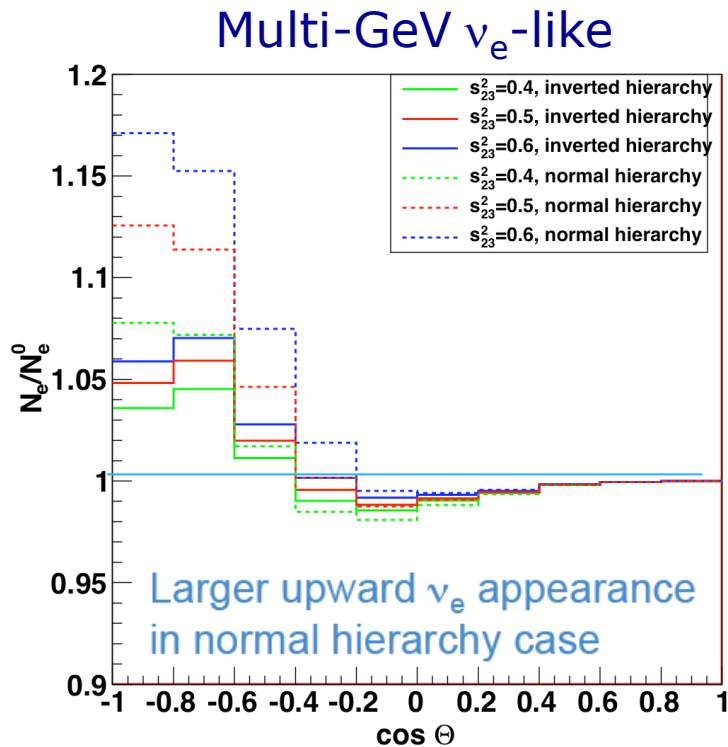
Super-K IV Multi-GeV 1ring e-like
CCnonQE interactions



$\bar{\nu}_e$ -like ← → ν_e -like



Expected zenith angle distributions for N_e/N_e^0 (MH, θ_{23})



$$\sin^2 \theta_{23} = 0.4$$

$$\sin^2 \theta_{23} = 0.5$$

$$\sin^2 \theta_{23} = 0.6$$

— Inverted hierarchy

- - Normal hierarchy

$$\Delta m_{12}^2 = 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{12} = 0.31$$

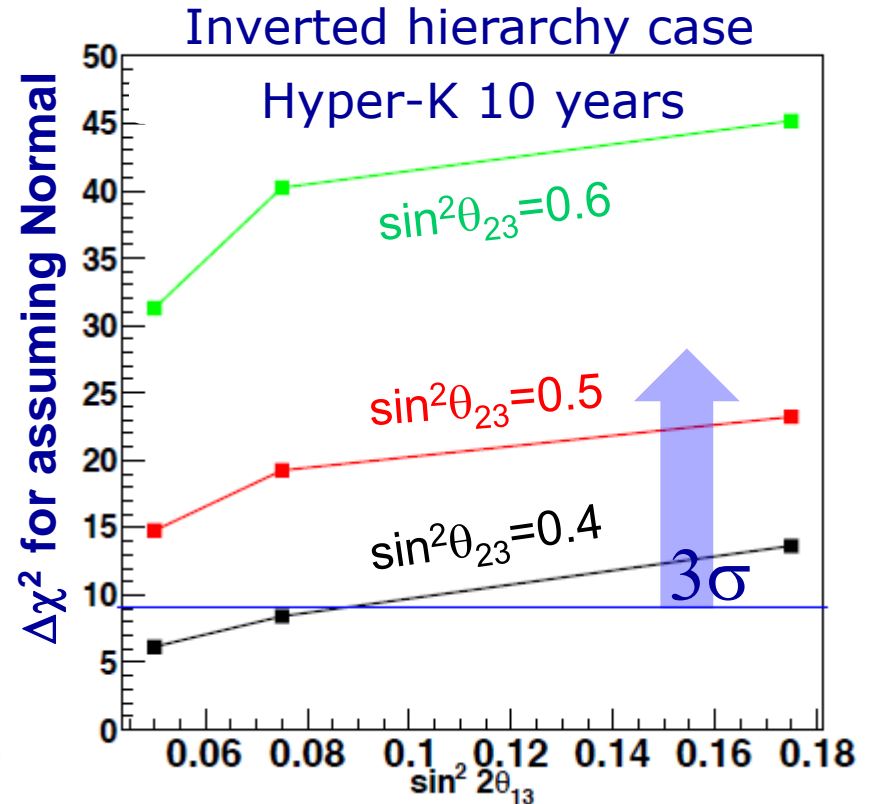
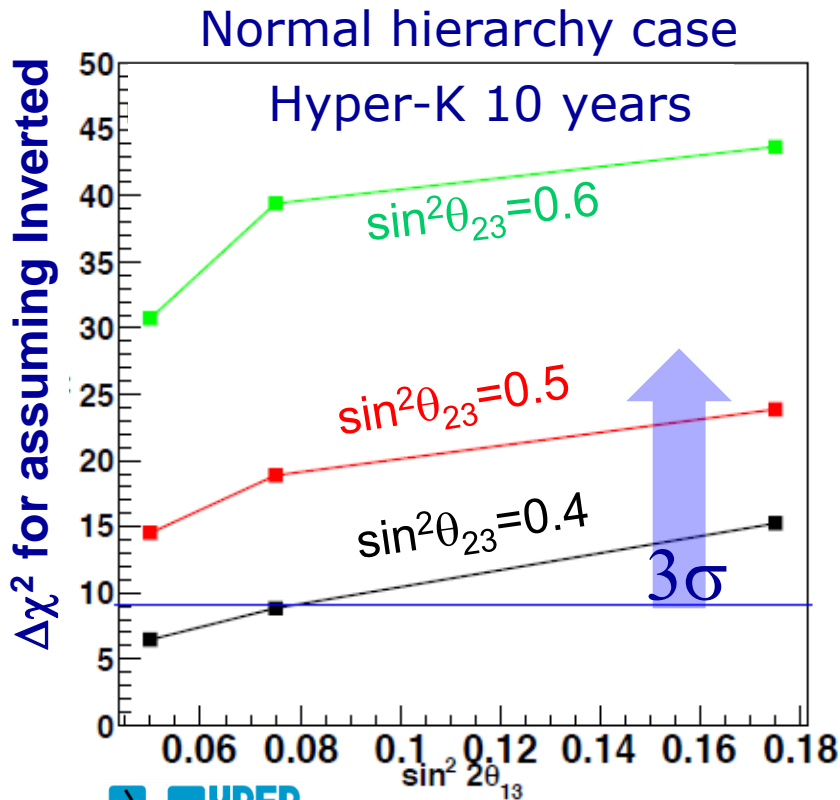
$$\sin^2 \theta_{13} = 0.025$$

$$\delta_{CP} = 40^\circ$$

- MH difference (btw solid and dashed)is clearly visible.

