Recent results of the atmospheric ν analysis in SK

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for the Super-Kamiokande collaboration

1. Introduction
2. Three flavor neutrino oscillation analysis using SK I~IV data
3. ν_τ appearance search using SK I~III data

Super-Kamiokande collaboration

- Kamioka Observatory, ICRR, University of Tokyo
- Research Center for Cosmic Neutrinos (RCCN),
  ICRR, University of Tokyo
- Gifu University
- Kobe University
- High Energy Accelerator Research Organization (KEK)
- Kavli Institute for the Physics and Mathematics of the Universe
  (IPMU), Todai Institutes for Advanced Study (TODIAS),
  The University of Tokyo
- University of Kyoto
- Miyagi University of Education
- Nagoya University
- Okayama University
- Osaka University
- Tokai University
- Junior College, Fukuoka Institute of Technology
- Shizuoka University of Welfare
- University of Tokyo
- Tokai University

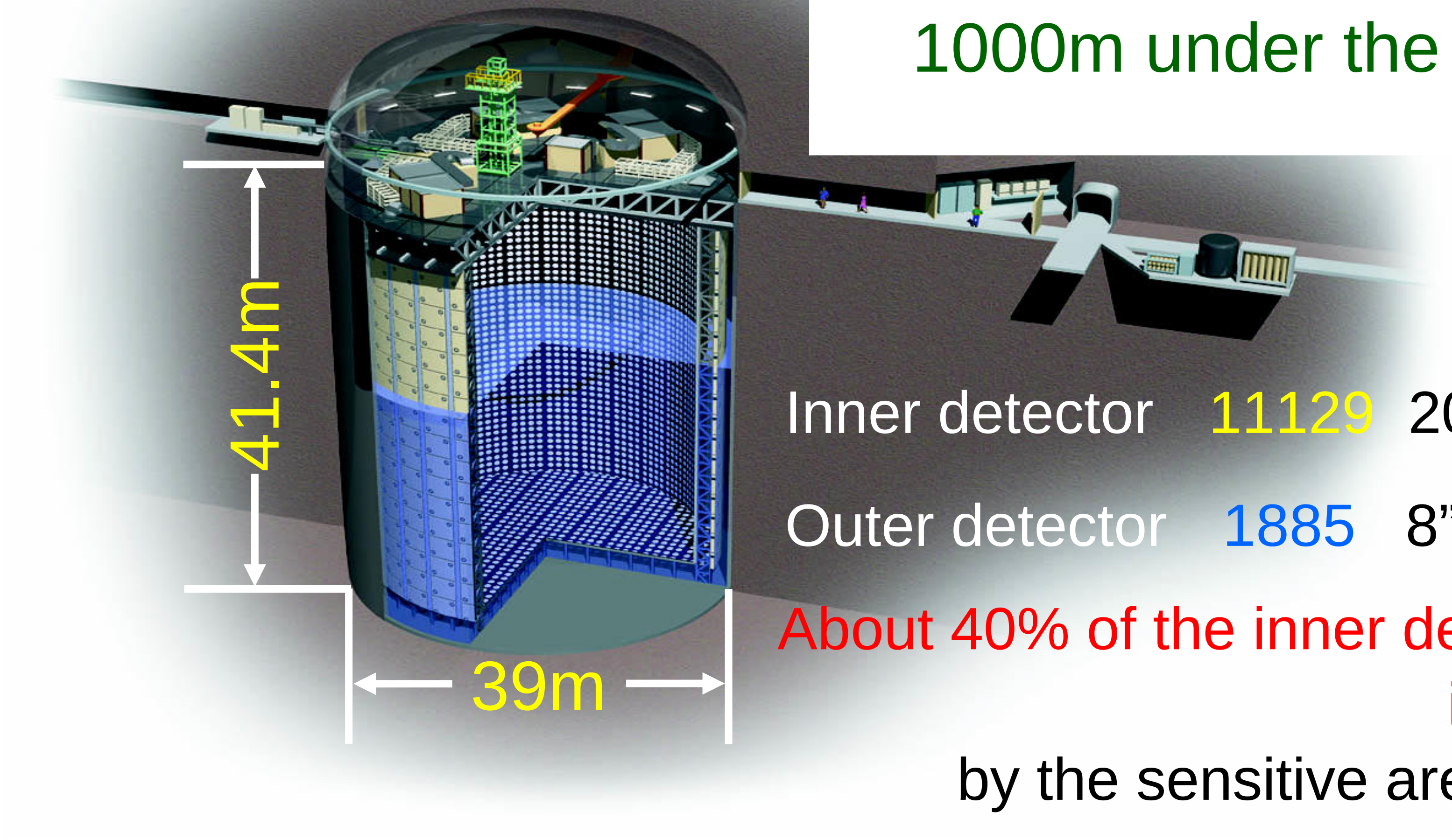
- Boston University
- University of British Columbia
- University of California, Irvine
- California State University
- Chonnam National University
- Duke University
- University of Hawaii
- University Autonoma Madrid
- University of Regina
- Stony Brook University
- Seoul National University
- Sungkyunkwan University
- University of Toronto
- TRIUMF
- Tsinghua University
- University of Warsaw
- University of Washington

Super-Kamiokande detector

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

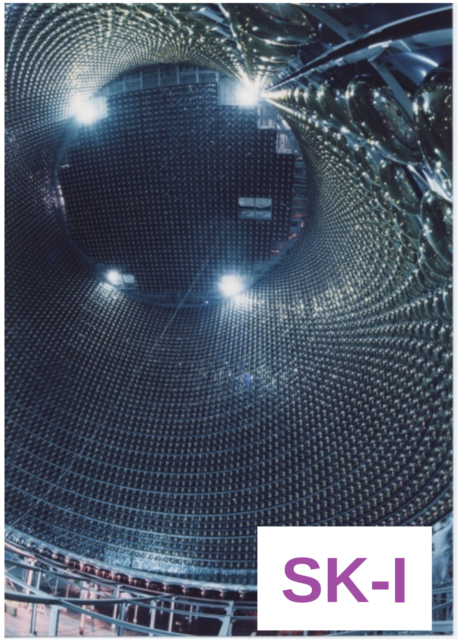
Operation started in Apr. 1996.

