

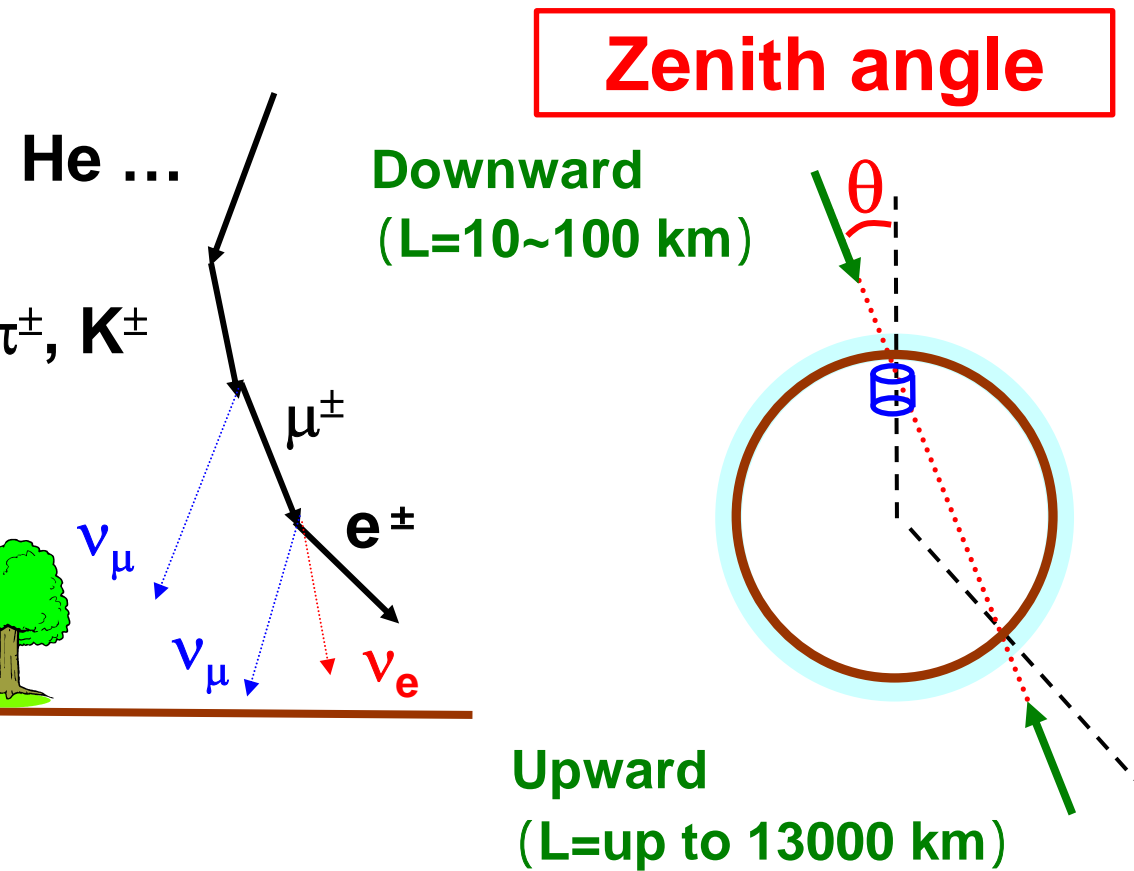
SK Atmospheric neutrino

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for the Super-Kamiokande collaboration

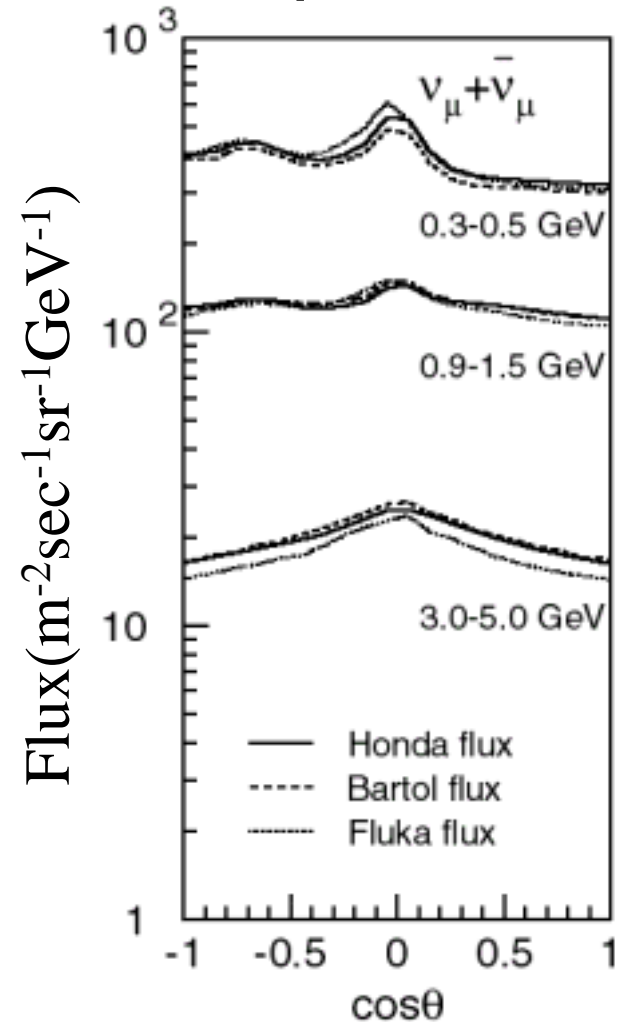
ontents

- **Atmospheric neutrino oscillation using full Super-Kamiokande I(SK-I) data**
 - $\nu_{\mu} \leftrightarrow \nu_{\tau}$ **oscillation analysis**
 - **CPT analysis**
- **Super-Kamiokande II(SK-II) current status**