Sensitivity to Mass Hierarchy

- Significance $\equiv \Delta\chi^2$ for wrong MH assumption



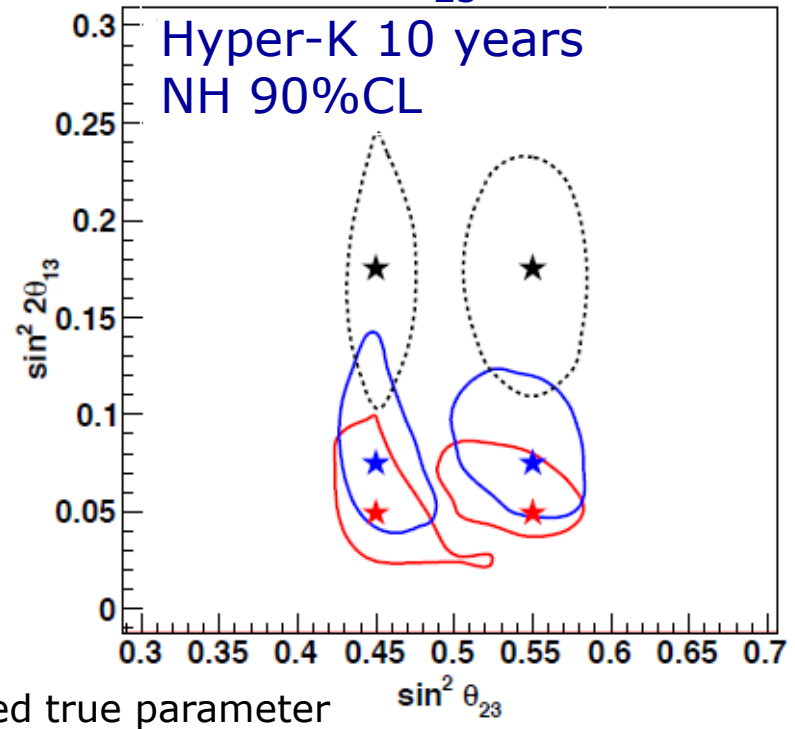
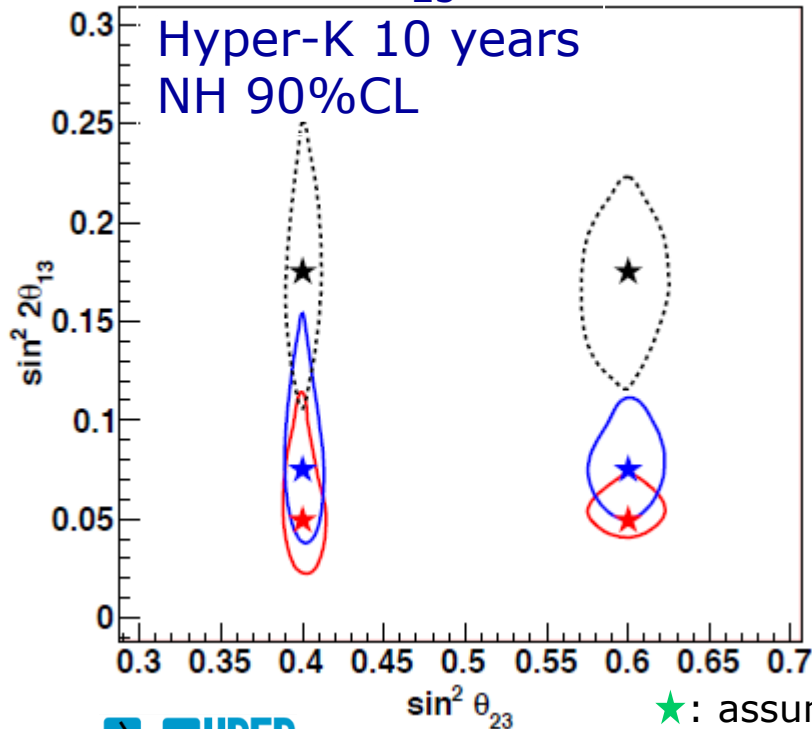
10 years operation

→ For most cases, MH is determined

Sensitivity to θ_{23} octant

$\sin^2 2\theta_{23} = 0.96$ case
 → $\sin^2 \theta_{23} = 0.4$ or 0.6

$\sin^2 2\theta_{23} = 0.99$ case
 → $\sin^2 \theta_{23} = 0.45$ or 0.55

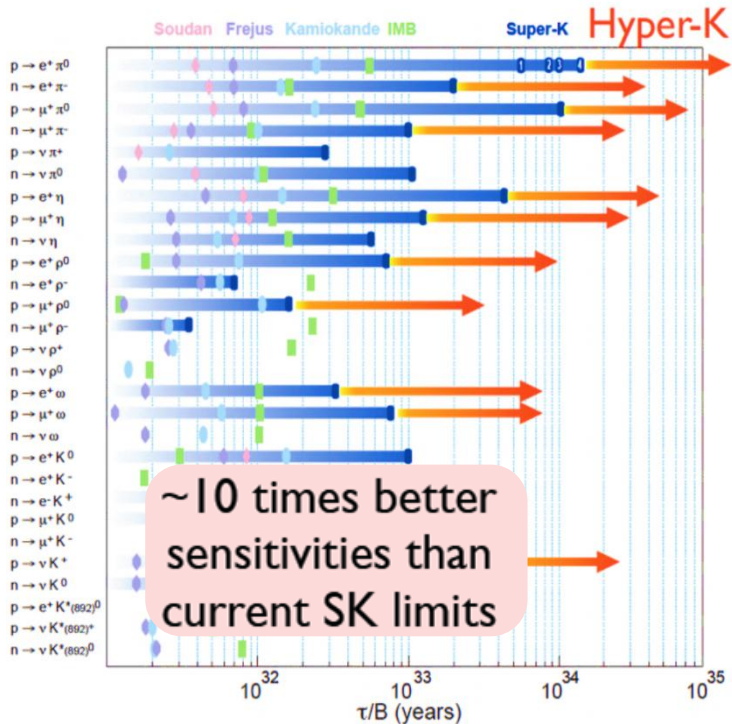


10 years operation

→ Could be discriminated even for $\sin^2 2\theta_{23} = 0.99$

Other Physics Topics

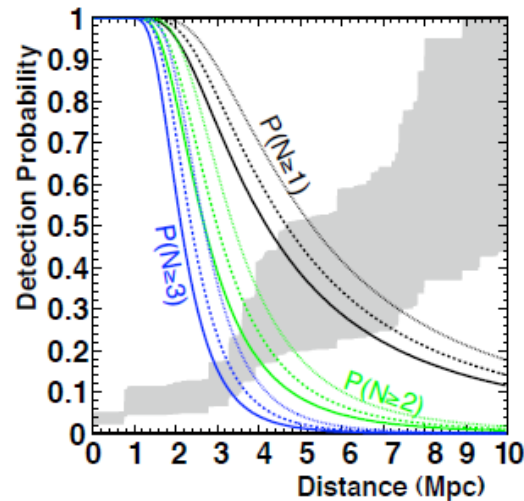
- Nucleon decay search



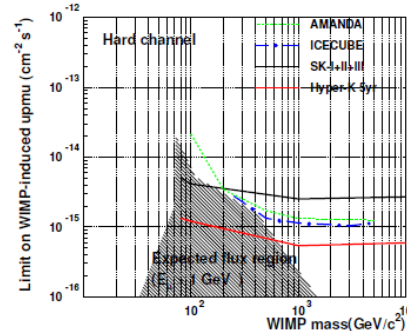
- $p \rightarrow e^+ \pi^0$: 1.3×10^{35} yrs (90%CL)
 - $p \rightarrow \nu K^+$: 2.5×10^{34} yrs (90%CL)

- Solar neutrino
- Neutrino geophysics

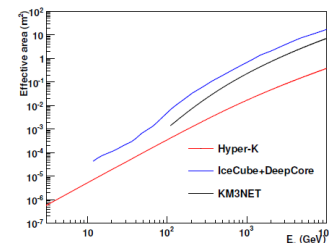
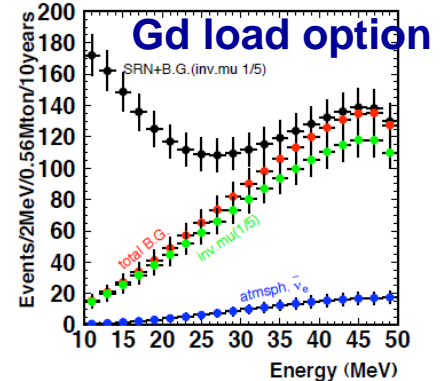
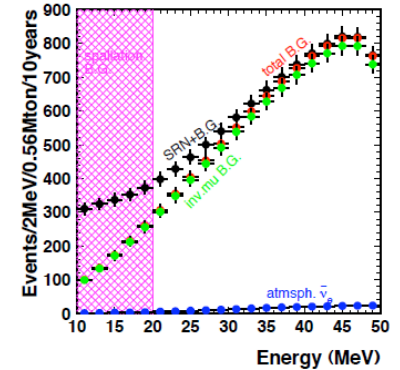
- Supernova burst neutrino



- WIMP search



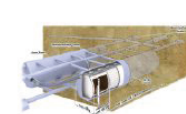
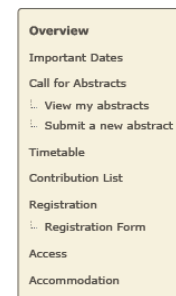
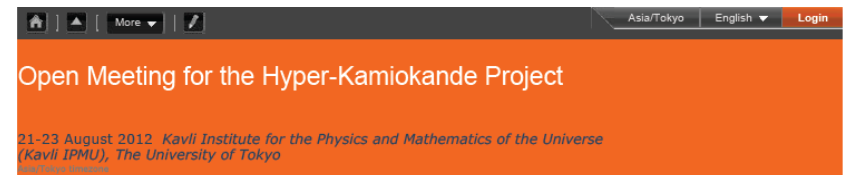
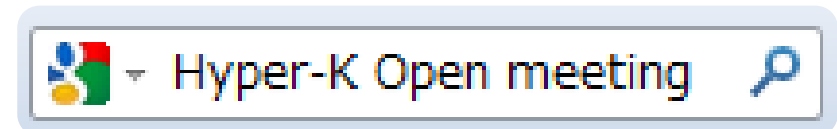
- Supernova relic neutrino (DSNB)



Conclusion

- It's time to start next generation ν detectors.
- A mega ton water Cherenkov detector, Hyper-Kamiokande provides a very rich physics program.
- Can be realized with well-established technology.
- Open Hyper-K meeting will be held.