Super-Kamiokande detector

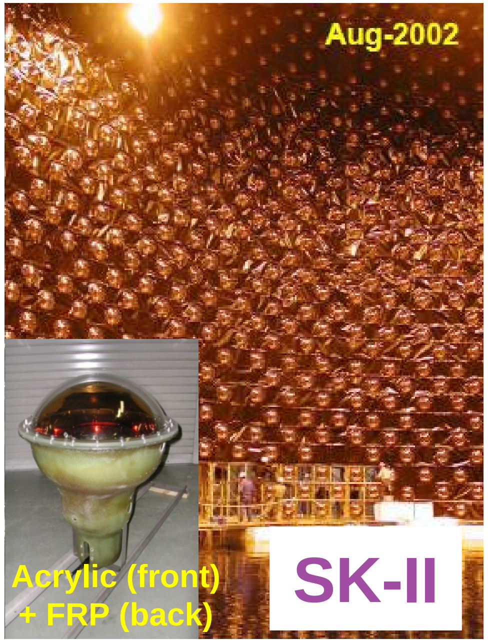
History of the SK detector

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

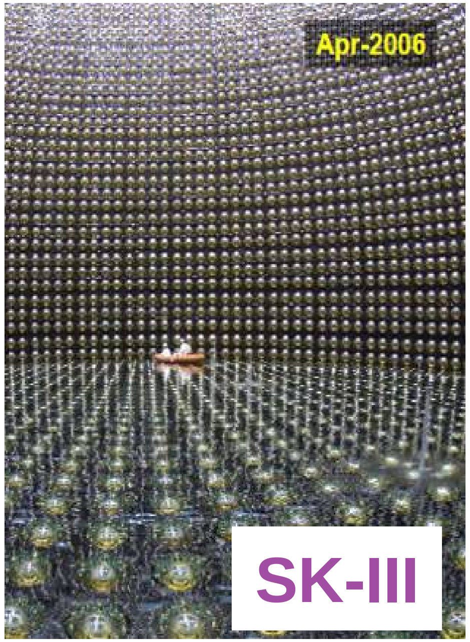
SK-I SK-II SK-III SK-IV



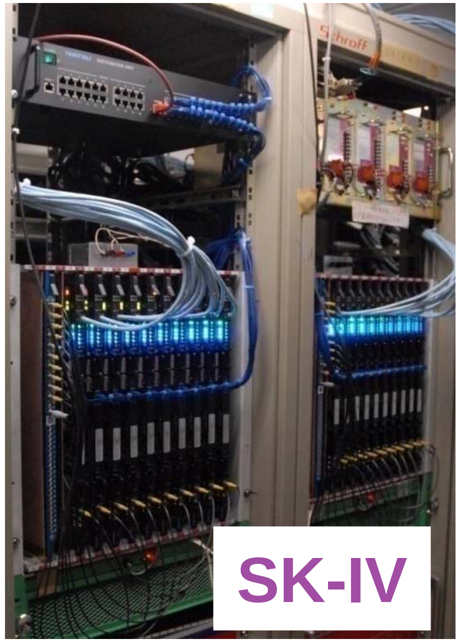
11146 ID PMTs
(40% coverage)



