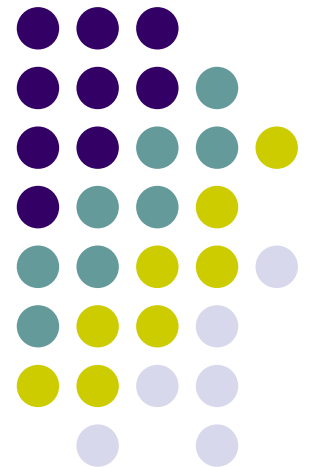


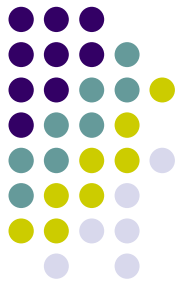
SK Atmospheric Neutrino Results

Kimihiro Okumura

okumura@icrr.u-tokyo.ac.jp

Institute for Cosmic Ray Research (ICRR),
Univ. of Tokyo
for the Super-Kamiokande collaboration



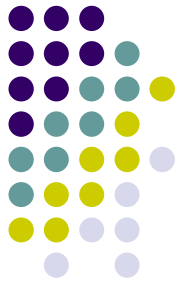


Super-Kamiokande Collaboration

S. Fukuda Y. Fukuda M. Ishitsuka Y. Itow T. Kajita J. Kameda K. Kaneyuki
K. Kobayashi Y. Koshio M. Miura S. Moriyama M. Nakahata S. Nakayama
T. Namba A. Okada K. Okumura N. Sakurai M. Shiozawa Y. Suzuki H. Takeuchi
Y. Takeuchi Y. Totsuka S. Yamada S. Desai M. Earl E. Kearns M.D. Messier
J.L. Stone L.R. Sulak C.W. Walter M. Goldhaber T. Barszczak D. Casper
W. Gajewski W.R. Kropp S. Mine D.W. Liu M.B. Smy H.W. Sobel
A. Gago K.S. Ganezer W.E. Keig R.W. Ellsworth S. Tasaka A. Kibayashi
J.G. Learned S. Matsuno D. Takemori Y. Hayato T. Ishii T. Kobayashi
T. Maruyama K. Nakamura Y. Obayashi Y. Oyama M. Sakuda M. Yoshida
M. Kohama T. Iwashita A.T. Suzuki A. Ichikawa T. Inagaki I. Kato T. Nakaya
K. Nishikawa T.J. Haines S. Dazeley S. Hatakeyama M.R. Vagins R. Svoboda
E. Blaufuss M.L. Chen J.A. Goodman G. Guillian G.W. Sullivan D. Turcan
K. Scholberg A. Habig M. Ackermann J. Hill C.K. Jung K. Martens
M. Malek C. Mauger C. McGrew E. Sharkey B. Viren C. Yanagisawa
T. Toshito C. Mitsuda K. Miyano C. Saji T. Shibata Y. Kajiyama Y. Nagashima
K. Nitta M. Takita H.I. Kim S.B. Kim J. Yoo T. Ishizuka M. Etoh Y. Gando
T. Hasegawa K. Inoue K. Ishihara J. Shirai A. Suzuki M. Koshiba
Y. Hatakeyama Y. Ichikawa M. Koike K. Nishijima H. Ishino M. Morii
R. Nishimura Y. Watanabe D. Kielczewska H.G. Berns S.C. Boyd
A.L. Stachyra R.J. Wilkes