Open Hyper-K Meeting
August 21-23, 2012
Kavli IPMU,
Kashiwa, Japan



Overview

We will hold an International Open Working Group Meeting for the Hyper-Kamiokande project. Hyper-K, which we are currently developing, is designed to be the next decade's flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos.

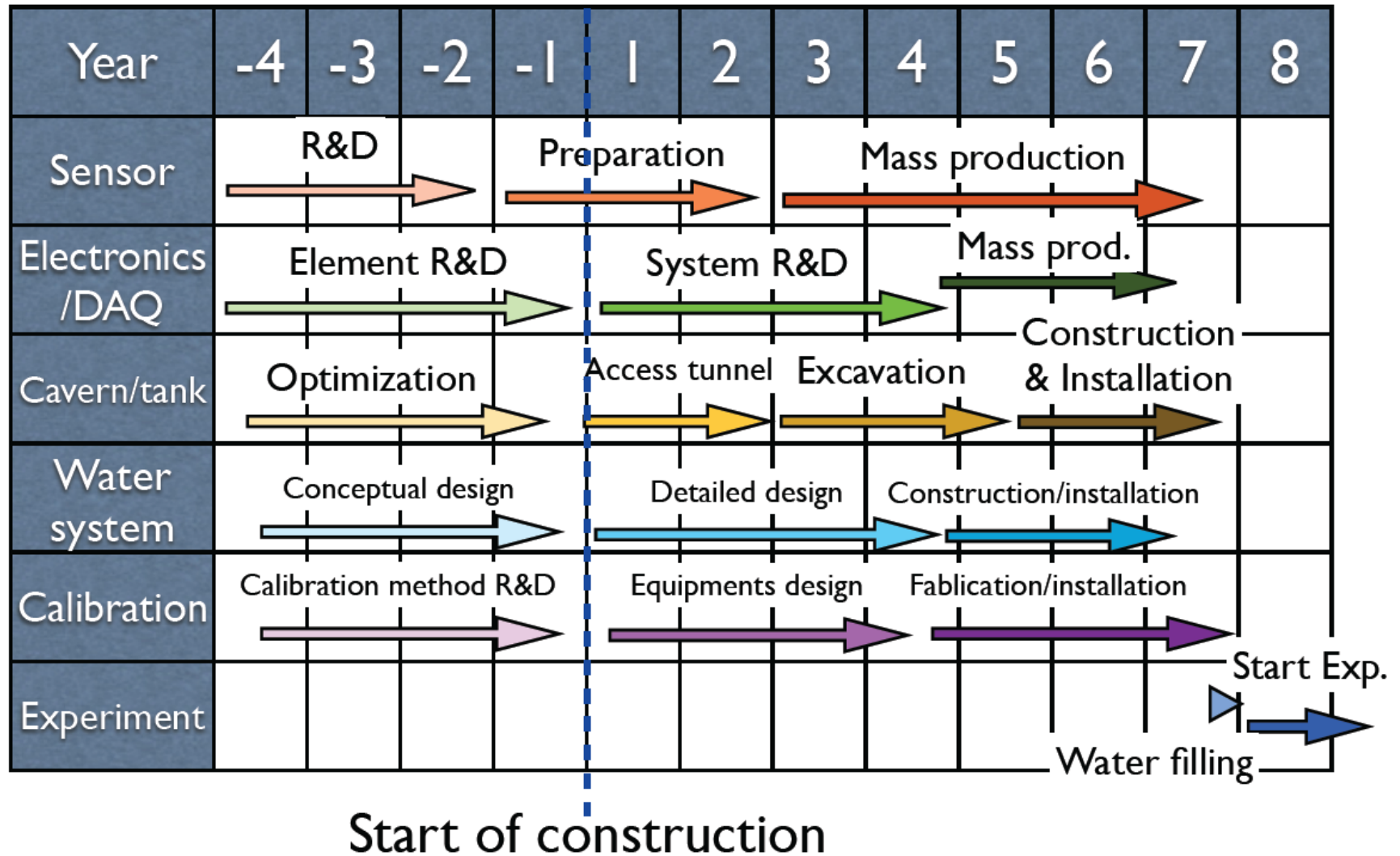
The goal of this meeting is to discuss the physics potentials of Hyper-K, the design of the detector, and necessary R&D items including:

- cavern excavation
- tank liner material and its design
- photo-sensors and their support structure
- DAQ electronics and computers
- calibration systems
- water purification systems
- software development, and so on.

All those interested are welcome to join the meeting!

Extra slides

Possible Schedule



Accelerator ν selection criteria

1. The event is fully contained (FC) inside the inner detector.
2. Reconstructed vertex is inside the fiducial volume (FV).
3. Visible energy (E_{vis}) is greater than 100 MeV.
4. Number of reconstructed rings is one.
5. The reconstructed ring is identified as electron-like (e -like).
6. There is no decay electron associated to the event.
7. The invariant mass (M_{inv}) of the reconstructed ring and a second ring force-found with a special π^0 fitter is less than $100 \text{ MeV}/c^2$. This selection is imposed in order to reduce the background from mis-reconstructed π^0 .
8. The reconstructed energy (E_{ν}^{rec}) is less than 2 GeV.

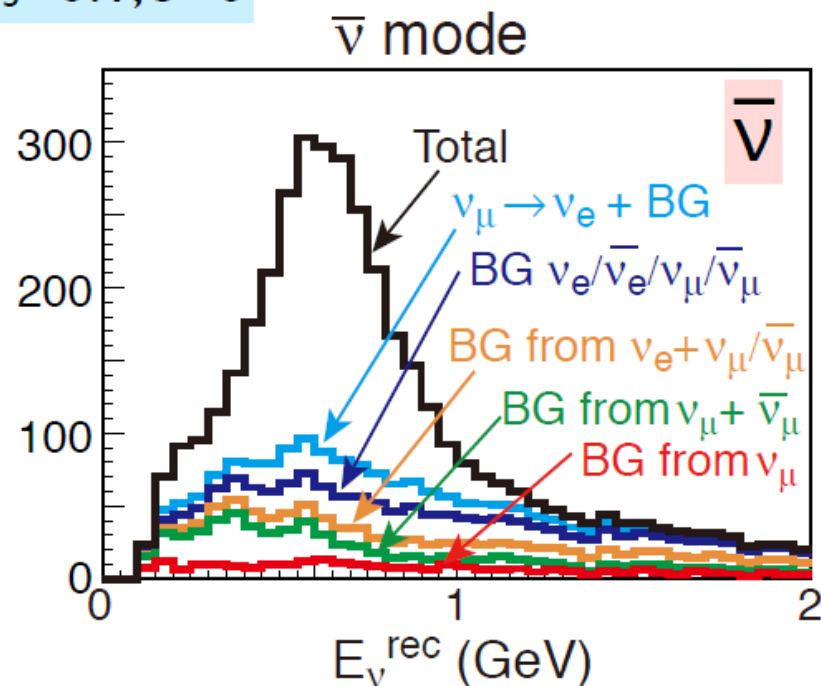
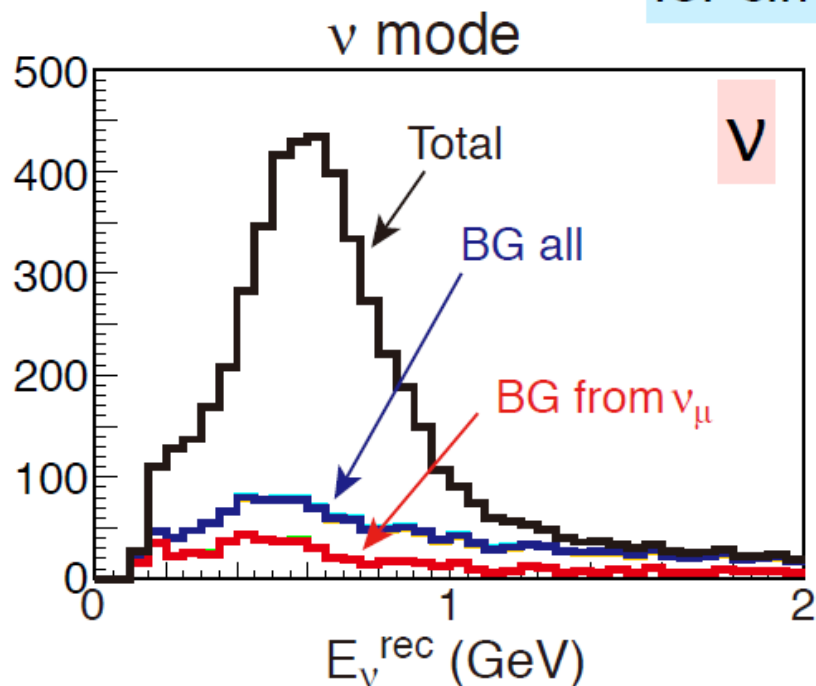
CCQE

