SK Atmospheric neutrino

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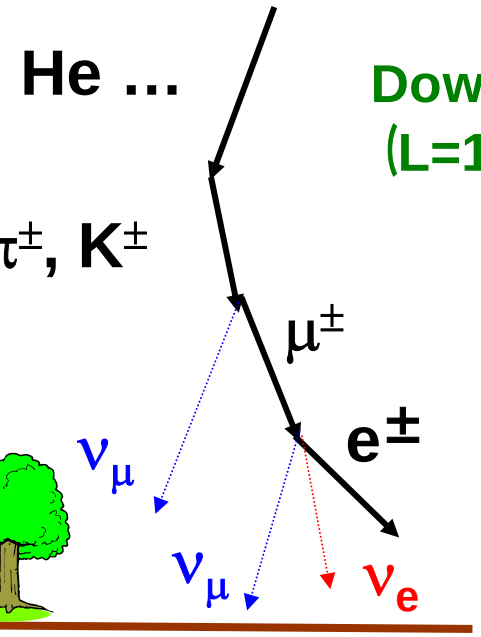
for the Super-Kamiokande collaboration

ontents

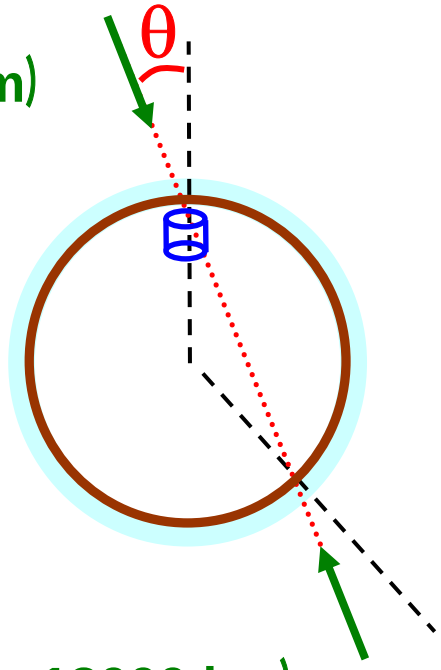
- **Atmospheric neutrino oscillation using full Super-Kamiokande I(SK-I) data**
  - $\nu_\mu \leftrightarrow \nu_\tau$ **oscillation analysis**
  - **CPT analysis**
- **Super-Kamiokande II(SK-II) current status**

tmospheric neutrinos



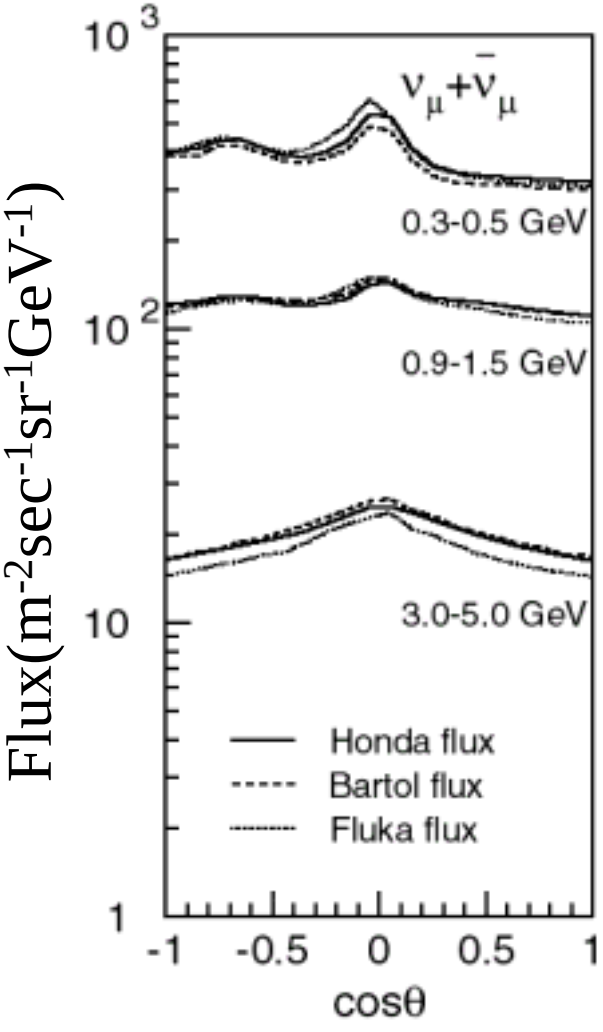
Zenith angle

Downward
(L=10~100 km)



