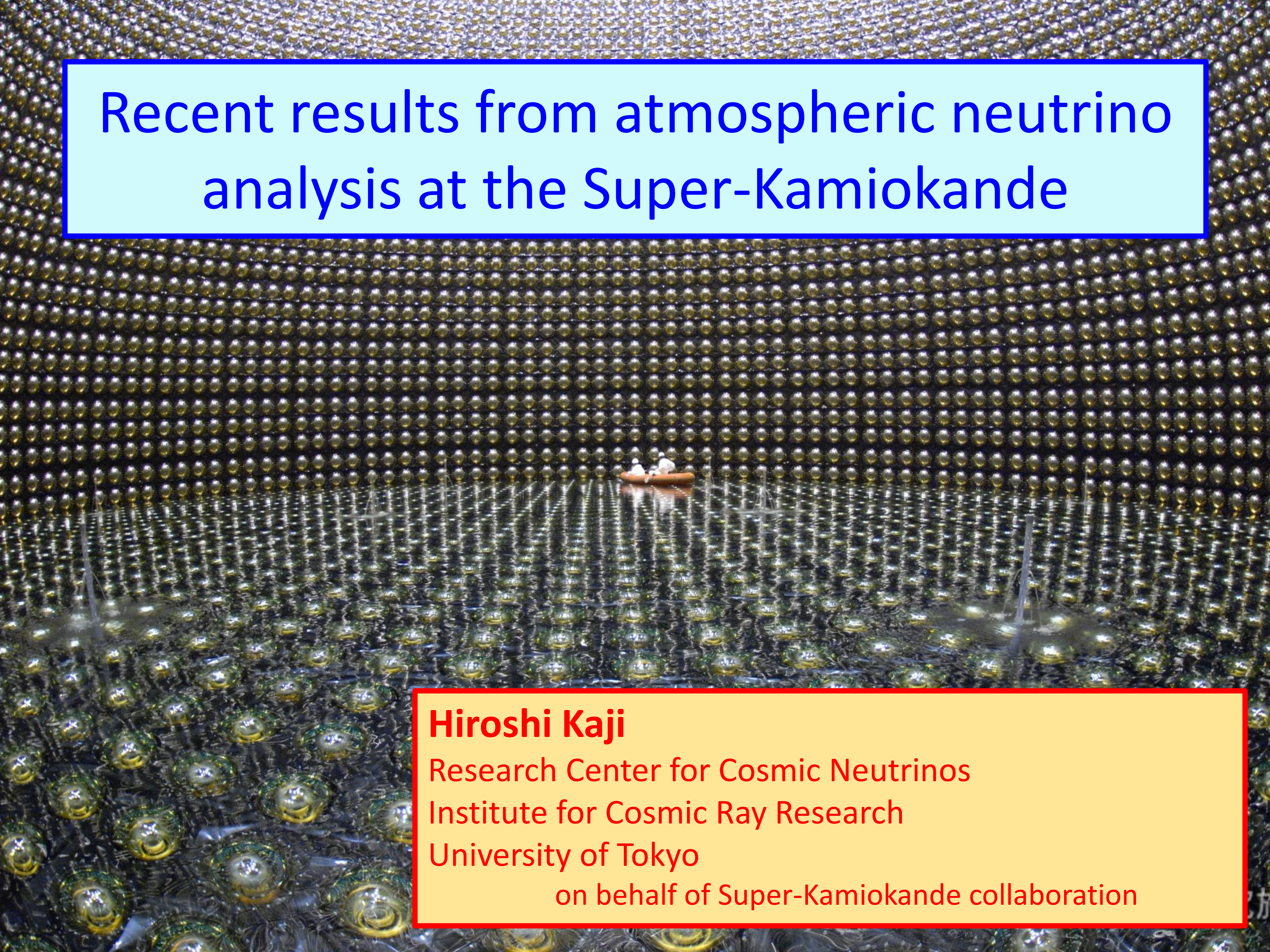

Recent results from atmospheric neutrino analysis at the Super-Kamiokande

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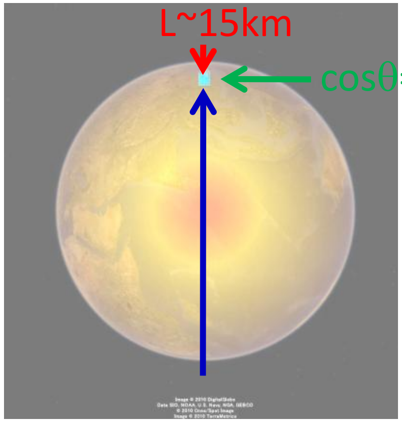
Institute for Cosmic Ray Research
University of Tokyo
on behalf of Super-Kamiokande collaboration

Atmospheric neutrino

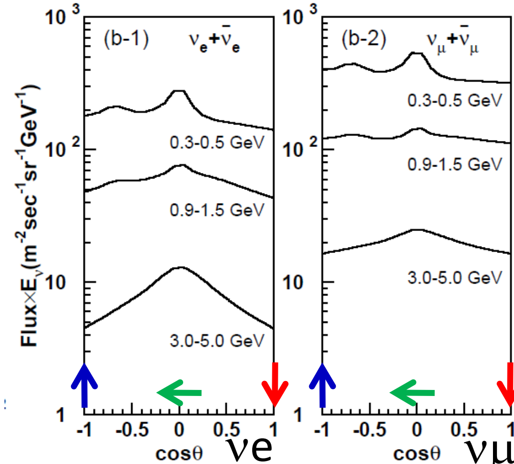
Flight length is usually described by zenith angle, θ.

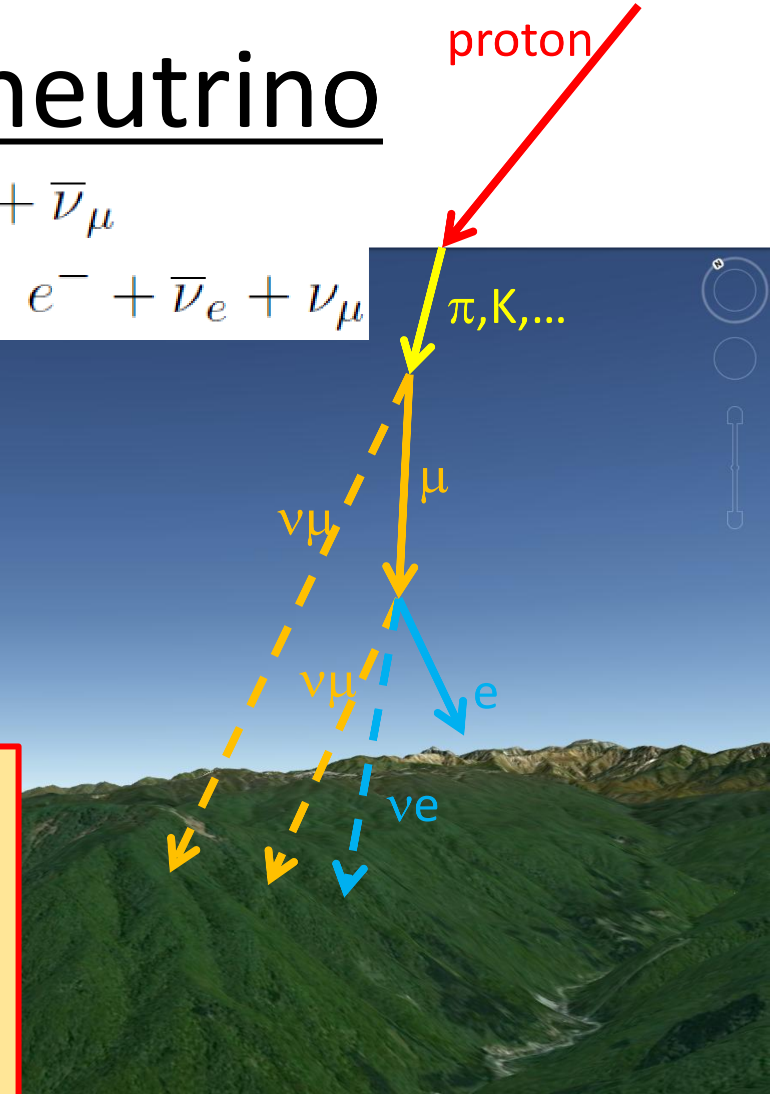
cosθ=1(down going)



cosθ=-1(up going)
L~13000km

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





Typically, νμ : νe = 2 : 1

<u>Famous as the disappearance of the ν_μ flux</u>

- The neutrino oscillation is firstly observed from this sample (θ_{23}, Δm_{23}^2)
- It sets the best limit to oscillation parameter, θ_{23}.

<u>The sub-dominant oscillation in the ν_e flux</u>

- Solar term (θ_{12}, Δm_{12}^2)
- Matter effect term (θ_{13})
- Interference (θ_{12}, θ_{13}, Δm_{12}^2, δ_{CP})

Atmospheric-ν sample is sensitive to all oscillation parameters.

Super-Kamiokande

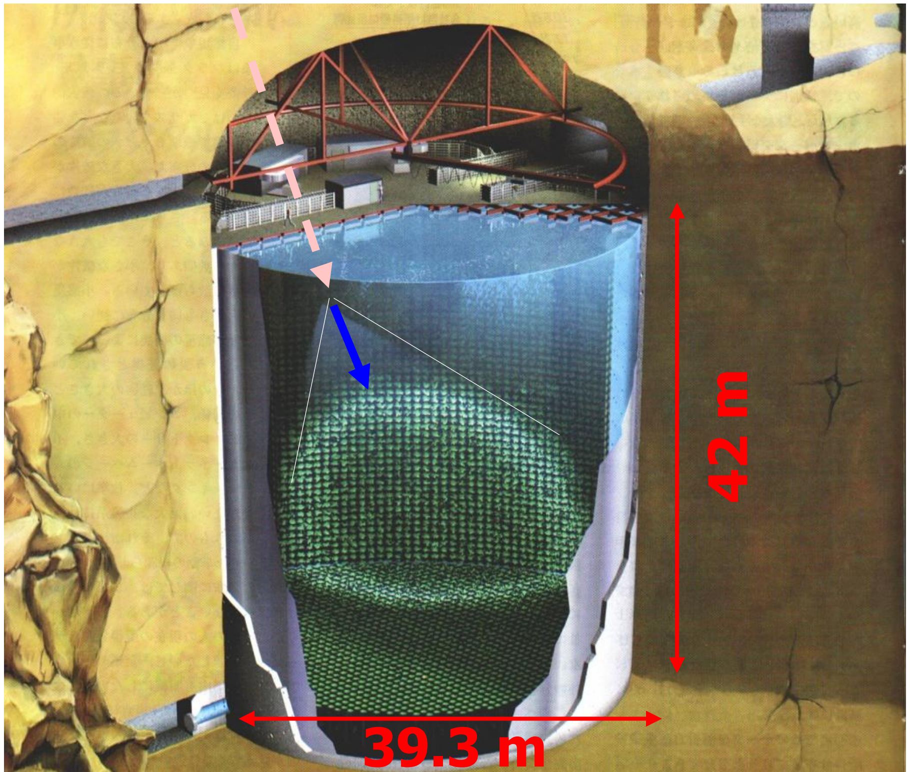
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

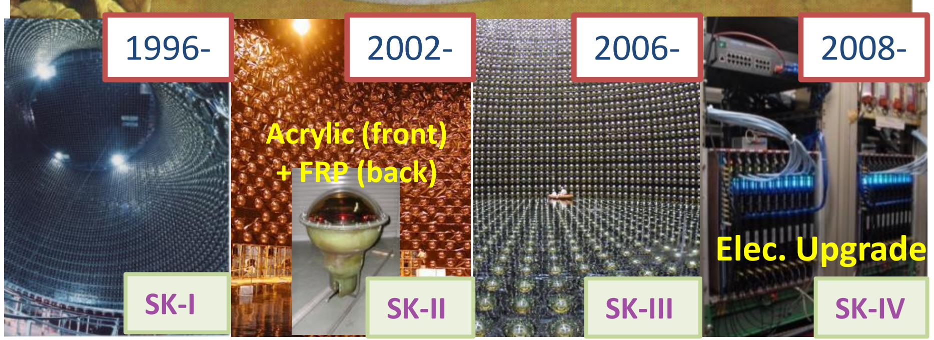
SK-I

SK-II (half PMT density)

SK-III (full density)

SK-IV (new electronics)





The Super-Kamiokande (SK) is the world's largest water Cherenkov detector.