5182 ID PMTs
(19% coverage)

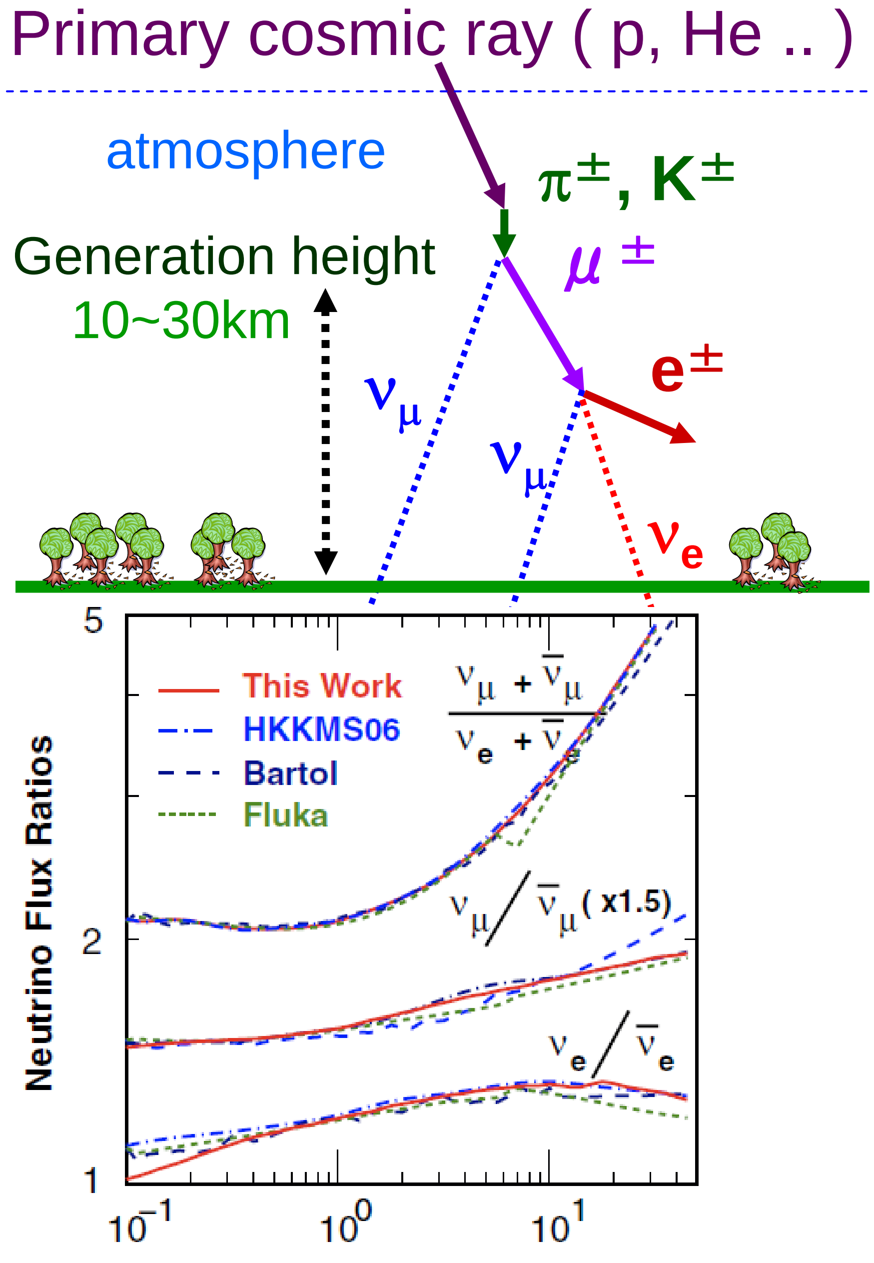


11129 ID PMTs
(40% coverage)

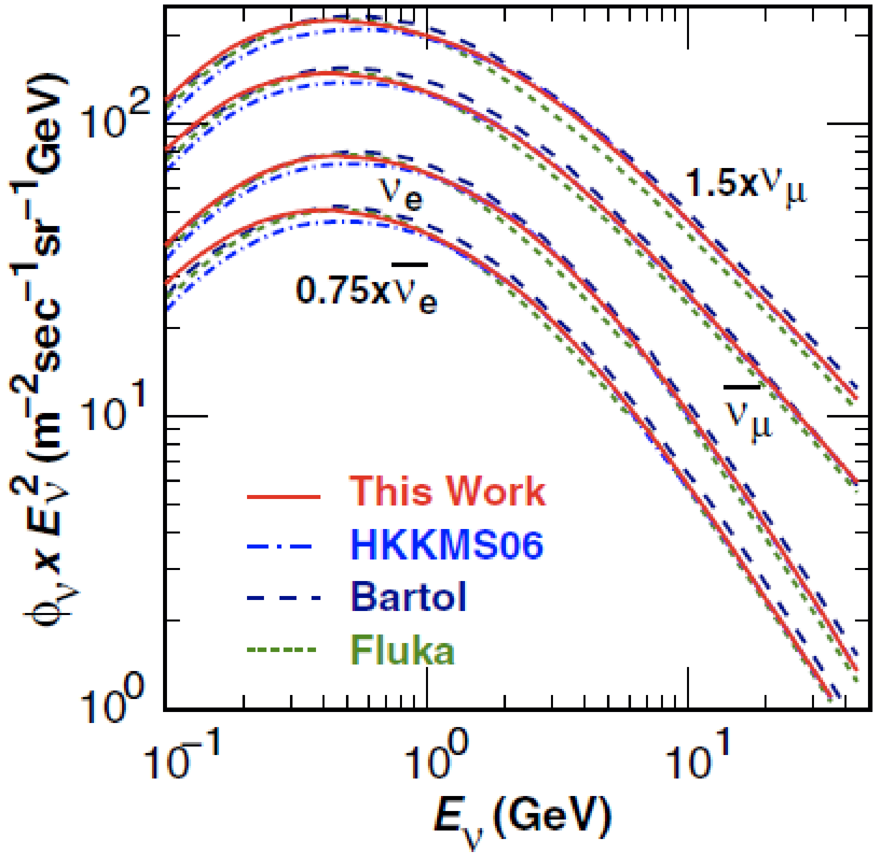


Electronics
Upgrade

Characteristics of atmospheric neutrino

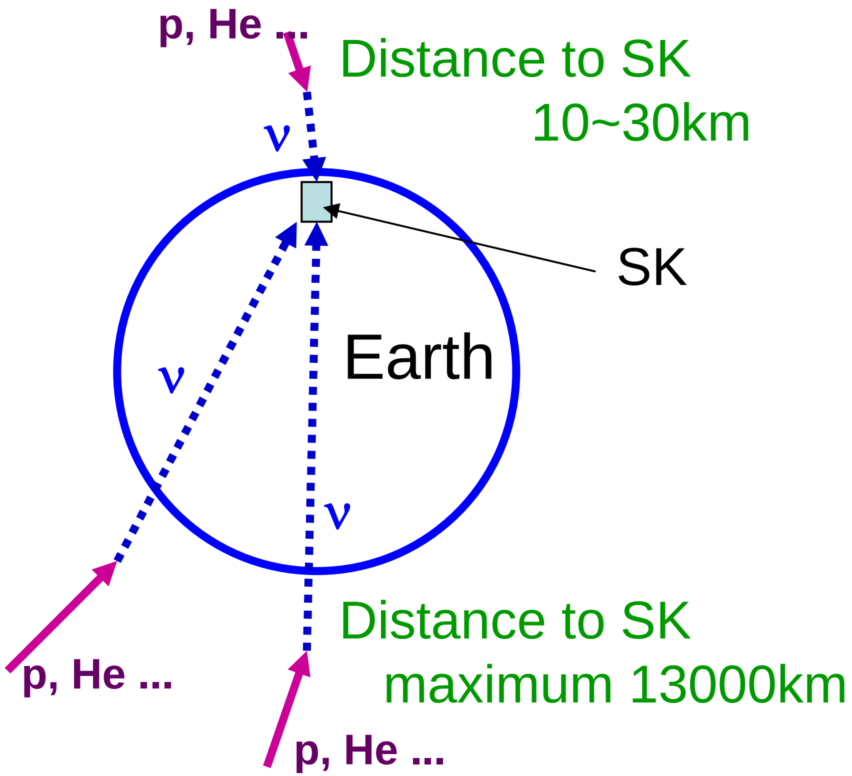


Atmospheric ν energy spectrum

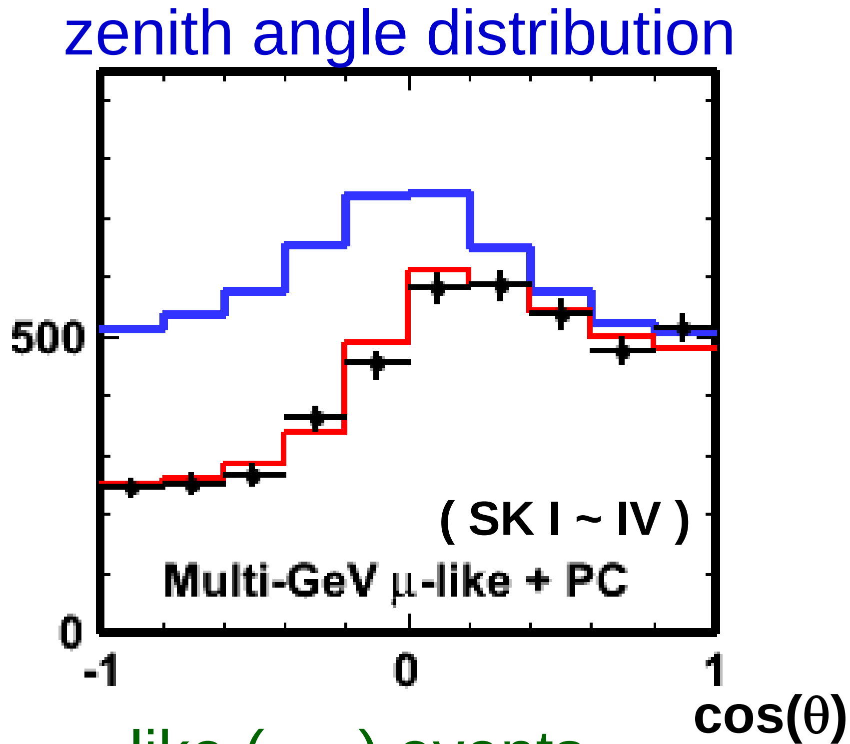


- Broad energy spectrum
- $\nu_\mu/\nu_e \sim 2$ (< ~1 GeV)
- $\nu_\mu/\nu_e > 2$ (> ~1 GeV)

Characteristics of atmospheric neutrino



- Neutrino oscillation base line
  from ~ 10 km to 13,000 km
- Zenith angle corresponds to
  travel length of neutrinos.



μ-like (ν_μ) events
up-down asymmetry

↓

ν_μ disappearance

First evidence of ν oscillation

(1998)

Neutrino oscillation and parameters

PMNS Matrix ($U_{\alpha i}$)

Finally, θ_{13} was confirmed to have non-zero value.

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

(Atm. + Accl.) $\sin^2 2\theta_{23} \sim 1 (>0.9)$

(T2K + Reactor) $\sin^2 2\theta_{13} \sim 0.1$ (0.099 ± 0.014)

(Solar + Reactor) $\sin^2\theta_{12} \sim 0.3$

Remaining questions

1) $\theta_{23} = 45^o$ or $< 45^o$ or $> 45^o$
2) CP violated or not ($\delta = 0$ or not)
3) Mass hierarchy $\Delta m_{32} > 0$ or < 0

Neutrino oscillation probability ~ ν_μ to ν_e oscillation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{a L}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

θ_{13} Leading term

CPV

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L / 4E_\nu$$
$$a = 2\sqrt{2} G_F n_e E_\nu$$

For anti neutrinos,

$a \to -a$, $\delta \to -\delta$

Now, θ_{13} is known to be (quite) large.

There are chances to observe the contributions from ***mass hierarchy*** and ***CPV (δ)*** !