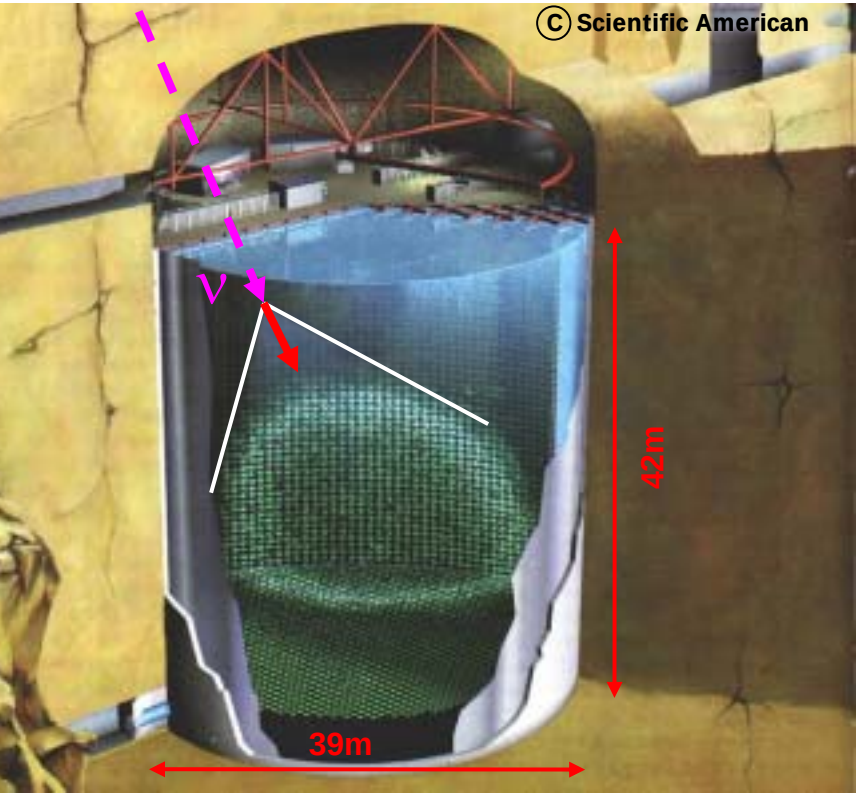
Upward
(L=up to 13000 km)

Zenith angle dist. of Atmospheric ν flux



Eν > a few GeV

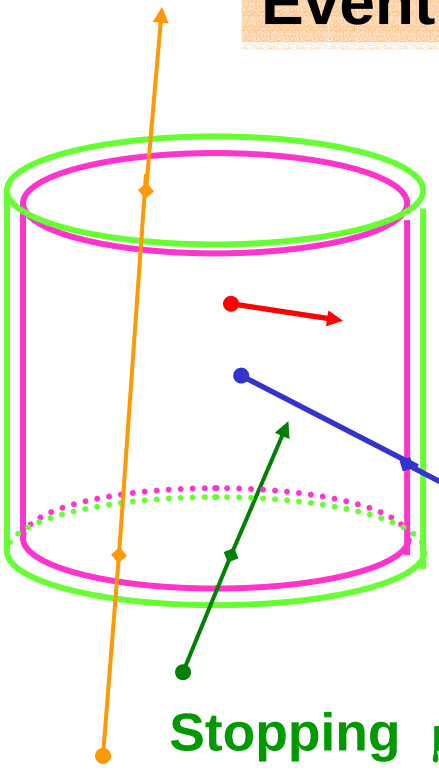
Up/Down Symmetry



Water Cherenkov detector

1000 m underground
50,000 ton (22,500 ton fid.)
nner-detector(ID): 11,146 20 inch PMTs(SK-I)
outer-detector(OD): 1,885 8 inch PMTs

Event classification



Fully Contained
(E_ν ~1GeV)

Partially Contained
(E_ν ~10GeV)

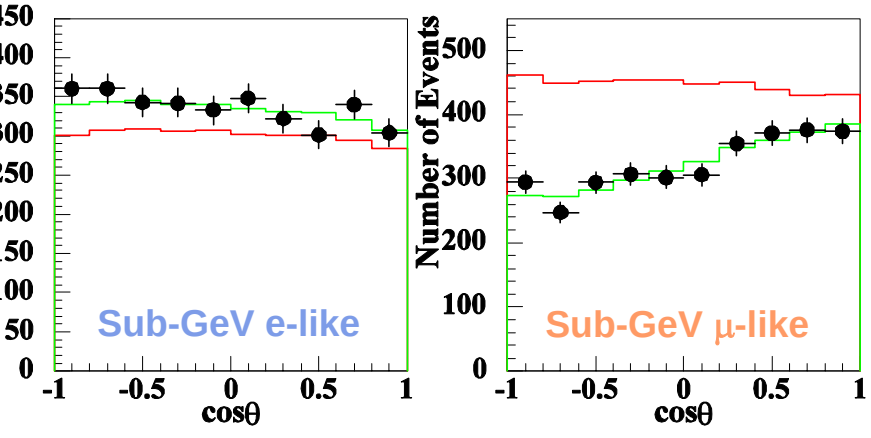
Stopping μ (E_ν ~10GeV)

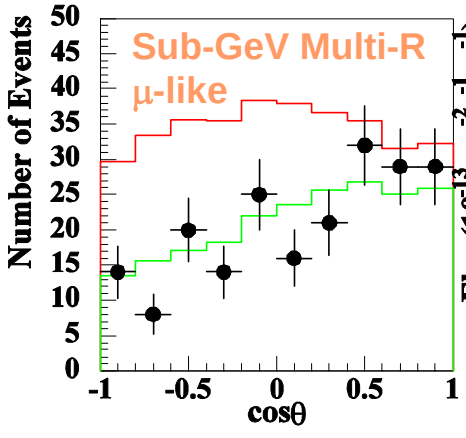
Through-going μ (E_ν ~100GeV)

