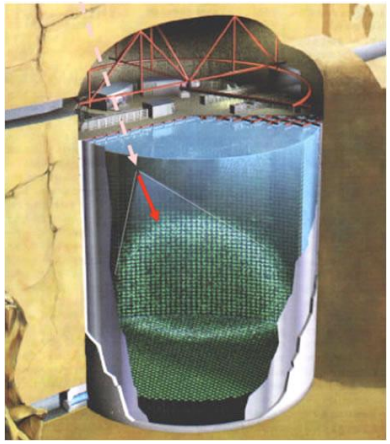
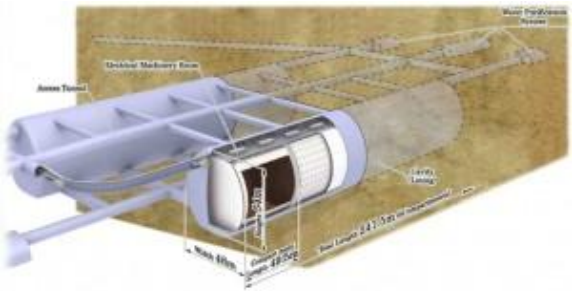
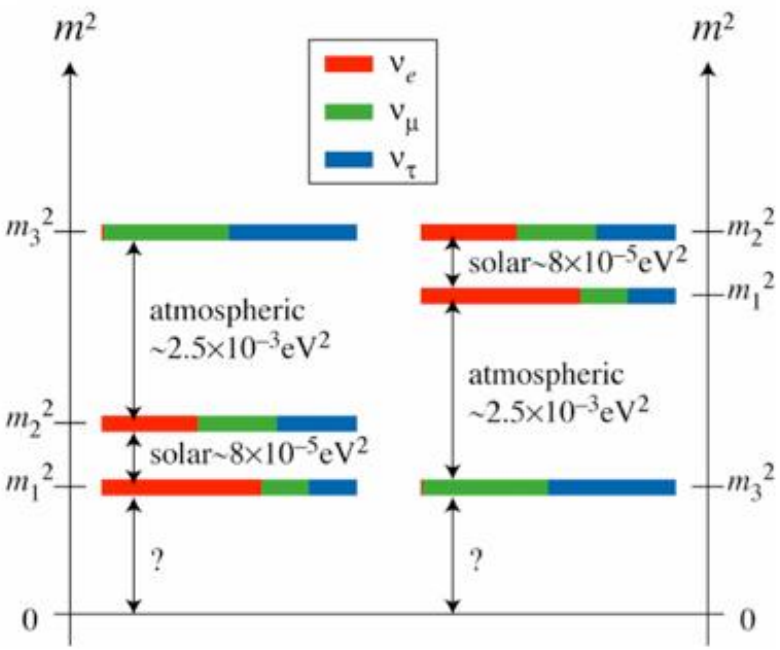
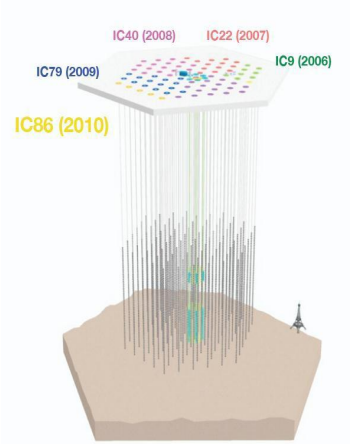
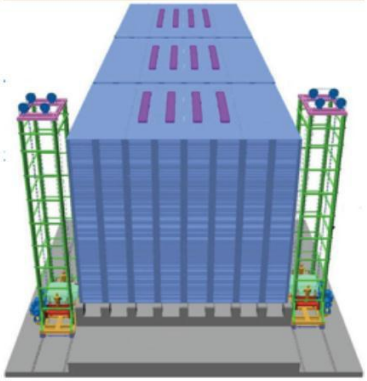
# 大気ニュートリノでの
# 質量階層性決定の可能性





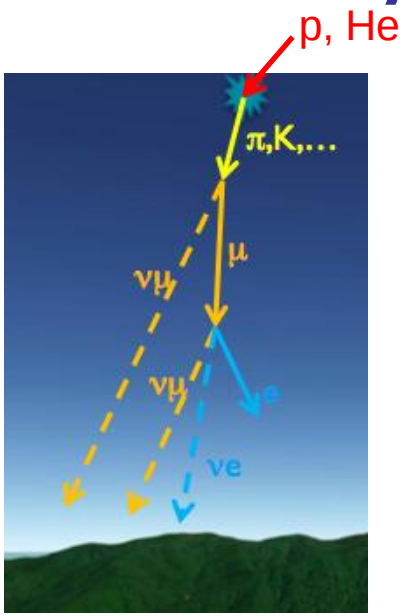


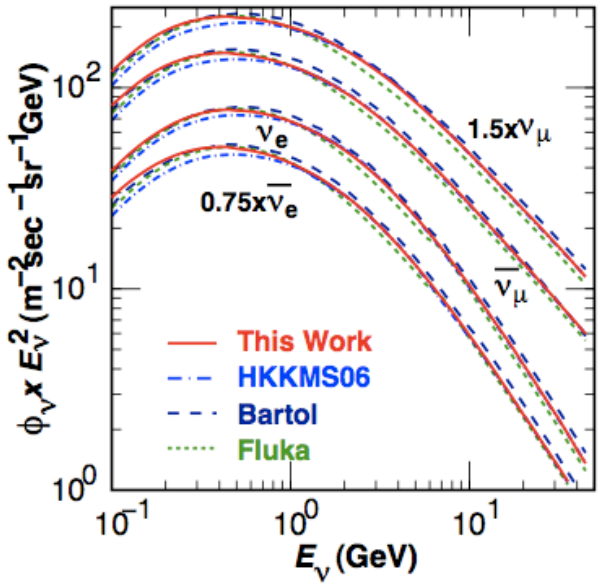
Kimihiro OKUMURA (ICRR, Univ. of Tokyo)
26th RCCN Neutrino Workshop

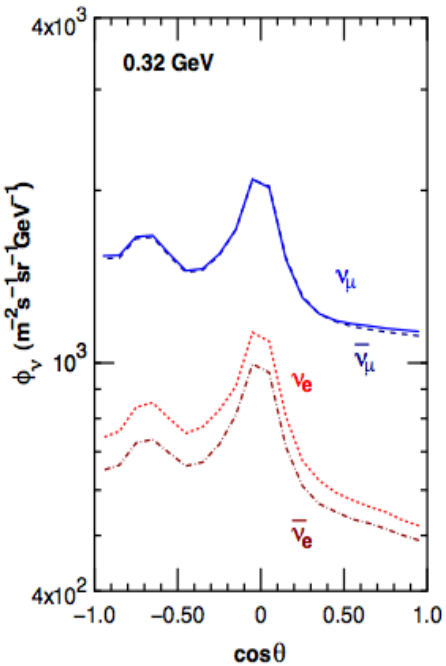
# Atmospheric neutrinos

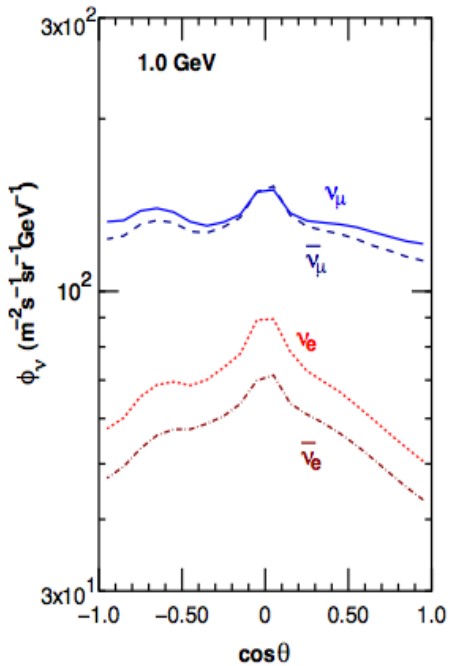


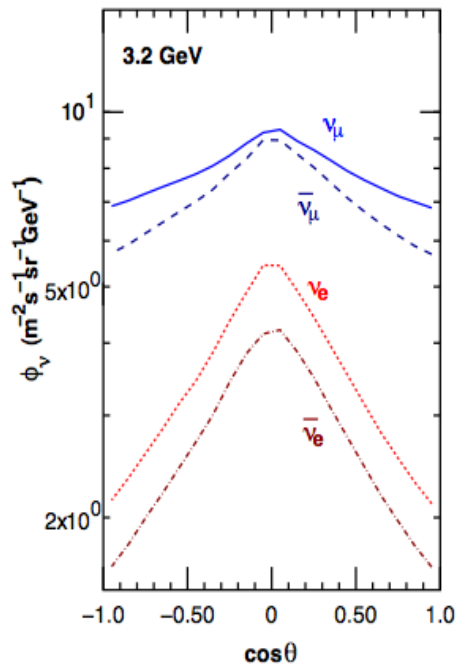

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

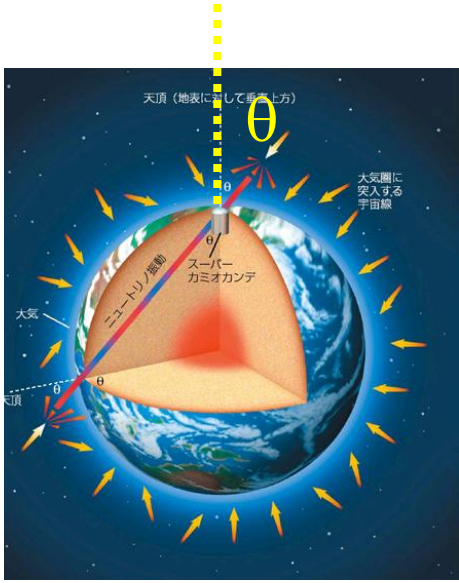
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



# 3 flavor oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

大気ニュートリノ
加速器ニュートリノ

加速器ニュートリノ
原子炉ニュートリノ
大気ニュートリノ

太陽ニュートリノ
原子炉ニュートリノ

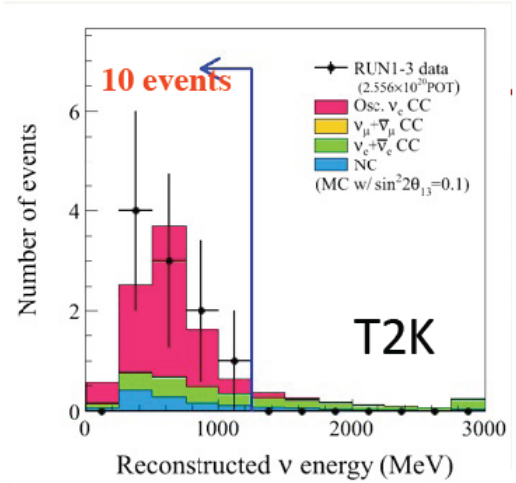
$$2.24\times10^{-3} < \Delta m^2_{23} < 2.44\times10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) > 0.90$$

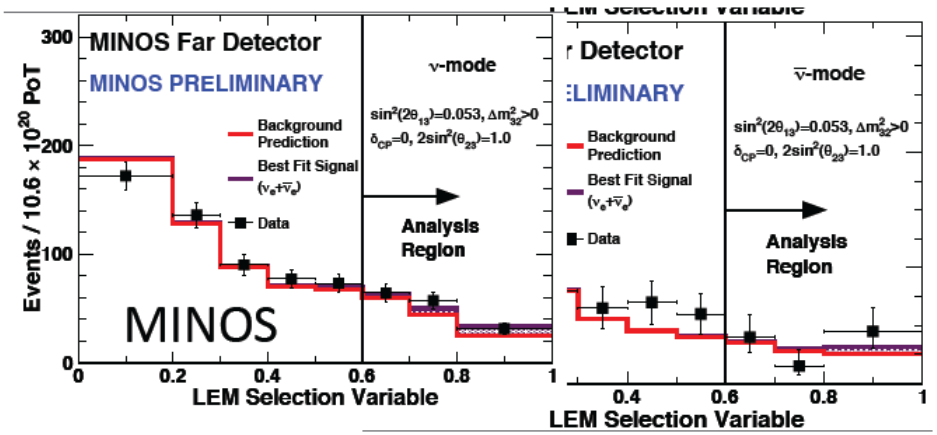
$$7.4\times10^{-5} < \Delta m^2_{12} < 7.8\times10^{-5} eV^2$$
$$0.30 < \sin^2\theta_{12} < 0.32$$

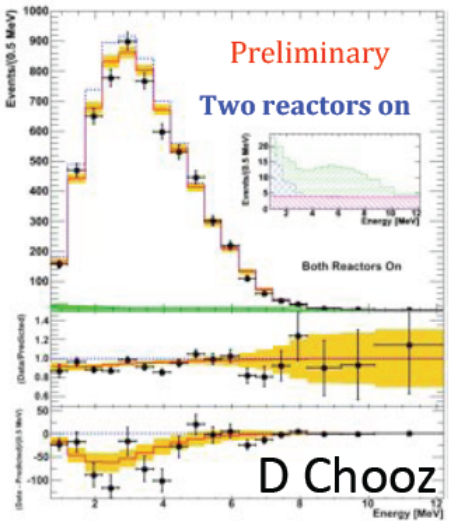
$\nu_\mu \leftrightarrow \nu_\tau$

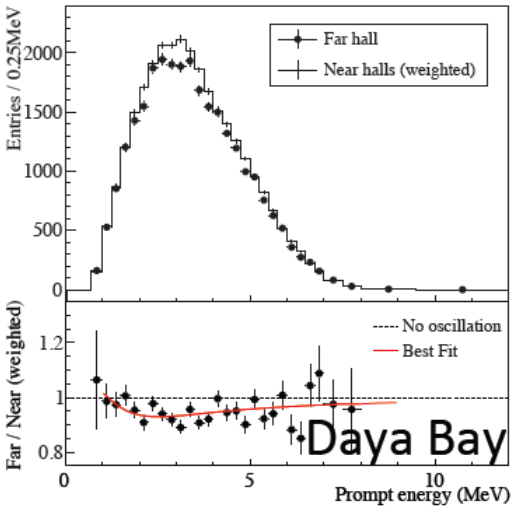
$\nu_\mu, \nu_\tau \leftrightarrow \nu_e$