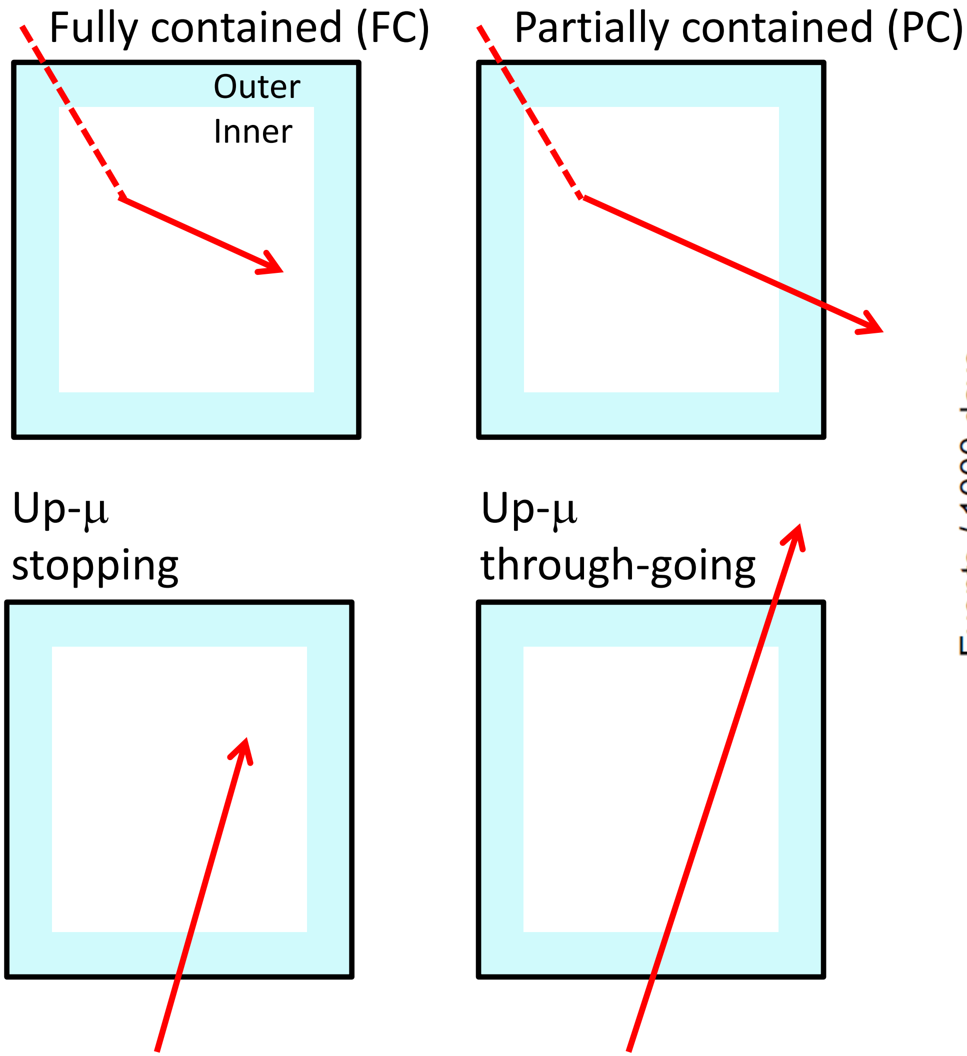
- Target mass 22.5kton (Fiducial volume)
  - Inner detector ~11000 20inch-PMTs
  - Outer detector ~2000 8inch-PMTs
- The operation is stared since 1996
  - Run-II : half PMT density
  - Run-IV (now) : with new electronics

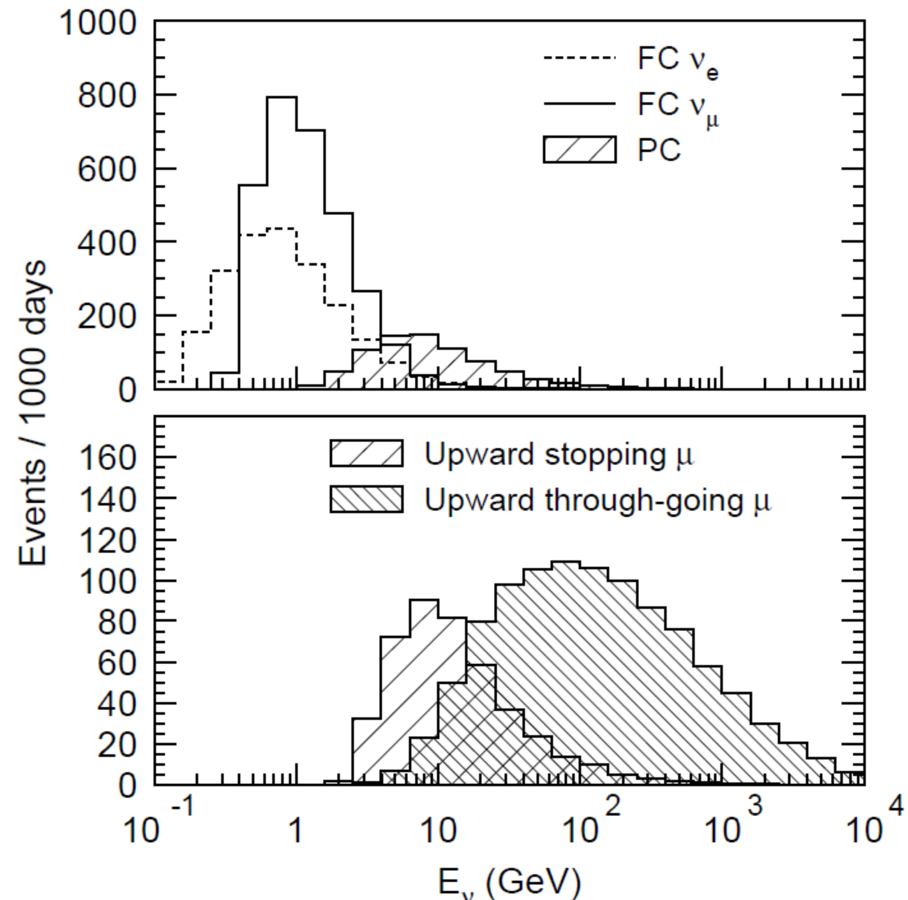
The atmospheric, solar, and Super Nova (relic) neutrinos are studied.
The proton-decay search is still on-going.

The far detector of Japanese LBL ν experiments, K2K and T2K.
The atmospheric ν data used also for the control sample of both experiments.

Atmospheric ν event category

We collect four kinds of events. They have different ν energy.





$10^{-1} – 10^4$ GeV

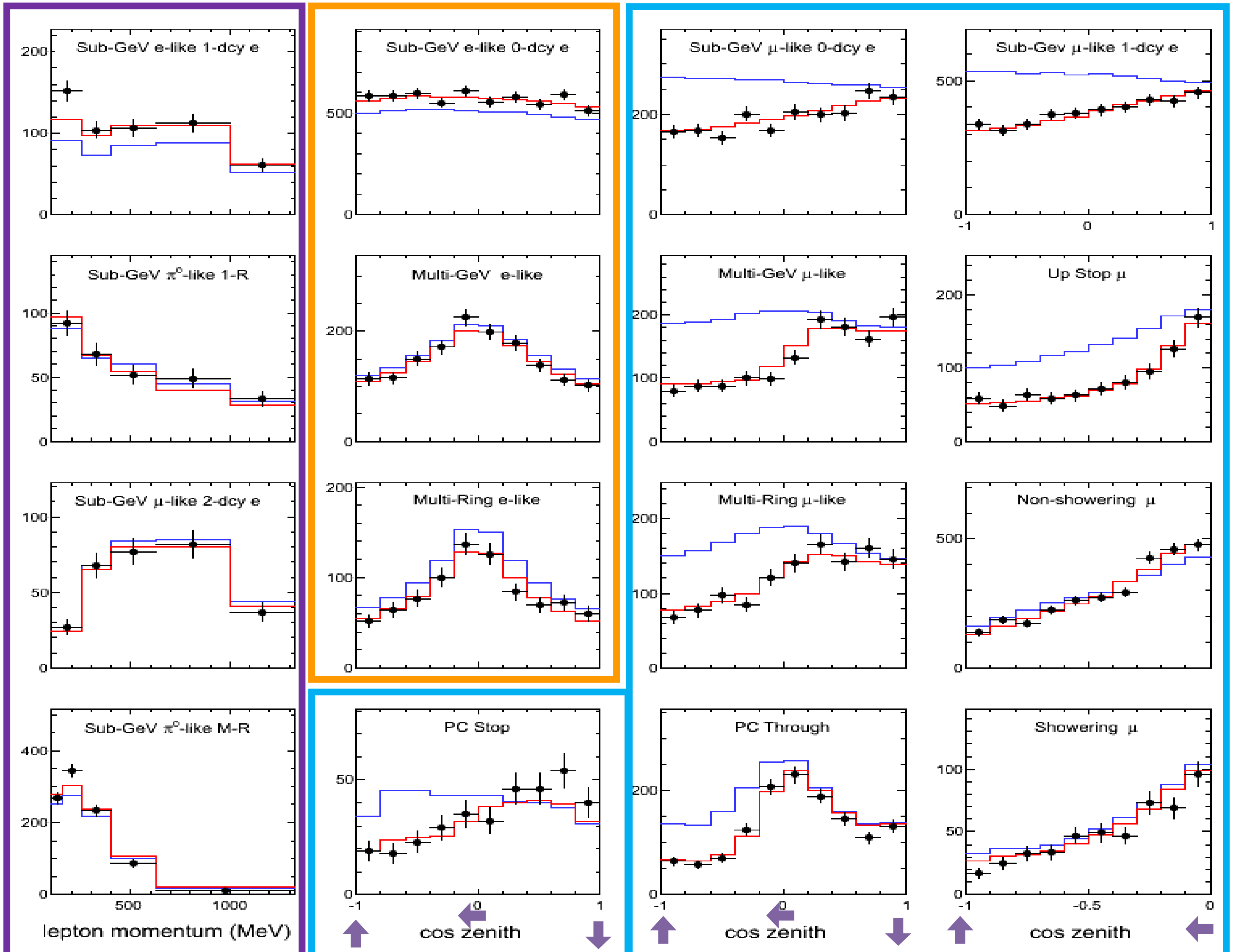
The large energy range is covered with these four kinds of event samples.

Zenith angle distribution

$\nu_\mu - \nu_\tau$ oscillation (best fit)
null oscillation

Live time:
SK-I
1489days (FCPC)
1646days (Up-μ)
SK-II
799days (FCPC)
827days (Up-μ)
SK-III
518days (FCPC)
636days (Up-μ)

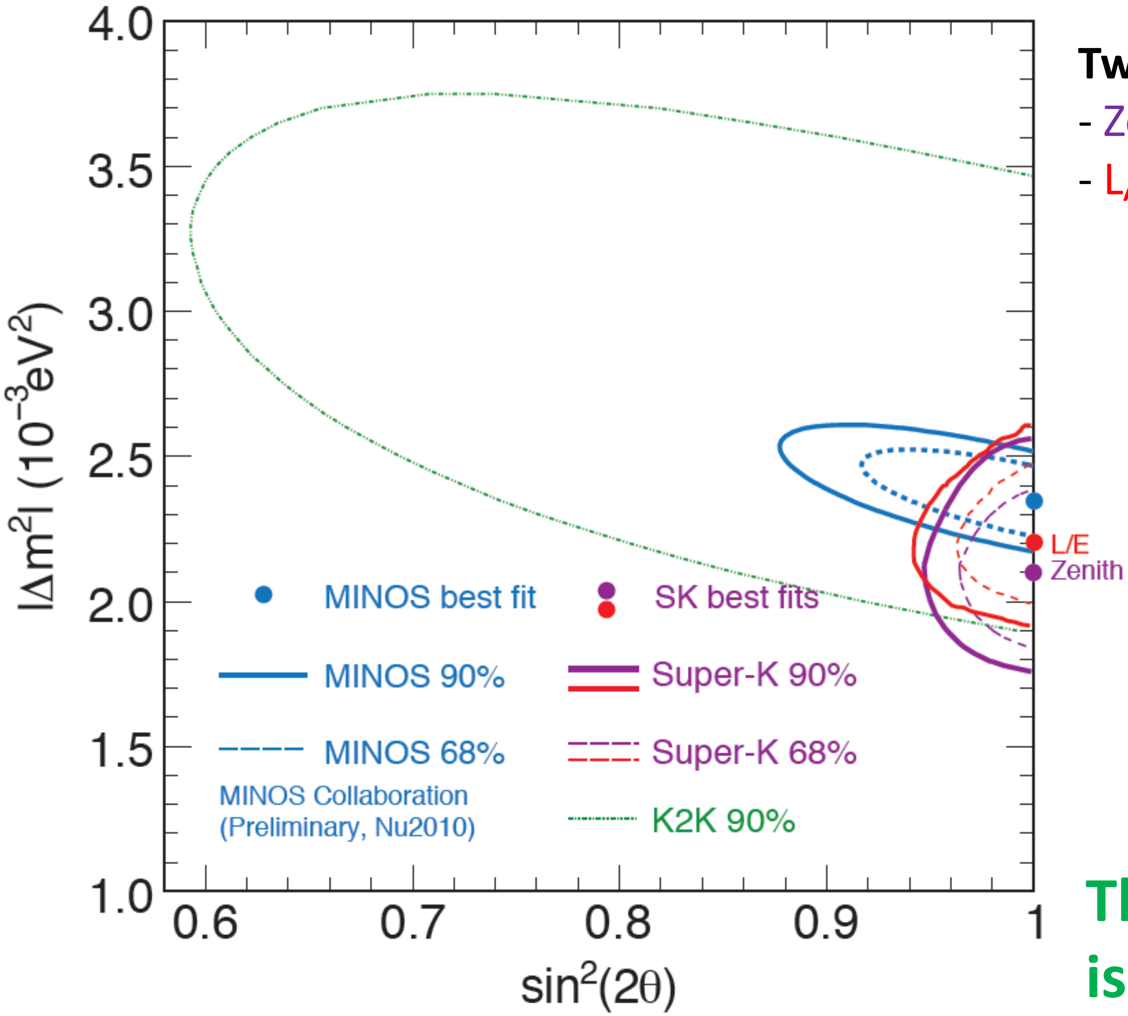
Momentum | e-like | μ-like



The samples with E<~1 GeV are further divided to improve sensitivity to low-energy oscillation effects.
Totally 420 bins are used in each SK run period.