Neutrino oscillation studies using atmospheric ν

High statistics atmospheric neutrino data

~ Possibility in observing small distortion in ν_e

- Matter effect ~ from mass hierarchy

  Possible ν_e enhancement in several GeV passed through the earth core

- Solar term ~ from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

- Interference

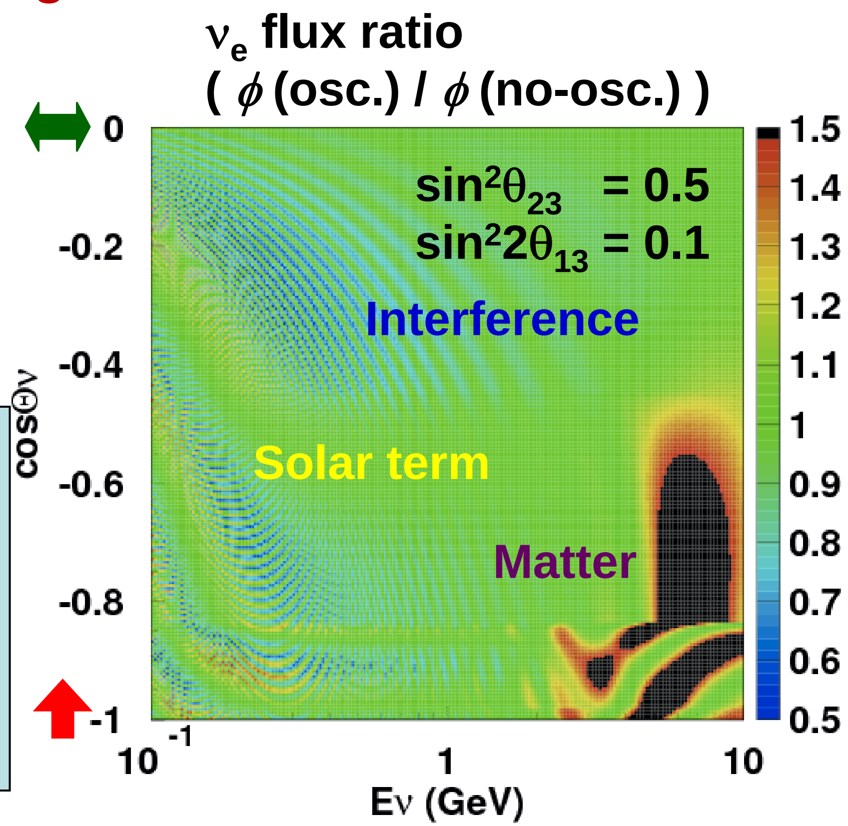
  CP phase could be studied.

Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \text{← Matter effect}$$

$$+ \Delta_2(\Delta m_{12}^2) \quad \text{← Solar term}$$

$$+ \Delta_3(\theta_{13}, \Delta m_{12}^2, \underline{\delta}) \quad \text{← Interference}$$



Updates of the atmospheric ν oscillation analysis in SK

- **First time to include SK4 data**
  in the atmospheric neutrino oscillation analyses.

  Increased statistics (***1.4 times larger stat.***)
  Live time 3903 days (240 kt·yr)
  (incl. 1096.7 days of SK-IV)
  Previous 2806 days
  SK-I + II + III (1489.2 + 798.6 + 518.1 days)

- **Use the latest atmospheric ν flux**
  (M. Honda et al. , PRD 83, 123001)

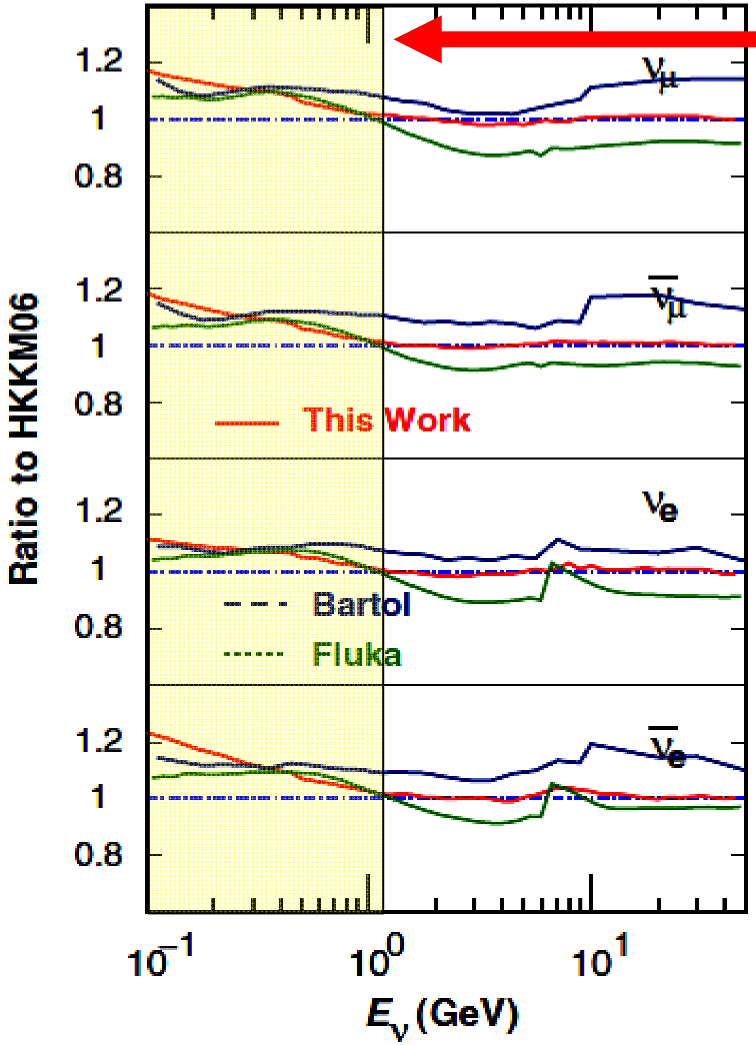
- **Improvements in neutrino interaction code (NEUT)**
  (especially handling of pion scatterings)

- **New ν_e / $\bar{\nu}_e$ separation**
  in 3 flavor neutrino oscillation analysis

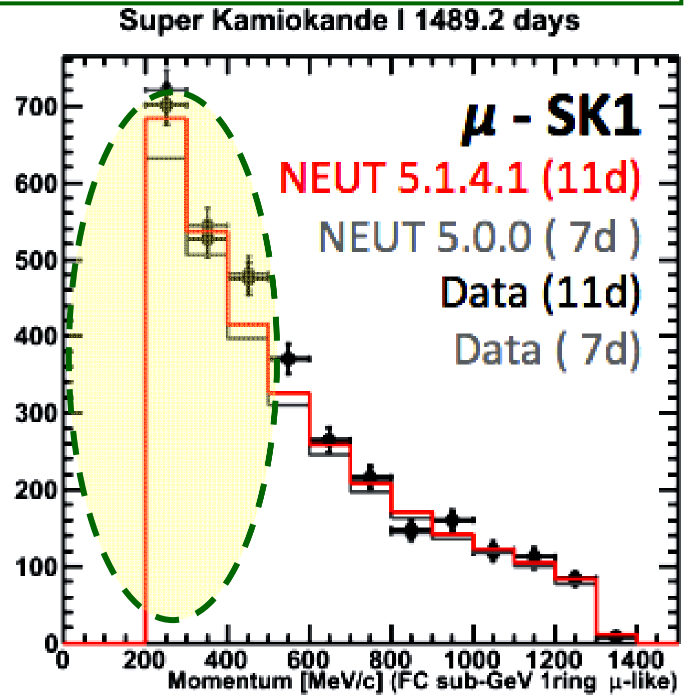
New atmospheric neutrino flux calculation (HKKM '11)

DPMJET-III → PHITS

Better agreements in *low energy μ below 1GeV/c* measured with balloon exp.