$$E_{\nu}^{\text{rec}} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e \cos \theta_e)}$$

BG

- ν_e contamination in $\bar{\nu}$ mode

for $\sin^2 2\theta_{13}=0.1, \delta=0$



MC Expected number of event

| ν mode 3 years | ν_μ CC | $\bar{\nu}_\mu$ CC | ν_e CC | $\bar{\nu}_e$ CC | NC | $\nu_\mu \rightarrow \nu_e$ CC | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC |
|-----------------------------------|--------------|--------------------|------------|------------------|-------|--------------------------------|--|
| Interaction in FV | 64843 | 2859 | 4548 | 368 | 69898 | 6024 | 81 |
| FCFV & $E_{\text{vis}} > 100$ MeV | 46106 | 2030 | 3742 | 297 | 17437 | 5858 | 79 |
| 1-ring | 24506 | 1436 | 2054 | 180 | 4201 | 4972 | 66 |
| e-like | 711 | 21 | 1993 | 175 | 3211 | 4893 | 65 |
| No decay-e | 145 | 4 | 1639 | 165 | 2795 | 4435 | 64 |
| $M_{\text{inv}} < 100$ MeV/ c^2 | 45 | 1 | 1173 | 100 | 811 | 3966 | 54 |
| $E_\nu^{\text{rec}} < 2$ GeV | 38 | 1 | 917 | 57 | 718 | 3940 | 51 |
| Efficiency(%) | 0.06 | 0.03 | 20.2 | 15.4 | 1.03 | 65.4 | 62.6 |
| $\bar{\nu}$ mode 7 years | ν_μ CC | $\bar{\nu}_\mu$ CC | ν_e CC | $\bar{\nu}_e$ CC | NC | $\nu_\mu \rightarrow \nu_e$ CC | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC |
| Interaction in FV | 34446 | 30121 | 2905 | 2335 | 58569 | 817 | 2983 |
| FCFV & $E_{\text{vis}} > 100$ MeV | 24981 | 20960 | 2470 | 1824 | 17677 | 798 | 2907 |
| 1-ring | 11830 | 15925 | 1168 | 1225 | 4433 | 604 | 2577 |
| e-like | 401 | 210 | 1131 | 1197 | 3412 | 596 | 2539 |
| No decay-e | 88 | 30 | 893 | 1148 | 3000 | 520 | 2526 |
| $M_{\text{inv}} < 100$ MeV/ c^2 | 20 | 11 | 564 | 803 | 834 | 439 | 2187 |
| $E_\nu^{\text{rec}} < 2$ GeV | 15 | 10 | 374 | 598 | 750 | 421 | 2168 |
| Efficiency(%) | 0.04 | 0.03 | 12.86 | 25.63 | 1.28 | 51.6 | 72.7 |

Accelerator ν χ^2

Analysis method A binned χ^2 is constructed from the E_ν^{rec} distribution, with 50 MeV bin width for the energy range of 0–2 GeV. As the systematic uncertainty, uncertainties in the normalizations of signal, background originating from ν_μ and $\bar{\nu}_\mu$, those from ν_e and $\bar{\nu}_e$, and the relative normalization between neutrino and anti-neutrino are taken into account. The χ^2 is defined as

$$\chi^2 = \sum_{\nu, \bar{\nu}} \sum_i \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\bar{\nu}} \right\} \cdot \left((1 + f_{\text{sig}}) \cdot n_{\text{sig}}^i + (1 + f_{\nu_\mu}) \cdot n_{\nu_\mu}^i + (1 + f_{\nu_e}) \cdot n_{\nu_e}^i \right) \right]^2 / N^i$$
$$+ \frac{f_{\text{sig}}^2}{\sigma_{\text{sig}}^2} + \frac{f_{\nu_\mu}^2}{\sigma_{\nu_\mu}^2} + \frac{f_{\nu_e}^2}{\sigma_{\nu_e}^2} + \frac{f_{\bar{\nu}/\nu}^2}{\sigma_{\bar{\nu}/\nu}^2},$$

where the index i runs over bins of reconstructed neutrino energy, and $+$ and $-$ are applied for neutrino and anti-neutrino mode, respectively.

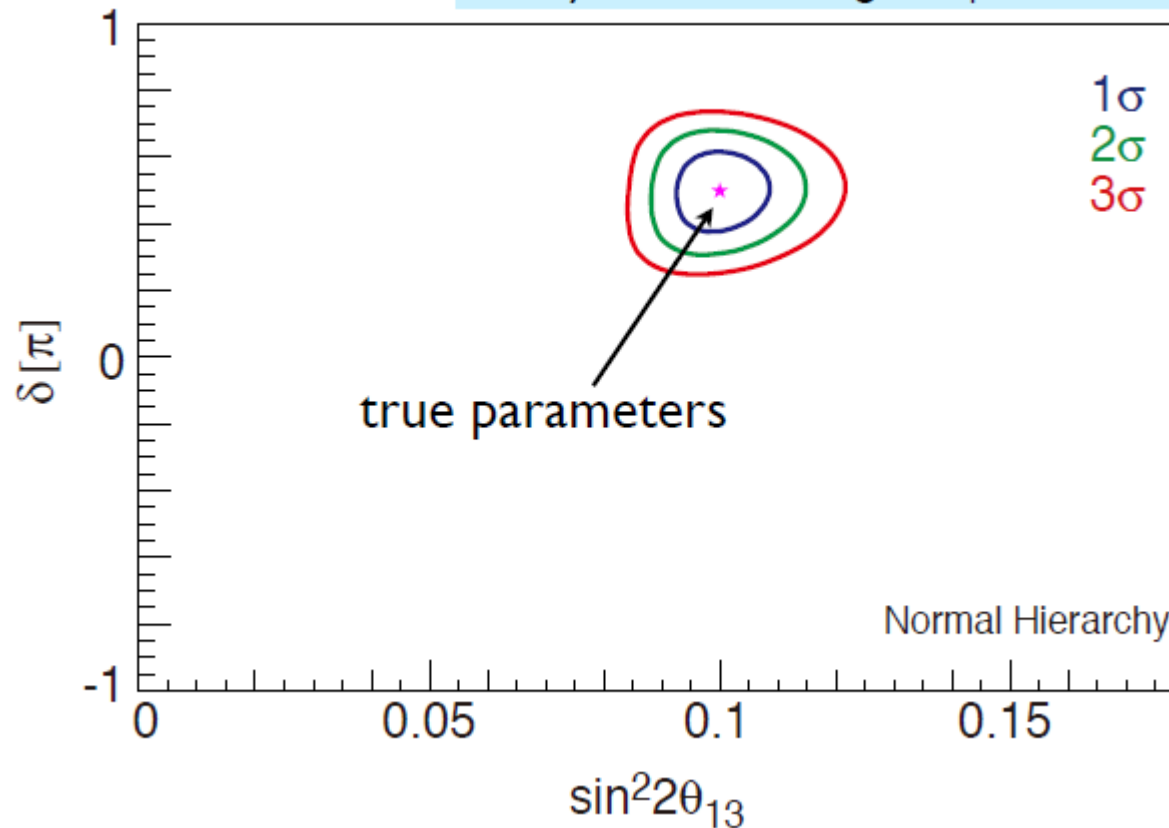
- i : Energy bin index (per 50MeV)
- f_x : systematic parameters
- N^i : # of events for i-th bin with “true” set of parameters
- n^i : # of events for i-th bin with “test” set of parameters
- σ_x : systematic errors for corresponding f_x (5% are assumed)