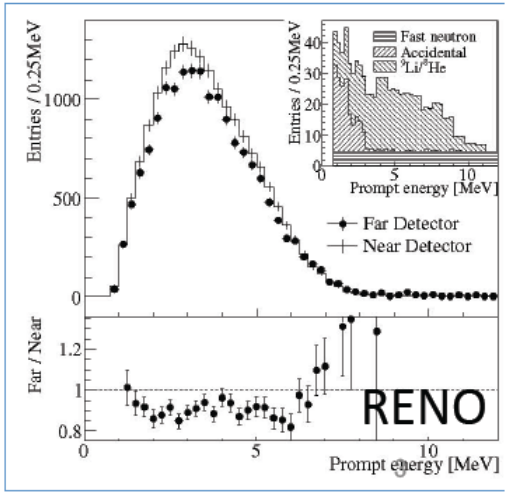
Nishikawa Neutrino2012



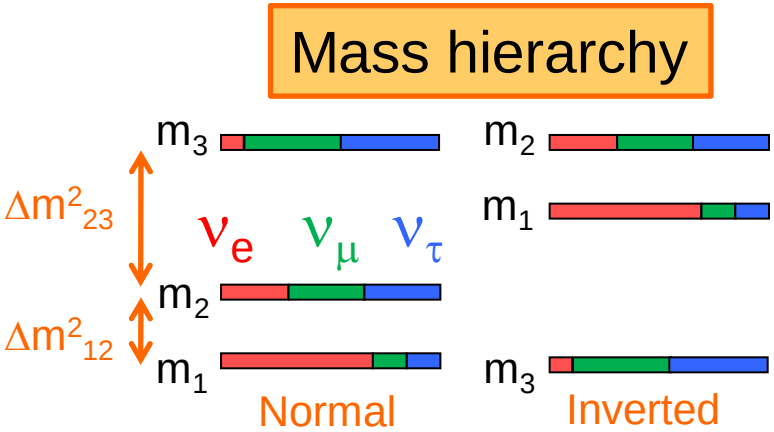




$\nu_\mu \rightarrow \nu_e$ appearance by T2K and MINOS
anti-$\nu_e$ disappearance in reactor neutrino

$$\sin^2(2\theta_{13}) \sim 0.1$$

# Remaining problems of neutrino physics

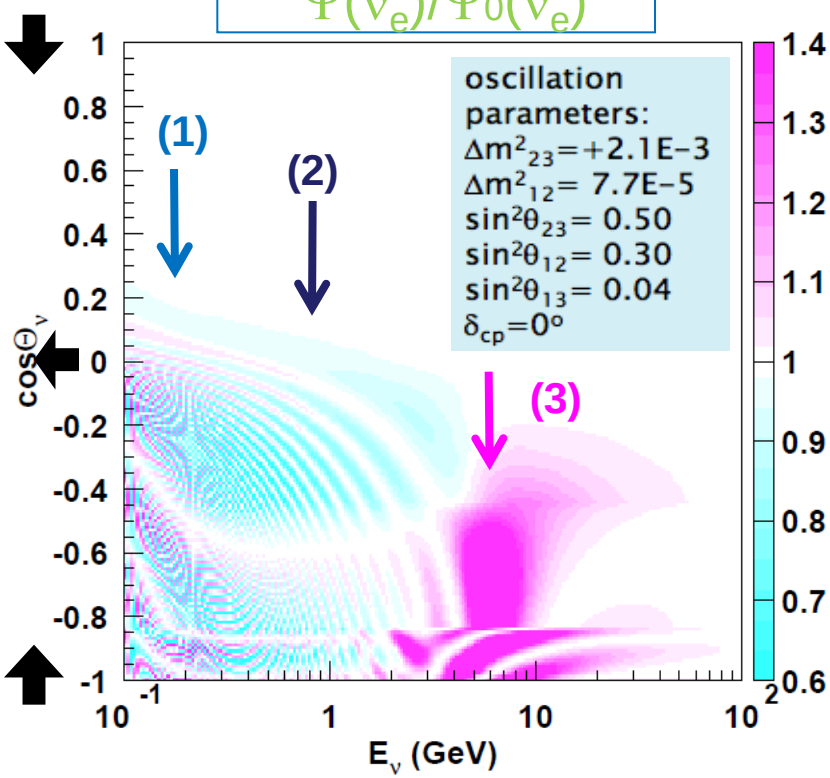
- CP violation ($\delta_{cp}$) search
  - accerlator neutrino（e.g. J-PARC to Hyper-K)
- Mass hierarchy (MH)
  - Normal or Inverted
- To determine MH:
  - Reactor (medium baseline)
  - Double-beta decay（e.g. KamLAND）
  - Measurement using matter effect
    - very long baseline experiment（~1000km）
    - atmospheric neutrino



# Sub-dominant effects in atm ν

$\nu_e$ flux ratio of
CHOOZ $\theta_{13}$ and $\theta_{13}$ =0

$\Psi(\nu_e)/\Psi_0(\nu_e)$




Pares and Smirnov
hep-ph/039312

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

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

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

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

$r$ : νμ/νe flux ratio (~2 at low energy)

(1) driven by $\Delta m^2_{sol}$ → sensitive to $\theta_{23}$ octant

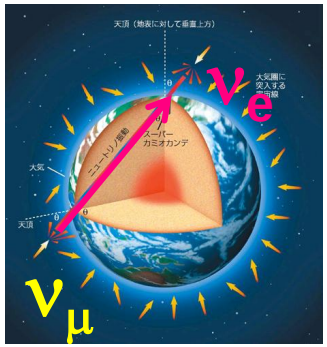
(2) Interference → sensitive to $\delta_{CP}$

(3) $\theta_{13}$ resonance → sensitive to $\theta_{23}$, $\theta_{13}$, MH

# $\nu_\mu \rightarrow \nu_e$ enhancement by matter effect

$$P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13,M}\sin^2\left(\frac{1.27\Delta m^2_{23,M}L_\nu}{E_\nu}\right)$$

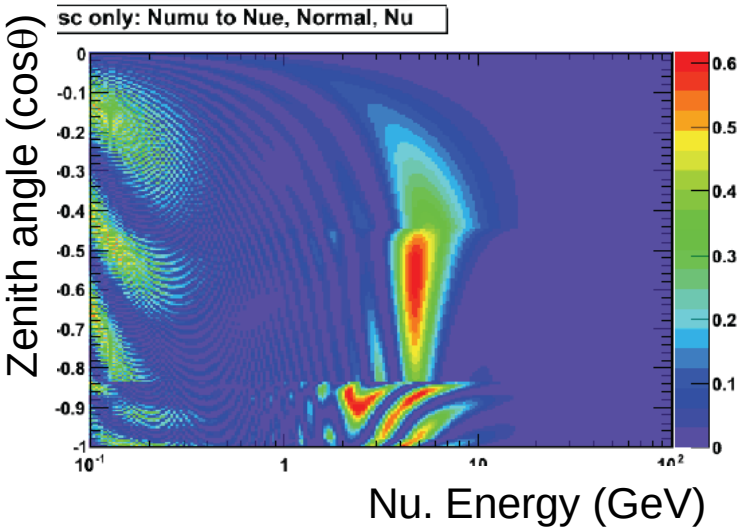
$$\begin{aligned}
\Delta m^2_{23,M} &= \Delta m^2_{23}\sqrt{(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{23})^2 + \sin^2\theta_{13}} \\
\sin^2\theta_{13,M} &= \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{23})^2 + \sin^2 2\theta_{13}} \\
A_{CC} &= 2\sqrt{2}G_F N_e E_\nu
\end{aligned}$$




Resonance happens when :

$$A_{cc} = \Delta m^2_{23}\cos 2\theta_{13}$$

$P(\nu_\mu \rightarrow \nu_e)$ for normal hierarchy, neutrino




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

In case of Inverted hierarchy:

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

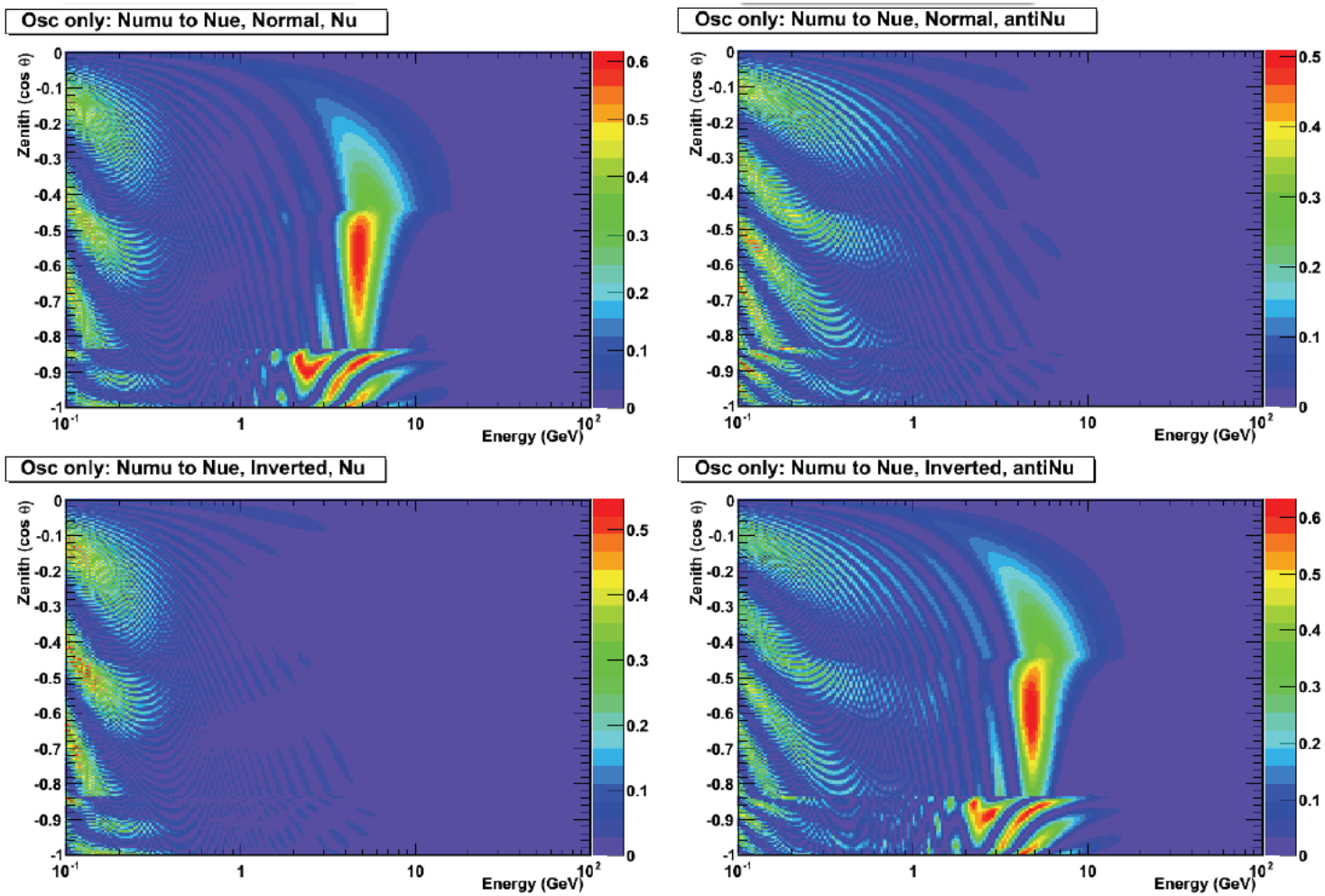
In case of anti neutrino :

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

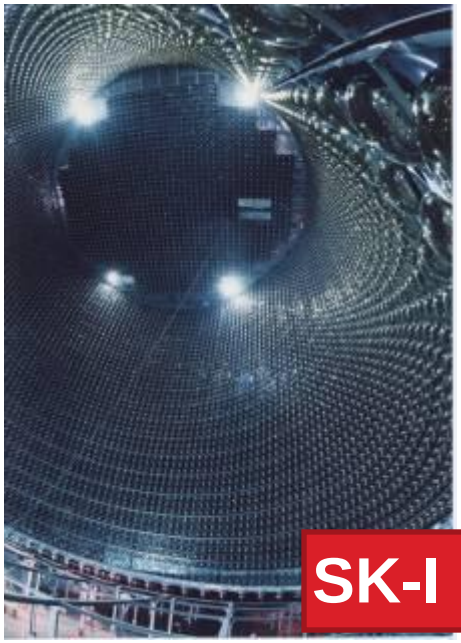
$\nu_\mu \rightarrow \nu_e$ | anti-$\nu_\mu \rightarrow$ anti-$\nu_e$

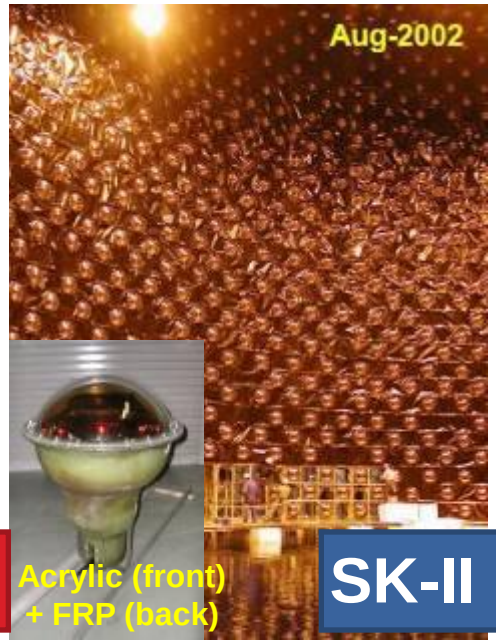
Normal hierarchy

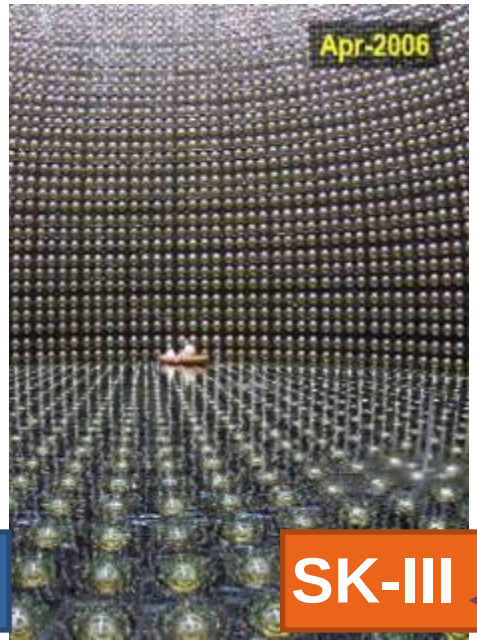
Inverted hierarchy



# 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 |

| 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

**SK-I (1646days)** — **SK-II (828days)** — **SK-III (636 days)** — **SK-IV (1097 days)**

50kt water Cherenkov detector（FV22.5kt）

# Neutrino interactions in multi-GeV

## Quasi-elastic

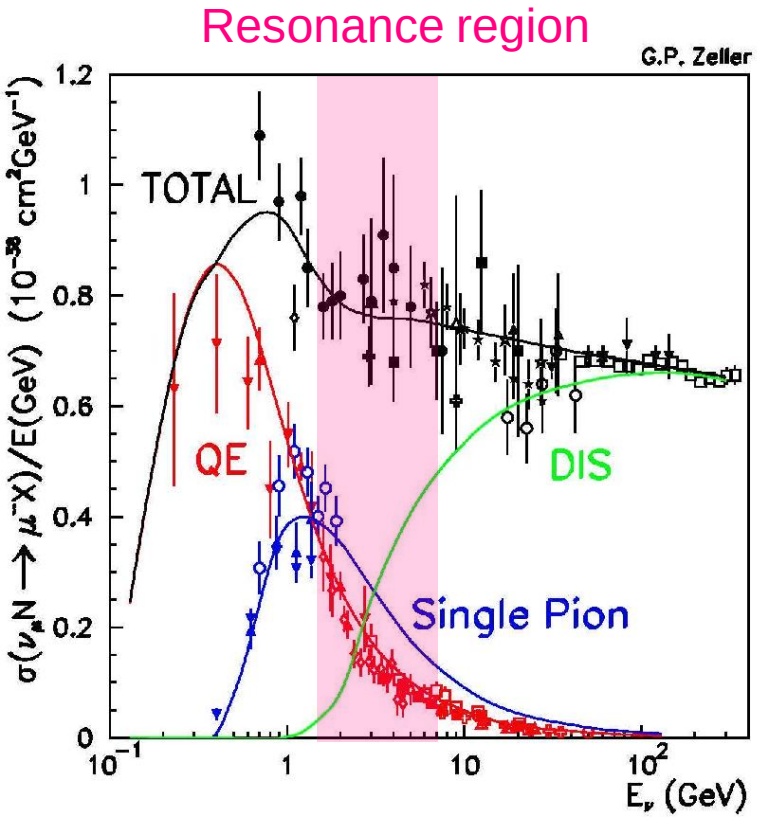
$$\nu + n \rightarrow l^- + p \qquad \bar{\nu} + p \rightarrow l^+ + n$$

## Single-pion production

$$\nu + p \rightarrow l^- + p + \pi^+ \qquad \bar{\nu} + n \rightarrow l^+ + n + \pi^-$$
$$\nu + n \rightarrow l^- + p + \pi^0 \qquad \bar{\nu} + p \rightarrow l^+ + n + \pi^0$$
$$\nu + n \rightarrow l^- + n + \pi^+ \qquad \bar{\nu} + p \rightarrow l^+ + p + \pi^-$$

## DIS

$$\nu + n \rightarrow l^- + N' + m\ \pi$$
$$\nu + p \rightarrow l^- + N' + m\ \pi$$
$$\bar{\nu} + p \rightarrow l^+ + N' + m\ \pi$$
$$\bar{\nu} + n \rightarrow l^+ + N' + m\ \pi$$




Difficult to distinguish $l^-$ and $l^+$ in Cherenkov detector

Try to probe ν and anti-ν from pions

$$\nu_e + n \rightarrow e^- + N' + pions$$ (*Total charge for the N' and pion system is +1)

$$\nu_e + p \rightarrow e^- + N' + pions$$ (*Total charge for the N' and pion system is +2)

where $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$ Decay $e^-$

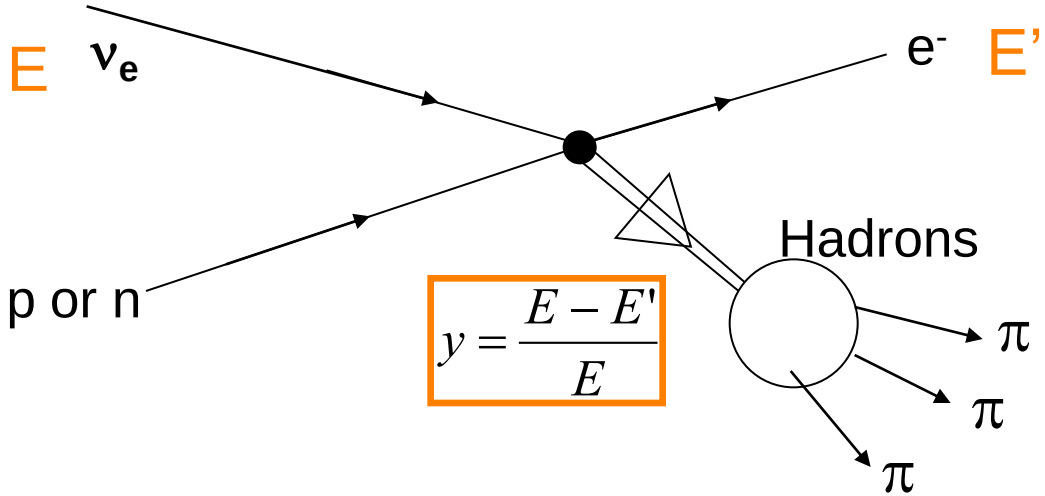
$$\bar{\nu}_e + p \rightarrow e^+ + N' + pions$$ (*Total charge for the N' and pion system is 0)

$$\bar{\nu}_e + n \rightarrow e^+ + N' + pions$$ (*Total charge for the N' and pion system is -1)

$\pi^-$ is absorbed in water, no decay-electrons emitted

- CC$\nu_e$ has more delayed decay-e than CC anti-$\nu_e$
- Tend to increase number of Cherenkov rings.