Atmospheric neutrinos

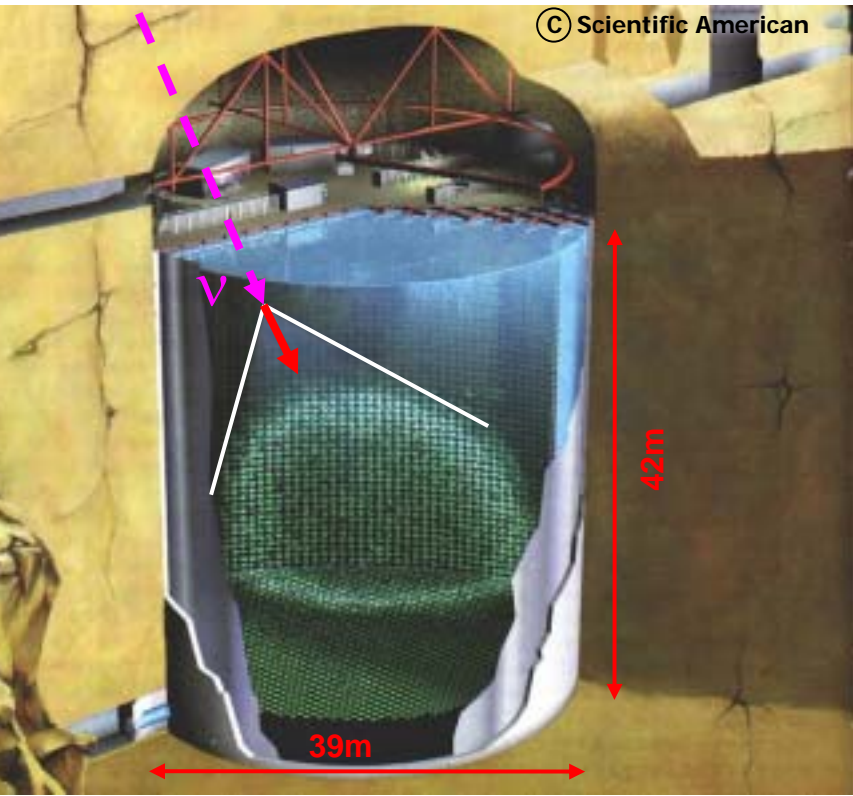


Zenith angle dist. of Atmospheric ν flux



$E_\nu > \text{a few GeV}$
Up/Down Symmetry

© Scientific American



Water Cherenkov detector

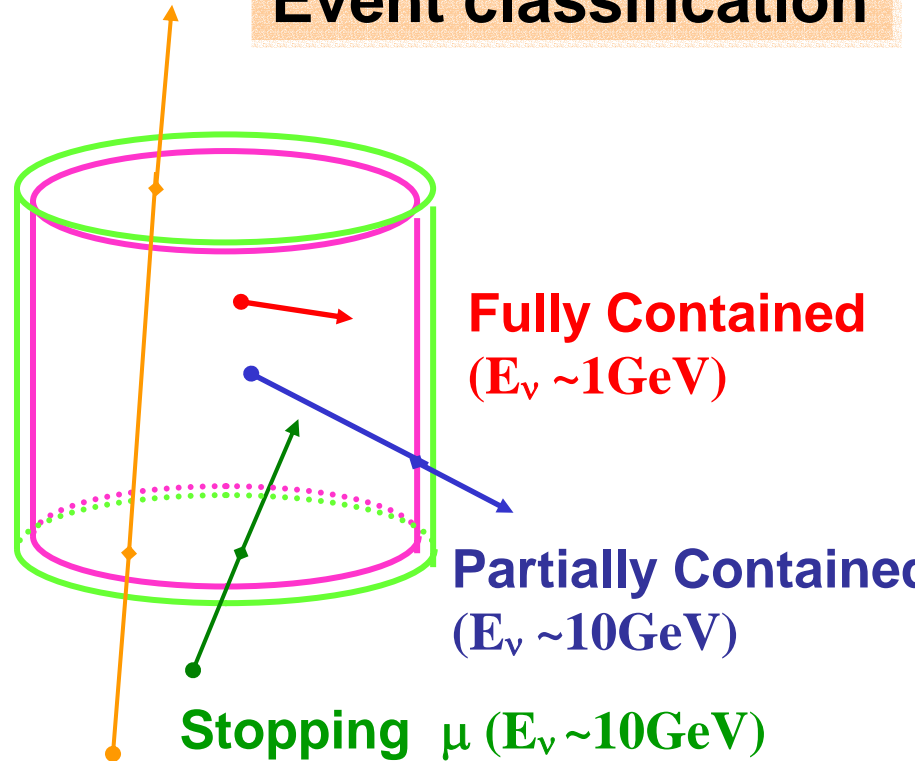
1000 m underground

50,000 ton (22,500 ton fid.)

inner-detector(ID): 11,146

outer-detector(OD): 1,885

Event classification



Through-going μ ($E_\nu \sim 100\text{GeV}$)

20 inch PMTs(SK-I)