Two flavor analysis

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Two analyses are performed at SK.

- Zenith angle analysis
- L/E analysis ← Better sensitivity to Δm^2

Allowed Region:

Zenith angle analysis

$\Delta m_{23}^2 = 2.11 + 0.11/-0.19 \times 10^{-3}$

$\sin^2 2\theta_{23} > 0.96$ (90% C.L.)

L/E analysis

$\Delta m_{23}^2 = 2.19 + 0.14/-0.13 \times 10^{-3}$

$\sin^2 2\theta_{23} > 0.96$ (90% C.L.)

Consistent results!

The current best limit to θ_{23} is provided.

Full three flavor analysis

"Full three flavor analysis"

takes into account the matter effect, solar, and their interference terms.
(Analysis which takes into account only one of matter or solar terms is called "Three flavor analysis".)

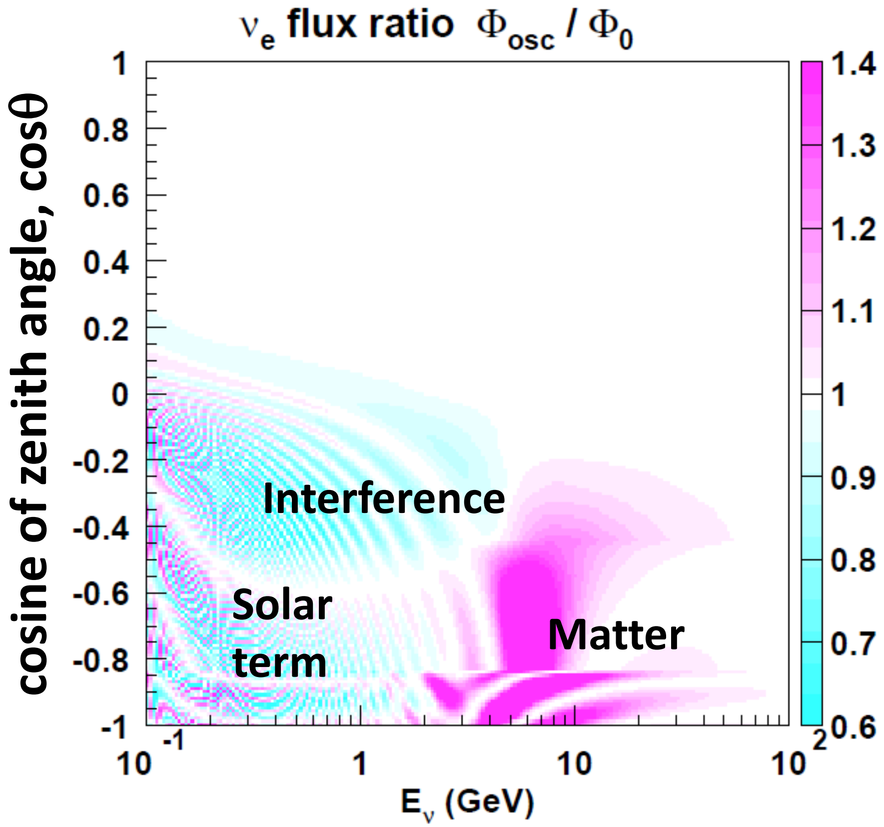
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m_{12}^2) + \Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

- $\Delta_1(\theta_{13})$ ← **Matter**
- $\Delta_2(\Delta m_{12}^2)$ ← **Solar**
- $\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$ ← **Interference**

The θ_{13} and CP phase, δ_{CP}, are studied in this analysis. The interesting behaviors are seen in the ν_e flux if sub-dominant terms are considered.
- The θ_{13} is in the matter and interference terms.
- The interference term includes δ_{CP}.
(The $\sin^2\theta_{12}$ and Δm_{12}^2 are fixed to be 0.304 and 7.66×10^{-5} eV^2.)

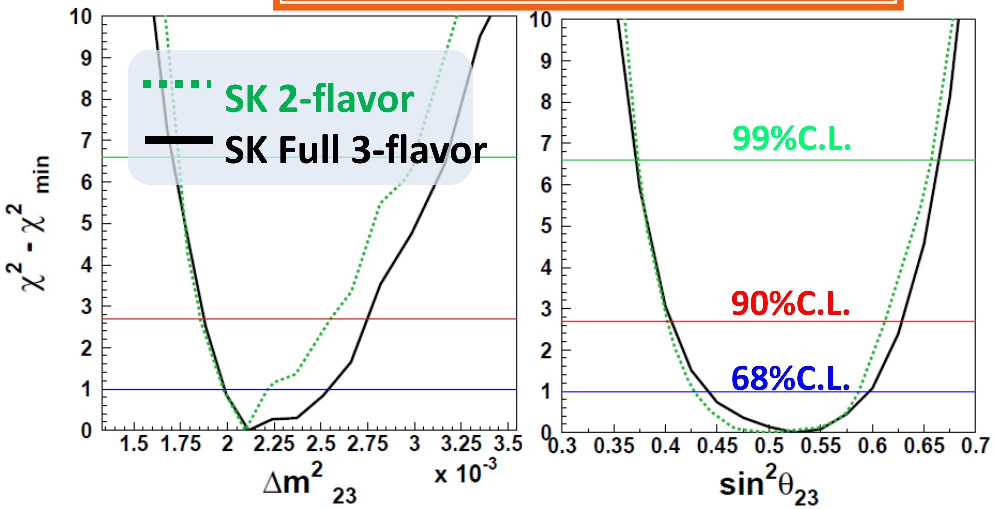
The resultant θ_{23} and Δm_{23}^2 are confirmed.
⇒ see next slide.



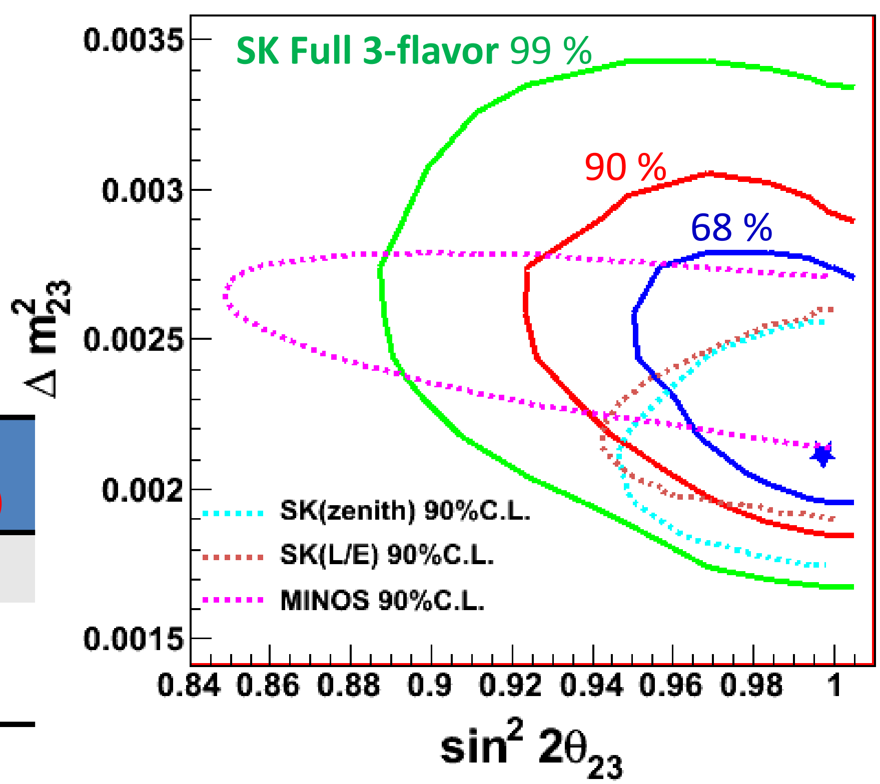
Confirmation of θ_{23} and Δm_{23}^2 results

The resultant θ_{23} and Δm_{23}^2 are consistent with both SK's two flavor and global three-flavor analyses.

χ^2-χ^2_{min} distributions

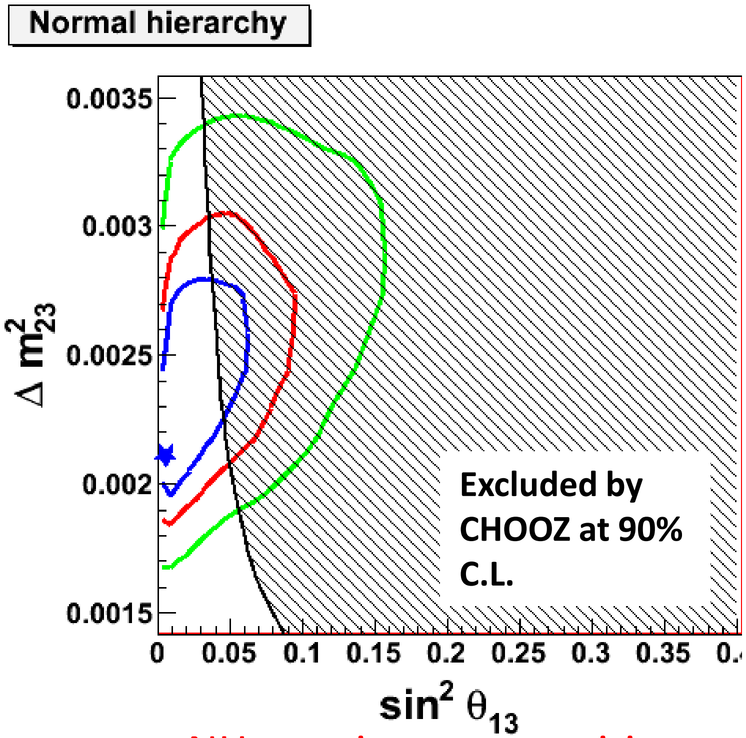


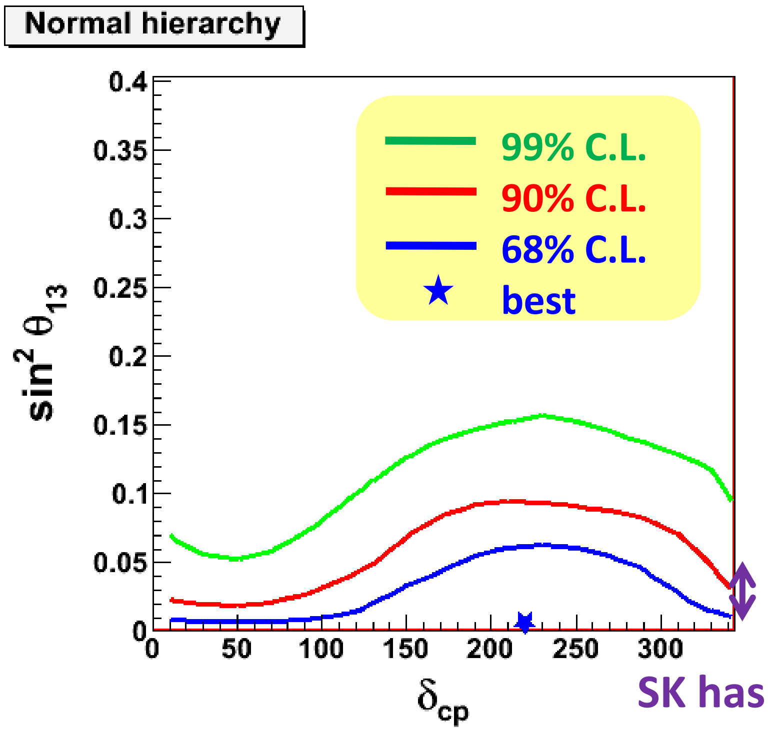
Comparison of 3-flavor and 2-flavor



SK Full 3-flavor (NH)	Global 3-flavor New J.Phys. 10 113001 (2008)
$(1.88<\Delta m^2_{23}<2.75)\times10^{-3}$	$(2.22<\Delta m^2_{23}<2.60)\times10^{-3}$
$0.406<\sin^2\theta_{23}<0.629$ $(0.93<\sin^2 2\theta_{23})$	$0.401<\sin^2\theta_{23}<0.615$ $(0.95<\sin^2 2\theta_{23})$

The $\sin^2\theta_{13}$ and δ_{CP} results – Normal hierarchy





NH case is more sensitive to $\sin^2\theta_{13}$ than IH case.