# Kinematical tendency between CC $\nu$ and anti-$\nu$



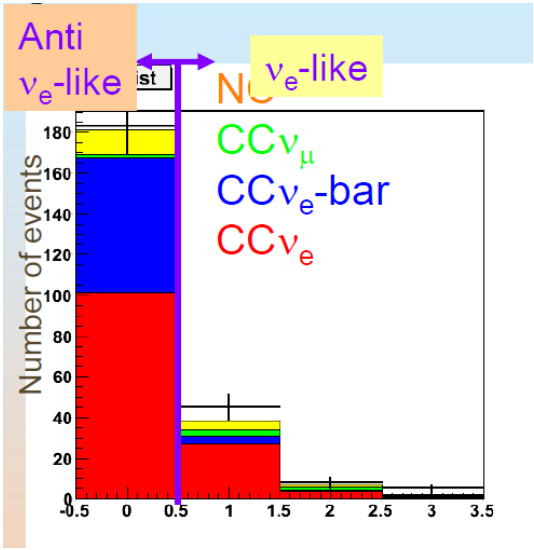

- As Feynman y distribution is larger for CC$\nu_e$ than CC anti-$\nu_e$, CC$\nu_e$ has small E', hence:

| | CC $\nu_e$ | CC anti-$\nu_e$ |
|---|---|---|
| MER (Most Energetic Ring) momentum fraction | Smaller | Larger |
| Number of identified Cherenkov rings | More | Less |
| Transverse momentum | Larger | Smaller |
| Decay-electron | More | Less |

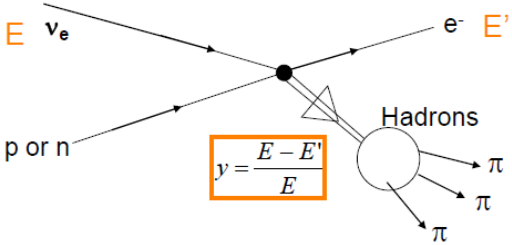
# Statistical ν / anti-ν separation

In case of single-ring：
sample divided by $N_{dcy}$

$$\bar{\nu}_e + n \rightarrow e^+ + n + \pi^-$$

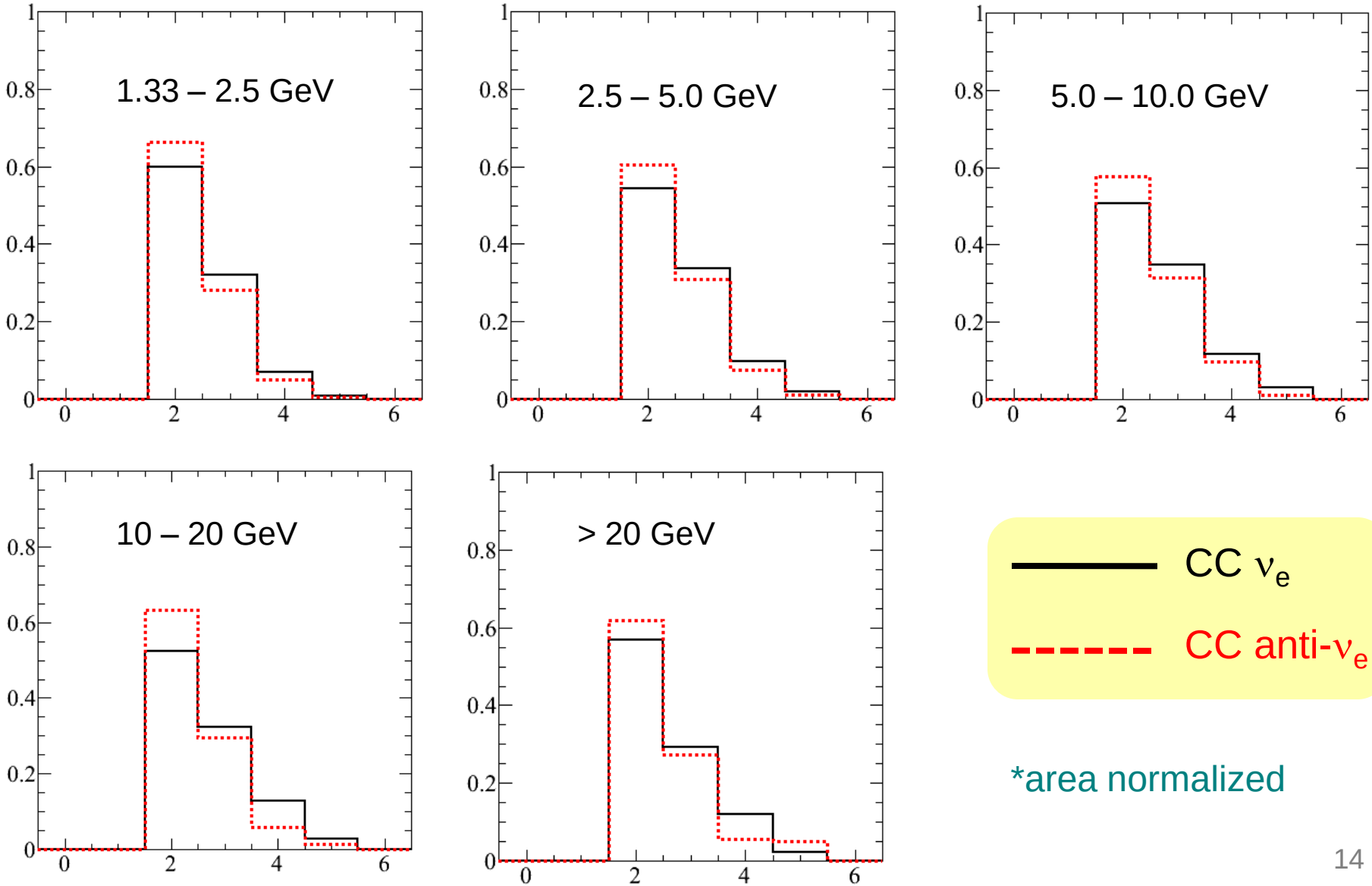



In case of multi-ring：
discriminate using Likelihood method



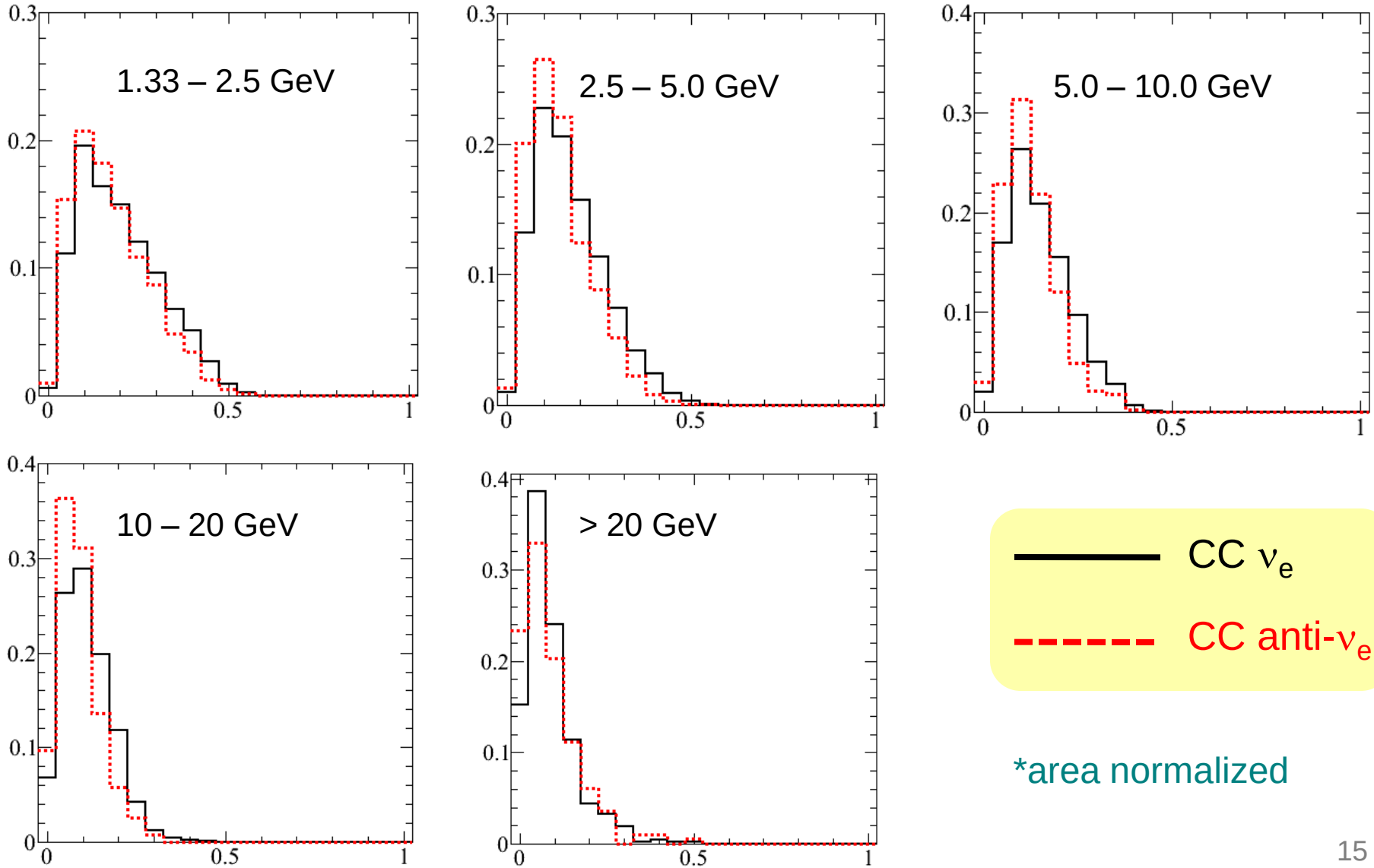

| | CC $\nu_e$ | CC anti-$\nu_e$ |
|---|---|---|
| レプトンエネルギーの割合 | 小 | 大 |
| チェレンコフリング数 | 多 | 少 |
| 横方向運動量 | 大 | 小 |
| 崩壊電子数 | 多 | 少 |