Increased low energy ν flux (below 1GeV)



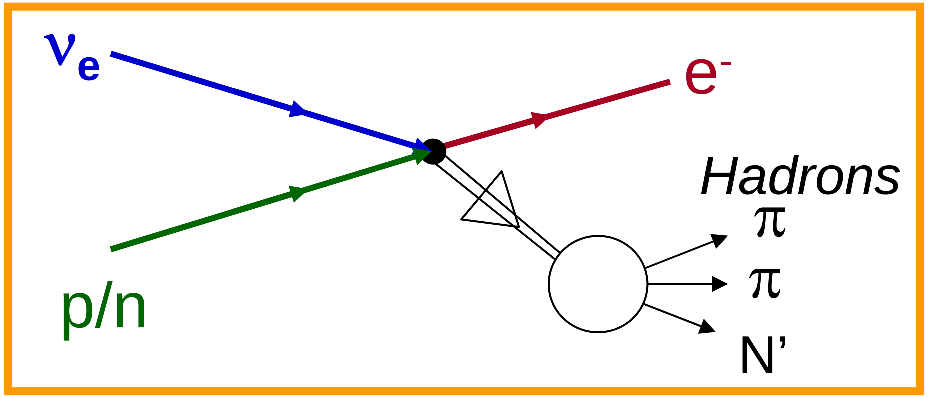
Increased low energy ν events

Agreement is better now.

Three flavor oscillation analysis using atmospheric ν in SK

ν_e / $\bar{\nu}_e$ difference is expected to be visible in ***a few ~ 10 GeV*** region

→ Dominant interaction : Deep inelastic scattering



Use cross-section difference
(energy transfer dependence)
between ν and $\bar{\nu}$.

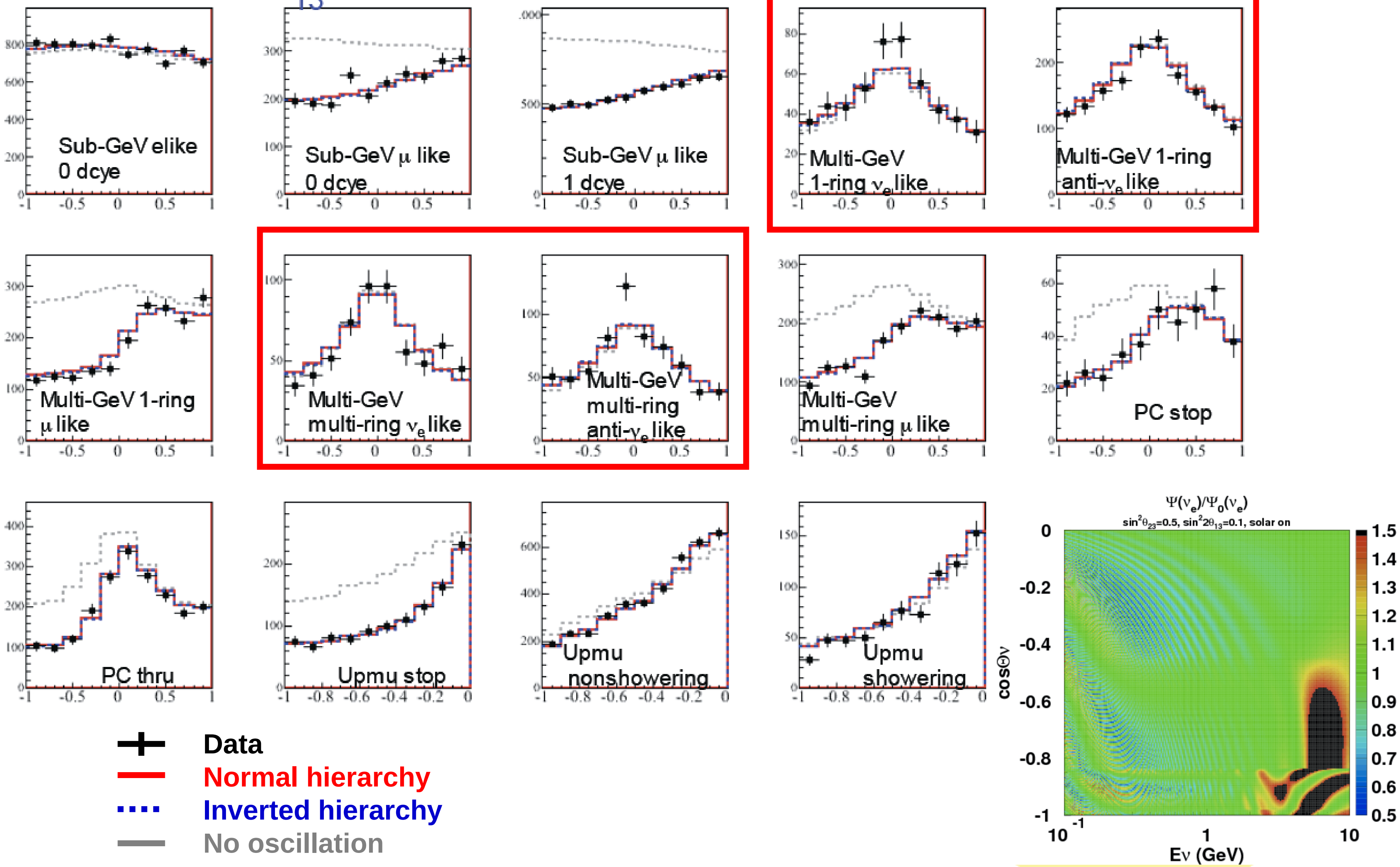
Observables	ν_e **CC**	$\bar{\nu}_e$ **CC**
Energy fraction of the most energetic ring	**Smaller**	**Larger**
Number of rings	**More**	**Fewer**
Transverse momentum	**Larger**	**Smaller**
# of decay electrons	**More**	**Fewer**