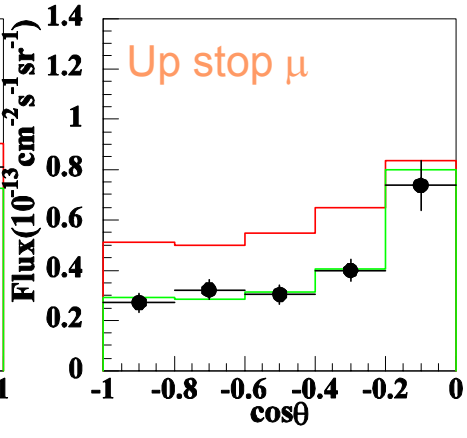
Zenith angle distributions

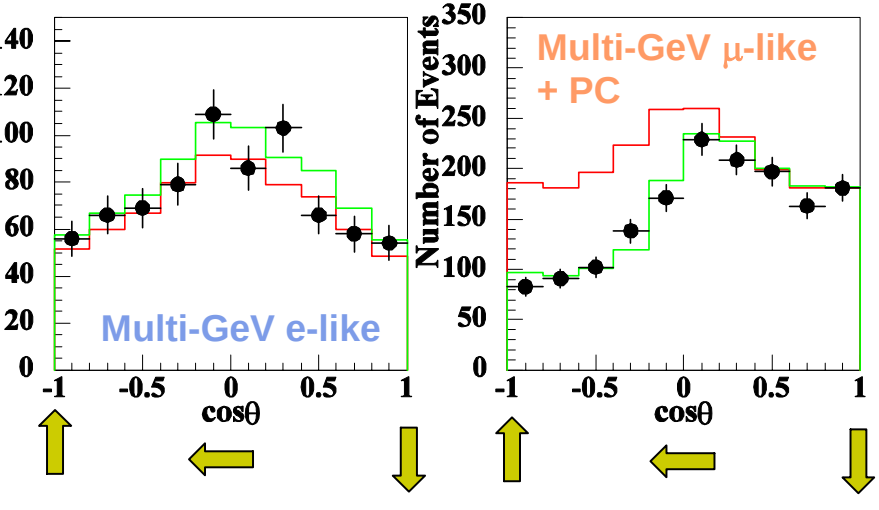
$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

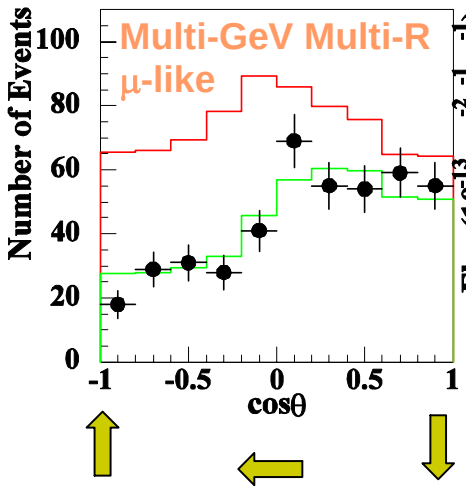
Best fit
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2
Null oscillation