8 inch PMTs

Zenith angle distributions

$$\nu_{\mu} \leftrightarrow \nu_{\tau}$$

2-flavor oscillations

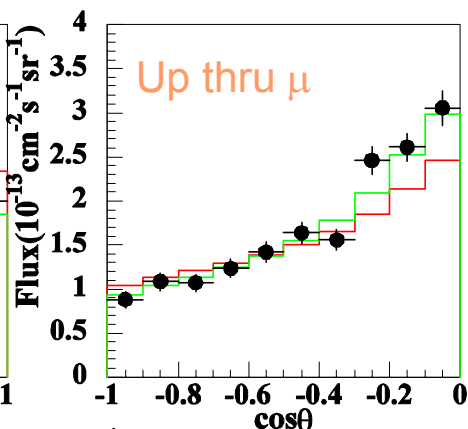
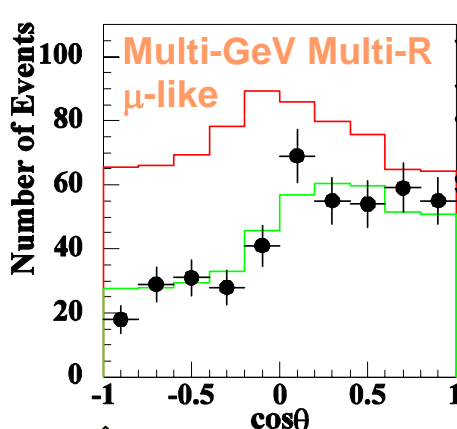
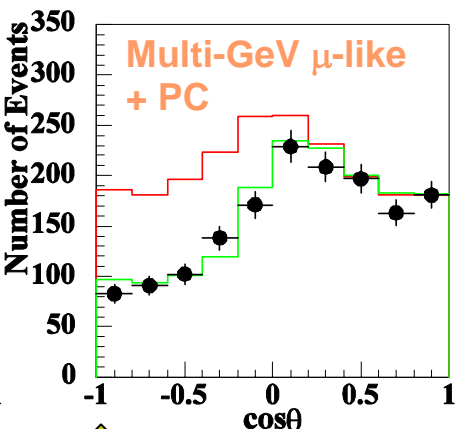
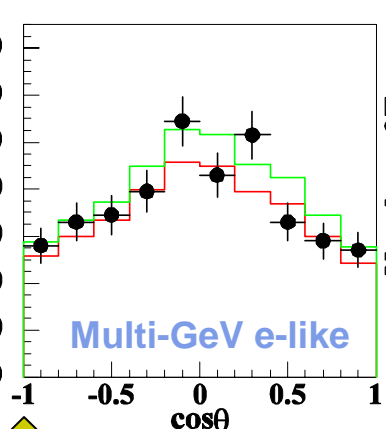
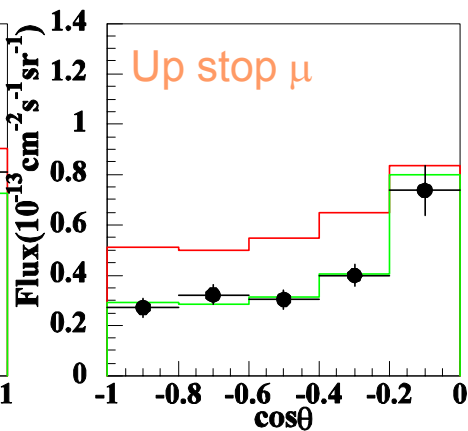
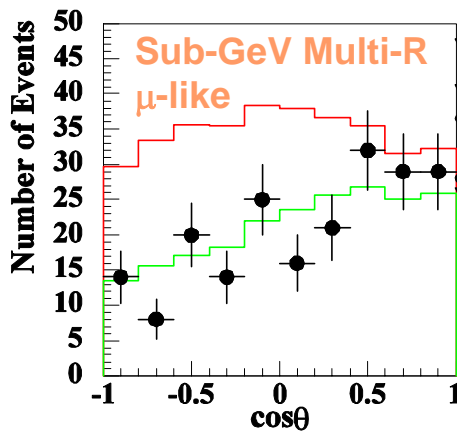
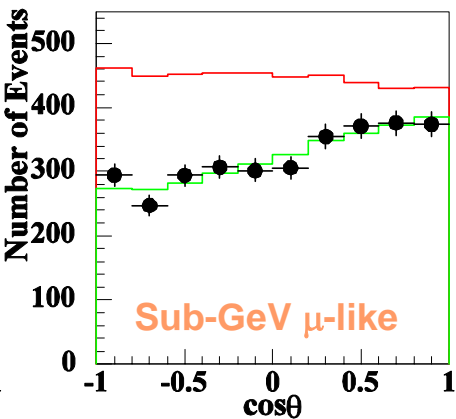
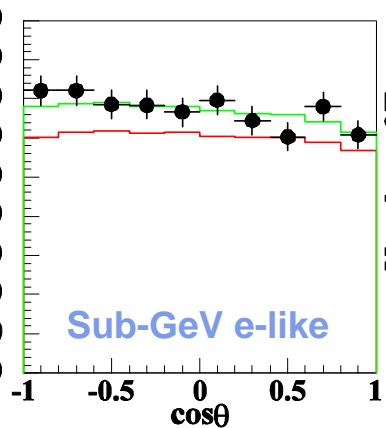