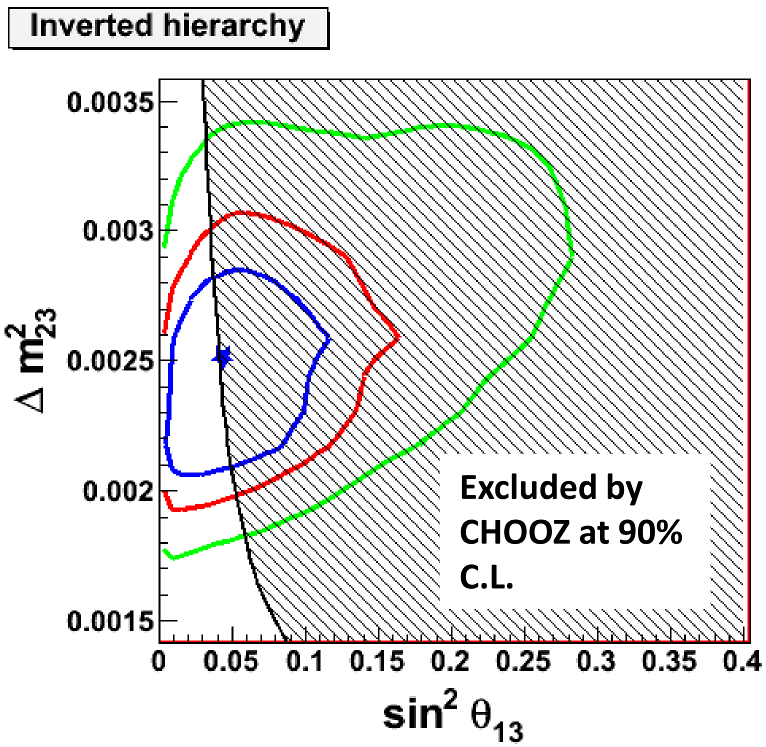
SK has sensitivity to δ_{CP} when large θ_{13}.

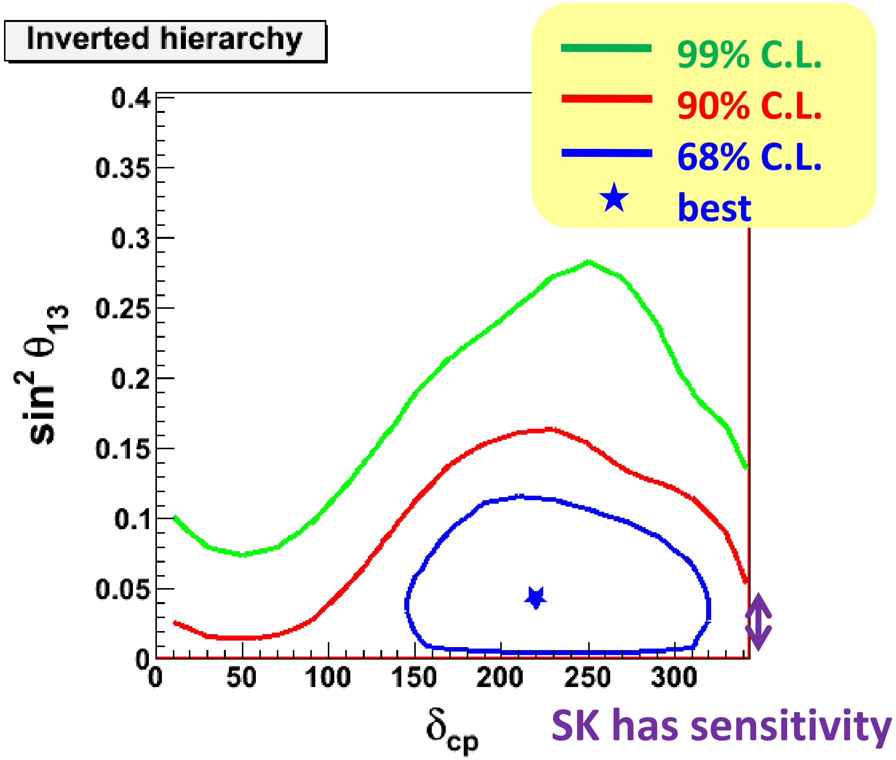
1D limit

	Best	90% C.L.
$\sin^2\theta_{13}$	0.006	< 0.066
CP-δ	220°	-

The CHOOZ limit to θ_{13} is confirmed.
No significant constraint to the δ_{CP} at 90 % C.L.

The $\sin^2\theta_{13}$ and δ_{CP} results – inverted hierarchy





SK has sensitivity to δ_{CP} when large θ_{13}.

1D limit

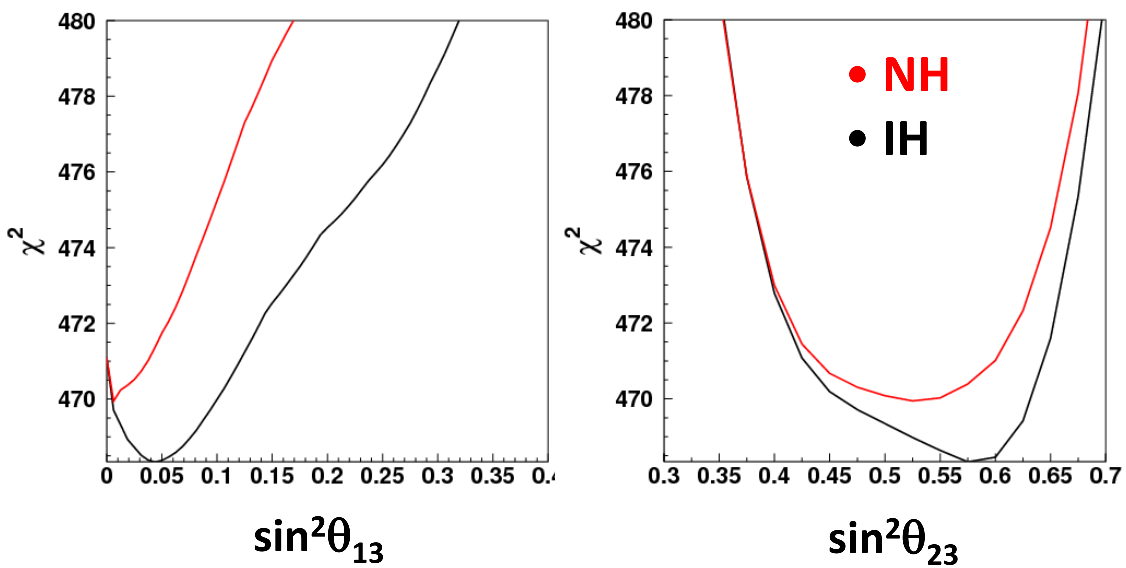
	Best	90% C.L.
$\sin^2\theta_{13}$	0.044	< 0.122
CP-δ	220º	121.4 - 319.1º

The CHOOZ limit to θ_{13} is confirmed.
No significant constraint to the δ_{CP} at 90 % C.L.

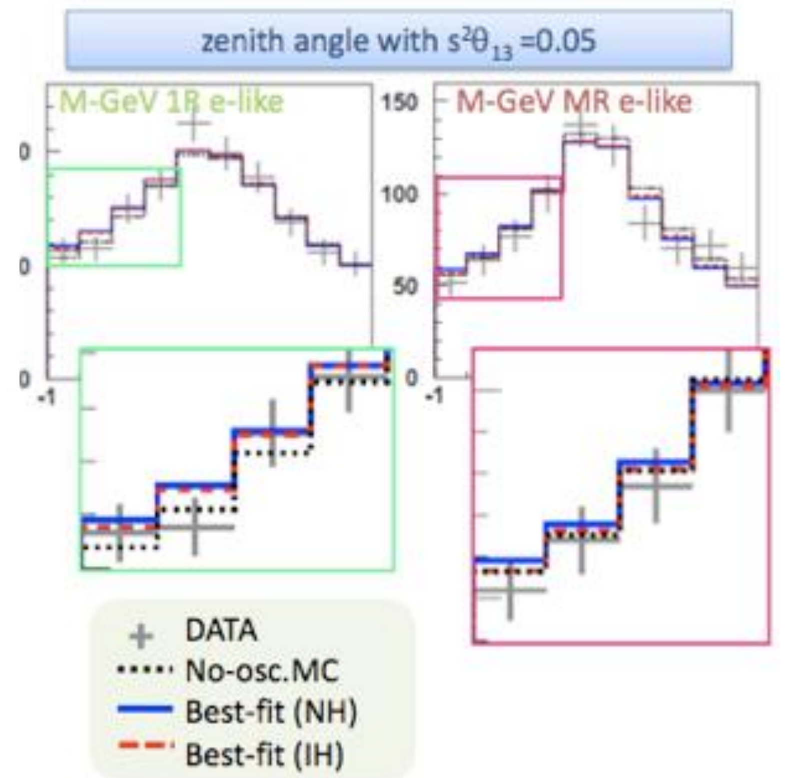
There is a possibility to make the first δ_{CP} result with “current” experiments.
SK can make a constraint to δ_{CP} if large θ_{13} is determined by LBL or reactor.

Mass hierarchy test

The χ^2 is compared between normal and inverted results.



E>~1GeV samples tend to favor inverted hierarchy.



Normal hierarchy (NH):

χ^2_{min}/dof= 469.94/416

Inverted hierarchy (IH):

χ^2_{min}/dof= 468.34/416

→ $\Delta\chi^2 = 1.6$

The χ^2 test is in favors of inverted hierarchy.

However, no significant difference.

Summary of full three-flavor result

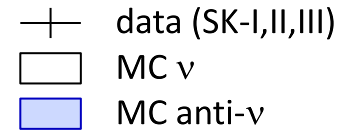
Normal hierarchy (χ^2_{min}/dof= 469.94/416)

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.11 eV^2	1.88 - 2.75 eV^2	1.99 - 2.54 eV^2
$\sin^2\theta_{23}$	0.525	0.406 - 0.629	0.441 - 0.597
$\sin^2\theta_{13}$	0.006	< 0.066	< 0.036
CP-δ	220º	-	140.8 - 297.3º

Inverted hierarchy (χ^2_{min}/dof= 468.34/416)

Parameter	Best point	90% C.L. allowed	68% C.L. allowed
Δm^2_{23} (x10^3)	2.51 eV^2	1.98 - 2.81 eV^2	2.09 - 2.64 eV^2
$\sin^2\theta_{23}$	0.575	0.426 - 0.644	0.501 - 0.623
$\sin^2\theta_{13}$	0.044	< 0.122	0.0122 - 0.0850
CP-δ	220º	121.4 - 319.1º	165.6 - 280.4º

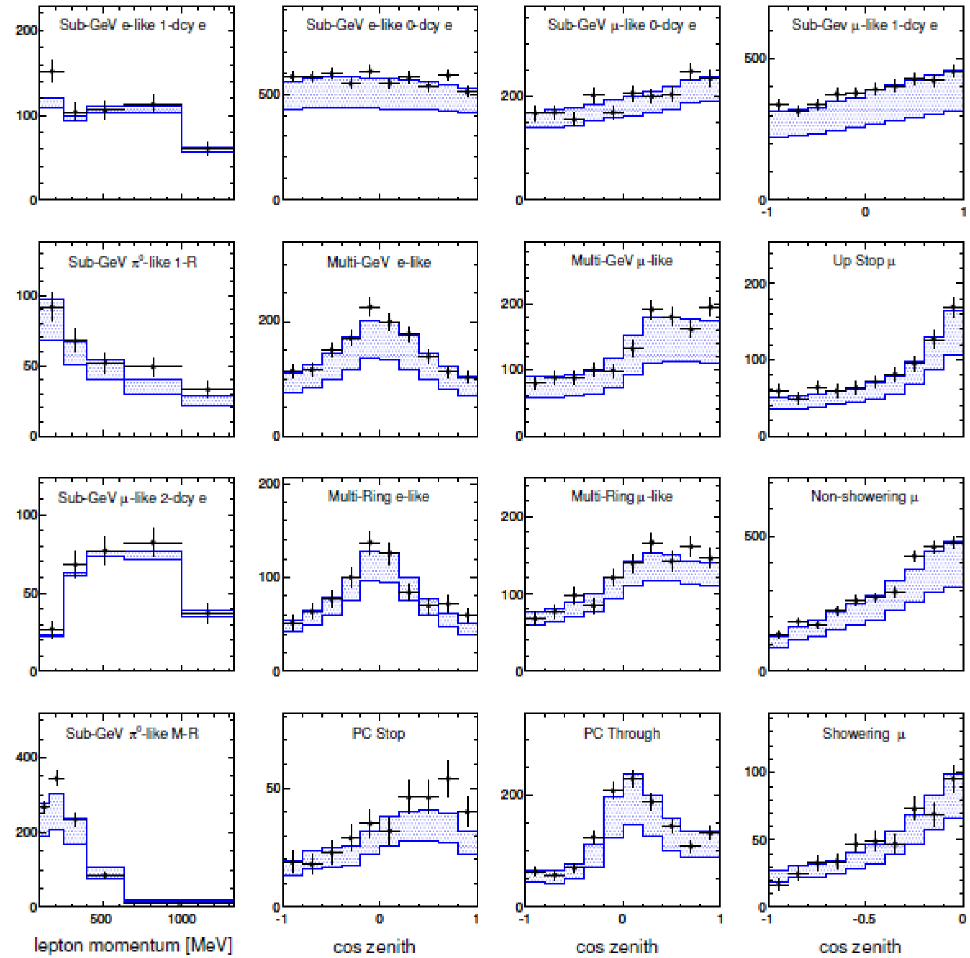
Search for CPT violation



$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

The CPT violation is suggested by
- LSND-MiniBooNE $\nu_\mu \to \nu_e$
- MINOS $\nu_\mu \to \nu_\mu$

SK can test MINOS result with same oscillation and same L/E range.
We cannot distinguish ν and anti-ν on an event by event.
We take statistical approach. The $\cos\theta_{zenith}$ comparison between samples with different ν, anti-ν compositions.