Expected allowed region

- Assuming true is ($\delta=\pi/2, \sin^2 2\theta_{13}=0.1$)

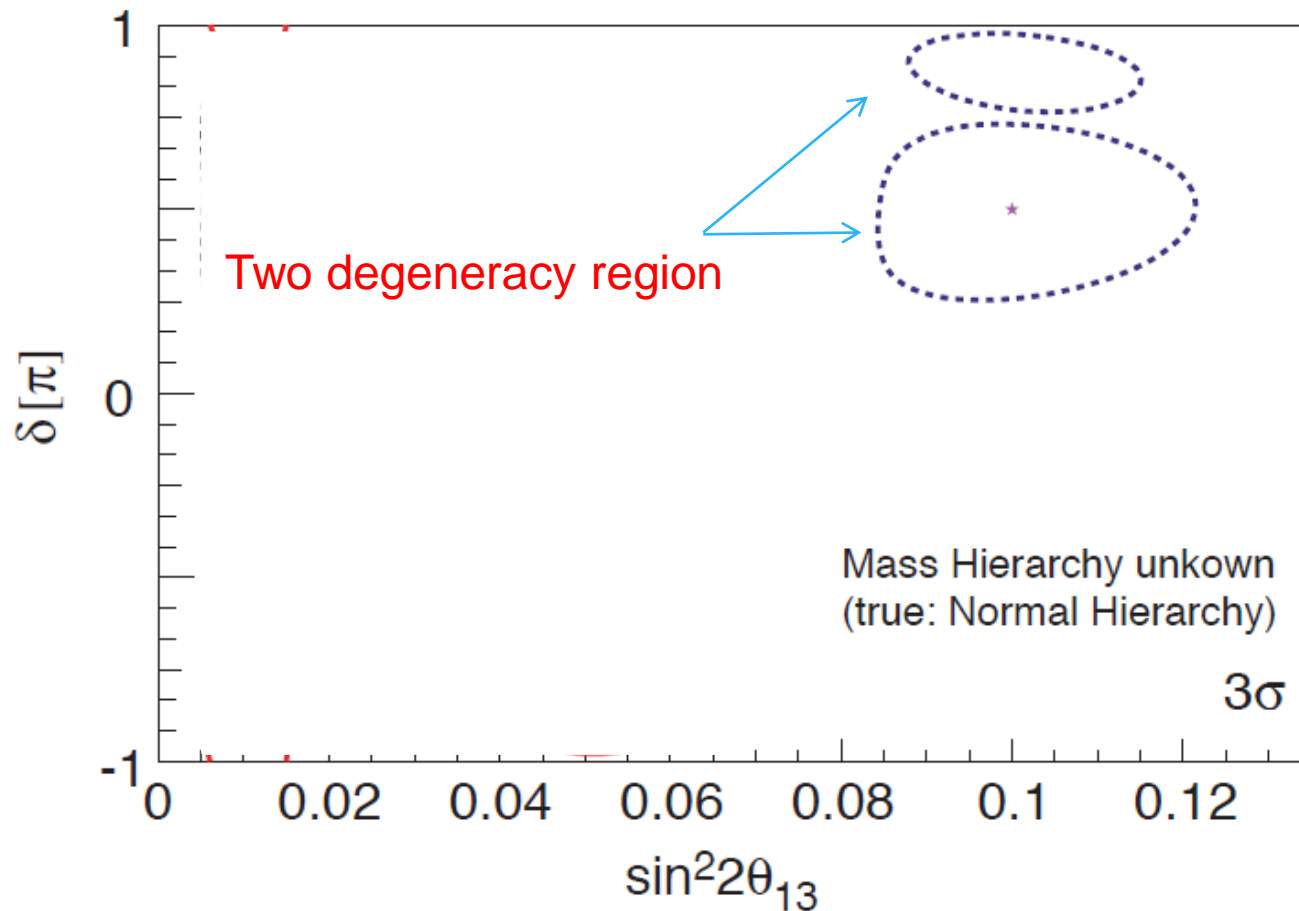
Total $7.5\text{MW}\times 10^7\text{s}$

5% systematics on signal, ν_μ BG, ν_e BG, $\nu\bar{\nu}$



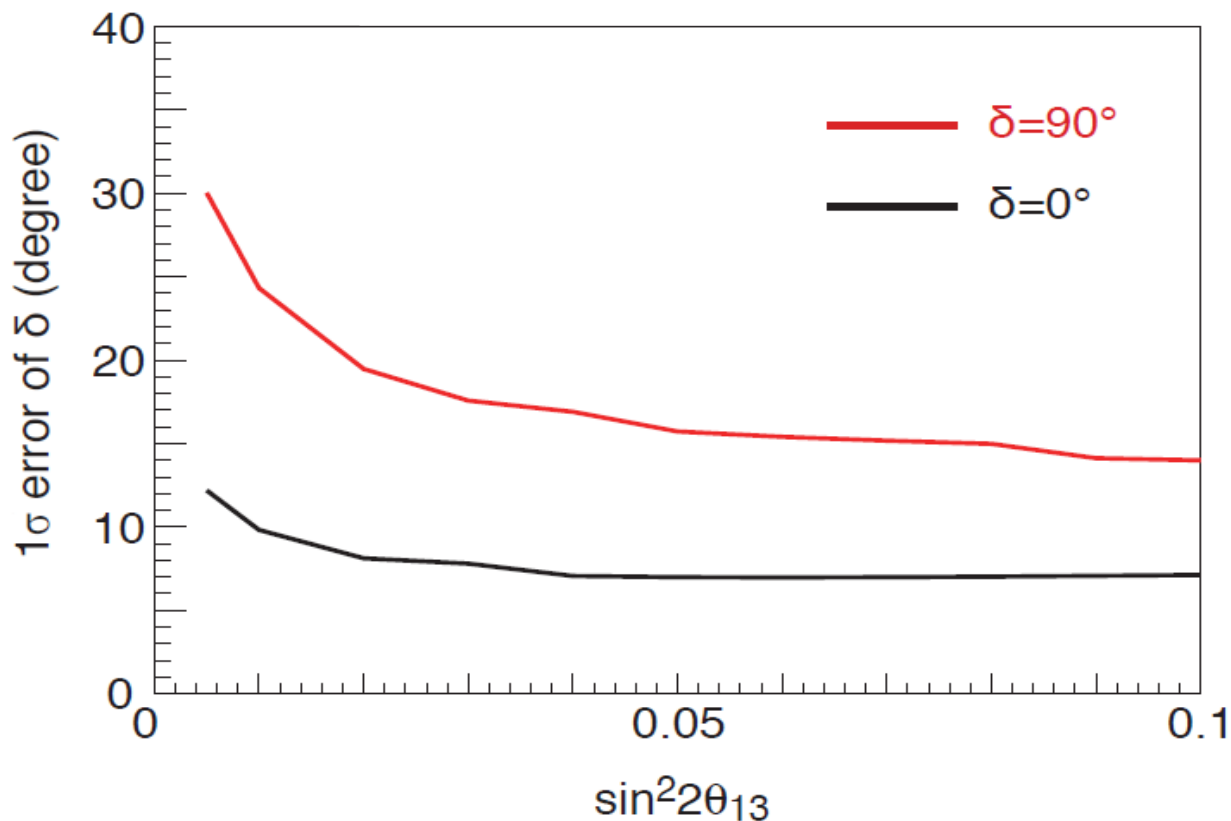
IF MH is unknown

- Assuming true is ($\delta=\pi/2, \sin^2 2\theta_{13}=0.1$)



θ_{13} dependence of δ measurement

- Too large θ_{13} is not so helpful...