Best fit

$$\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2$$



Null oscillation



~13000km ~500km ~15km



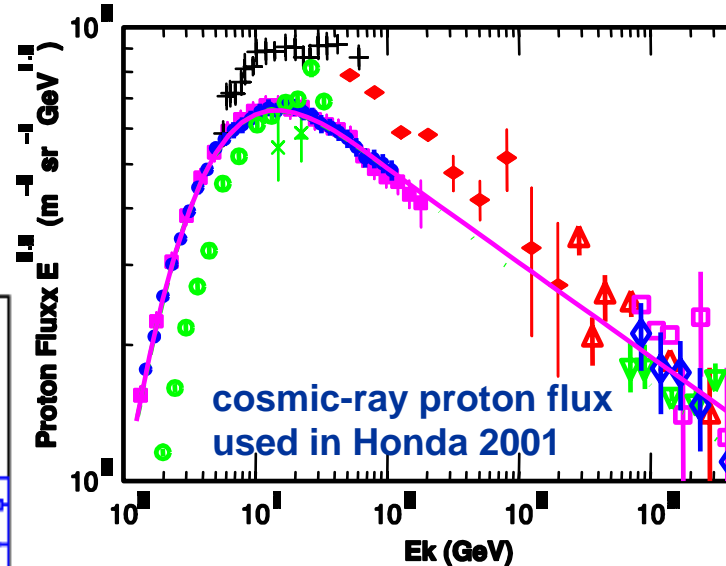
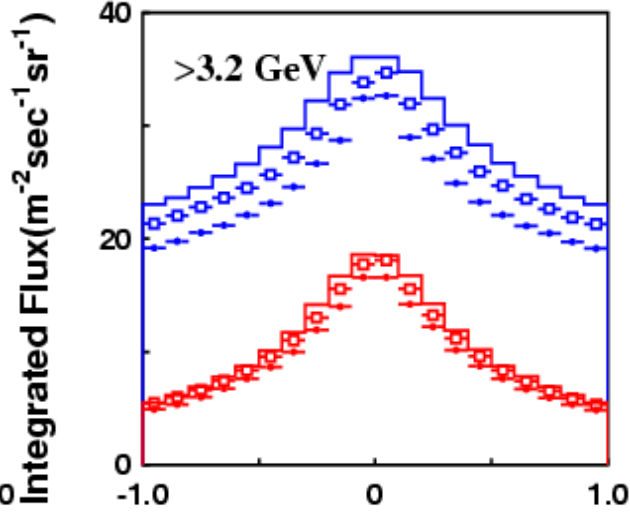
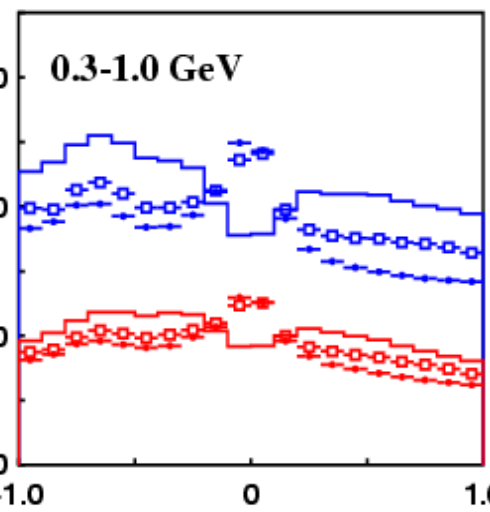
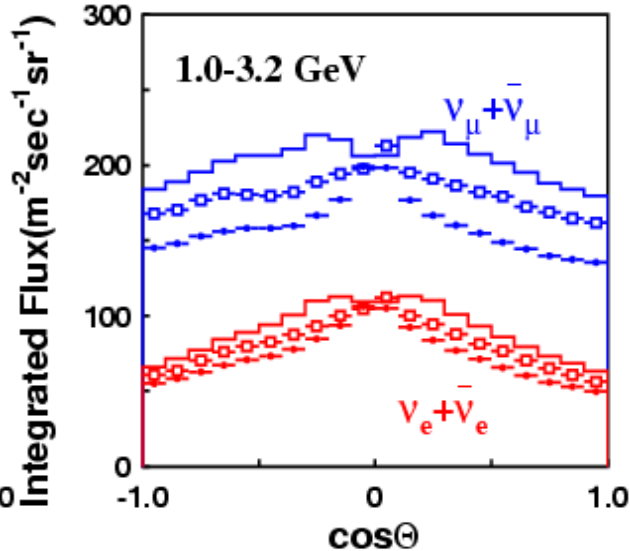
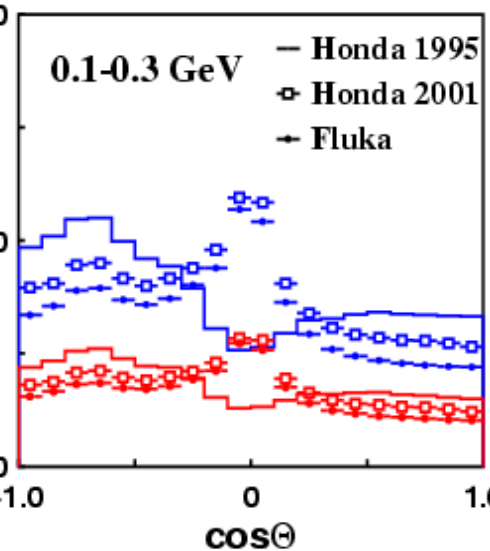
~13000km ~500km

Recent Improvements (after v2002)

- **MC improvements**
 - **Three dimensional (3D) ν flux calculation**
 - **ν interaction parameters**
 - **Axial vector mass**
 - **Fermi-momentum, nuclear potential**
- **Data analysis**
 - **Ring selection, Particle ID, multi-ring fits**
 - **Up- μ new automated precise fitter**
- **New calibs. and improved detector simulation**

Flux Calculation

- Honda1D (Old)
- Honda3D (New)
- + Fluka3D



Honda 2001(3D)

- Absolute normalization lower
- Enhancement in horizontal direction low energies



Not appear in observed zenith angle distribution due to μ scattering angle $\theta(\nu \rightarrow \mu)$

Other improvements

Neutrino interactions

- Axial vector mass (M_A) was modified to agree with K2K near data

Q.E. $M_A=1.0$ \longrightarrow 1.1

Single π $M_A=1.0$ \longrightarrow 1.1

Analysis tools

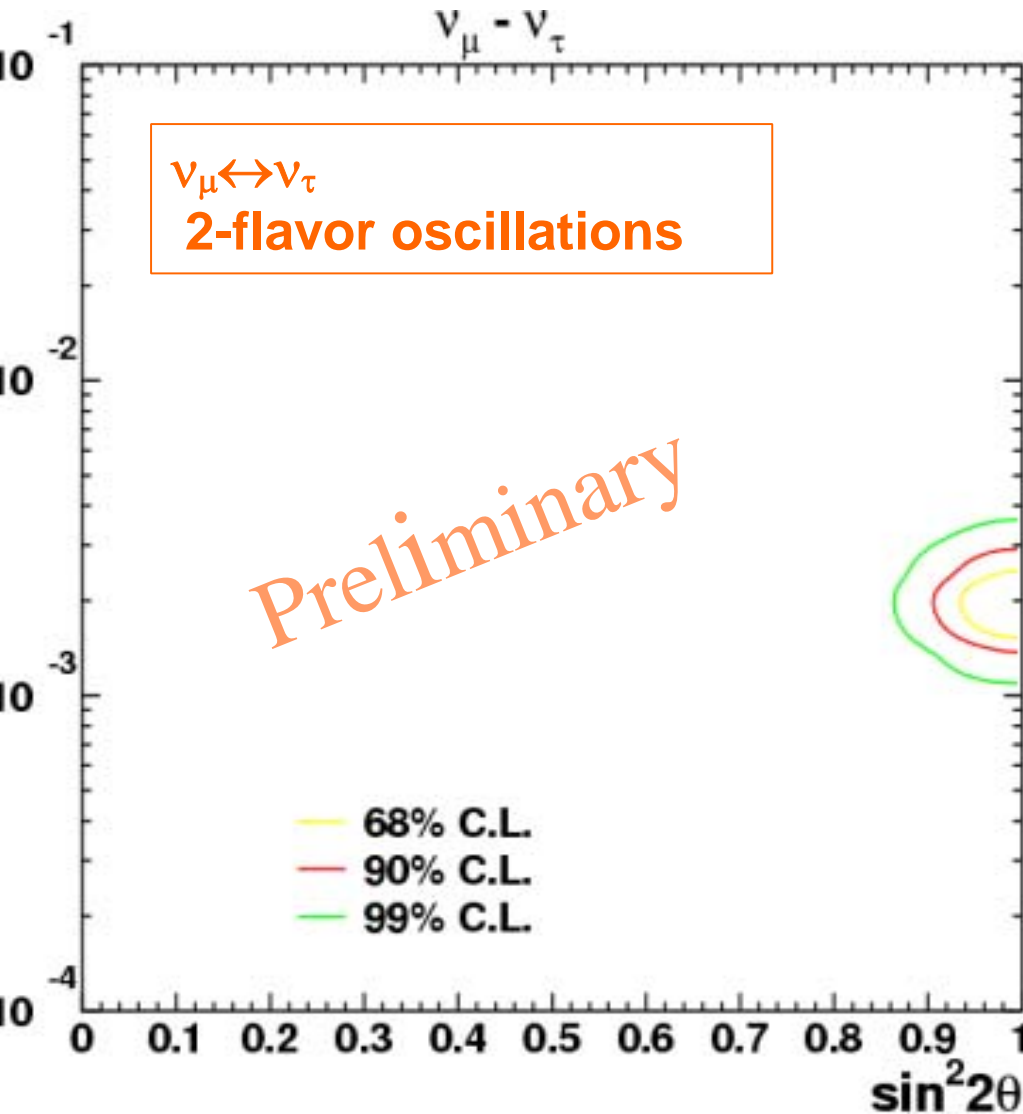
- Improved detector simulation
- Data reduction