Two flavor scheme with four oscillation parameters:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin\left(\frac{\Delta m^2 L}{E}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2 2\bar{\theta} \cdot \sin\left(\frac{\Delta \bar{m}^2 L}{E}\right)$$

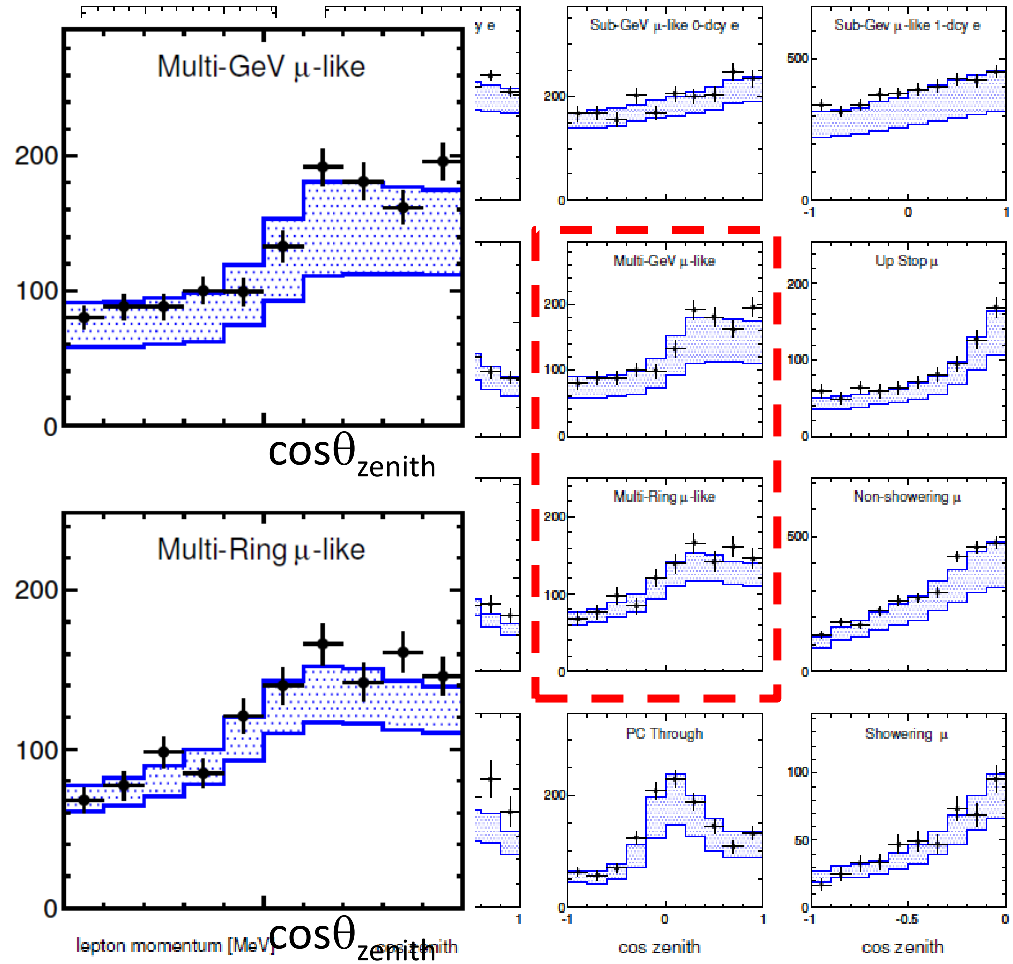
Search for CPT violation

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$$

+ data (SK-I,II,III)
MC ν
MC anti-ν

The CPT violation is suggested by
- LSND-MiniBooNE $\nu_\mu \rightarrow \nu_e$
- MINOS $\nu_\mu \rightarrow \nu_\mu$

SK can test MINOS result with same oscillation and same L/E range.
We cannot distinguish ν and anti-ν on an event by event.
We take statistical approach. The $\cos\theta_{zenith}$ comparison between samples with different ν, anti-ν compositions.



Two flavor scheme with **four oscillation parameters**:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \underline{\sin^2 2\theta} \cdot \sin\left(\frac{\underline{\Delta m^2} L}{E}\right)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \underline{\sin^2 2\bar{\theta}} \cdot \sin\left(\frac{\underline{\Delta \bar{m}^2} L}{E}\right)$$

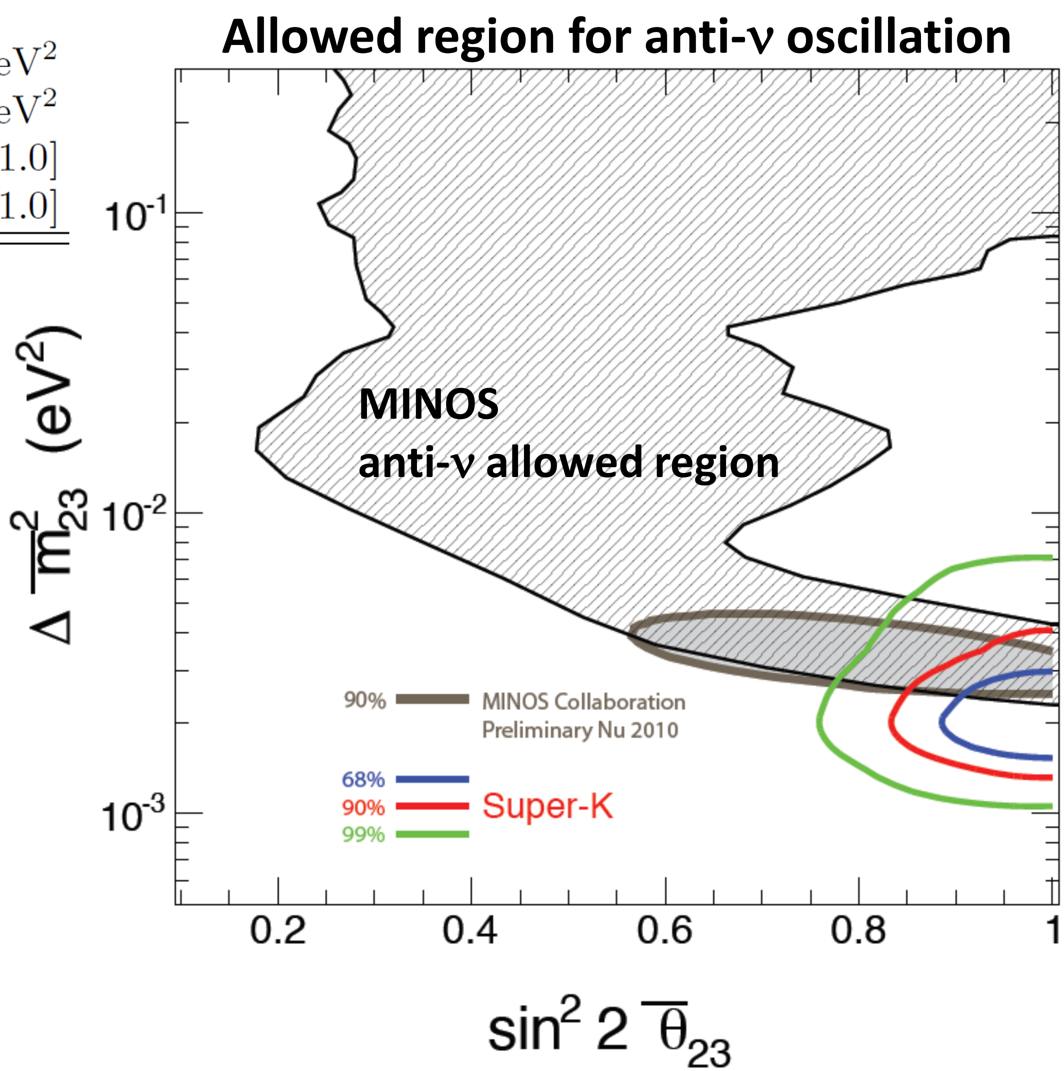
Composition differences
⇒ Determine ν and anti-ν oscillations, separately.

Arrowed region for anti-neutrino

Parameter	Best Fit	90% C.L. Bound
Δm^2	$2.1 \times 10^{-3}\text{eV}^2$	$[1.8, 2.7] \times 10^{-3}\text{eV}^2$
$\Delta \bar{m}^2$	$2.0 \times 10^{-3}\text{eV}^2$	$[1.5, 3.1] \times 10^{-3}\text{eV}^2$
$\sin^2 2\theta$	1.0	[0.92, 1.0]
$\sin^2 2\bar{\theta}$	1.0	[0.88, 1.0]

The oscillation parameters for ν and anti-ν are consistent.
No evidence for CPT violation is observed.

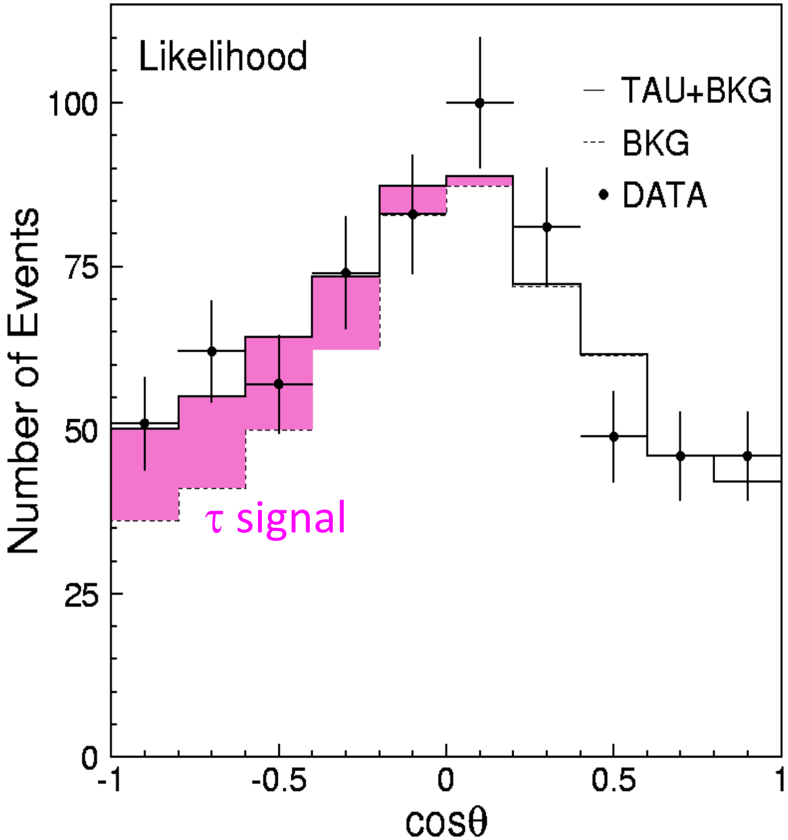
However, there is no inconsistency between the MINOS and our results since partially same region is allowed by both experiments.



Tau appearance analysis

SK-I only
PRL97,171801 (2006)

Best fit $\cos\theta_{zenith}$ distribution after standard+likelihood



($\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.4\times10^{-3}eV^2$ assumed for MC)

	Data	Signal	Background
Fiducial Vol.	-	78.4 (100%)	17135 (100%)
E_{vis}>1330MeV	2888	51.5 (65.7%)	2943 (17.2%)
1st-ring e-like	1803	47.1 (60.1%)	1765 (10.3%)
Likelihood	**649**	**33.8 (43.1%)**	**647 (3.79%)**
Neural Network	**603**	**30.6 (39.0%)**	**577 (3.36%)**

Two approaches are performed.

Likelihood (χ^2/dof =7.6/8)

Best fit: $N_\tau = 138 \pm 48(\text{stat.})^{+15}_{-32}(\text{syst})$

Expected: $N_\tau = 78 \pm 26(\text{syst})$

The τ enrich sample is consistent with $\nu_\mu - \nu_\tau$ oscillation.
The 2.4 σ signal is determined.

The analysis will be updated with SK-I,II,III, soon.