Atmospheric ν 3 flavor oscillation

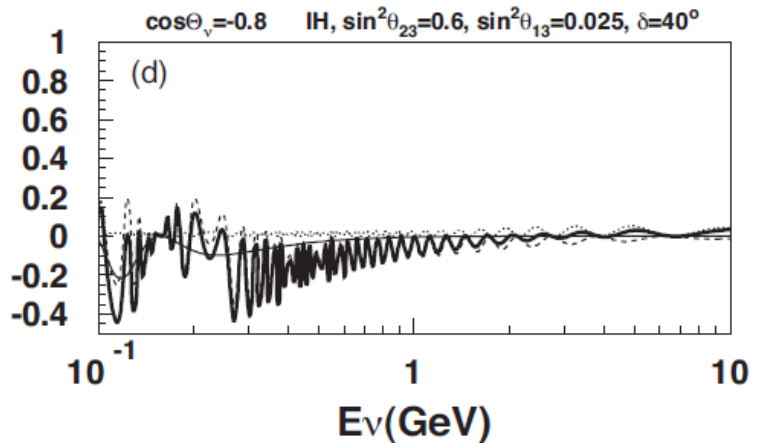
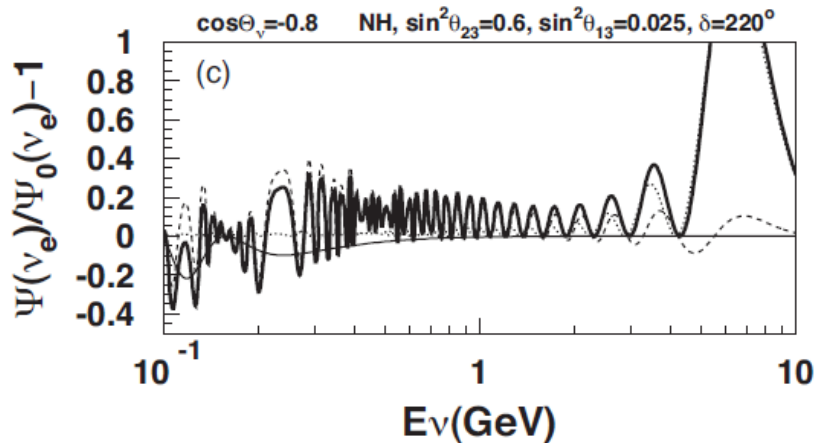
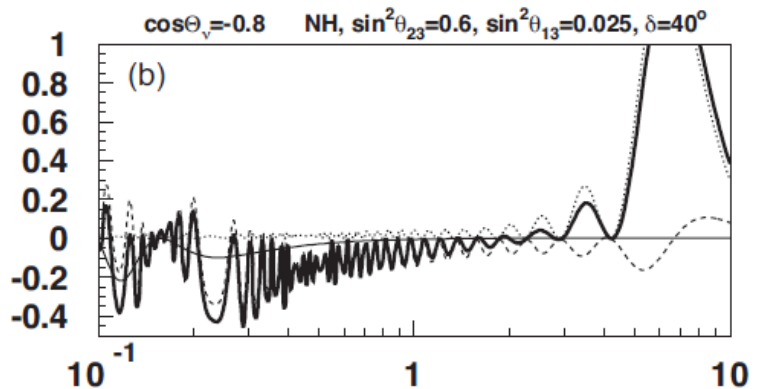
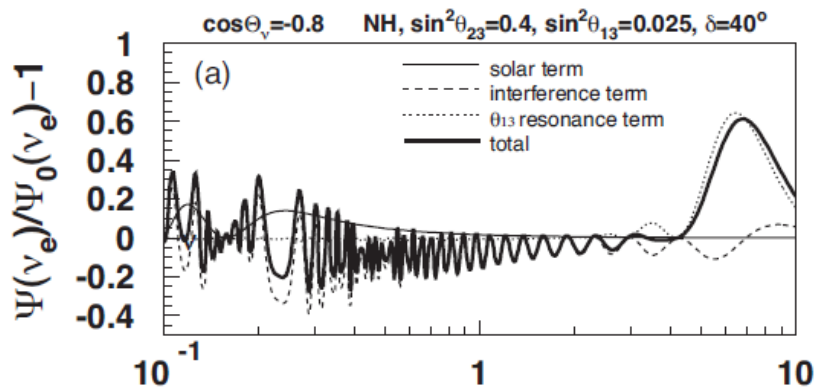
Oscillation probabilities of atmospheric neutrinos in the three flavor neutrino mixing scheme have been discussed by many authors, and the oscillation effect in electron neutrino flux is analytically calculated [64] as:

$$\begin{aligned} \frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx & P_2 \cdot (r \cdot \cos^2 \theta_{23} - 1) \\ & - r \cdot \sin \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos \delta \cdot R_2 - \sin \delta \cdot I_2) \\ & + 2 \sin^2 \tilde{\theta}_{13} \cdot (r \cdot \sin^2 \theta_{23} - 1) \end{aligned} \quad (5)$$

where we call the first, second, and third terms the “solar term”, “interference term”, and “ θ_{13} resonance term”, respectively. P_2 is the two neutrino transition probability of $\nu_e \rightarrow \nu_{\mu,\tau}$ which is driven by the solar neutrino mass difference Δm_{21}^2 . R_2 and I_2 represent oscillation amplitudes for CP even and odd terms. For anti-neutrinos, the probabilities P_2, R_2, I_2 are obtained by replacing the matter potential $V \rightarrow -V$, and the sign of the δ (see [64] for details). r is the ν_{μ}/ν_e flux ratio as a function of neutrino energy; $r \approx 2$ at sub-GeV energies, starts deviating from 2 at 1 GeV, and reaches to ~ 3 at 10 GeV. The $\tilde{\theta}_{13}$ is an effective mixing angle in the Earth; $\sin^2 \tilde{\theta}_{13}$ could become large at 5 \sim 10 GeV neutrino energy due to the matter potential [65–67]. This MSW resonance happens with neutrinos in the case of normal mass hierarchy ($\Delta m_{32}^2 > 0$), and with anti-neutrinos in the case of inverted mass hierarchy ($\Delta m_{32}^2 < 0$).

Atmospheric ν MSW resonance

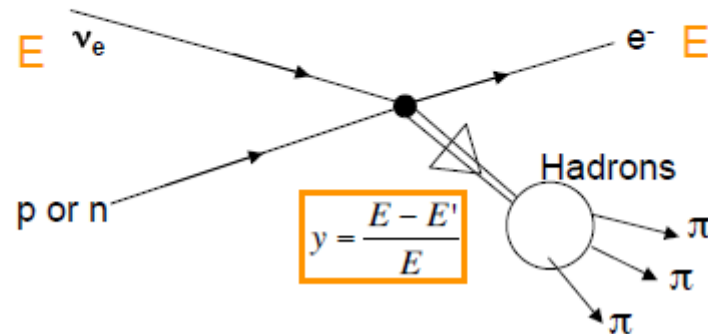
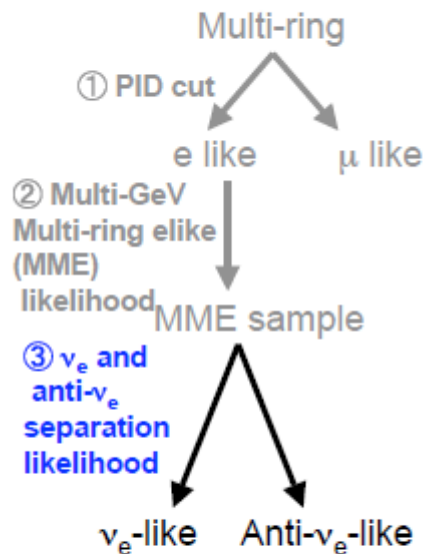
- ν_e for NH, $\bar{\nu}_e$ for IH