Fully automated FC and PC data reduction

Event scanning for upward going muon analysis is greatly reduced (~ 100 events/day \rightarrow 3 events/day)

Oscillation Analysis Results

(FC + PC + UP- μ)



- **Best fit:**

$$\sin^2 2\theta = 1.0$$

$$\Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2$$

$$\chi^2 = 170.8/170 \text{ dof}$$

- **90% C.L. region:**

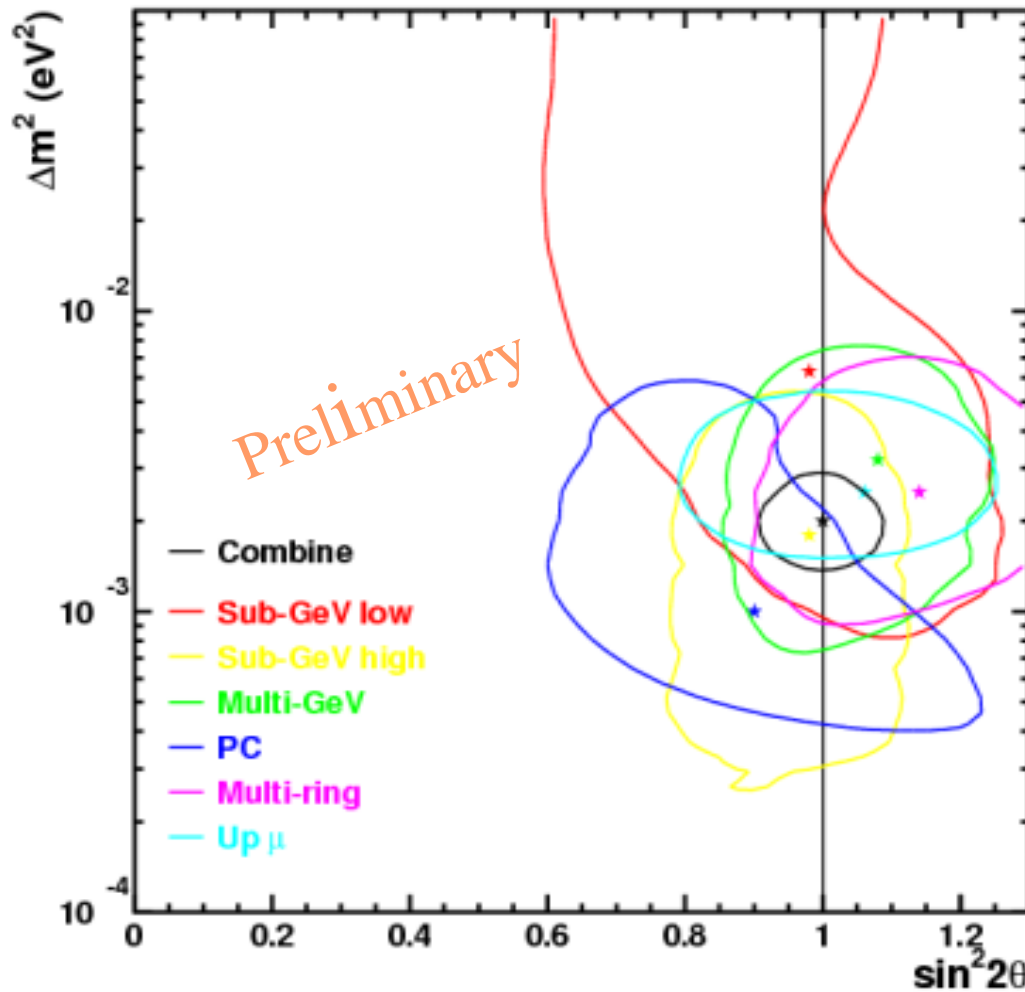
$$\sin^2 2\theta > 0.90$$

$$1.3 < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$$

Sub-Sample Consistency

Check oscillation fit using different samples of data independently

- each allowed region overlaps with best fit point



To finalize SK-I Results

- **Re-estimation of systematic errors and improvements of the treatment of systematic errors**
- **Improvement of up- μ flux predictions**
 - analytical calculation → full detector simulation

Treatment of systematic errors in χ^2 calculation

Old systematic errors

Absolute Normalization
Uncertainty

SubGeV Multi-ring
Absolute Normalization Uncertainty

MultiGeV Multi-ring
Absolute Normalization Uncertainty

E_ν Spectrum Index

SubGeV μ/e Ratio

MultiGeV μ/e Ratio

FC/PC Relative
Normalization

SubGeV Up/Down
Asymmetry

MultiGeV Up/Down
Asymmetry

FC+PC/Stop $\uparrow\mu$
Relative Normalization

Through $\uparrow\mu$ /Stop $\uparrow\mu$
Relative Normalization

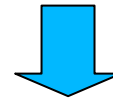
FC+PC Horizontal/Vertical
Uncertainty

$\uparrow\mu$ Horizontal/Vertical
Uncertainty

L/E Uncertainty

These systematic errors are estimated as independent error terms

But some error sources are multiply used (e.g. E_ν spectrum index is used in δ , β_1 , β_2 , ρ , β_L , β_H)