Summary of results

Neutrino oscillation

	Data-set	Remarks
Two flavor	SK-I,II,III	Zenith, L/E
Three flavor	SK-I,II,III	Solar term(θ_{12}, Δm_{12}^2), matter effect(θ_{13})
Full three flavor	SK-I,II,III	θ_{13}, δ_{CP}
CPT violation	SK-I,II,III	No evidence
Non-standard interactions	SK-I,II	No evidence
Tau appearance	SK-I	2.4σ, will be updated soon

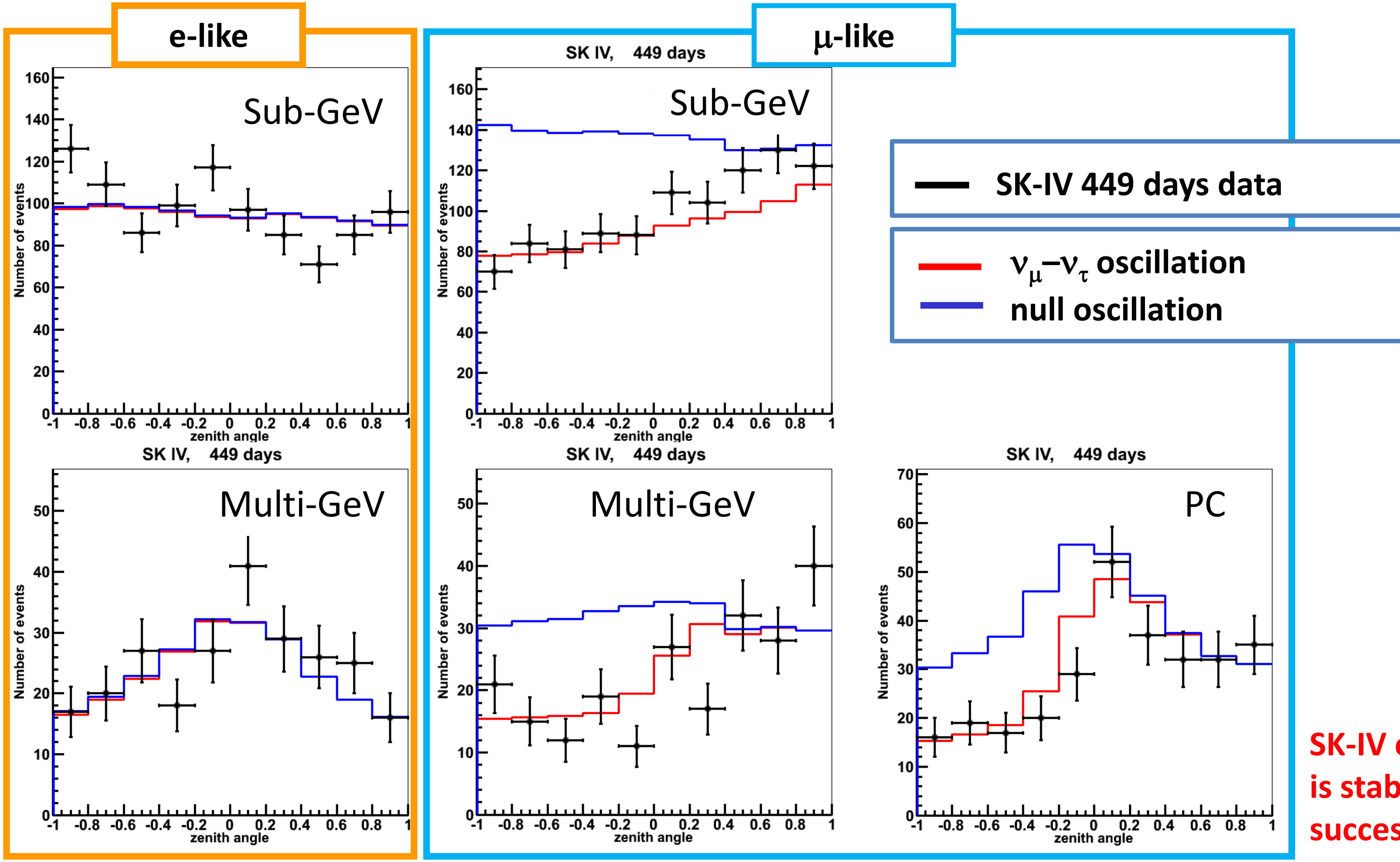
Proton decay

	Data-set	Remarks
$p \rightarrow e^+\pi^0$	SK-I,II,III	Life time>1.0×10^{34} years

Astro-physics

	Data-set	Remarks
WIMP search	SK-I,II,III	Galactic Center, Diffuse source

SK-IV preliminary result



SK-IV operation is stable and successful.

- This result is released for supporting the T2K analysis.
- The oscillation analysis is on-going and will be released in next summer.

Conclusion

Super-Kamiokande plays important roles for the ν-oscillation analysis.

Atmospheric-ν sample is sensitive to all oscillation parameters.

- The best limit to θ_{23} is produced.
- We focus on the sub-dominant effects. The CHOOZ limit to θ_{13} is confirmed. The CP phase, δ_{CP}, analysis is performed.

Search for CP violation in ν-oscillation is no longer future plan.

- There is a possibility to make the first result by global analysis of "current" experiments.
- The constraint to δ_{CP} can be made by atmospheric-ν sample if large θ_{13} is determined by LBL or reactor experiments.

There is no evidence for CPT violation at atmospheric-ν flux.

- SK tests the "MINOS-type" CPT violation.
- The SK allowed region suggest CPT conservation. However, there is no inconsistency since MINOS also allows this region.

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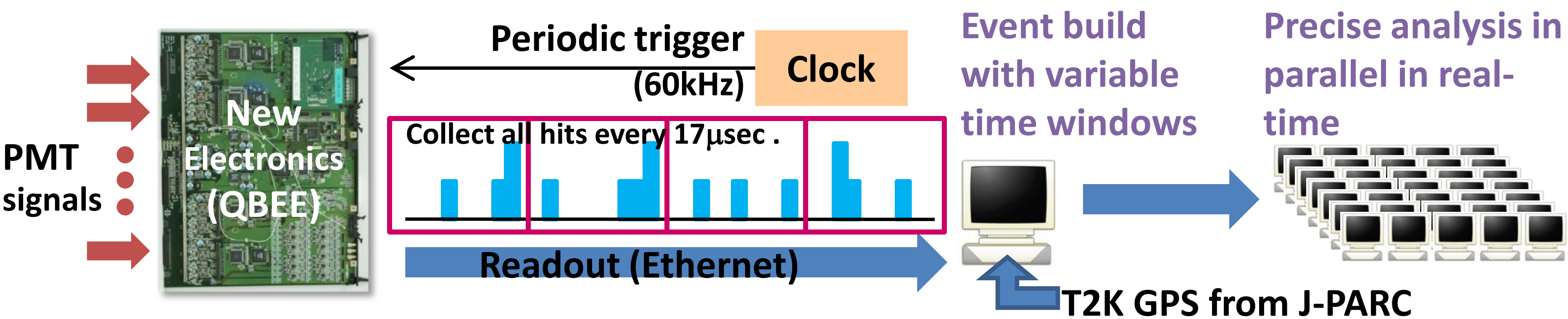
DAQ system in SK-IV

SK-I,II,III: partial data above threshold (Num. of hits) were read (1.3μsec window x3kHz)
SK-IV: All hits above pulse height threshold are read, then apply complex triggers by software.

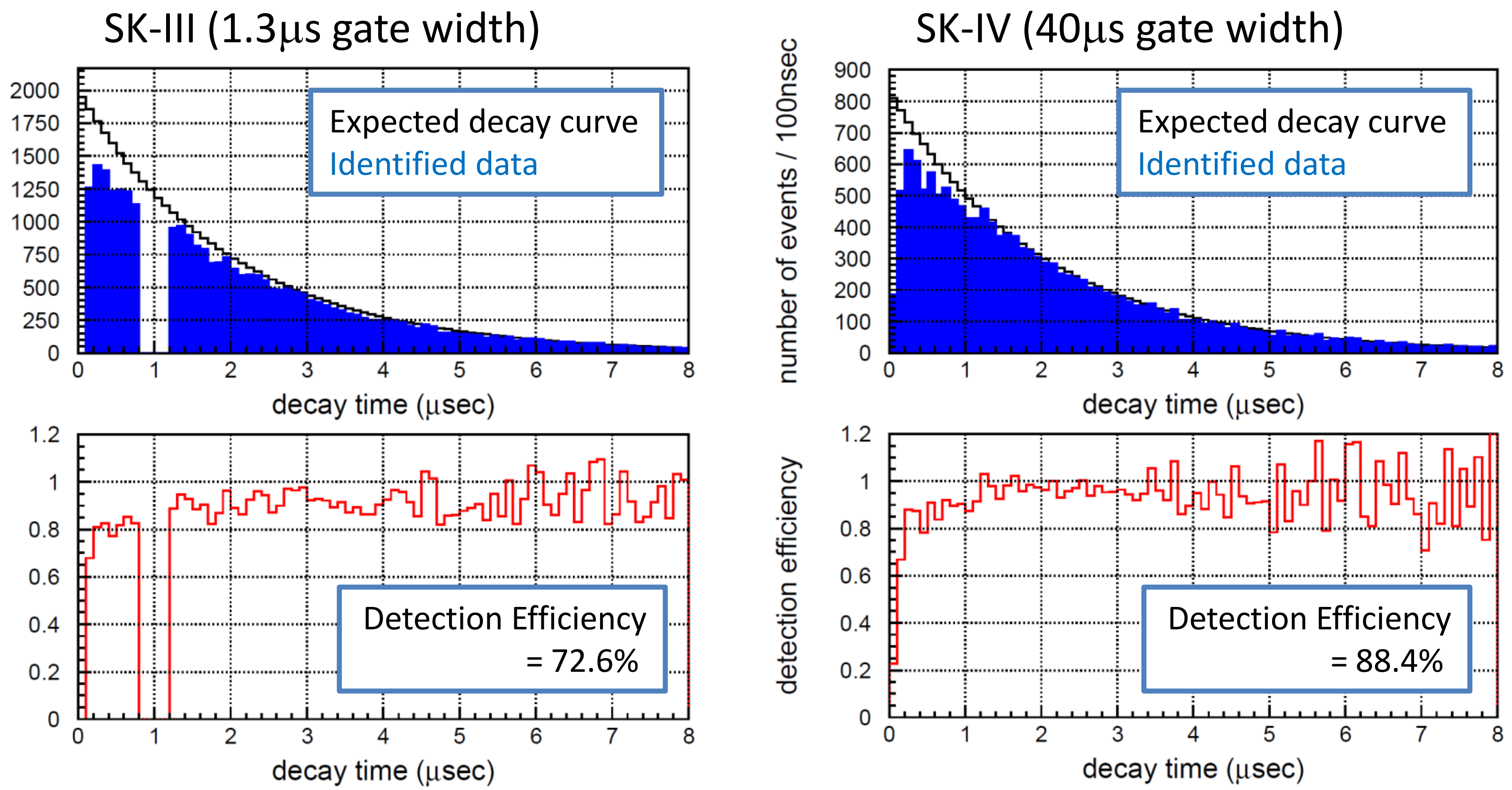


Typical event time windows:

- Super-Low-Energy (SLE) events (<~6.5MeV): -0.5/+1.0μsec — high rate (~3kHz)
- Normal events(>~6.5MeV): -5/+35μsec — decay electrons
- Supernova Relic ν (SRN) candidates(>~10MeV, No OD): -5/+535μsec — neutrons
- T2K events: -512/+512μsec at T2K beam spill timing

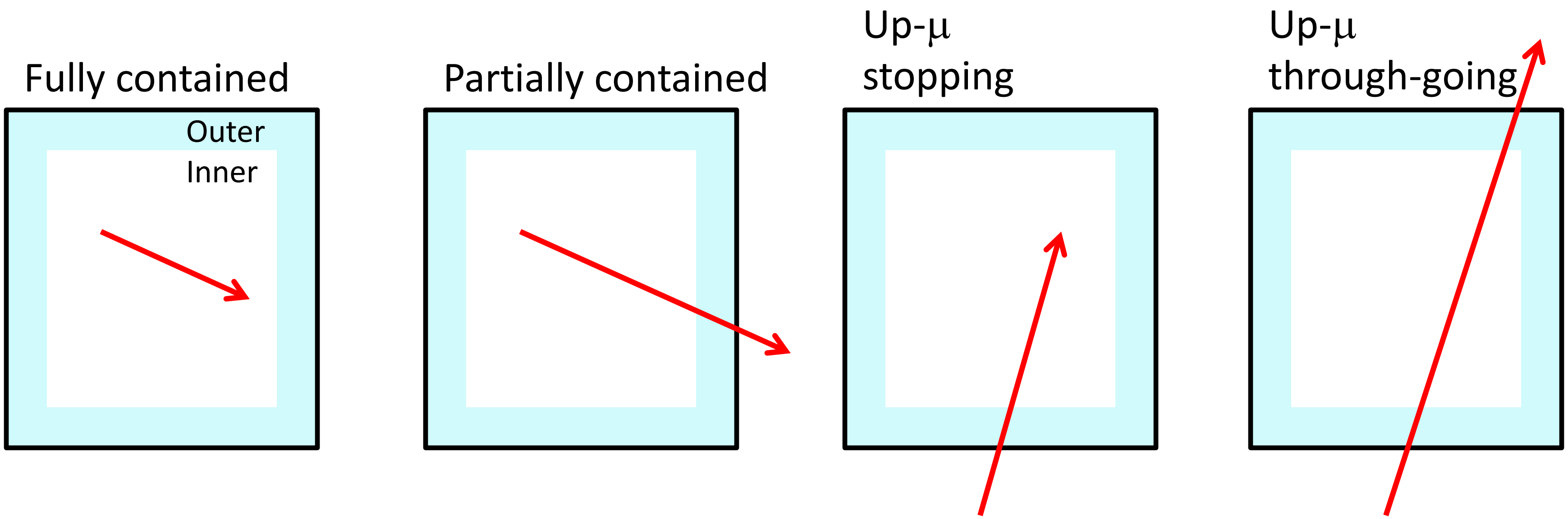
Wider dynamic range for charge measurement of each channel (>2000pC)	x5
No dead time up to ~6MHz/10sec for Supernova burst neutrinos	x100
Apply precise event reconstruction to remove more low-e BG events in real-time	

Michel electron tagging in SK-IV



Wider gate width of SK-IV enables detection of muon decay electrons at T~1 μs.