# Multi-GeV multi-ring $\nu_e$ and anti-$\nu_e$ separation likelihood (number of rings)



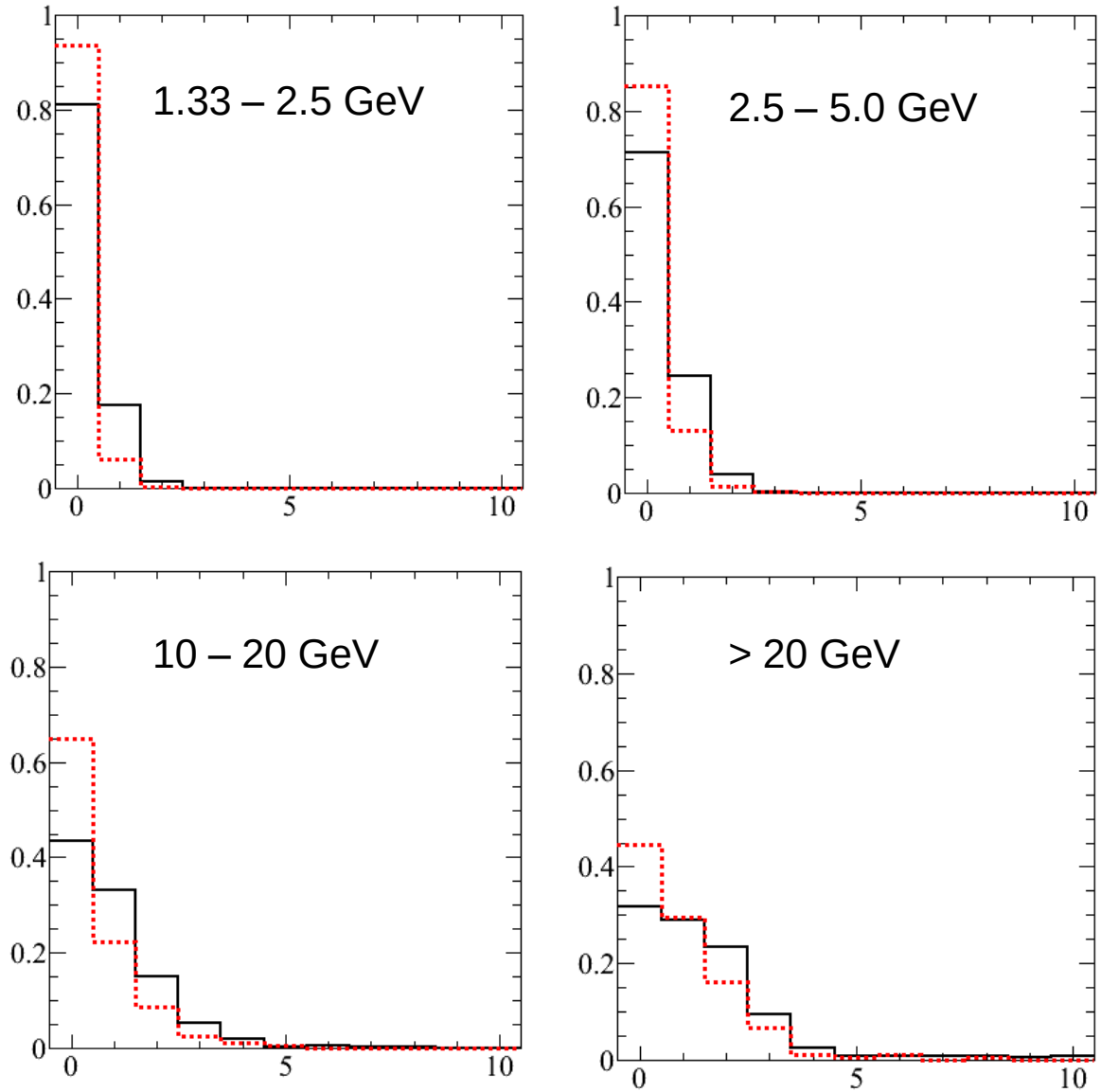

*area normalized

# Multi-GeV multi-ring $\nu_e$ and anti-$\nu_e$ separation likelihood (Transverse momentum)




*area normalized

# Multi-GeV multi-ring $\nu_e$ and anti-$\nu_e$ separation likelihood (number of decay-electrons)




CC $\nu_e$

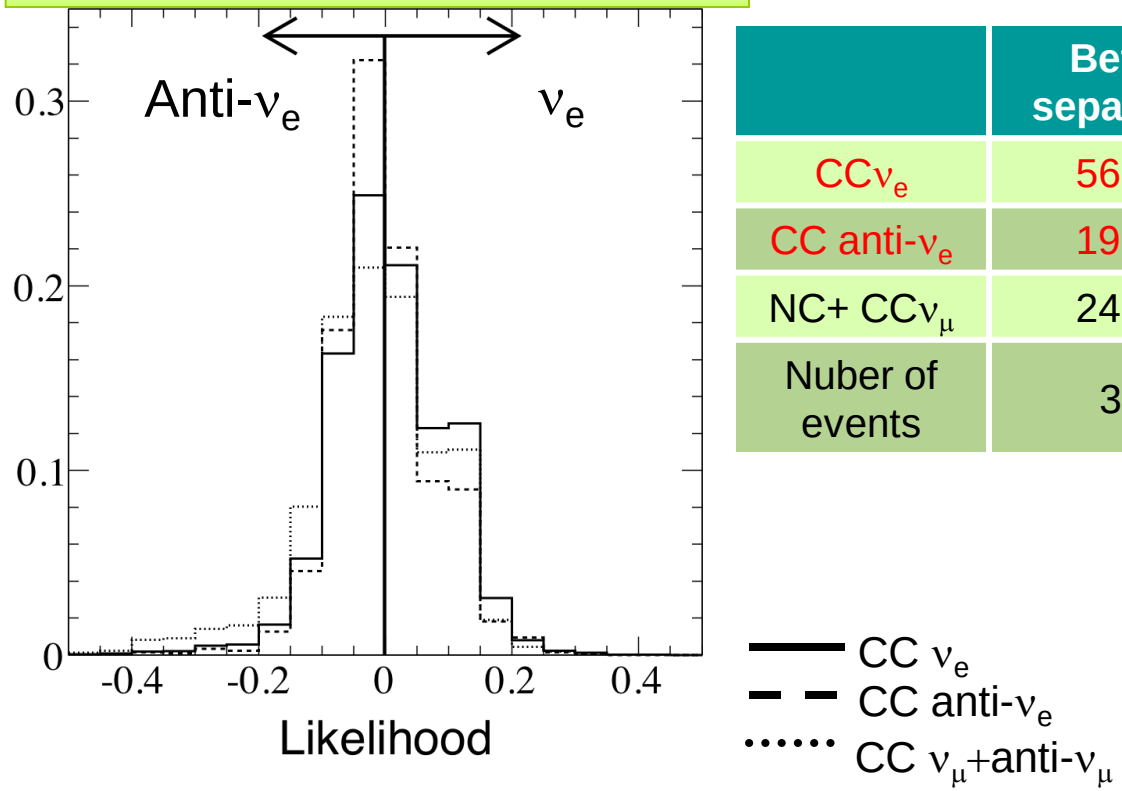
CC anti-$\nu_e$

*area normalized

# Multi-GeV multi-ring $\nu_e$ and anti-$\nu_e$ enriched samples

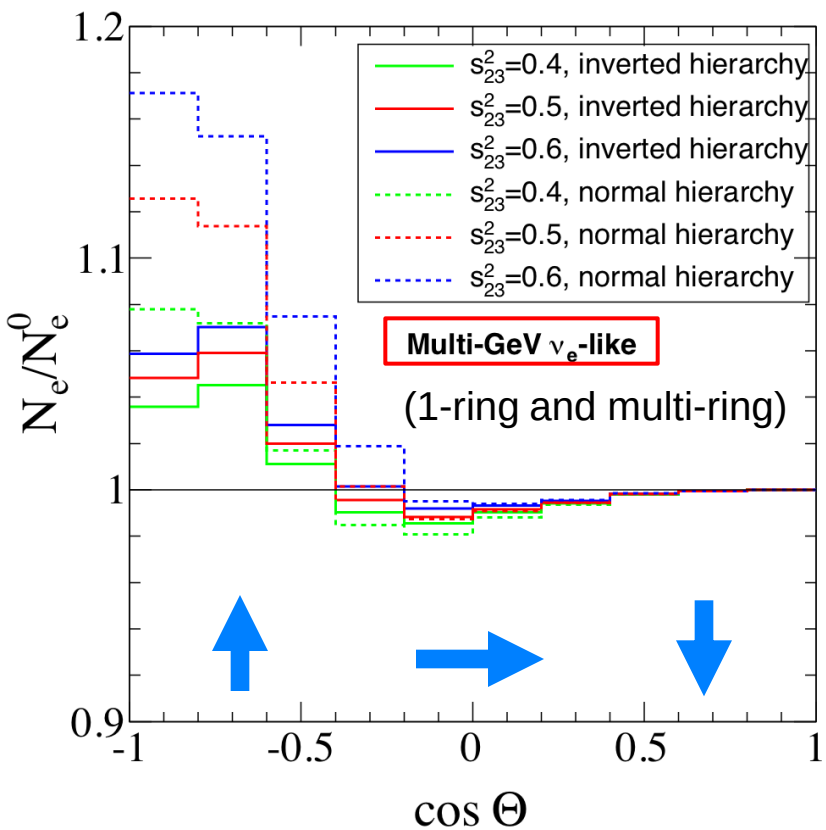
- The Multi-GeV Multi-ring e-like (MME) $\nu_e$ and anti-$\nu_e$ likelihood includes:
  - Number of decay-electrons
  - Number of identified Cherenkov rings
  - Transverse momentum (divided by total momentum of rings)

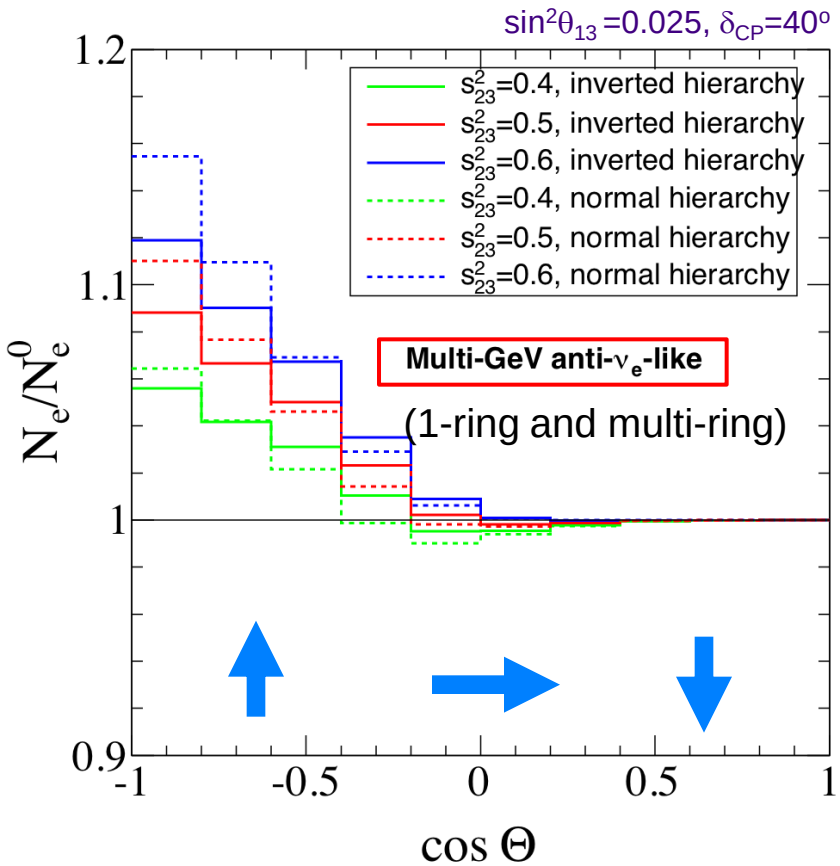
Likelihood to separate $\nu_e$ and anti- $\nu_e$(SK4)




| | Before separation | $\nu_e$-like | Anti-$\nu_e$-like |
|---|---|---|---|
| CC$\nu_e$ | 56.1% | 59.4% | 53.1% |
| CC anti-$\nu_e$ | 19.5% | 17.9% | 21.0% |
| NC+ CC$\nu_\mu$ | 24.5% | 22.7% | 25.9% |
| Nuber of events | 341 | 161.9 | 168.1 |

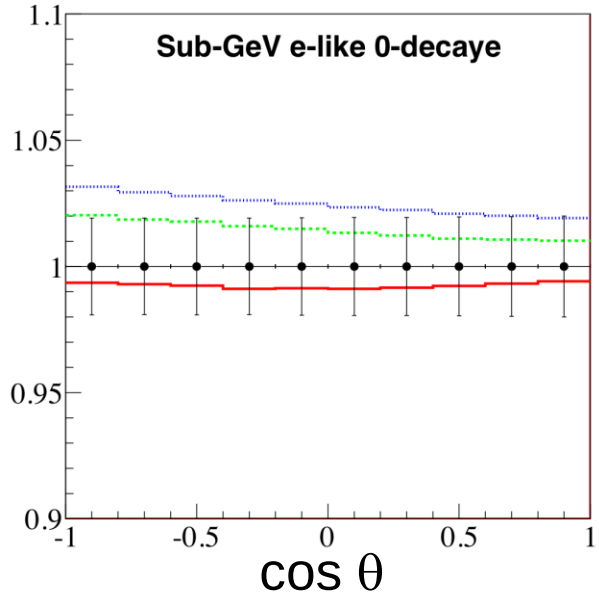
# Electron enhancement in zenith angle plot

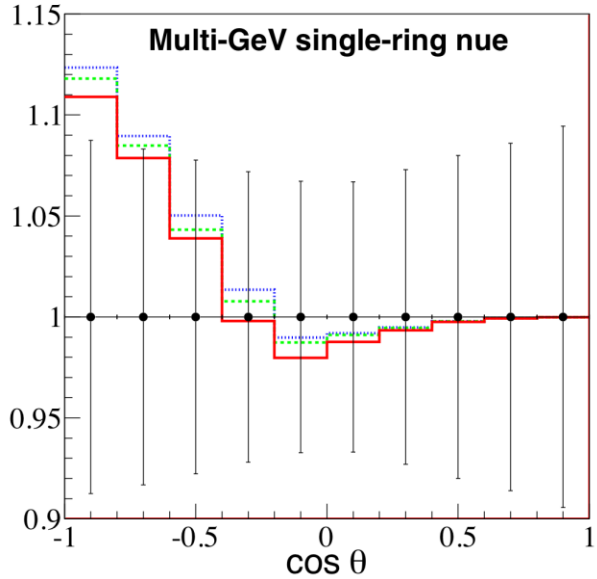


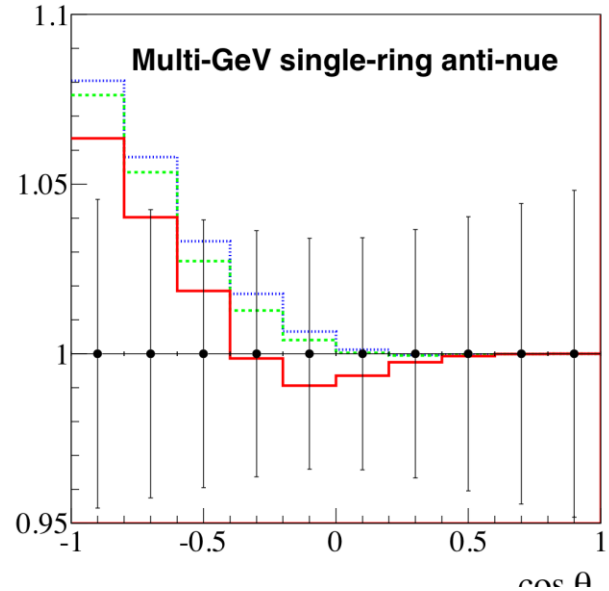



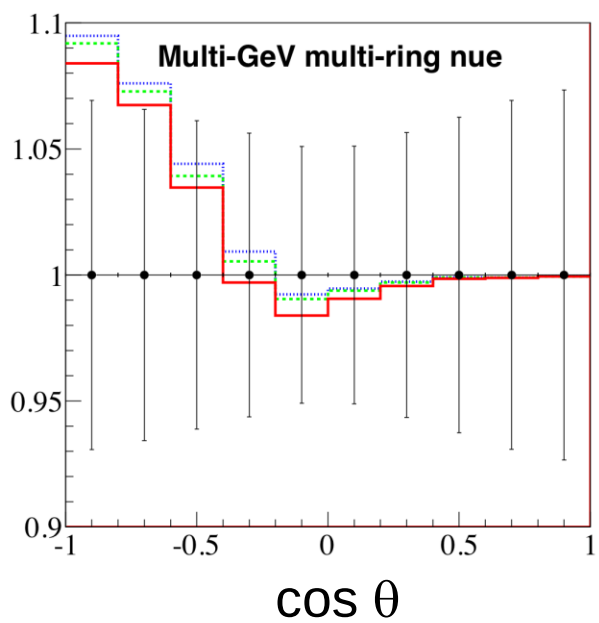

Normal、Invertedとも上向き方向に電子事象の超過が見られるが、$\nu_e$-likeとanti-$\nu_e$-likeでは増加量に違いがみられる。

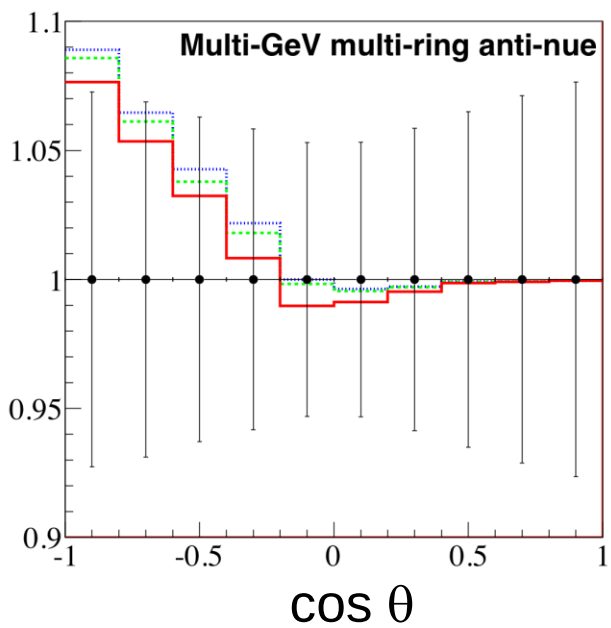
# Oscillation Effect (CP phase)




80°

220°

300°

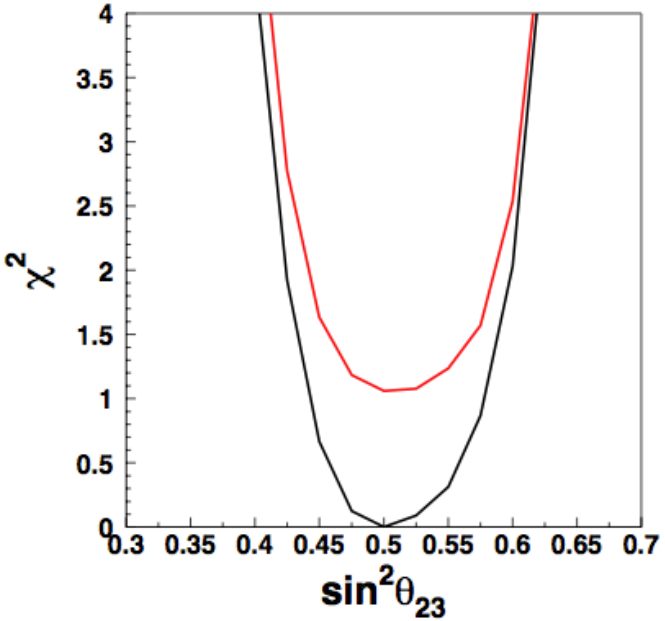
Livetime: 10 years

$\Delta m^2_{12} = 7.6 \times 10^{-5}\ eV^2$
$\Delta m^2_{23} = 2.66 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12}=0.304$
$\sin^2\theta_{13}=0.025$
$\sin^2\theta_{23}=0.425$

# Expected hierarchy sensitivity

| | Assumed |
|---|---|
| $\Delta m^2_{23}$ | 2.66 x $10^{-3}$ $eV^2$ |
| $\sin^2\theta_{23}$ | 0.5 |
| $\delta$CP | 300 deg |
| | Normal hierarchy |

$\sin^2\theta_{13}$ =0.025 fixed
($\sin^2 2\theta_{13}$ =0.1)