Each systematic error source is treated as independent error term



Neutrino flux

flux absolute normalization

flavor ratios($E_\nu < 1.33\text{GeV}$, $E_\nu > 1.33\text{GeV}$)

anti-neutrino/neutrino ratio(ν_e, ν_μ)

Up/down ratio

Horizontal-vertical ratio(3D calc., K/π)

Neutrino flight length

Energy spectrum

Sample-by-sample normalization
(FC multi-GeV, PC+up stop μ)

Neutrino interaction

M_A in quasi-elastic and single-pi

Quasi elastic scattering (model dependence)

Quasi elastic scattering (cross section)

single-pion production (cross section)

multi-pion production (model dependence)

multi-pion production (cross section)

coherent pion production (cross section)

NC/CC ratio

Nuclear effect in ^{16}O

Charged current ν_τ interaction

(C) Event selection

a. FC reduction

b. PC reduction

c. Up- μ detection efficiency

d. FC/PC relative normalization

e. Hadron simulation

f. Non- ν BG (e-like, μ -like)

g. Through-going/stopping μ separation

(D) Event reconstruction(6)

a. 1-ring/multi-ring separation

b. Particle ID (single-ring, multi-ring)

c. Energy calibration for FC

d. Energy cut for upward stopping μ

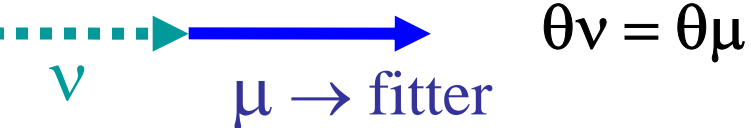
e. Up-down asymmetry of energy calibration

Total number of errors: 36

**Treated as independent
error term in χ^2 calculation**

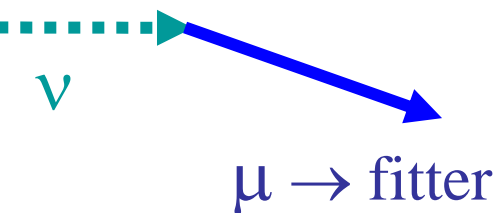
Improvement of up- μ flux predictions

analytical calculation (Old)



$$\theta\nu = \theta\mu$$

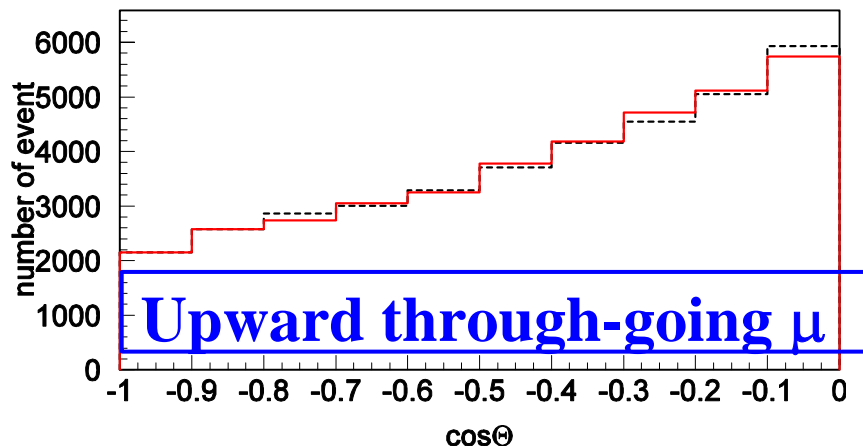
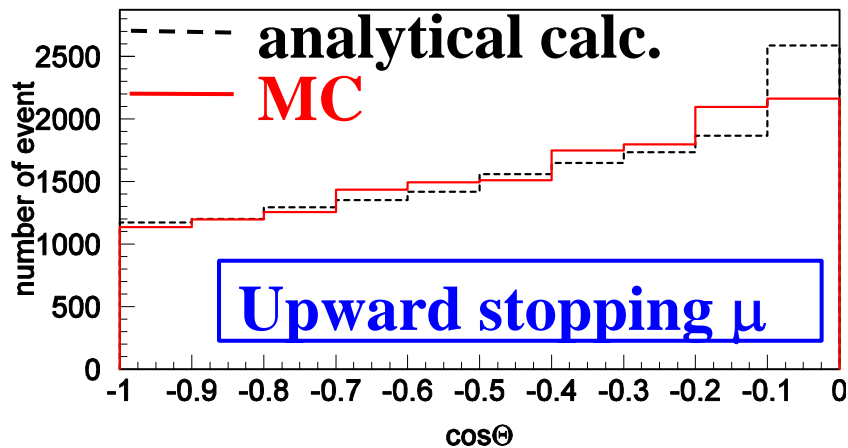
MC (New)