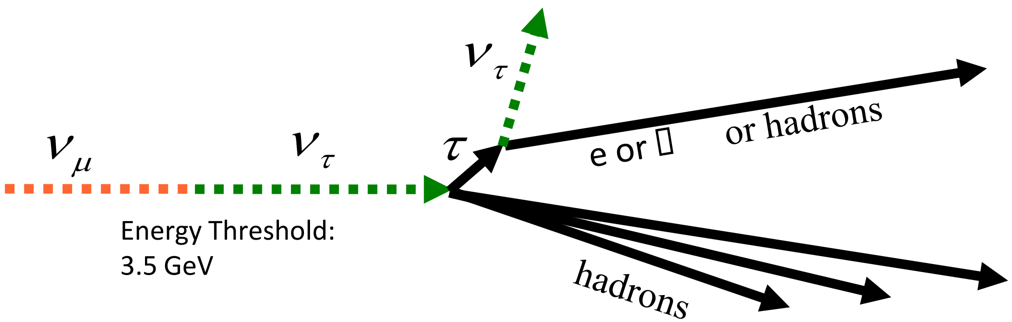
Event rates

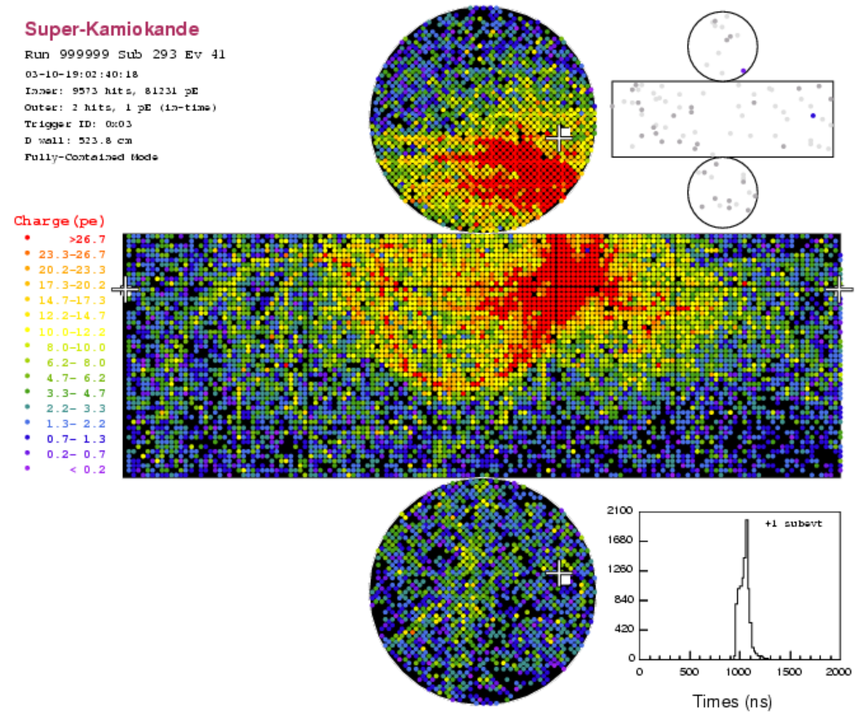


	SK-I (1489 days)	**SK-II (798 days)**	**SK-III (518 days)**
Fully contained 0.1-10 GeV	8.18±0.07 (events/day)	8.22±0.10	8.31±0.22
Partially contained 1-100 GeV	0.61±0.02	0.54±0.03	0.66±0.04
Up-μ stopping 3-100 GeV	0.25±0.01	0.28±0.02	0.24±0.03
Up-μ through-going 5-1000 GeV	1.12±0.03	1.07±0.04	1.11±0.06

Tau Leptons in Super-K

A search for another smoking gun of neutrino oscillation:
tau *neutrino appearance*.

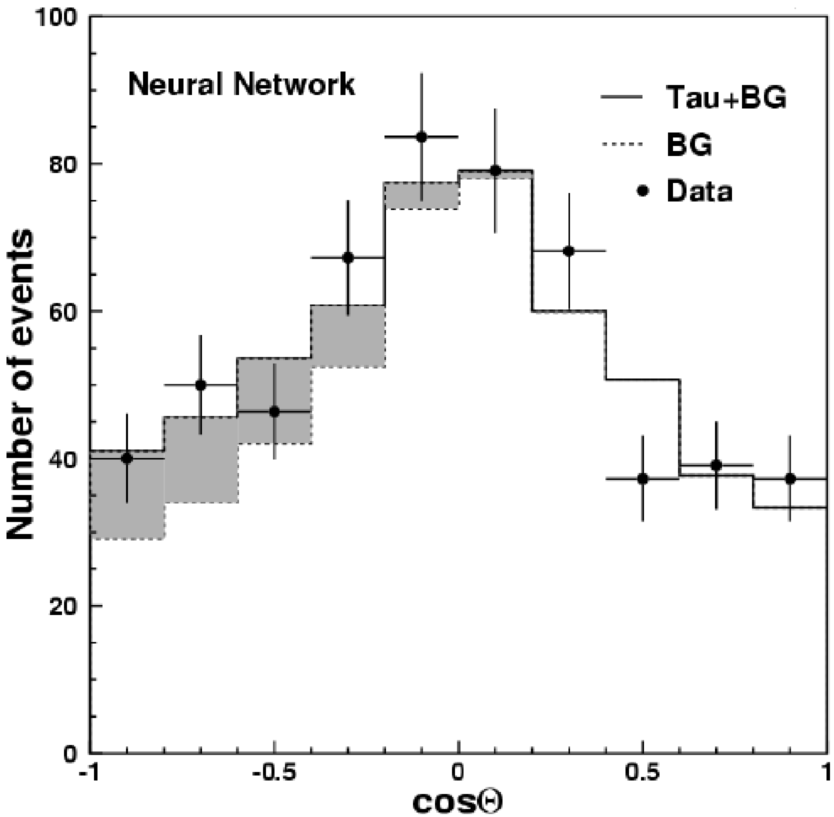




Signal: high energy, extra pions from tau decay,
more spherically symmetric due to decay of heavy tau.

Tau appearance Neural Network

Best fit $\cos\theta_{zenith}$ distribution
after standard+Neural Network



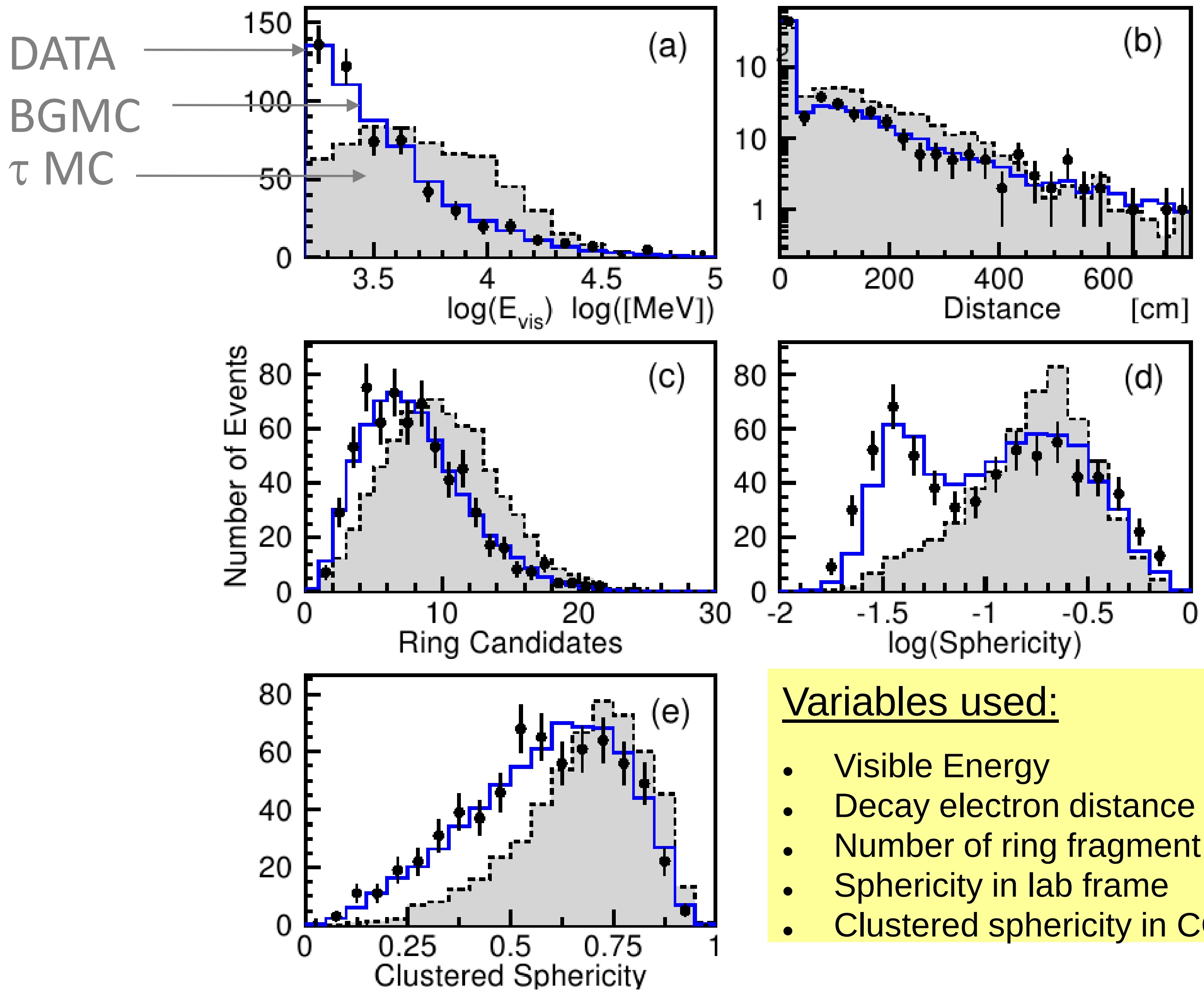
Neural Network (χ^2/dof =9.8/8)

Best fit: $N_\tau = 134 \pm 48(\text{stat.})^{+16}_{-27}(\text{syst.})$

Expected: $N_\tau = 78 \pm 26(\text{syst.})$

Five variables used for analysis

Compare the likelihood variables with down-going data.



There should be no tau events in the down-going data.

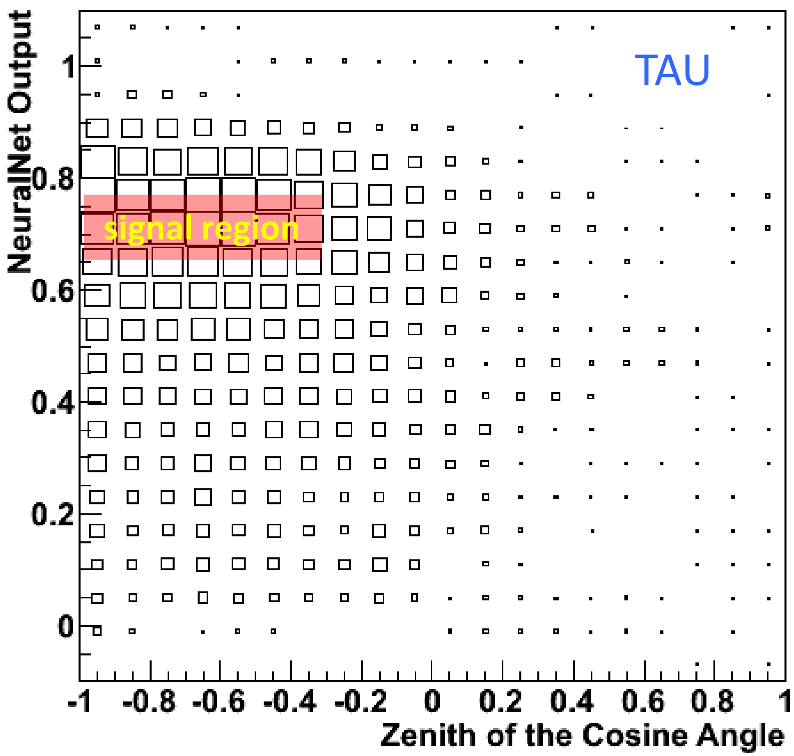
Variables used:

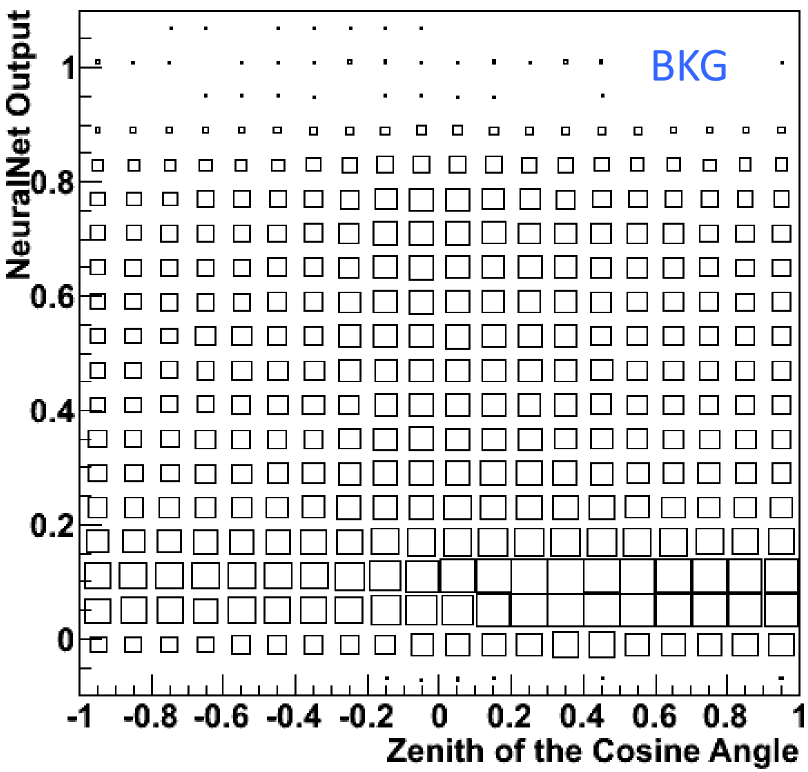
- Visible Energy
- Decay electron distance from vertex
- Number of ring fragment candidates
- Sphericity in lab frame
- Clustered sphericity in COM frame

Coming Soon: Analysis with new data and techniques

SKI: 1489 Days / SKII: 799 Days / SKIII: 518 Days ADDED

Use all of the information to perform a 2D un-binned likelihood fit of signal and background.