Statistical PID

- Multi-ring case: Likelihood method

Division into ν_e and anti- ν_e
 ~Multi-GeV Multi-ring e-like~

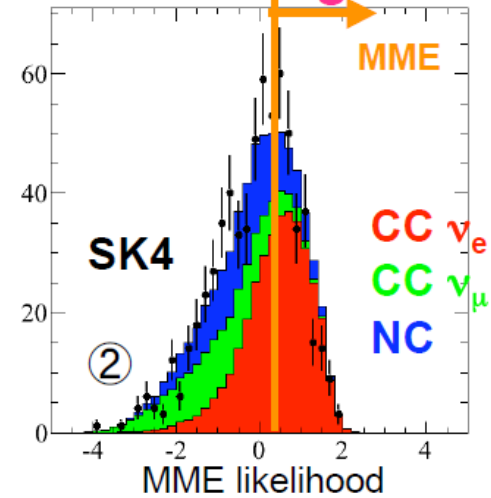
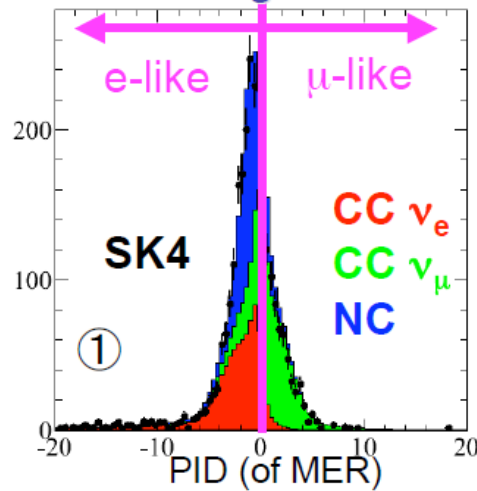
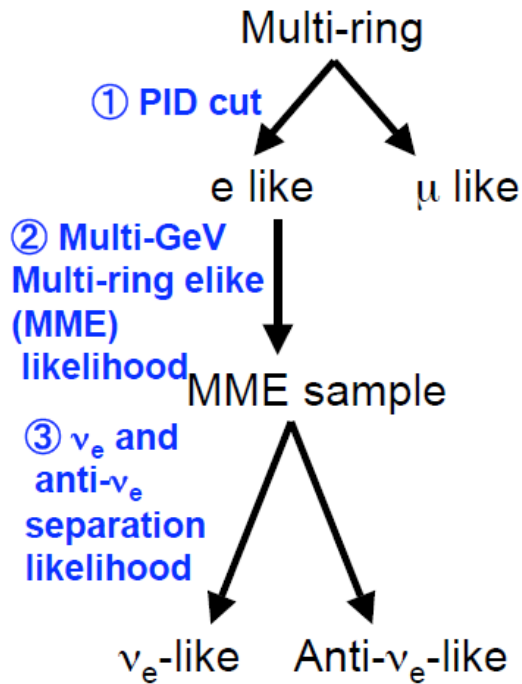


- As Feynman y distribution is larger for CC ν_e than CC anti- ν_e , CC ν_e has small E' , hence:

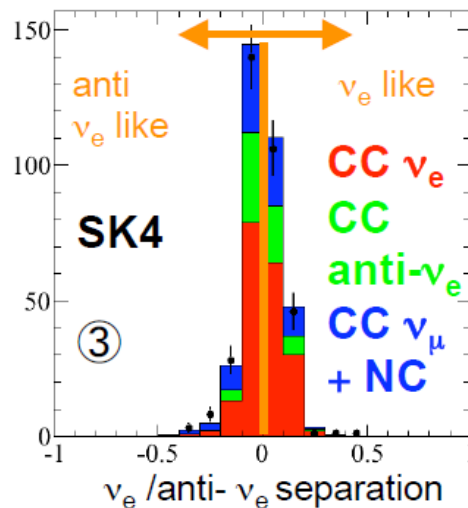
| | CC ν_e | CC anti- ν_e |
|---|------------|------------------|
| MER (Most Energetic Ring) momentum fraction | Smaller | Larger |
| Number of rings | More | Less |
| Transverse momentum | Larger | Smaller |
| Decay-electron | More | Less |

Statistical PID

Division into ν_e and anti- ν_e ~ Multi-GeV multi-ring e-like ~



Multi-GeV multi-ring ν_e -like



| | Purity |
|------------------|--------|
| CC ν_e | 55.1% |
| CC anti- ν_e | 11.5% |
| NC+ CC ν_μ | 33.3% |
| Total | 100% |

Multi-GeV multi-ring anti- ν_e -like

| | Purity |
|------------------|--------|
| CC ν_e | 53.1% |
| CC anti- ν_e | 24.7% |
| NC+ CC ν_μ | 22.2% |
| Total | |

MC Expected number of ν_e -like, $\bar{\nu}_e$ -like

TABLE XII. Expected number of ν_e -like and $\bar{\nu}_e$ -like events in 10 Hyper-K years for each int
ponent.

| | CC ν_e | CC $\bar{\nu}_e$ | CC $\nu_\mu + \bar{\nu}_\mu$ | NC | Total |
|----------------------------|------------|------------------|------------------------------|------|-------|
| ν_e -like sample | 15247 | 2831 | 3731 | 4792 | 26601 |
| - single-ring | 6356 | 1086 | 1682 | 1740 | 10864 |
| - multi-ring | 8891 | 1745 | 2049 | 3052 | 15737 |
| Percentage (%) | 57.3 | 10.6 | 14.0 | 18.0 | 100.0 |
| $\bar{\nu}_e$ -like sample | 28309 | 17255 | 1232 | 4559 | 51355 |
| - single-ring | 20470 | 13401 | 444 | 2496 | 36811 |
| - multi-ring | 7839 | 3854 | 788 | 2063 | 14544 |
| Percentage (%) | 55.1 | 33.6 | 2.4 | 8.9 | 100.0 |

Atmospheric ν χ^2

These MC events are used as fake data as well as expectation. To make fake data, the MC is weighted by livetime and oscillation probabilities. The χ^2 is defined by comparing each fake data set with the expectation in terms of Poisson statistics:

$$\chi^2 \equiv \sum_n \left[2 \left(N_{\text{MC}}^n (1 + \sum_i f_i^n \cdot \epsilon_i) - N_{\text{DT}}^n \right) + 2N_{\text{DT}}^n \ln \left(\frac{N_{\text{DT}}^n}{N_{\text{MC}}^n (1 + \sum_i f_i^n \cdot \epsilon_i)} \right) \right] + \sum_i \left(\frac{\epsilon_i}{\sigma_i} \right)^2 \quad (6)$$

where

n : counter for event type, momentum, and zenith angle

N_{MC}^n : the number of MC events in the n -th bin

N_{DT}^n : the number of fake data events in the n -th bin

i : counter for uncertainties

ϵ_i : the list of systematic uncertainties (nuisance parameters)

f_i^n : error coefficients for i -th uncertainty and n -th event bin

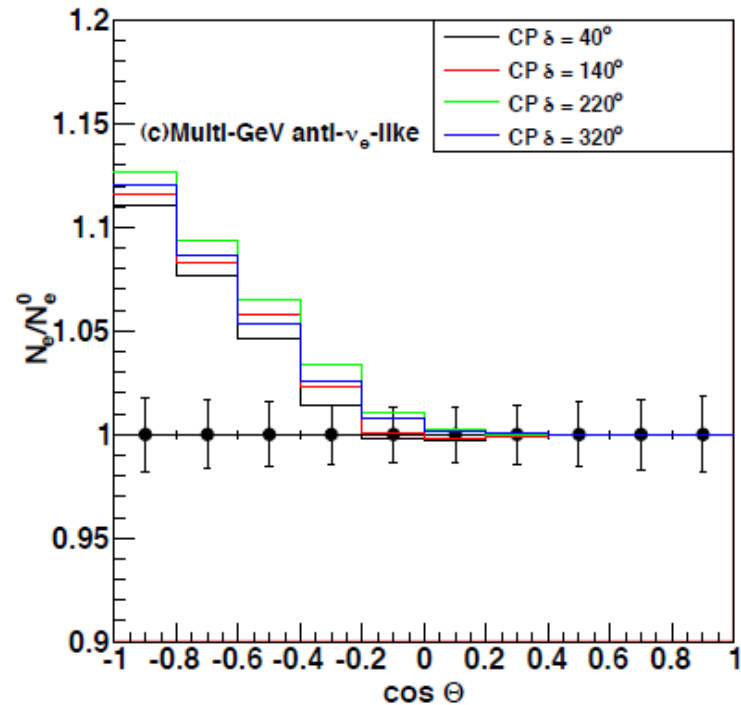
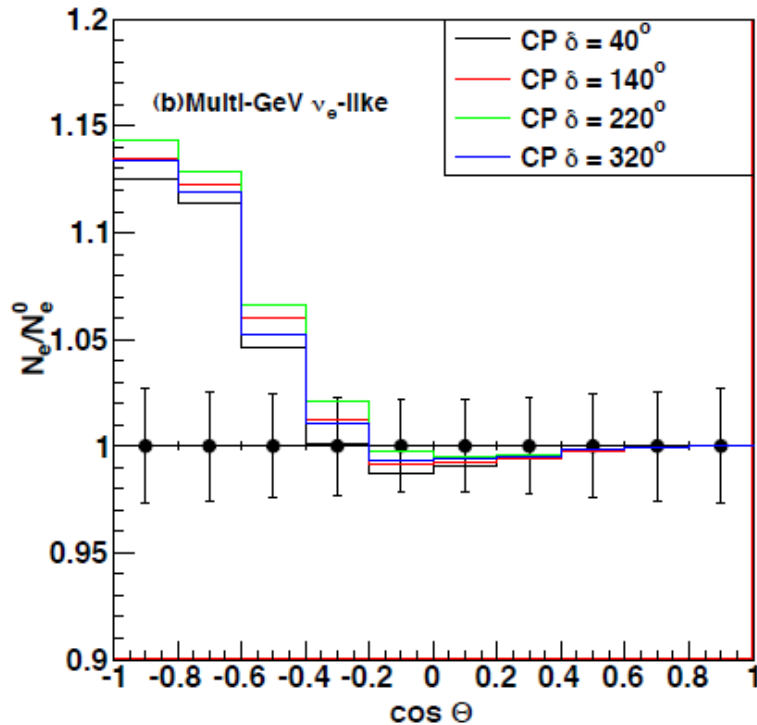
σ_i : estimated size of systematic uncertainties