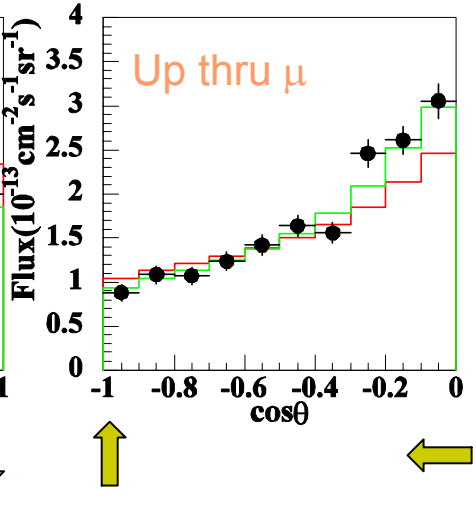












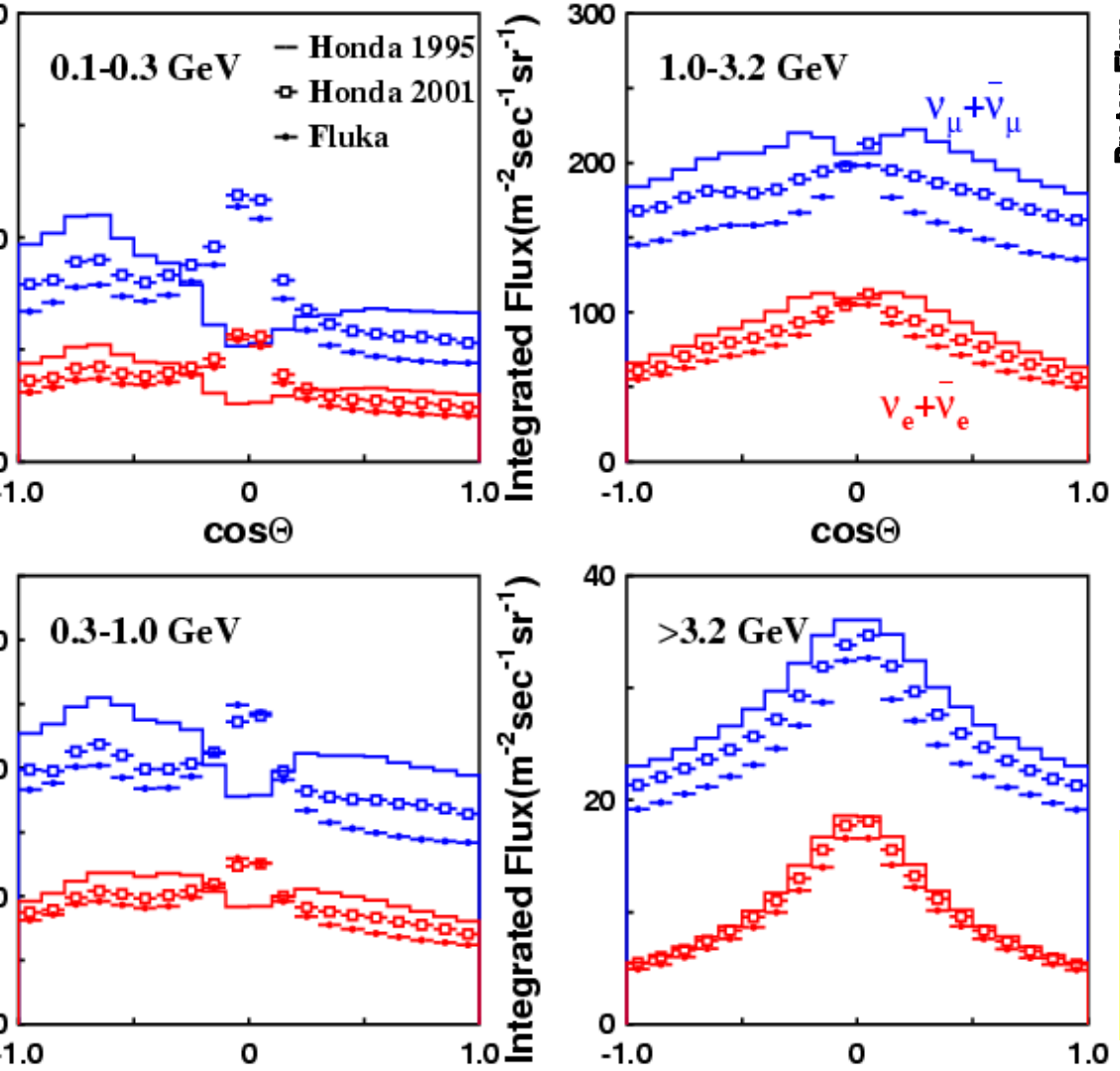
~13000km ~500km ~15km ~13000km ~500km

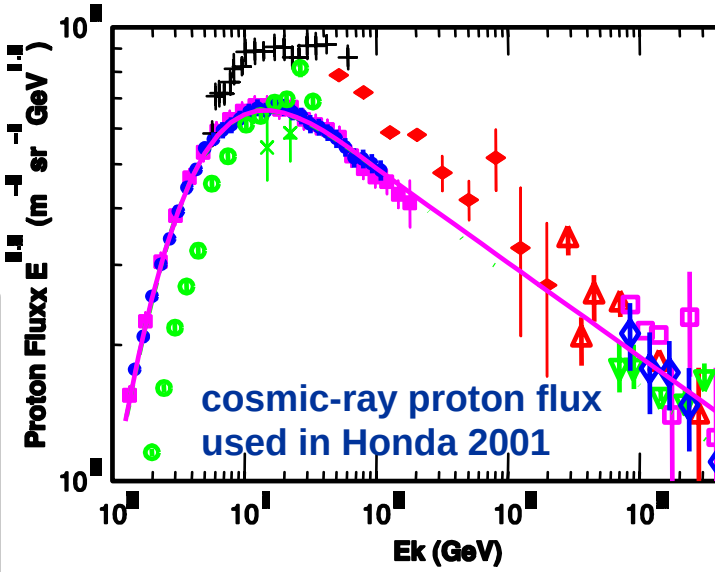
Recent Improvements (after ν2002)

- **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**

D Flux Calculation

Honda1D (Old)
Honda3D (New)
Fluka3D





Honda 2001(3D)

- Absolute normalizat
  lower
- Enhancement in
  horizontal direction
  low energies

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

ther improvements

Neutrino interactions

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

Q.E.	M_A=1.0	→	1.1
Single π	M_A=1.0	→	1.1

Analysis tools

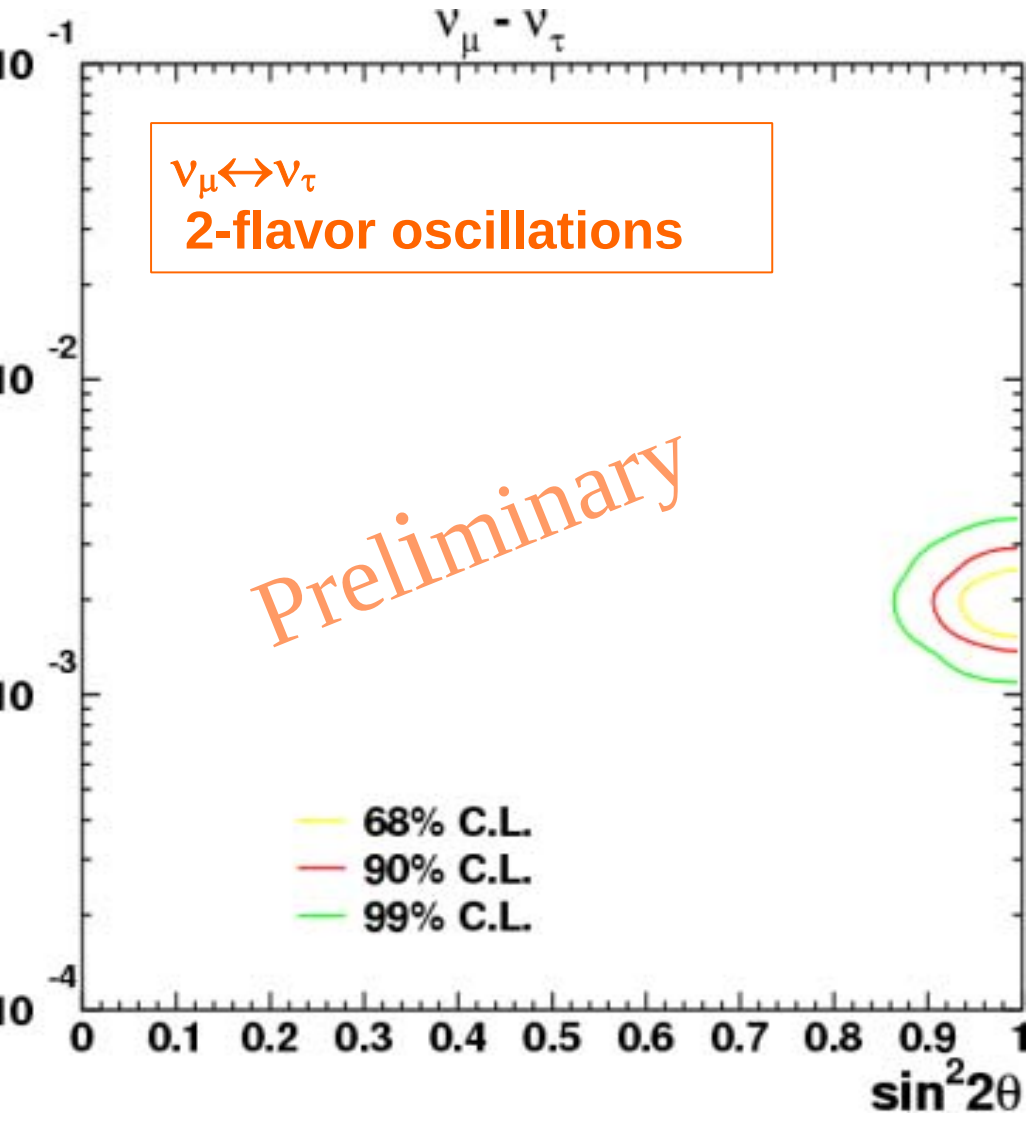
- Improved detector simulation
- Data reduction