Purity of selected samples 59% 32%

Three flavor oscillation analysis using atmospheric ν in SK

SK I~IV zenith angle distributions

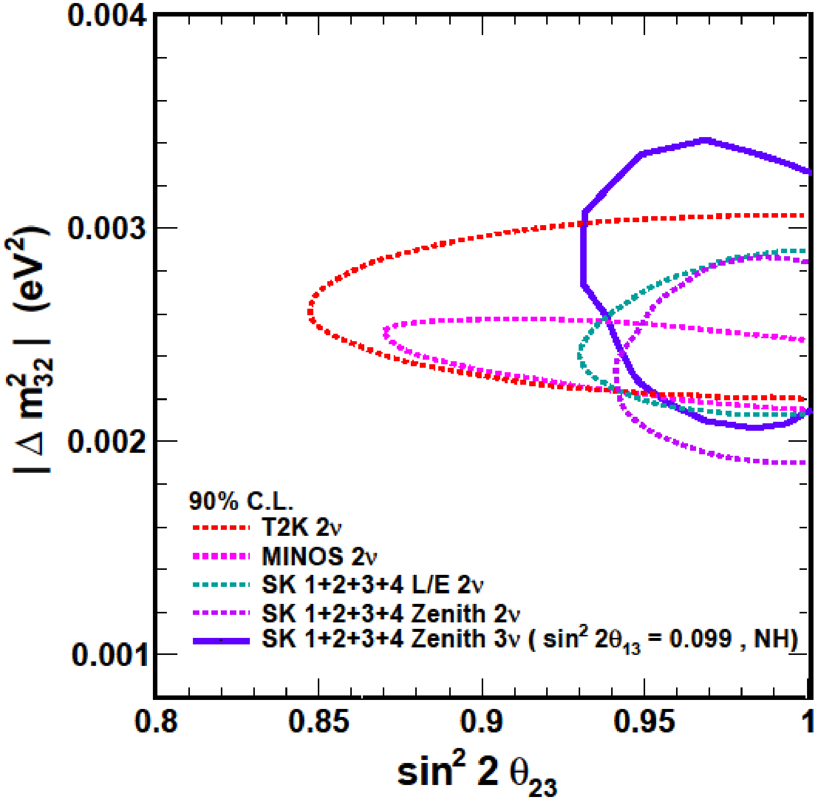
*fixed reactor θ_{13}



Three flavor oscillation analysis using atmospheric ν in SK

Normal hierarchy

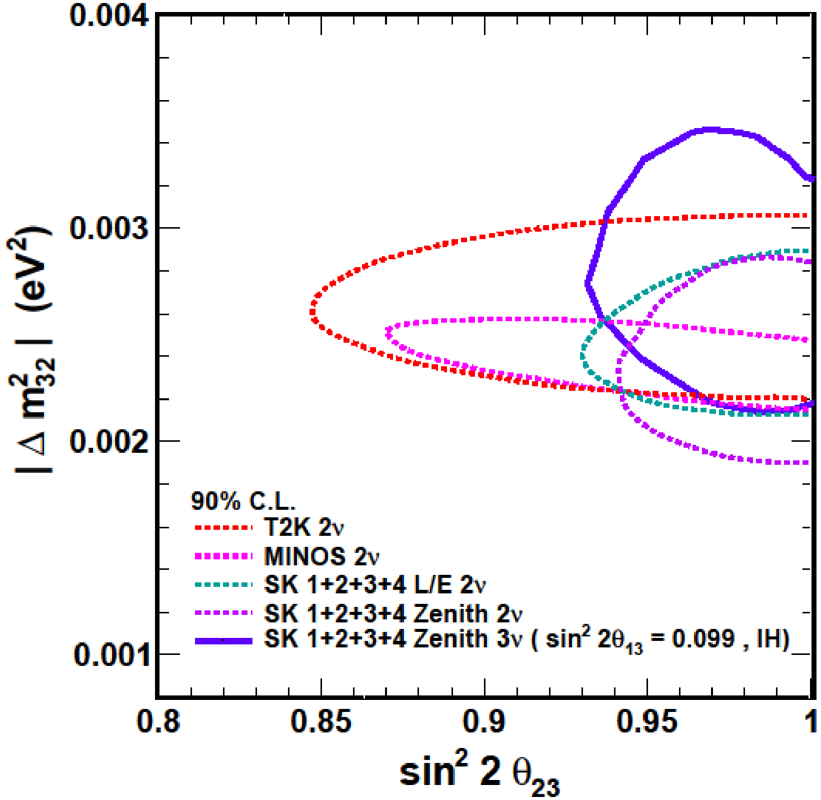
	Best fit	90% C.L
Δm^2_{32}	2.66×10^{-3}	2.06×10^{-3} - 3.04×10^{-3} eV^2
$\sin^2\theta_{23}$	0.425	0.391 - 0.619



χ^2_{min} = 556.7 / 477 dof

Inverted hierarchy

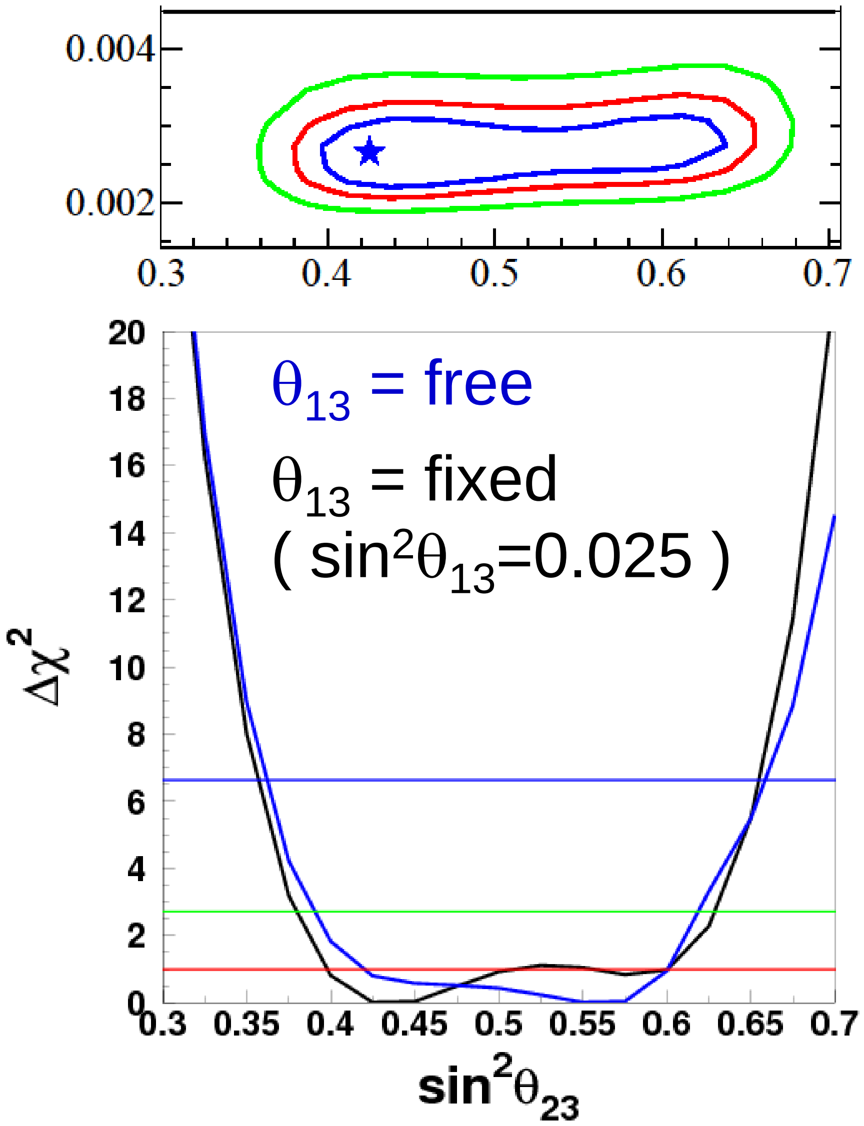
	Best fit	90% C.L.
Δm^2_{32}	2.66×10^{-3}	2.14×10^{-3} - 3.04×10^{-3} eV^2
$\sin^2\theta_{23}$	0.575	0.393 - 0.630