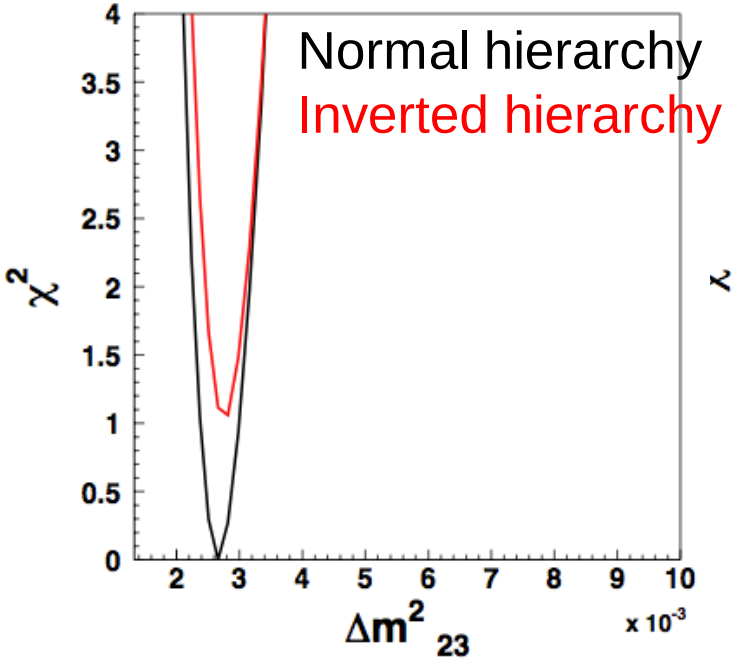


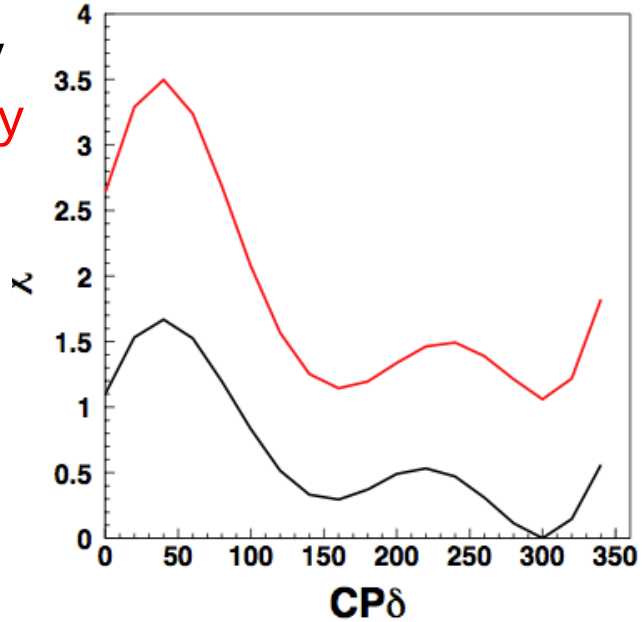

In case of NH :

$\chi^2$(IH)- $\chi^2$(NH) = 1.06

In case of IH :

$\chi^2$(NH)- $\chi^2$(IH) = 0.90

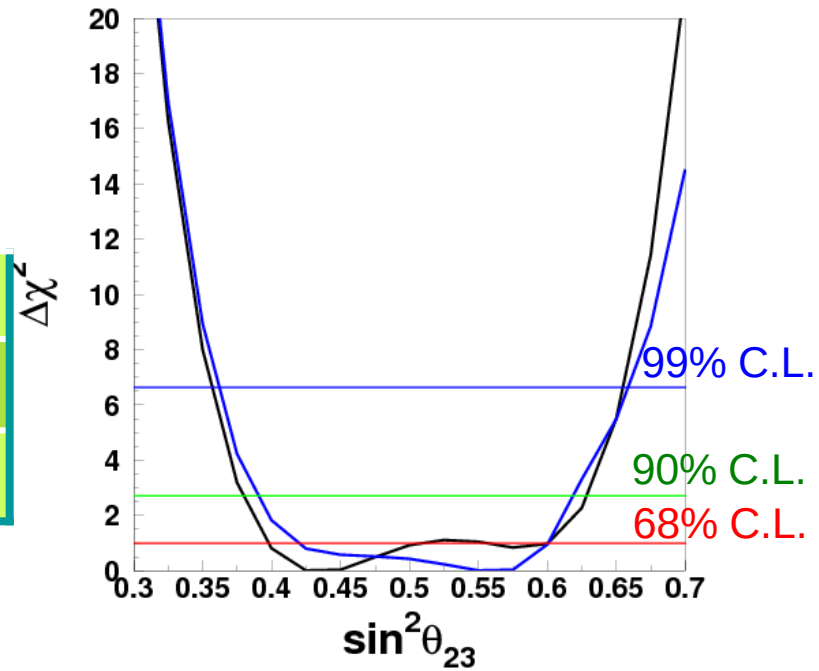


# Fitting result assuming NH

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

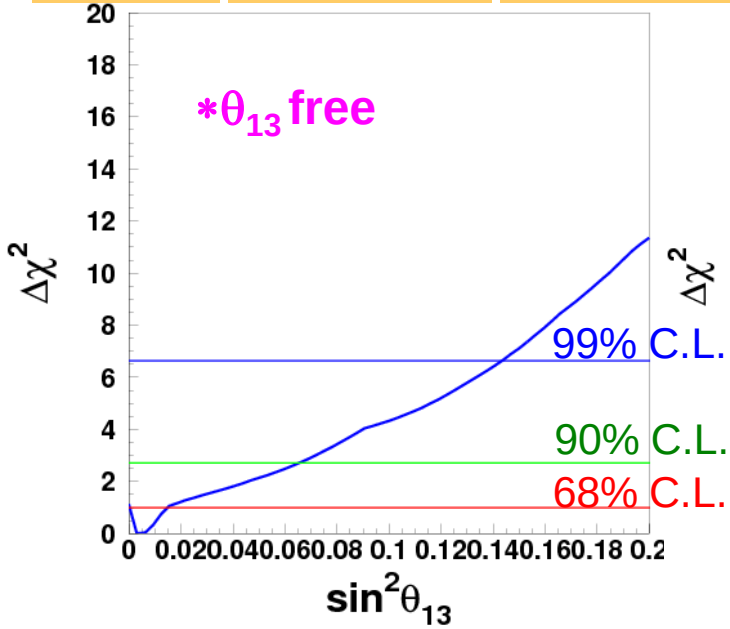
| | | |
|---|---|---|
| $\Delta m^2_{32}$ | $\Delta m^2_{32} = 2.66 \pm^{0.15}_{0.40} \times 10^{-3} eV^2 (1\sigma)$ | |
| $\sin^2\theta_{23}$ | 0.425 | 0.380 - 0.628 (90%CL) |
| $\delta$CP | 300° | All allowed at 90% C.L. |

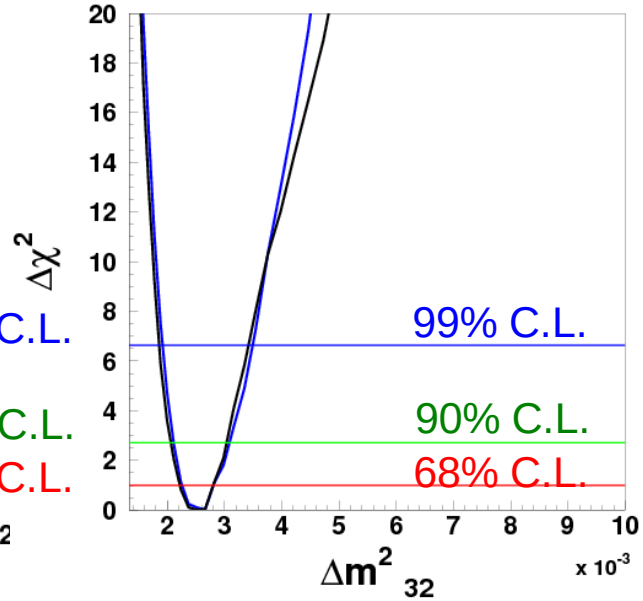


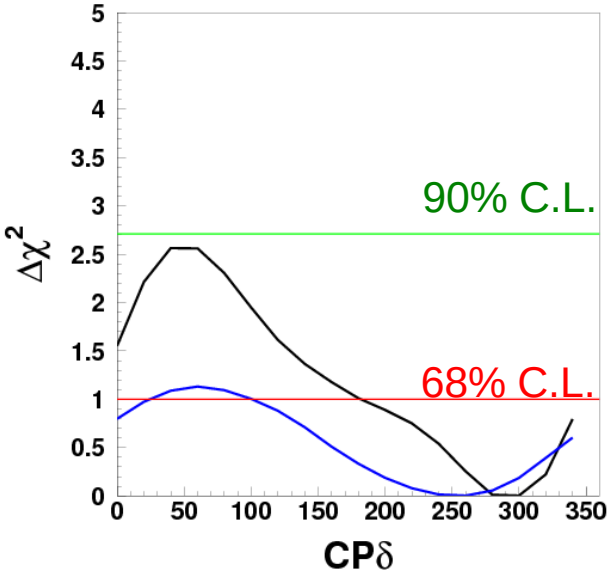

$\chi^2_{min}$ = 556.7 / 477 dof

| | | |
|---|---|---|
| $\sin^2\theta_{13}$ | 0.003 | 0 - 0.0655 |

Free $\theta_{13}$
Fixed reactor $\theta_{13}$



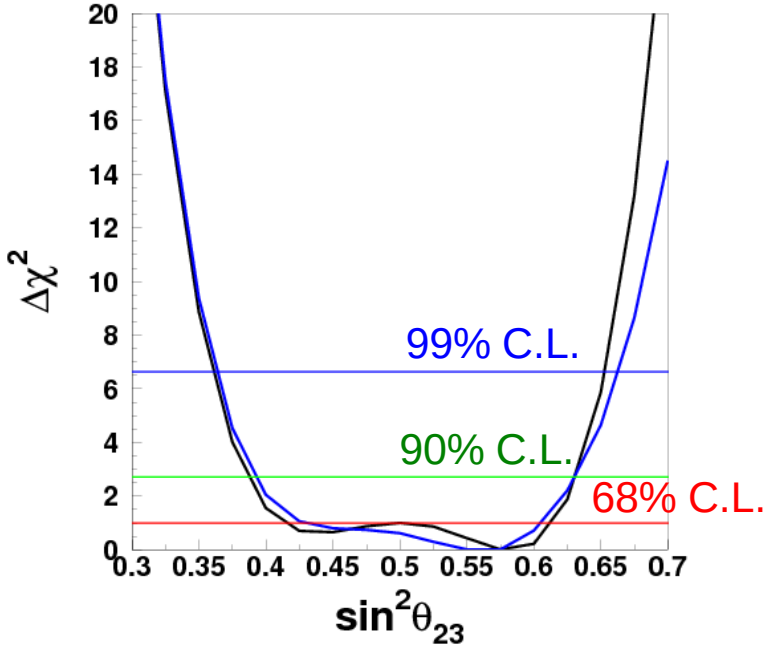



# Fitting result assuming IH

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

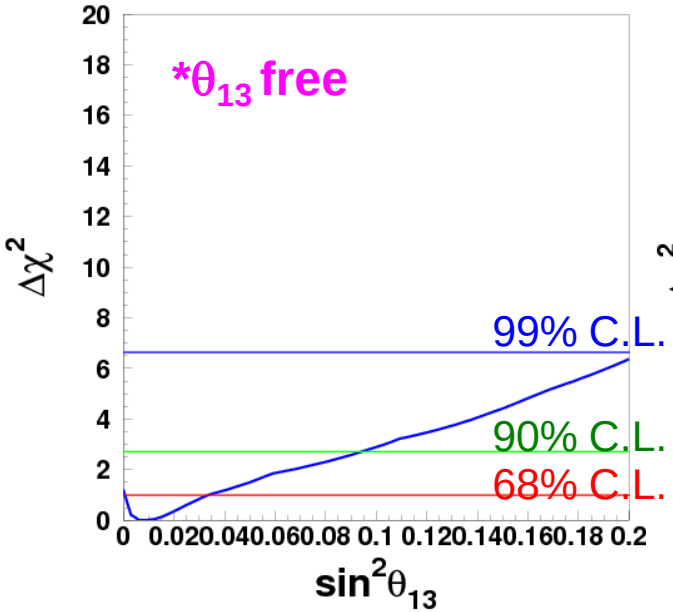
| | | |
|---|---|---|
| $\Delta m^2_{32}$ | $\Delta m^2_{32} = 2.66 \pm^{0.17}_{0.23} \times 10^{-3} eV^2 (1\sigma)$ | |
| $\sin^2\theta_{23}$ | 0.575 | 0.388 - 0.630 (90%CL) |
| $\delta$CP | 260° | All allowed at 90% C.L. |