  Fully automated FC and PC data reduction

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

Oscillation Analysis Results

(FC + PC + UP-μ)



- **Best fit:**

  $\sin^2 2\theta = 1.0$

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

  $\chi^2 = 170.8/170$ dof

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

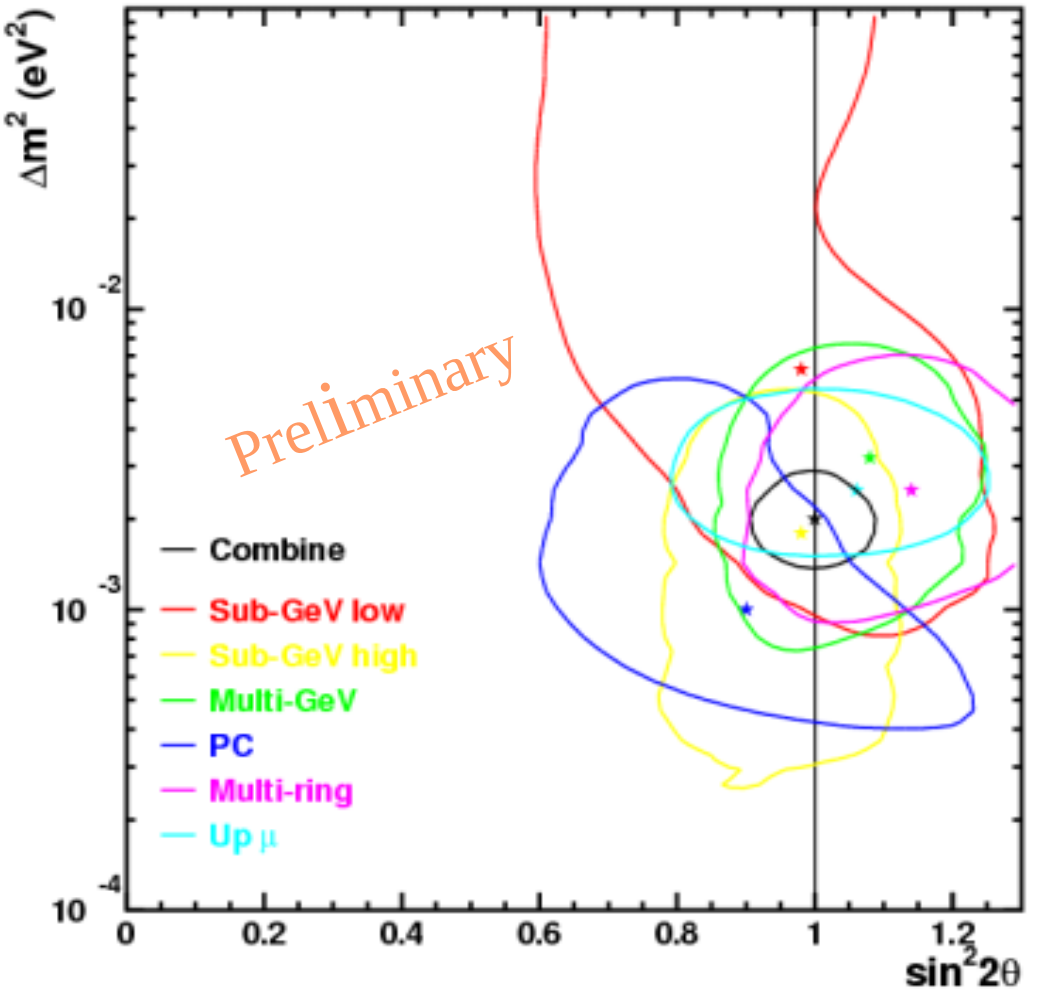
  $\sin^2 2\theta > 0.90$

  $1.3 < \Delta m^2 < 3.0 \times 10^{-3}$ 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 $\rightarrow$ full detector simulation**

Treatment of systematic errors in χ^2 calculation

Old systematic errors

	Absolute Normalization Uncertainty
L	SubGeV Multi-ring Absolute Normalization Uncertainty
H	MultiGeV Multi-ring Absolute Normalization Uncertainty
	Eν Spectrum Index
L	SubGeV μ/e Ratio
H	MultiGeV μ/e Ratio
	FC/PC Relative Normalization
L	SubGeV Up/Down Asymmetry
H	MultiGeV Up/Down Asymmetry
1	FC+PC/Stop ↑μ Relative Normalization
2	Through ↑μ/Stop ↑μ Relative Normalization
1	FC+PC Horizontal/Vertical Uncertainty
2	↑μ Horizontal/Vertical Uncertainty
	L/Æ Uncertainty