$$\theta\nu \neq \theta\mu$$

smeared

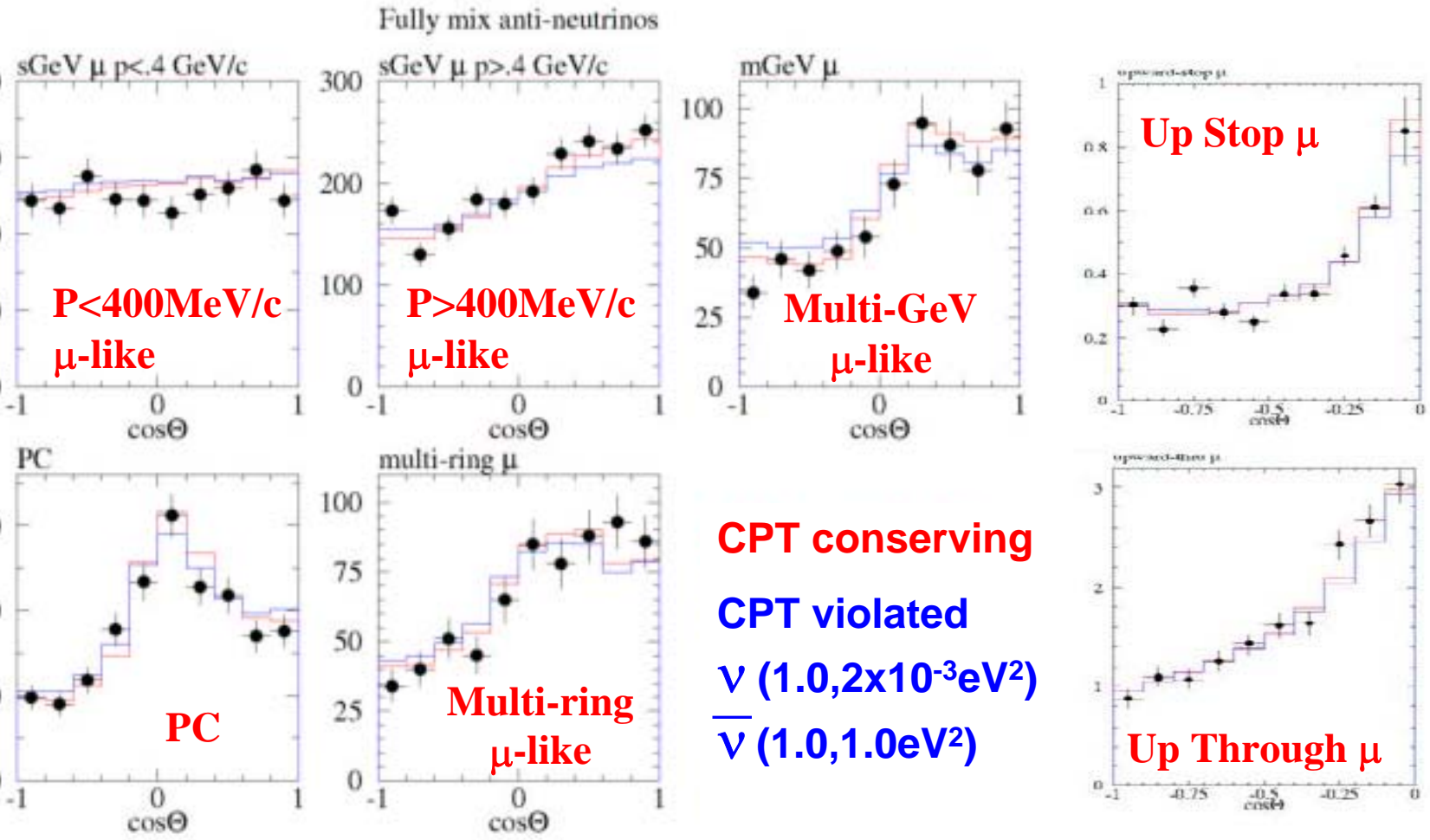
consider $\nu \rightarrow \mu$
scattering angle



Final SK-I result

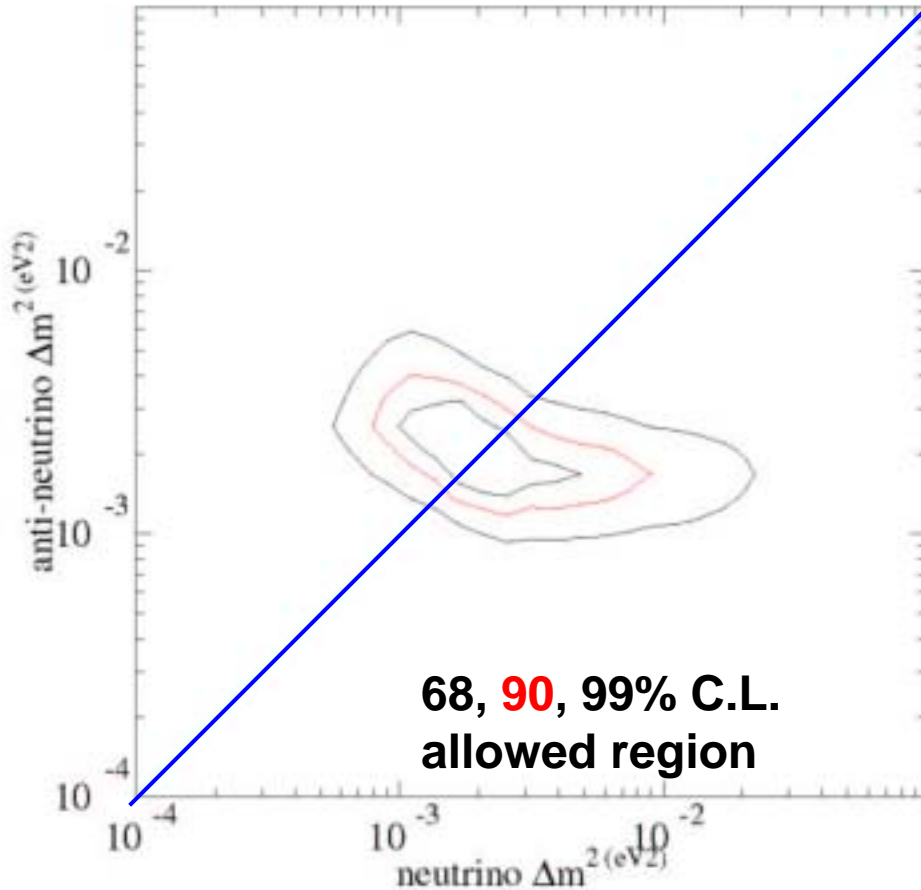
full paper (including $\nu\mu \leftrightarrow \nu\tau$
oscillation analysis) is coming soon

CPT violation analysis ($\Delta m^2_{\nu} = \Delta m^2_{\bar{\nu}}$)



CPT violation ($\Delta m^2_\nu = \Delta m^2_{\bar{\nu}}$)

no CPT violation



using 4 free parameters
(Δm^2 , $\sin^2 2\theta$) for ν and $\bar{\nu}$

Best fit :