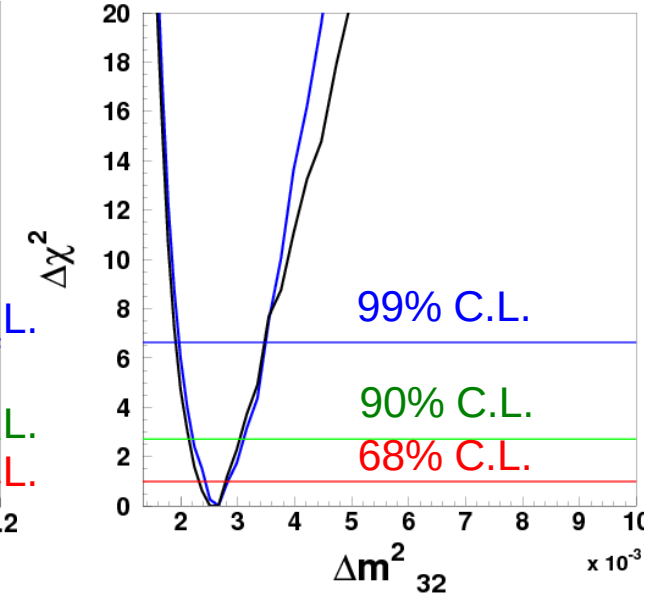


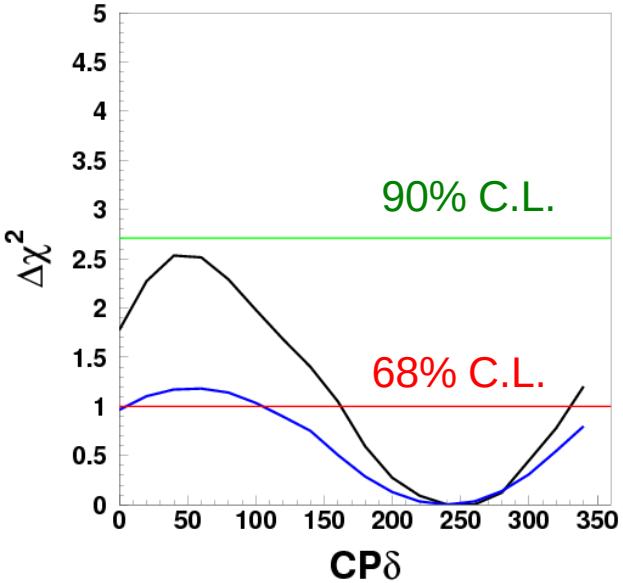

**$\chi^2_{min}$ = 555.5 / 477 dof**

| | | |
|---|---|---|
| $\sin^2\theta_{13}$ | 0.006 | 0 - 0.0944 |

Free $\theta_{13}$
Fixed reactor $\theta_{13}$



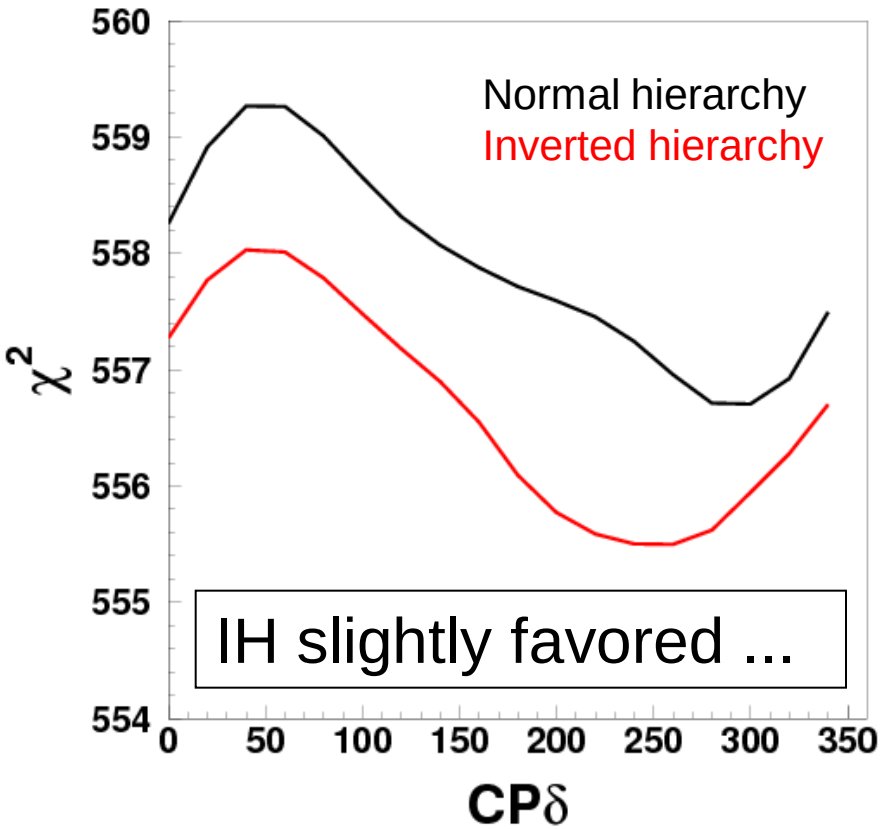



**Normal hierarchy: $\chi^2_{min}$ = 556.7 / 477 dof**

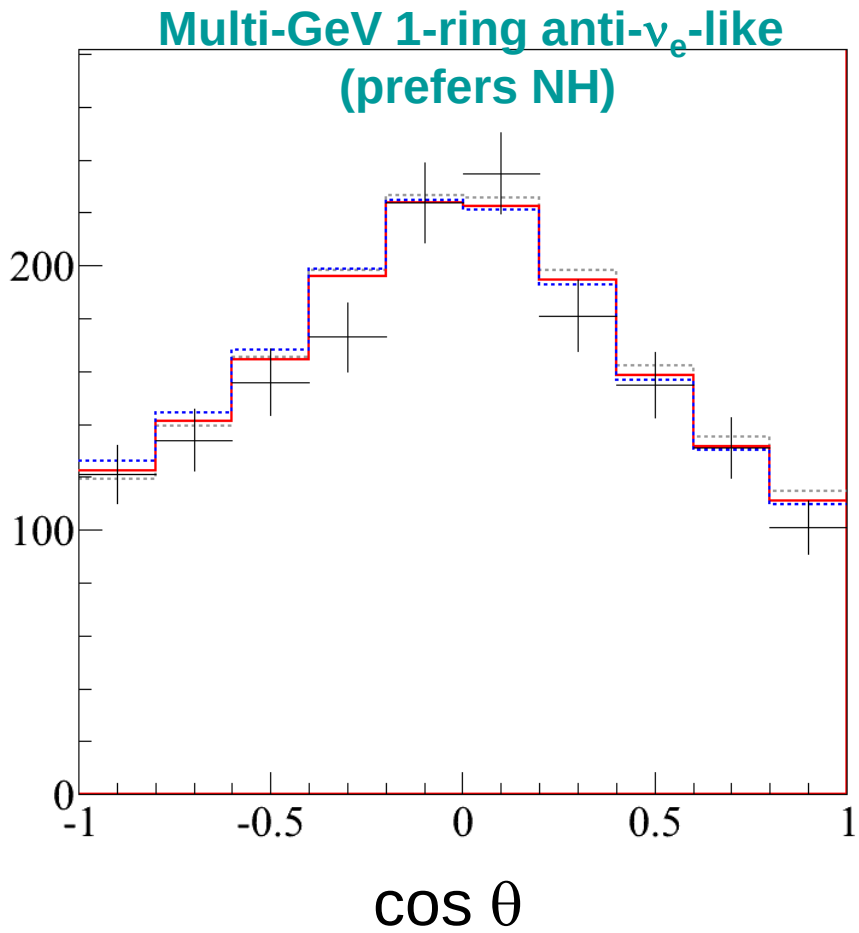
**Inverted hierarchy: $\chi^2_{min}$ = 555.5 / 477 dof**

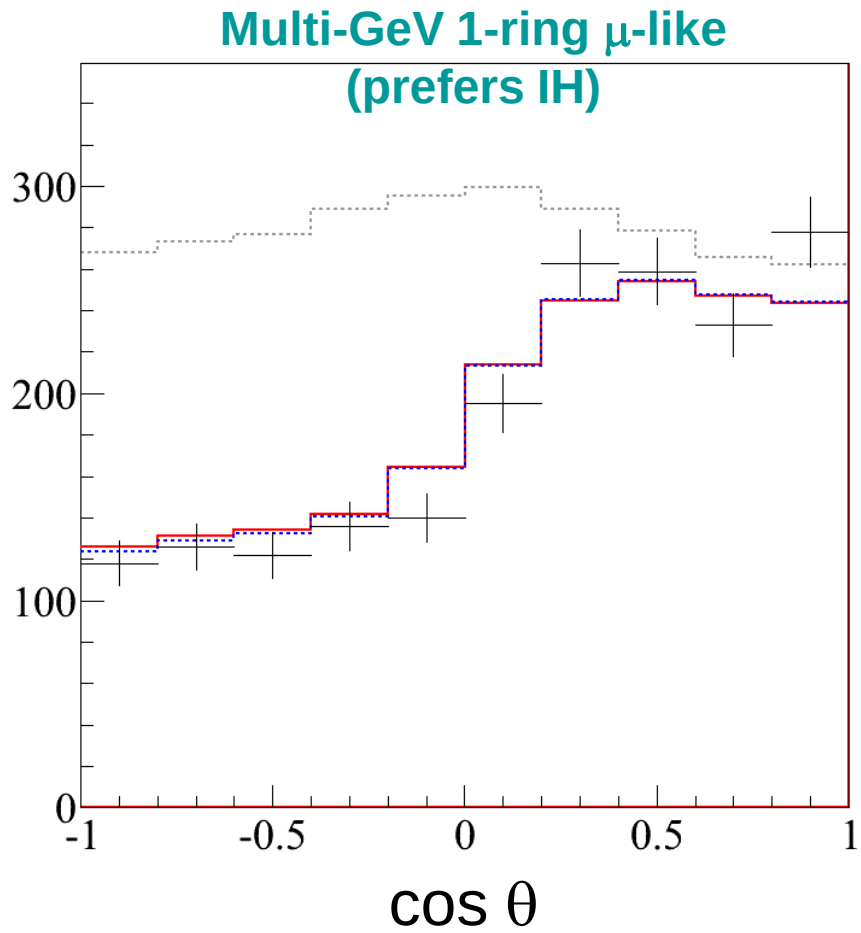
$$c^2_{\min}(NH) - c^2_{\min}(IH) = 1.2$$

(Sensitivity for mass hierarchy:
$\chi^2$(IH)- $\chi^2$(NH) = 1.06
$\chi^2$(NH)- $\chi^2$(IH) = 0.90)



# samples to provide large $\Delta\chi^2$ for MH




+ data

Normal hierarchy

Inverted hierarchy

No osc

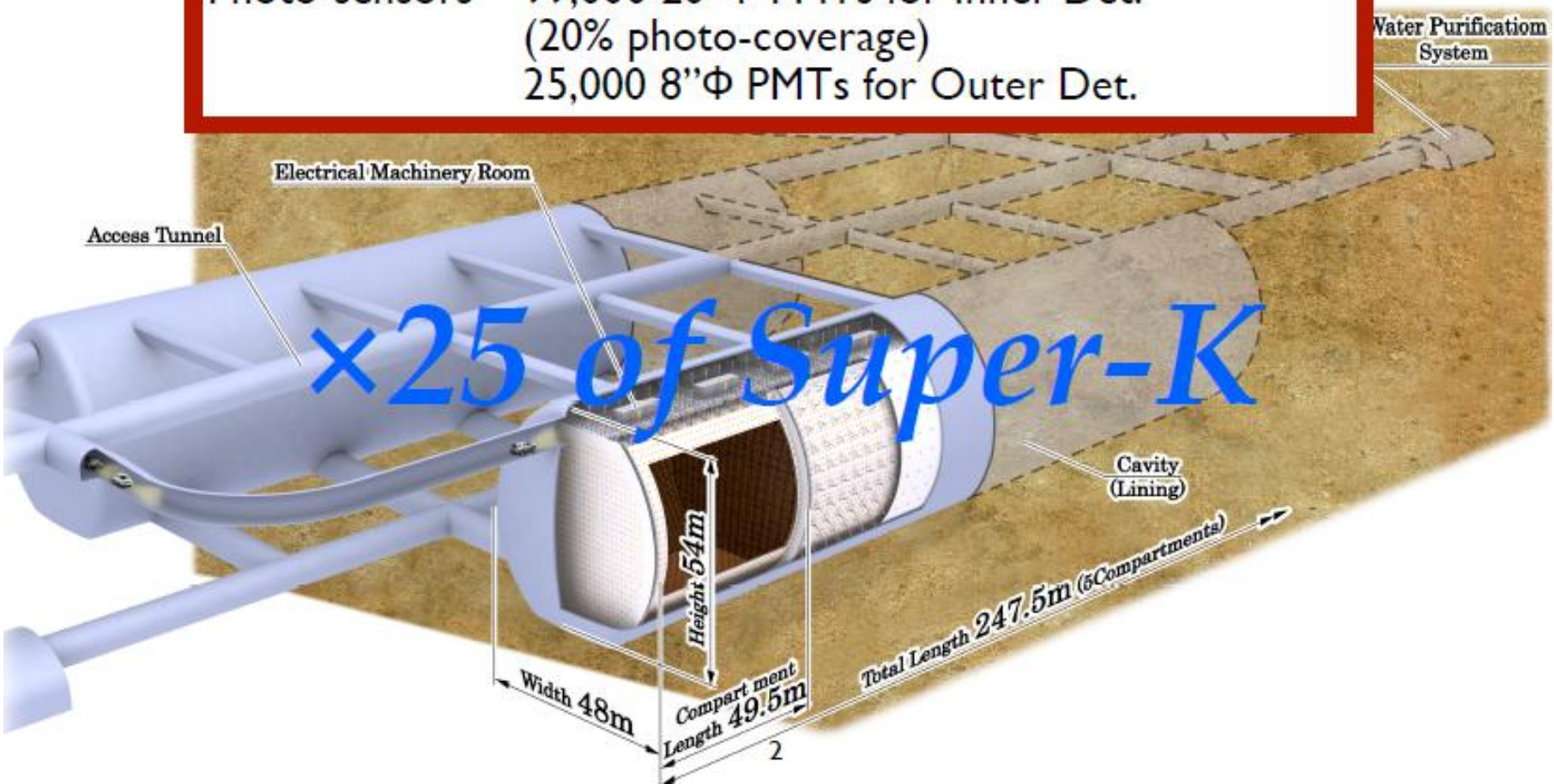
NH: $\sin^2\theta_{23} = 0.425$ (best fit)
IH: $\sin^2\theta_{23} = 0.575$ (best fit)

*SK1+2+3+4 data

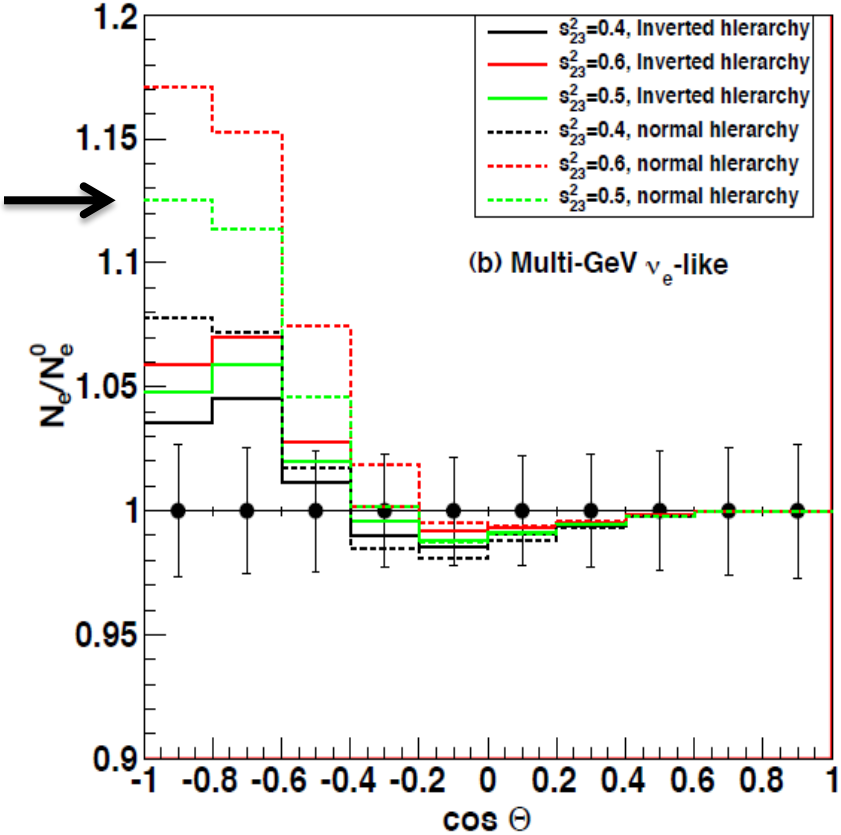
# FUTURE POSSIBILITIES

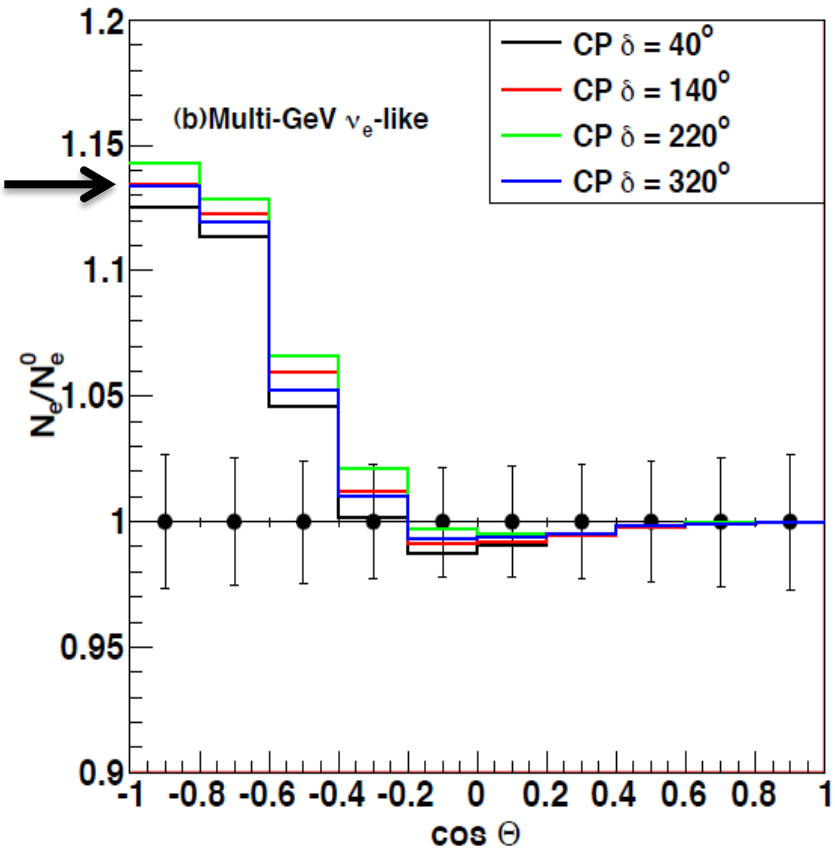
# Hyper-Kamiokande

| | |
|---|---|
| Total Volume | 0.99 Megaton |
| Inner Volume | 0.74 Mton |
| Fiducial Volume | 0.56 Mton (0.056 Mton × 10 compartments) |
| Outer Volume | 0.2 Megaton |
| Photo-sensors | 99,000 20"Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8"Φ PMTs for Outer Det. |