These systematic errors are estimated as independent error terms

But some error sources are multiply us
(e.g. Eν spectrum index is used in δ, β1
β2, ρ, βL, βH)

Each systematic error source is treated as independent error term

Neutrino flux

- flux absolute normalization
- flavor ratios($E\nu<1.33GeV, E\nu>1.33GeV$)
- anti-neutrino/neutrino ratio($\nu e, \nu\mu$)
- 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 interactioin

(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)

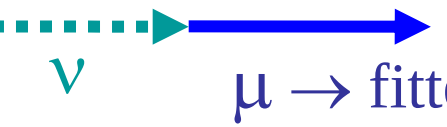
a. 1-ring/multi-ring separation
b. Particle ID (single-ring, multi-ring)
c. Energy calibration for FC
d. Energy cut for upward stopping μ
e. Up-down asymmetry of energy calibration

Total number of errors: 36

Treated as independent error term in χ2 calculation

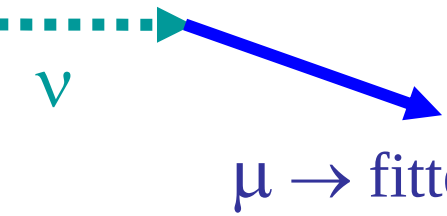
Improvement of up-μ flux predictions

Analytical calculation (Old)



$\theta\nu = \theta\mu$

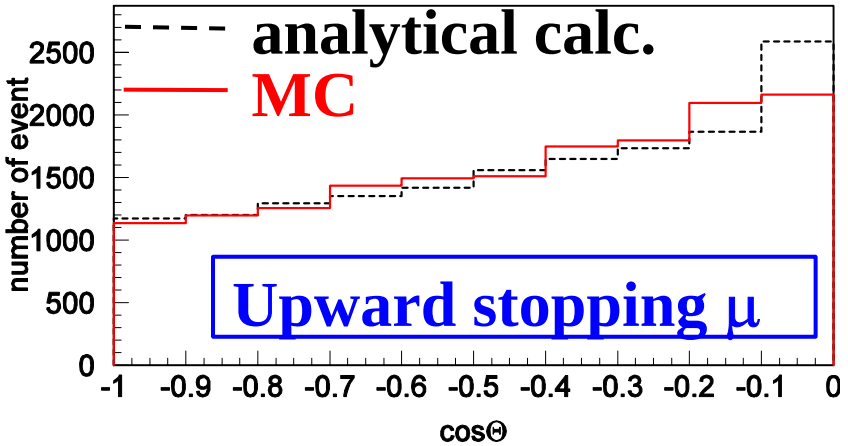
MC (New)