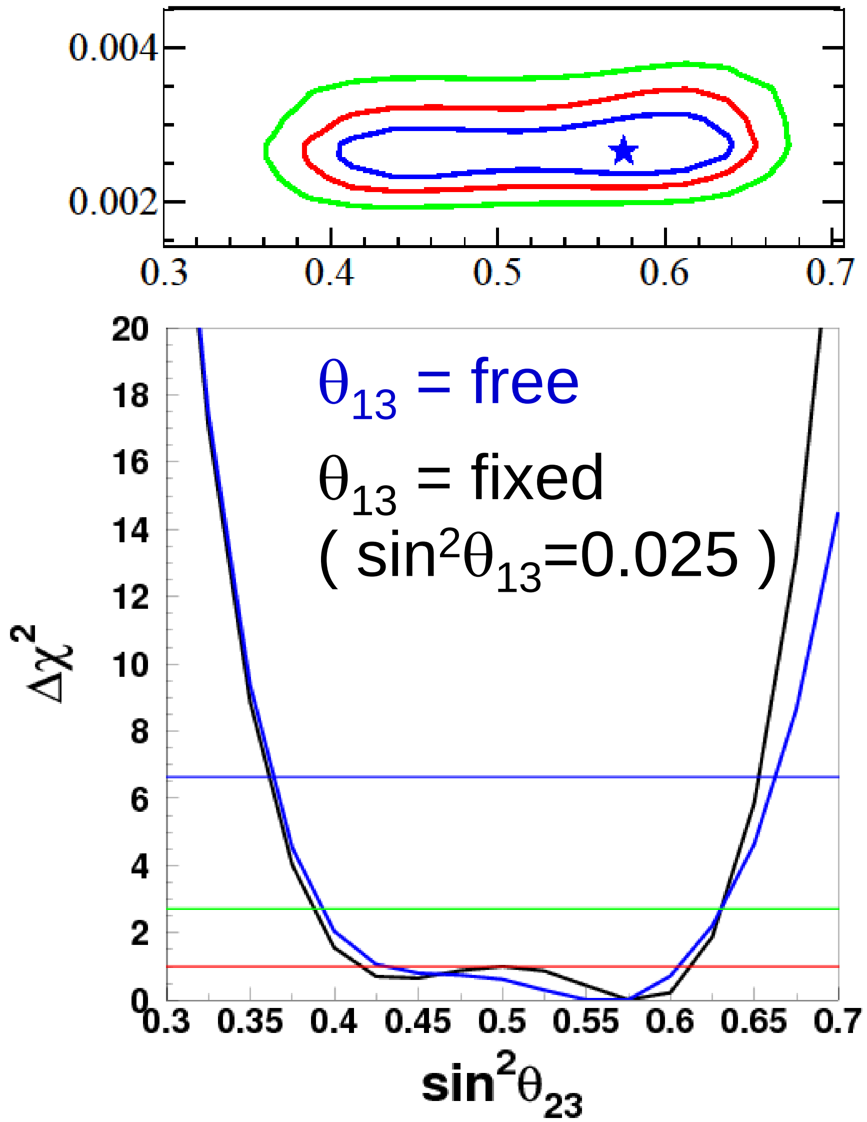
χ^2_{min} = 555.5 / 477 dof

Three flavor oscillation analysis using atmospheric ν in SK

Normal hierarchy



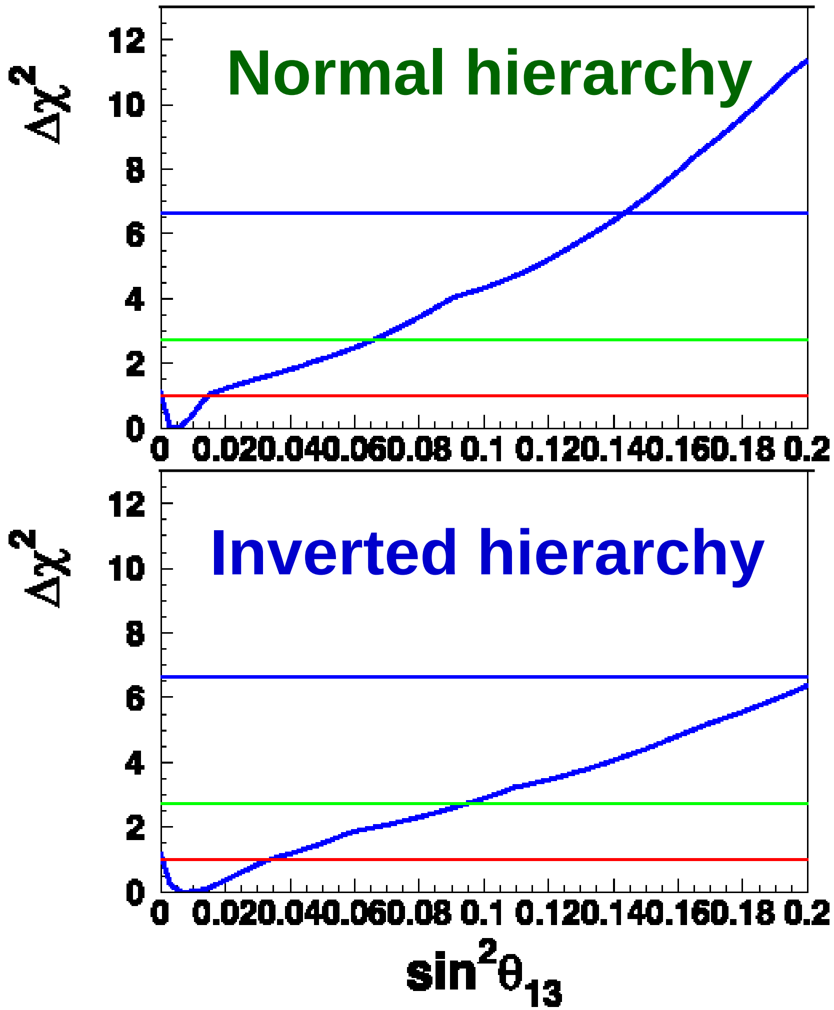
Inverted hierarchy



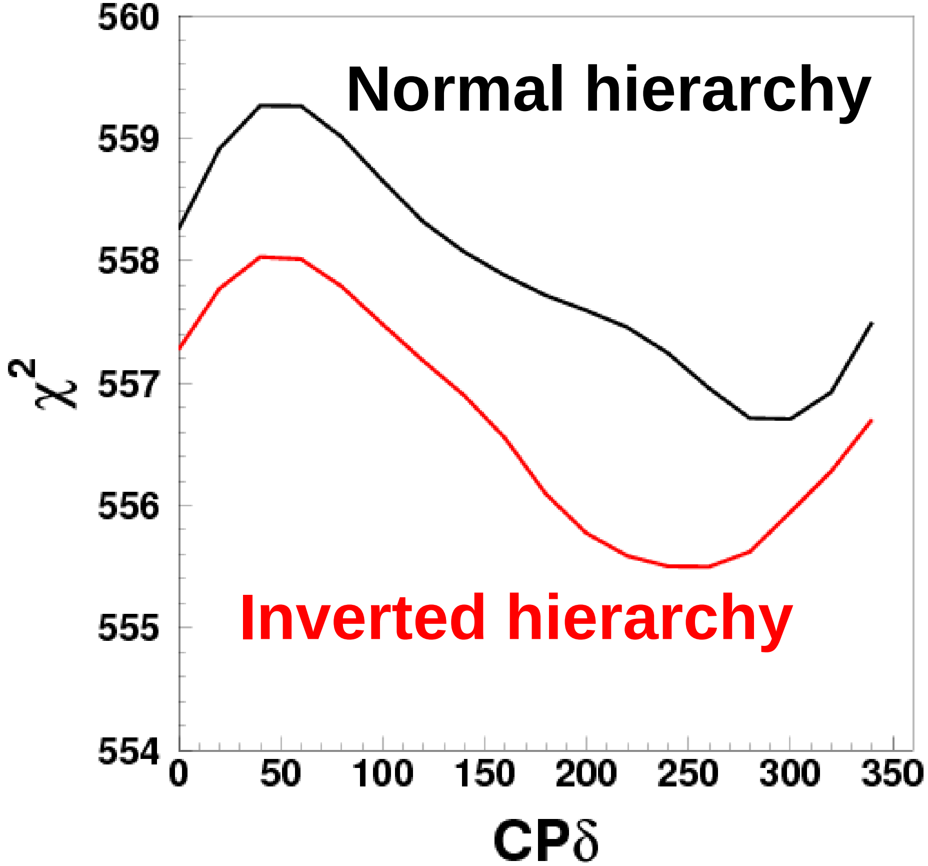
Three flavor oscillation analysis using atmospheric ν in SK

- No significant electron appearance observed in atmospheric ν data

$\chi^2(\sin^2\theta_{13} = 0) - \chi^2_{min}$ = **1.1 (NH) , 1.2 (IH)**



- No CP δ constraint at 90%C.L.



Search for the signature of ν_τ in SK ~ appearance ~

Statistically, we can separate tau-like events
using the event topology.

SK is not a suitable detector to identify ν_τ event-by-event.

~ Search for hadronic decay of τ.

Isotropic ring distributions
compared to ν_μ/ν_e CC interactions

- Select energetic Fully Contained multi-ring events
  (total visible energy > 1.33 GeV)
- Most energetic ring : e-like

Use neural net for further separation
(7 parameters)

Study of background events

➡ Use downward going events
(oscillation probability is small)

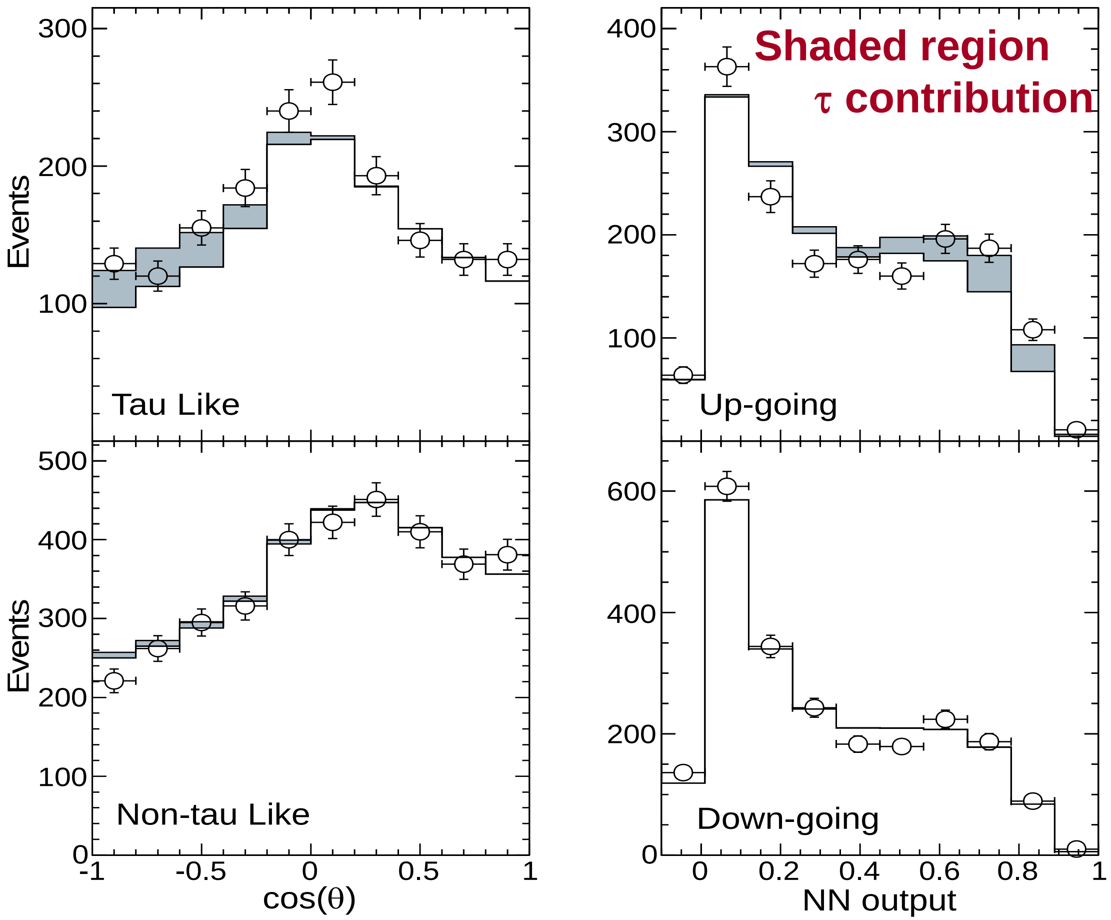