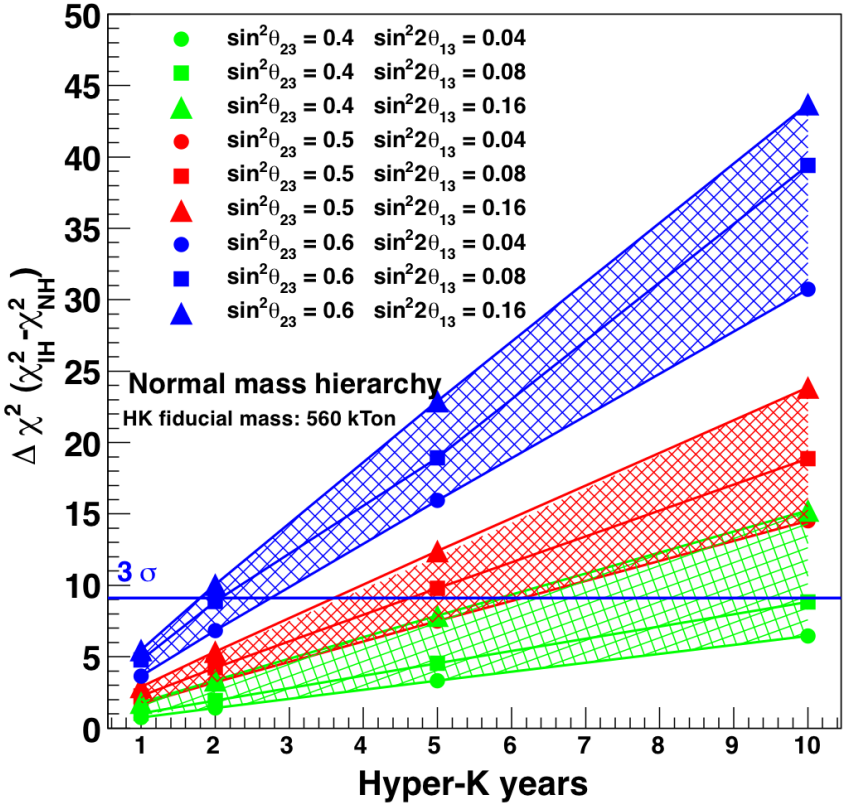


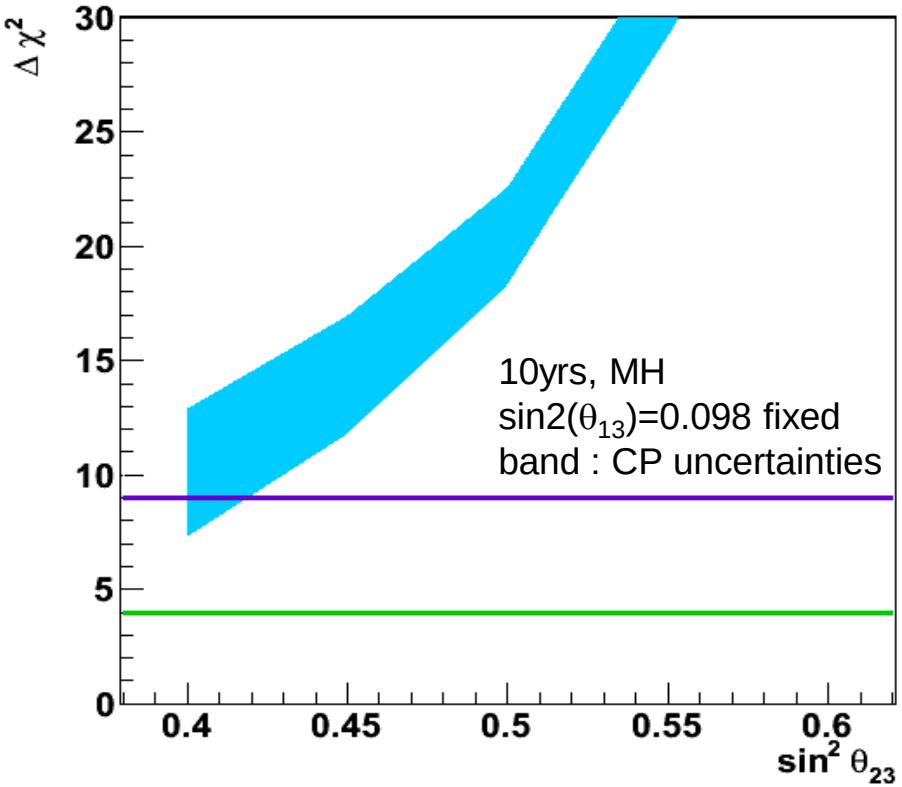
# Expected Effects : electron-like samples



# Hyper-K sensitivity

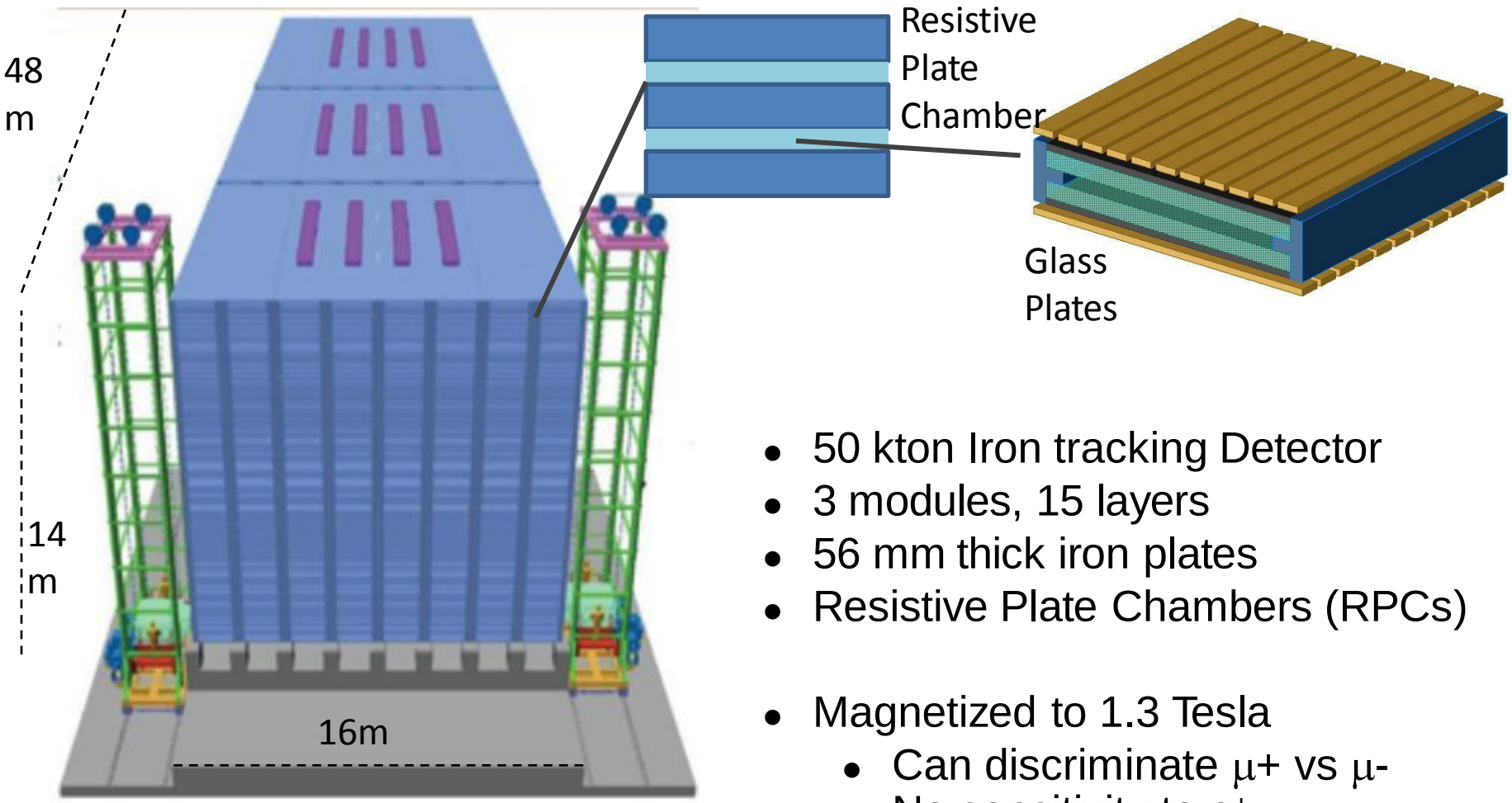



In 5 yrs, 3 sigma sensitivity for $\sin^2(\theta_{23})>0.5$

In 10 yrs, 3 sigma sensitivity for $\sin^2(\theta_{23})>0.4$

# ICAL at the India-based Neutrino Observatory (INO)

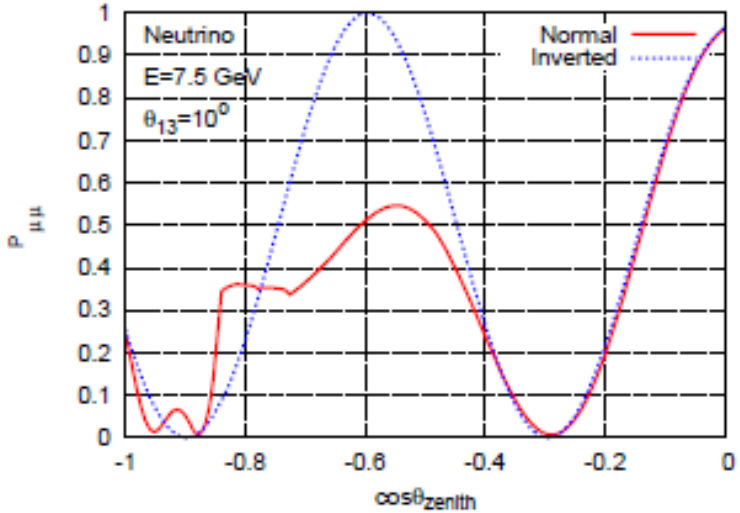


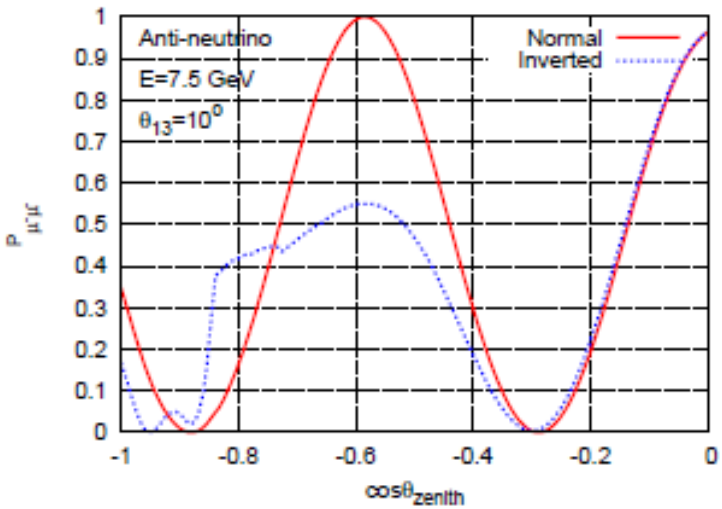

- 50 kton Iron tracking Detector
- 3 modules, 15 layers
- 56 mm thick iron plates
- Resistive Plate Chambers (RPCs)

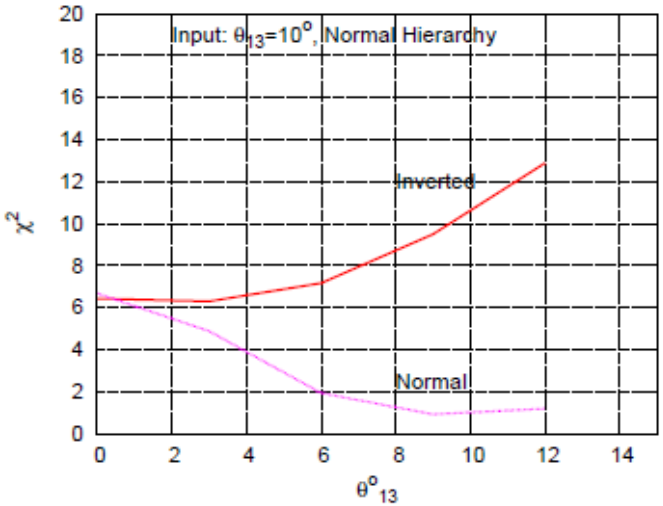
- Magnetized to 1.3 Tesla
  - Can discriminate $\mu$+ vs $\mu$-
  - No sensitivity to $e^{+,-}$