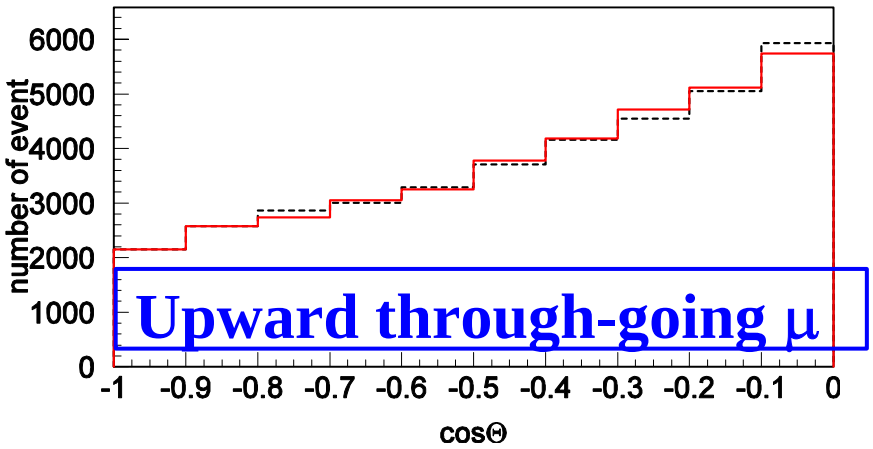


$\theta\nu \neq \theta\mu$

smeared

consider $\nu \rightarrow \mu$ scattering angle

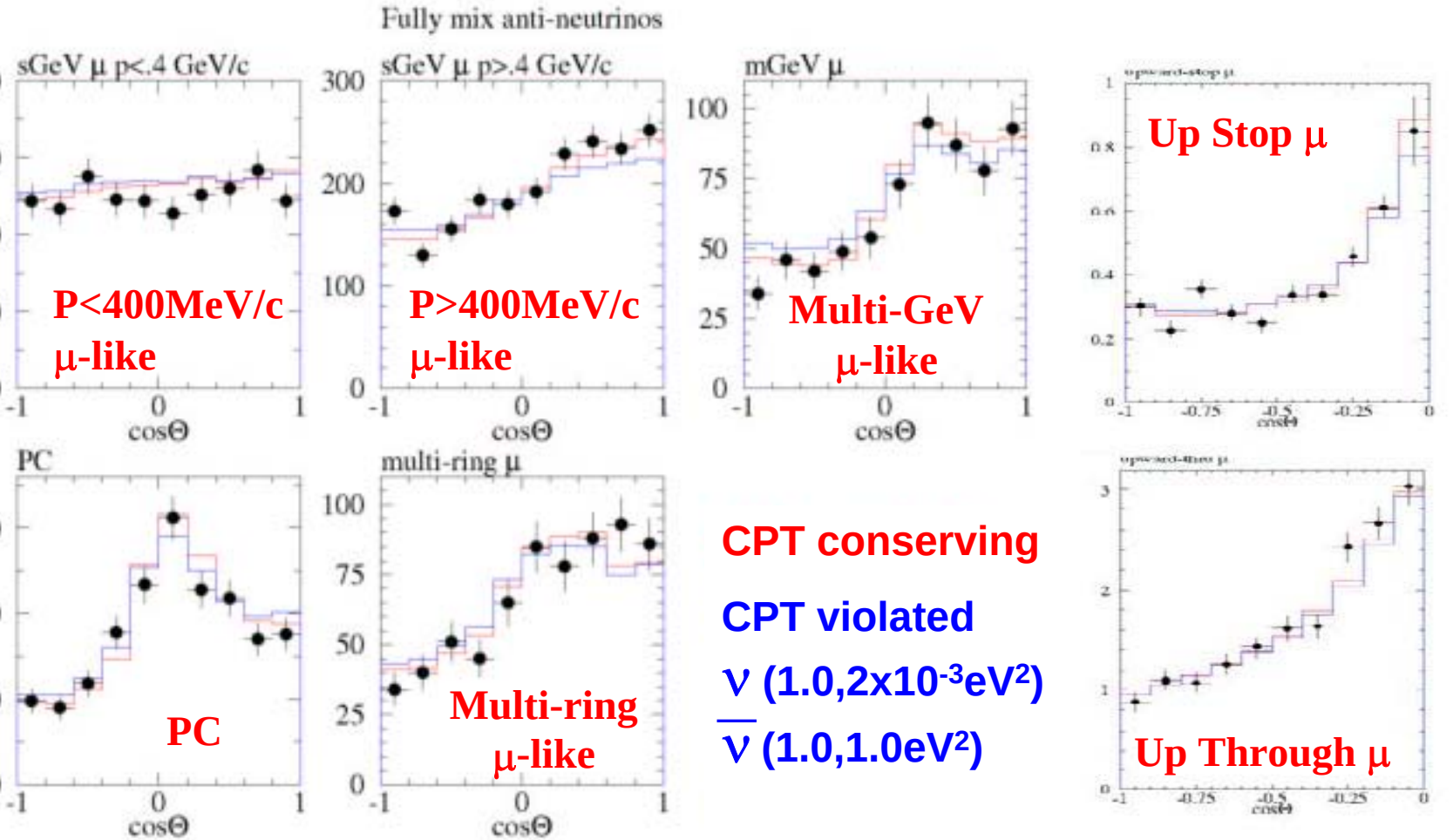




Final SK-I result

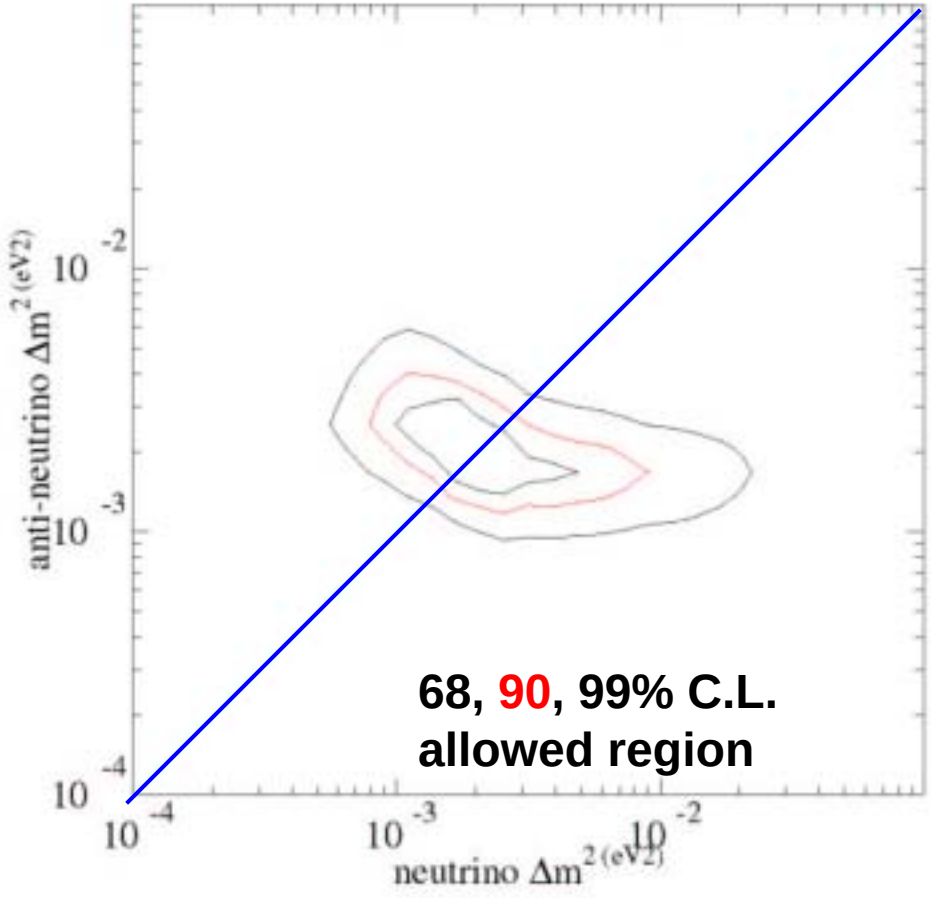
full paper (including $\nu\mu \leftrightarrow \nu\tau$ oscillation analysis) is coming soon