Expected zenith angle distributions for $N_e/N^0_e(\delta)$

Multi-GeV ν_e -like

Full MC

Multi-GeV anti- ν_e -like



- δ difference is visible.

| | |
|---|------------------------------|
| $\Delta m^2_{12} = 7.6 \times 10^{-5} \text{ eV}^2$ | $\sin^2 \theta_{12} = 0.31$ |
| $\Delta m^2_{23} = 2.4 \times 10^{-3} \text{ eV}^2$ | $\sin^2 \theta_{13} = 0.025$ |

Sensitivity to δ atmospheric ν by itself

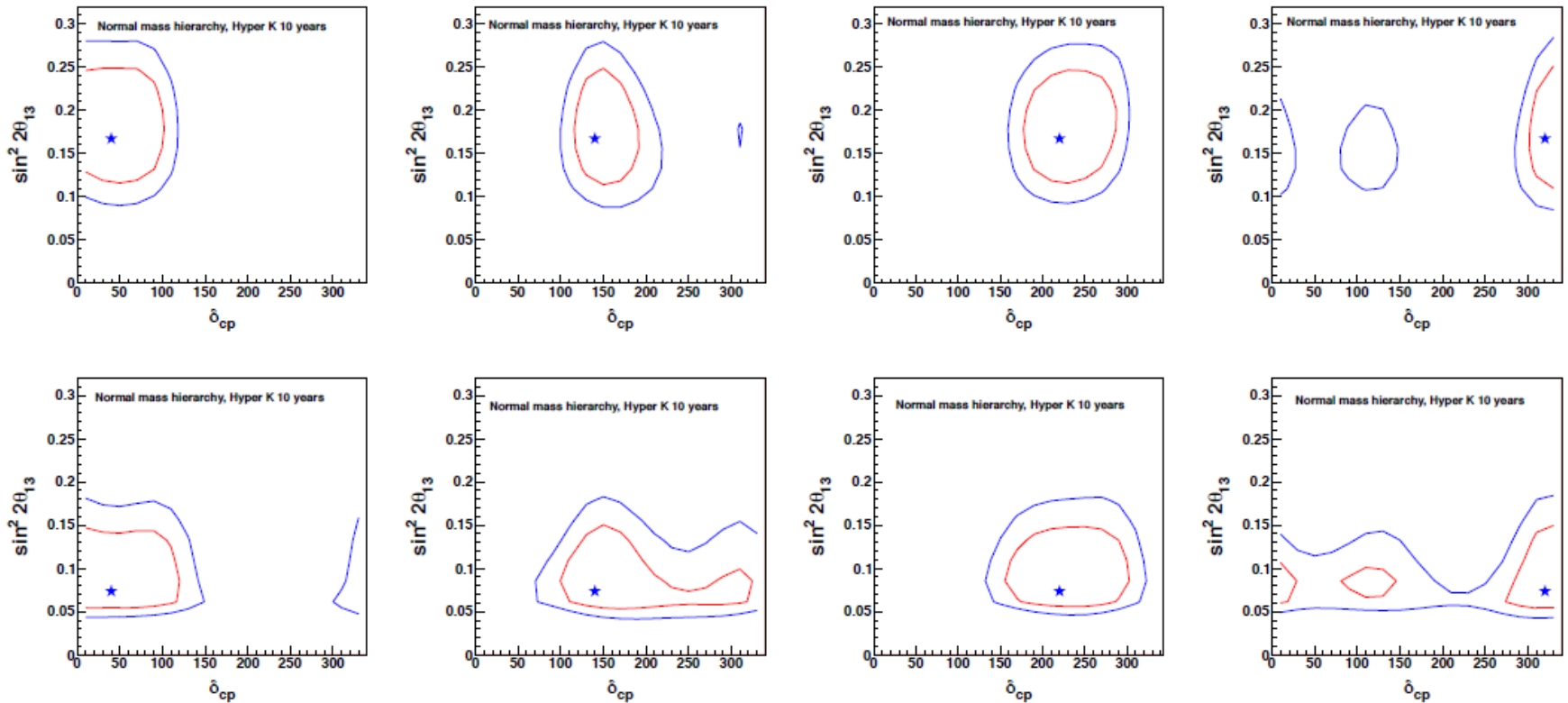
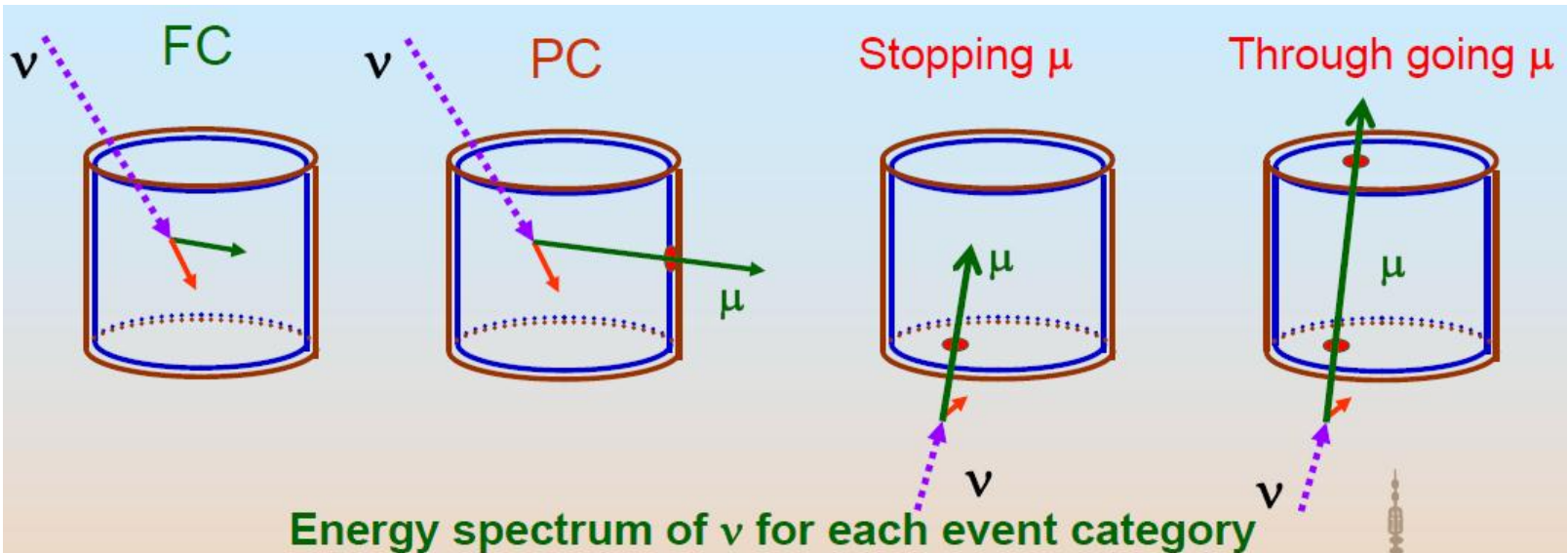


FIG. 41. Expected sensitivities for δ and $\sin^2 2\theta_{13}$ at 90% CL (red) and 99% CL (blue) with a livetime of 10 Hyper-K years. Stars in the contours represent the true parameter set of θ_{13} and δ . Normal mass hierarchy

Super-K atmospheric event categories



Energy spectrum of ν for each event category