Search for the signature of ν_τ in SK ~ appearance ~

Used data set (arXiv:1206.0328 [hep-ex], submitted to PRL)

SK-I: 1489 Days, SK-II: 799 Days and SK-III: 518 Days

(previous analysis : Only SK-I = statistics almost doubled)

$$Data = \alpha \times bkg + \beta \times signal$$



$$\beta = 1.42 \pm 0.35_{(stat)} \,{}^{+0.14}_{-0.12}(sys)$$

Estimated # of ν_τ events

$$170.8 \pm 44.3_{(stat)} \,{}^{+17.8}_{-15.2}(sys)$$

3.8 σ deviation from "*no ν_τ appearance*"

Summary

Three flavor oscillation analysis and ν_τ appearance analysis in SK

Δm^2_{32}	$2.66 \pm^{0.15}_{0.40} \times 10^{-3}$ eV^2 (NH, 1σ) $2.66 \pm^{0.17}_{0.23} \times 10^{-3}$ eV^2 (IH, 1σ)
$\sin^2\theta_{23}$	0.391 ~ 0.619 (NH, 90% C.L.) 0.393 ~ 0.630 (IH, 90% C.L.)
θ_{13}	No significant appearance of ν_e SK alone, $\Delta\chi^2$ ~ 1
CP δ	No constraint at 90% C.L.
Mass hierarchy	No strong conclusion (χ^2(NH)-χ^2(IH) ~ 1.2)
τ appearance	3.8 σ deviation from "no ν_τ appearance"

More statistics and further understanding of the data is necessary to solve the remaining questions.