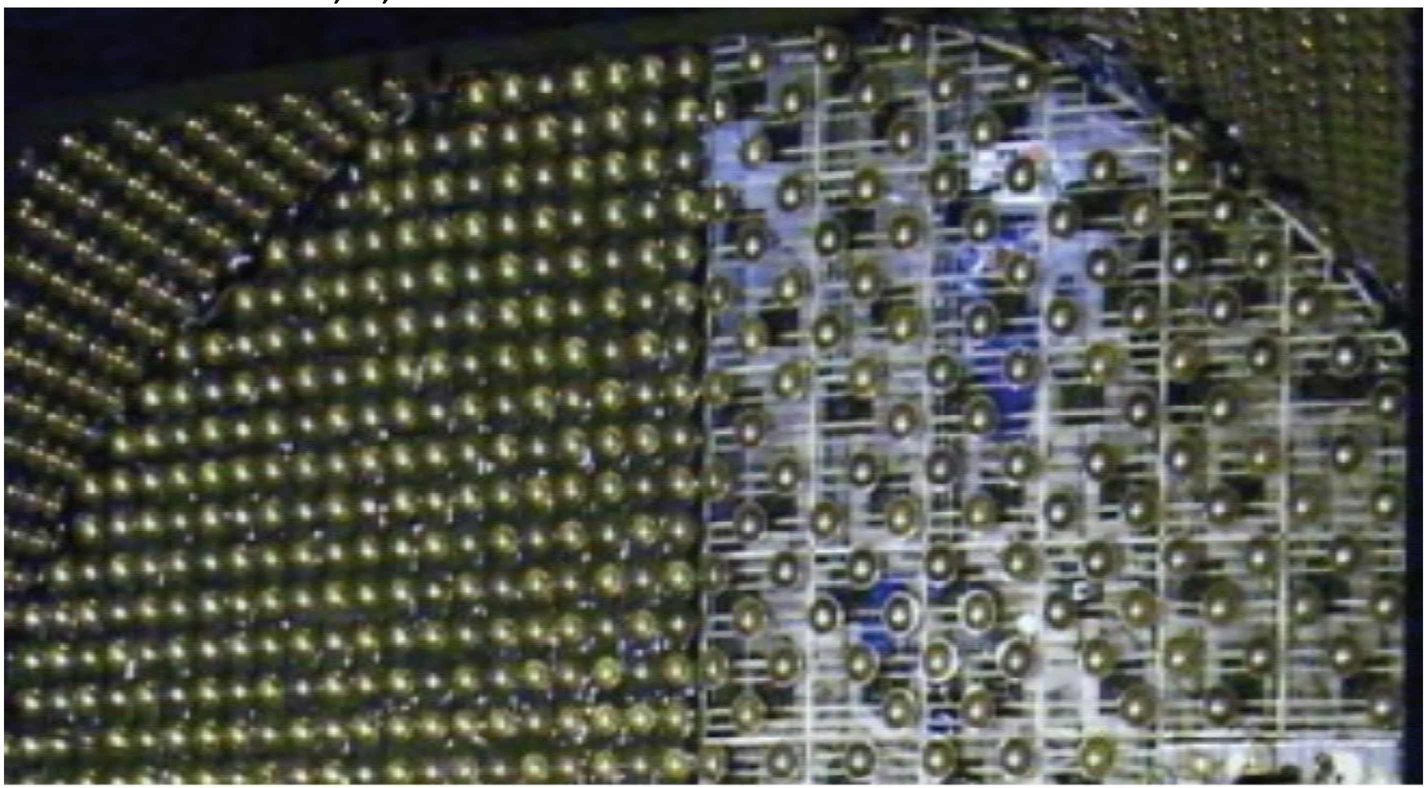




Previously used the projection of the upper ½ of plots. In 2D the shape is very different!

PMT density

SK-I,III,IV SK-II



Atmospheric ν flux

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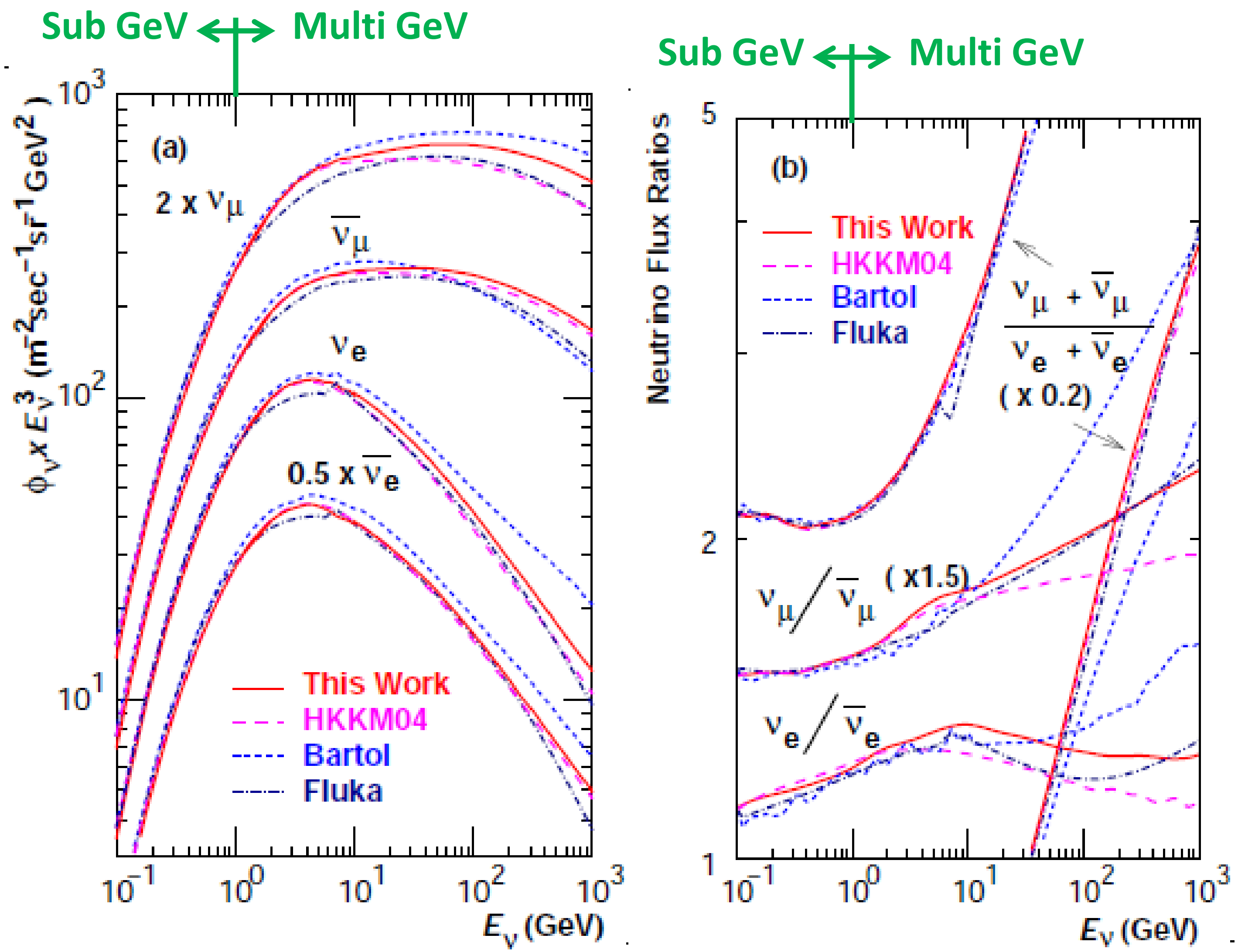
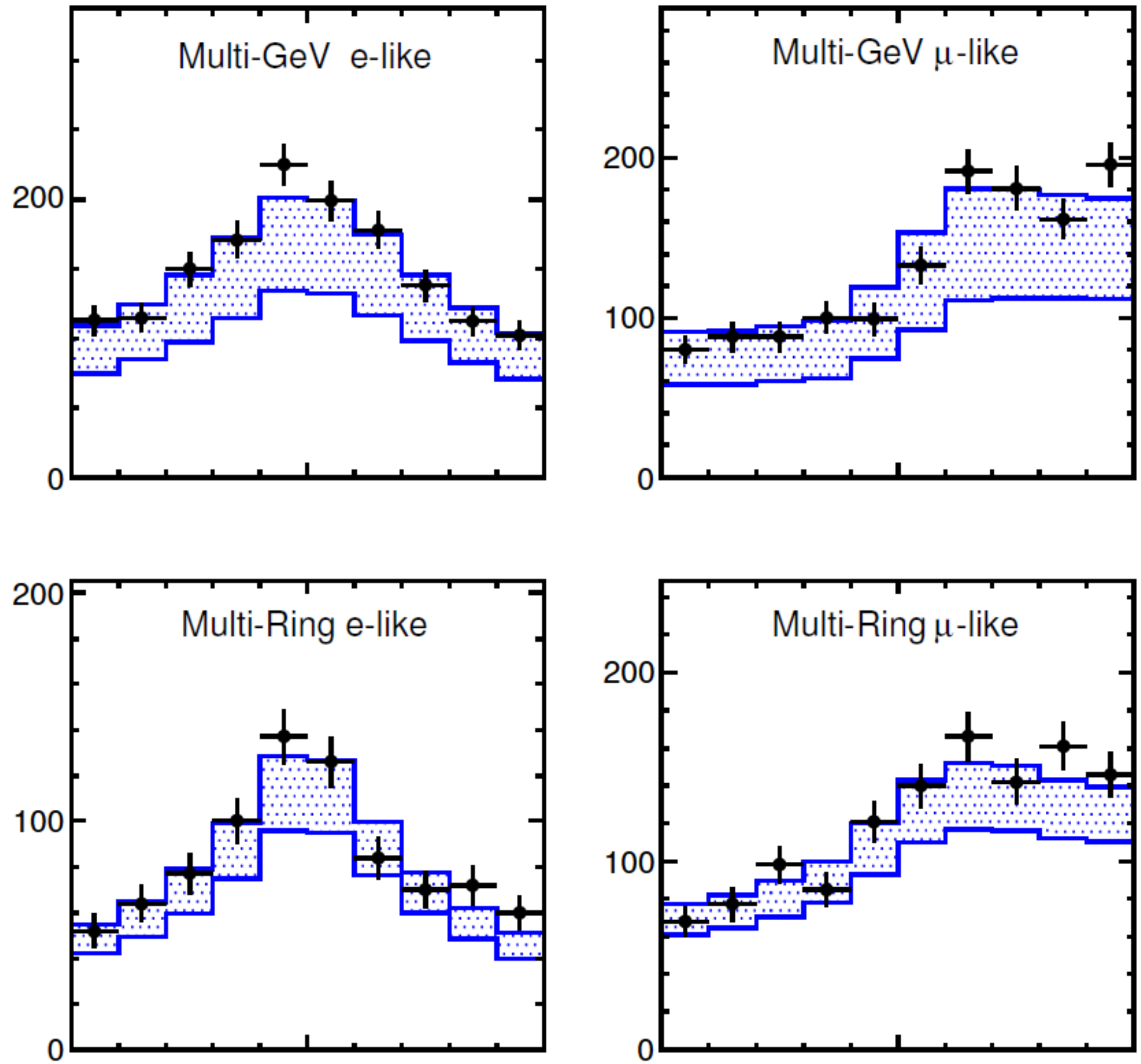


ν and ν-bar compositions



Kamioka site-map