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



68, 90, 99% C.L. allowed region

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

Best fit :

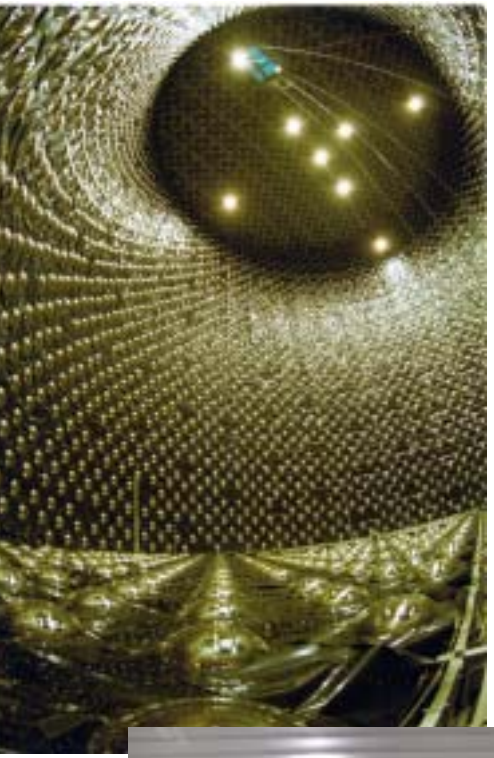
$\sin^2(2\theta) = 1.0$ for ν and $\bar{\nu}$

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

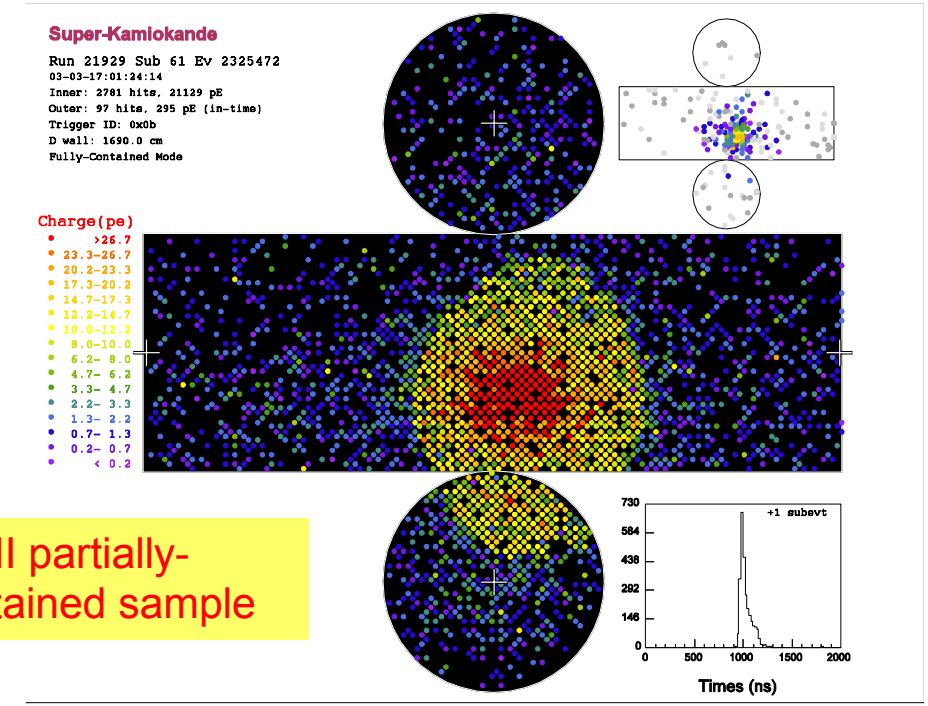
no evidence for CPT violation

SK-II

SK-II is taking data



20inch PMT with Acrylic + FRP vessel



SK-II partially-contained sample

- **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**

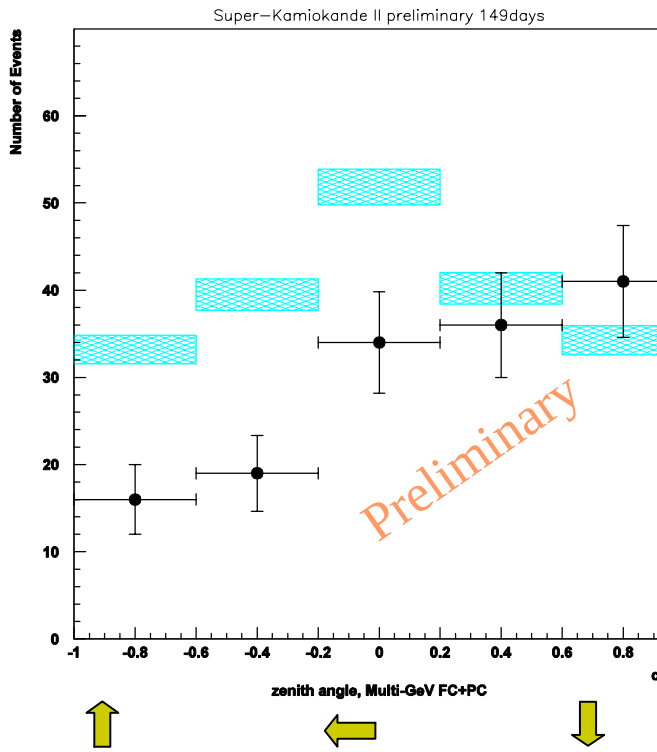
tatus of SK-II Analysis

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



Multi-GeV FC μ-like +P

lumber 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)

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.
  $1.3 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$, $\sin^2 2\theta > 0.90$ (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