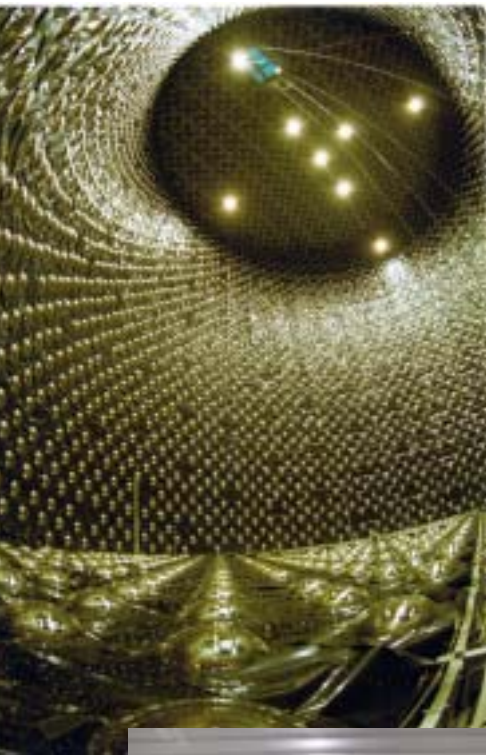
$\sin^2(2\theta) = 1.0$ for ν and $\bar{\nu}$

$\Delta m^2 = 1.7 \times 10^{-3} \text{eV}^2$ for ν
 $2.1 \times 10^{-3} \text{eV}^2$ for $\bar{\nu}$

no evidence for CPT violation

SK-II

SK-II is taking data

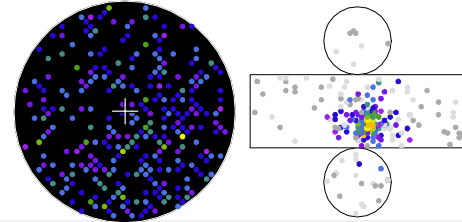
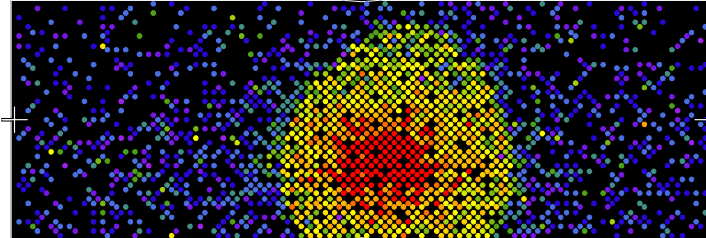


Super-Kamiokande

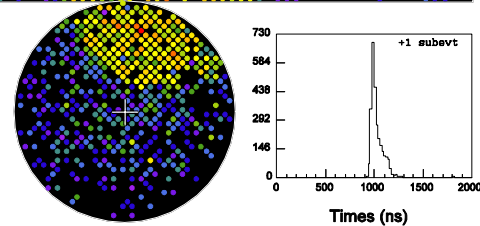
Run 21929 Sub 61 Ev 2325472
03-03-17:01:24:14
Inner: 2781 hits, 21129 pE
Outer: 97 hits, 295 pE (in-time)
Trigger ID: 0x0b
D well: 1690.0 cm
Fully-Contained Mode

Charge (pe)

- >25.7
- 23.3-25.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



SK-II partially-contained sample



20inch PMT with
Acrylic + FRP
vessel

- **Rebuilt in summer 2002**
 - Has 47% of original ID 20inch PMTs (~520)
 - 20inch PMTs in acrylic shells to prevent future chain implosions
 - Has full OD 8inch PMTs (1885)
- **Started data taking in Dec. 2002**

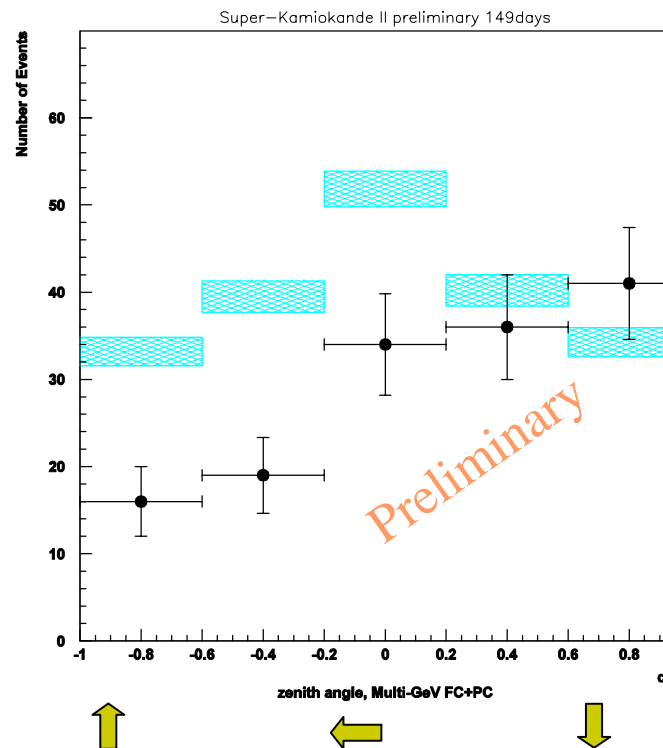
Status of SK-II Analysis

149 days of FC & PC data

- Now checking detector simulator and reconstruction tools

Consistent event rate with SK-I

Clear deficit in upward-going ν_μ events



Number of events & Event rate (Preliminary)

	SK-II 149.3 days	SK-I 1489 days
Fully-contained	1245 (8.33 ± 0.24)	12180 (8.18 ± 0.07)
Partially-contained	80 (0.54 ± 0.06)	911 (0.62 ± 0.02)

Multi-GeV FC μ -like + F

Summary

K-I analysis

- SK-I full data set (FC,PC 1489days, up- μ 1646 days)
- Improved data analysis and MC predictions
- $\nu_{\mu} \leftrightarrow \nu_{\tau}$ allowed region @ 90% C.L.
 $1.3 < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta > 0.90$ (Preliminary)
- SK-I final result will be published soon with updated systematic errors
- no evidence for CPT violation

K-II analysis is in progress

- Event rate is consistent with SK-I
- Deficit in upward going event in Multi-GeV μ -like + PC sample