# $\nu_\mu \rightarrow \nu_\mu$ probability

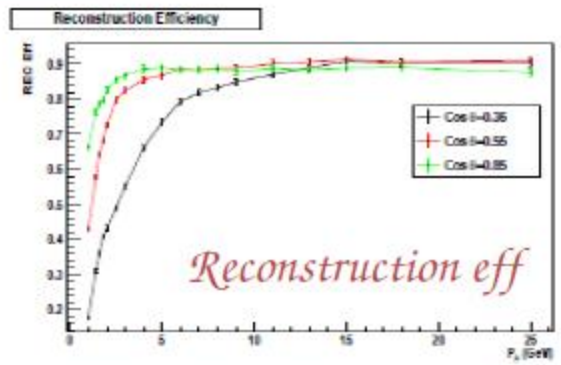
E=7.5GeV, θ13=10 degree

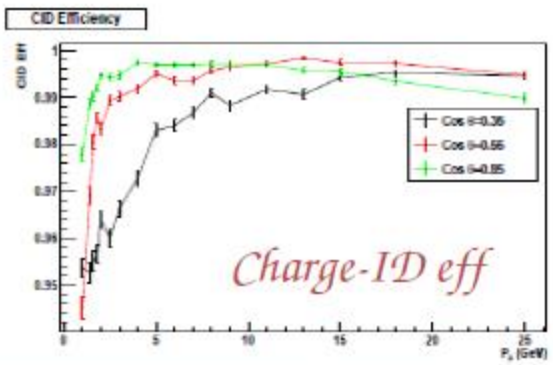


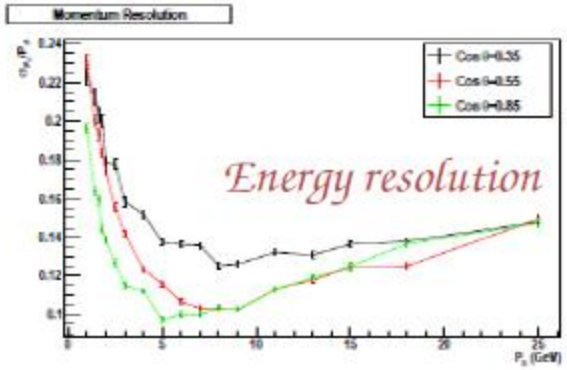



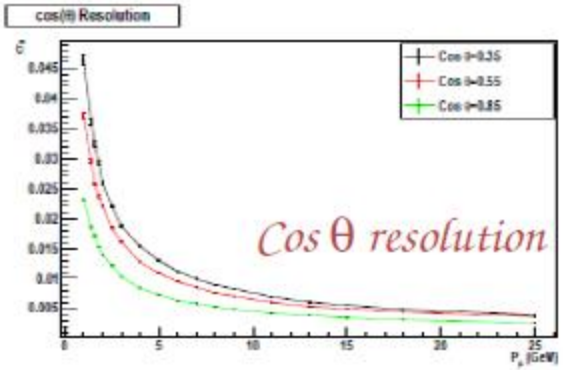



# Muon efficiencies and resolutions



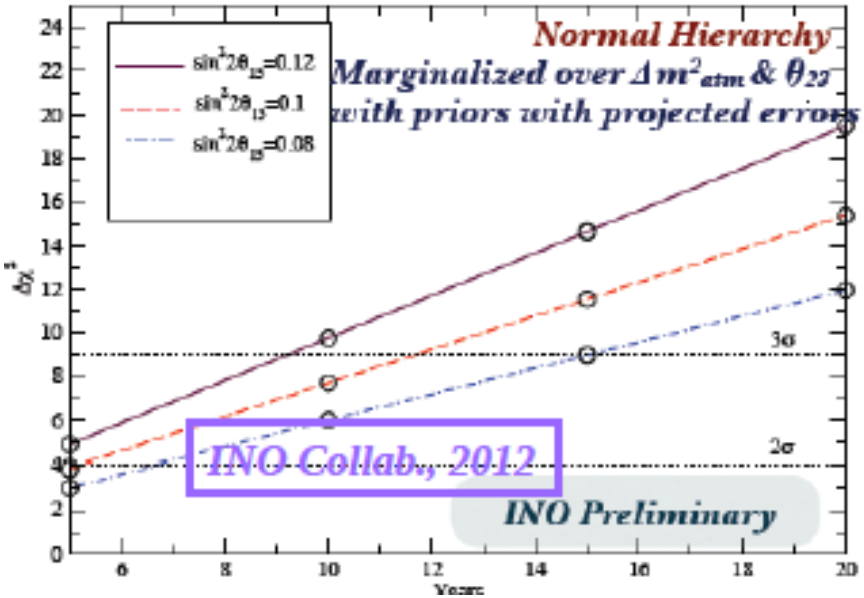



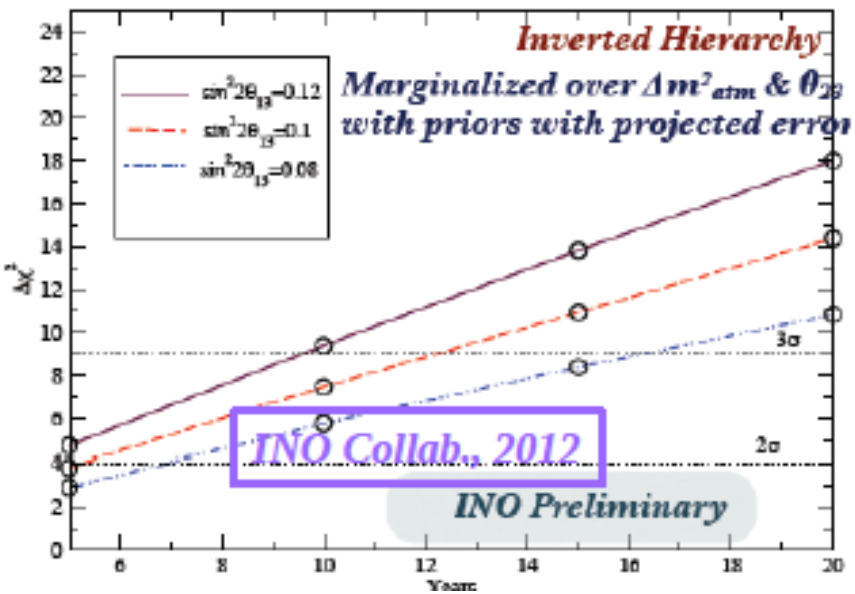




*Talk by Meghna*

# Mass hierarchy sensitivity with ICAL-INO



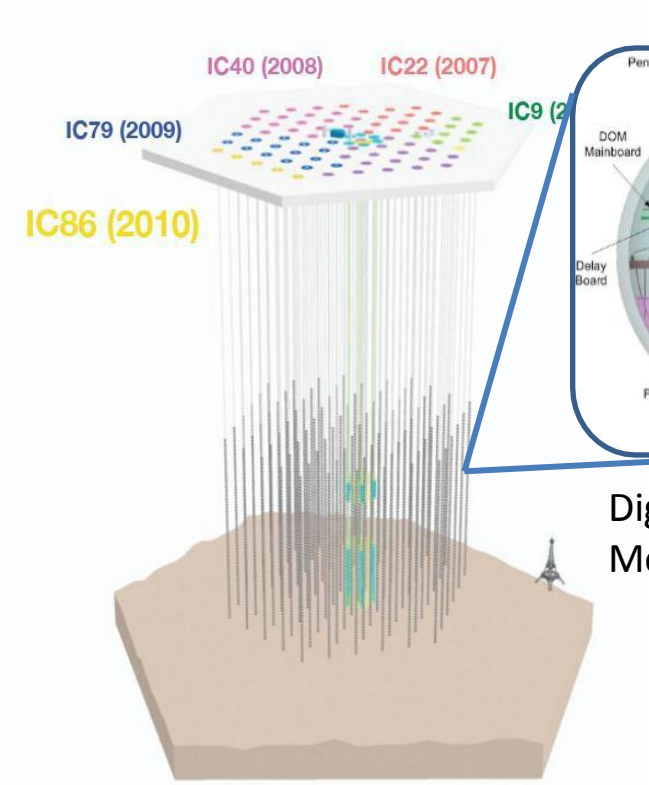



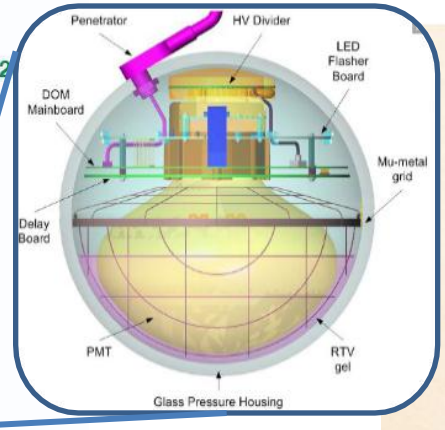

For $\sin 2(\theta_{23})=0.5$, $\sin 2(2\theta_{13})=0.1$:

In 5 yrs (250kt-yr), 2 sigma sensitivity for MH

In 10 yrs (500kt-yr), 2.7 sigma sensitivity for MH

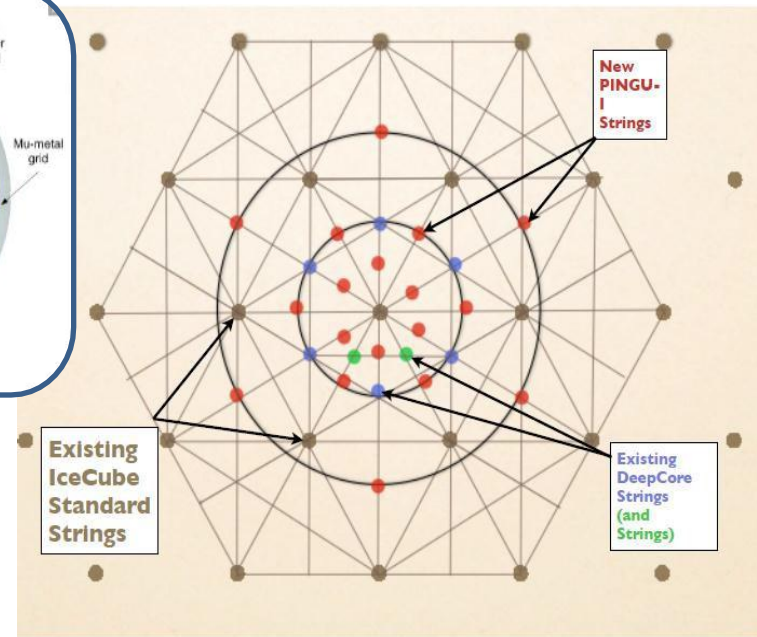
## IceCube + DeepCore




Digital Opitical Module (DOM)

## PINGU



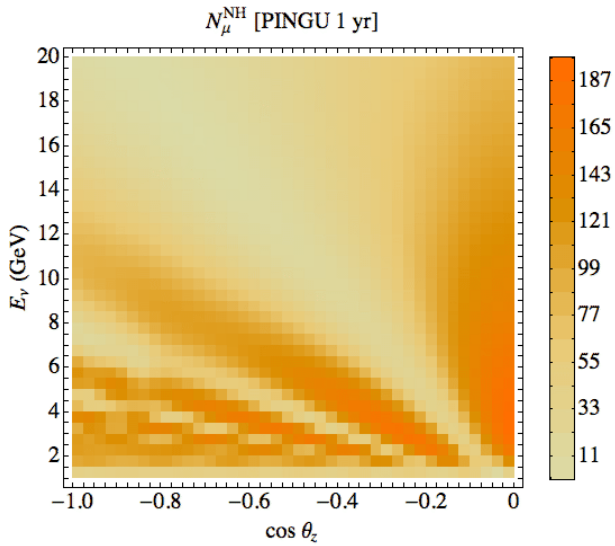

- Higher phototube densities lower the energy threshold of the detector
- Less densely instrumented volume can be used as a veto

| IceCube | DeepCore | PINGU | PINGU-II |
|---|---|---|---|
| PMT density | | | |
| Energy Threshold | | | |
| ~100 GeV | ~10 GeV | ~1 GeV | ~100 MeV |

Oscillation sensitivity →

*E. Kh. Akhmedov, S. Razzaque, A. Y. Smirnov.*
*arXiv: 1205.7071*

Expected events for $E_\nu$ vs $\cos\theta$ :



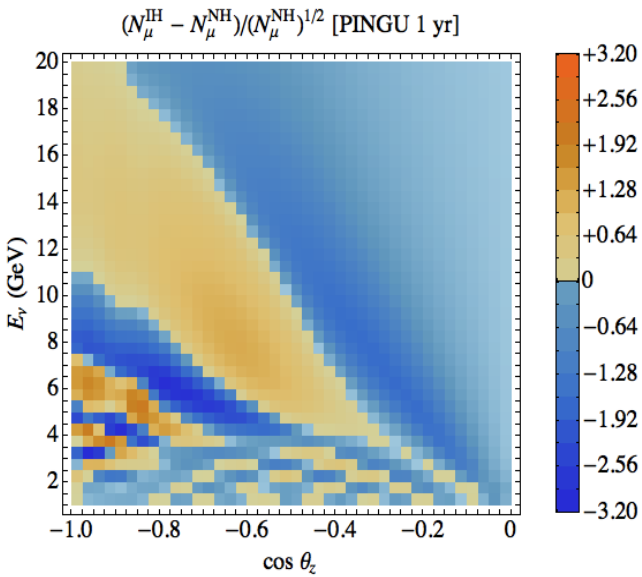

Hierarchy asymmetry:

$$S_{ij} = \frac{[N_{ij}^{IH} - N_{ij}^{NH}]}{\sqrt{N_{ij}^{NH}}}$$

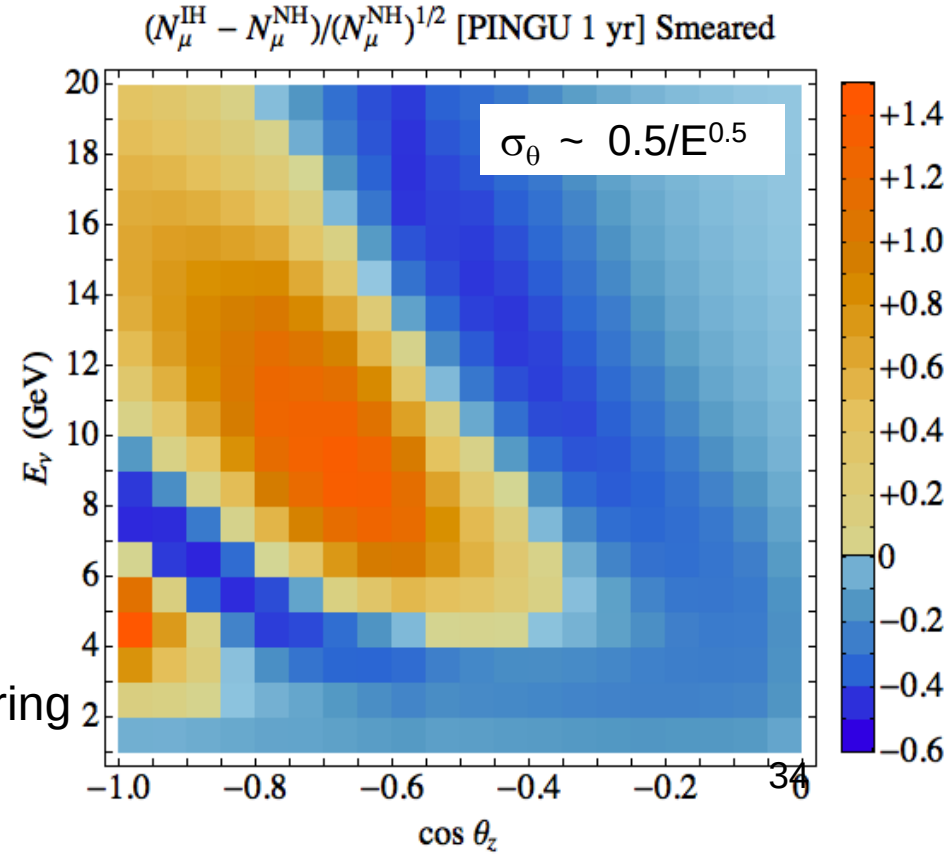
Smearing due to event reconstruction:

$\sigma_E = A\,E_\nu$ $\qquad$ $\sigma_\theta = B\,(m_p / E_\nu)^{1/2}$

Asymmetry



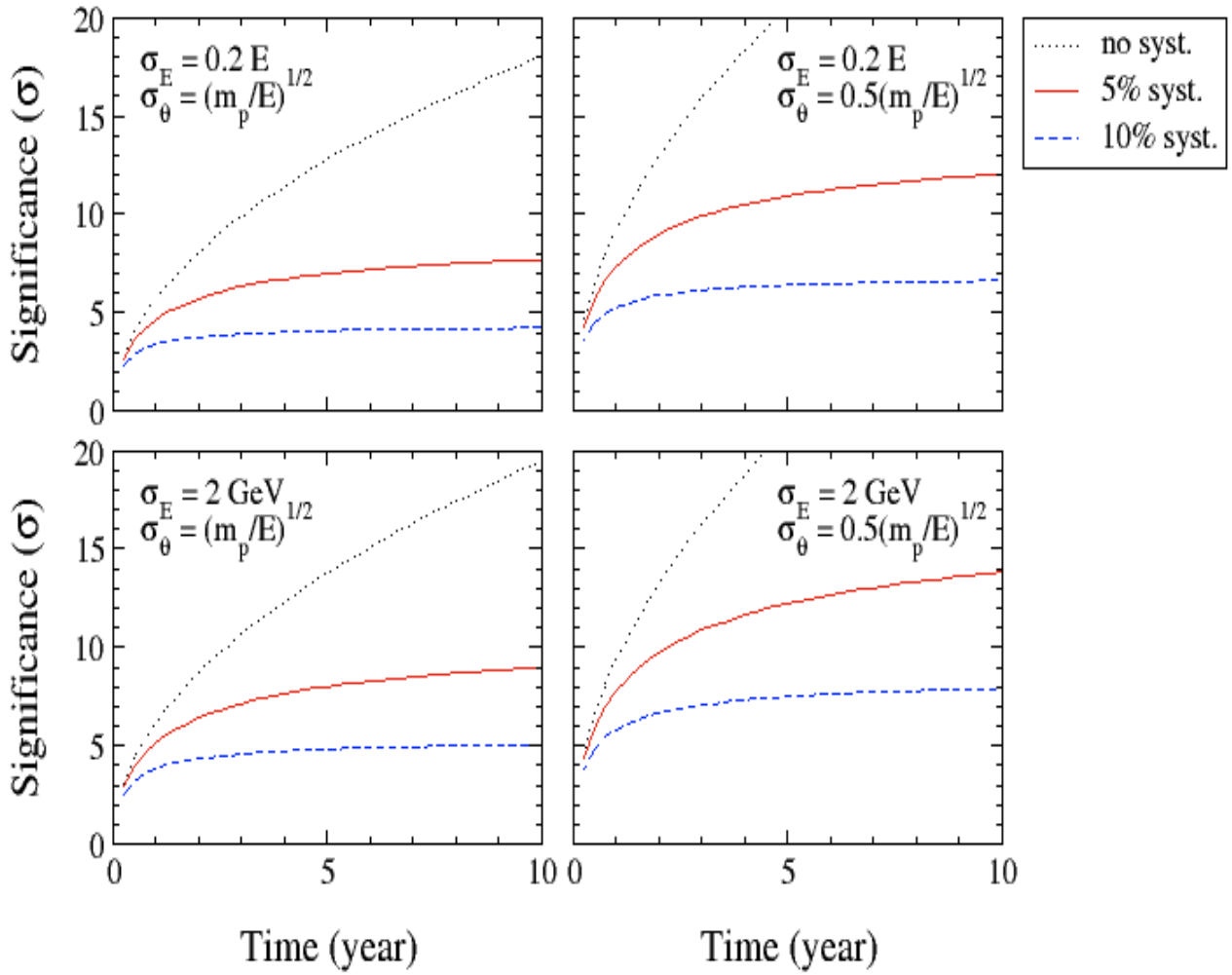

Smearing



# Total significance

$$S^{tot} = \sqrt{\sum_{ij} S_{ij}^2}$$

Could increase significance by improvement of reconstruction for neutrino energy and direction



# Summary

- Mass hierarchy will be measured by atmospheric neutrinos due to non-zero $\theta_{13}$ and matter effect in the Earth
  - $\nu\mu \rightarrow \nu e$ resonance happens for either $\nu$ or anti-$\nu$ depending on MH
- Super-K has ~1 sigma sensitivity by statistical $\nu$ and anti-$\nu$ separation → Need more statistics !
- MH determination is promising in future experiments using Mega-ton detector
  - Hyper-K
  - INO
  - IceCube/DeepCore/PINGU