Outline

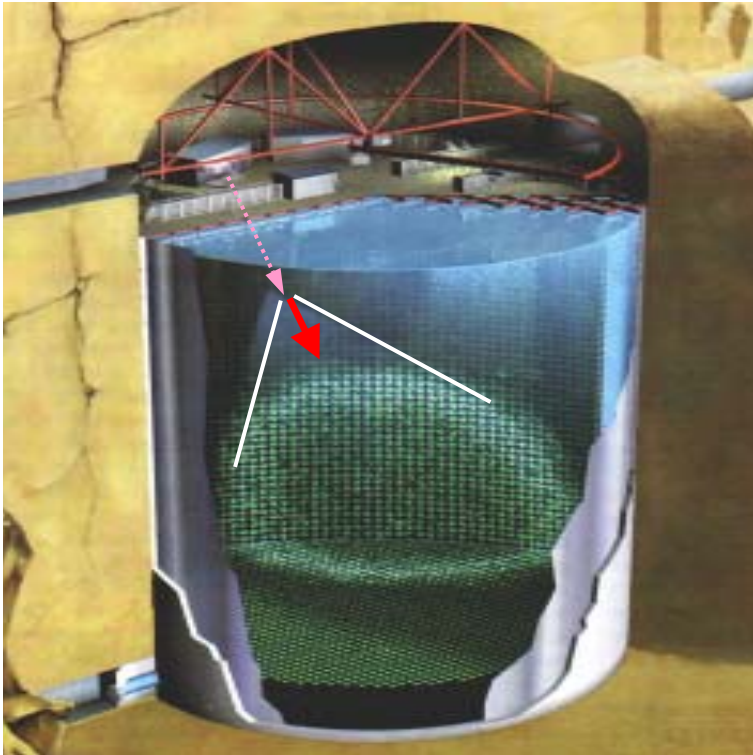
- SK-I oscillation analysis
 - $\nu_{\mu} \leftrightarrow \nu_{\tau}$ oscillation
 - other hypothesis
- SK-II status



Observation of Atmospheric Neutrinos in SK

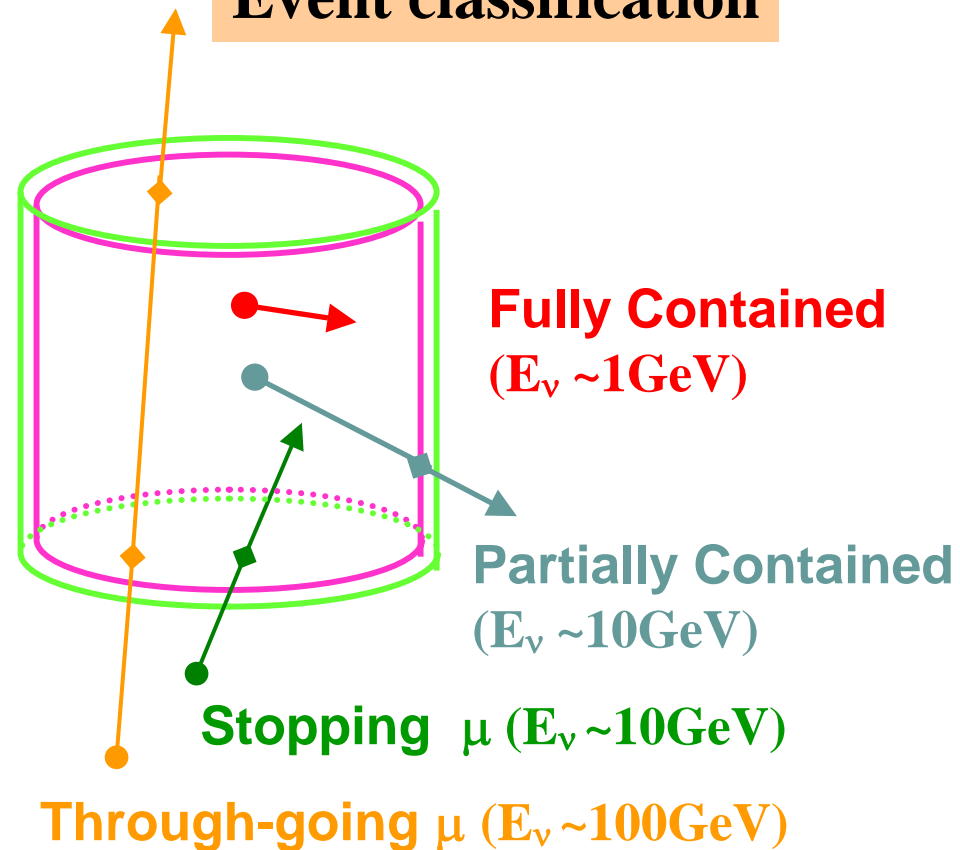


Water Cherenkov detector



- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs (SK-I)
- 1,885 anti-counter PMTs

Event classification



SK-I full data

FC, PC 1489days

Sub-GeV (Evis<1.33GeV)

	Data	MC
1-R e-like	3353	3013.9
FC 1-R μ -like	3227	4466.9
≥ 2 -R μ -like	208	346.4

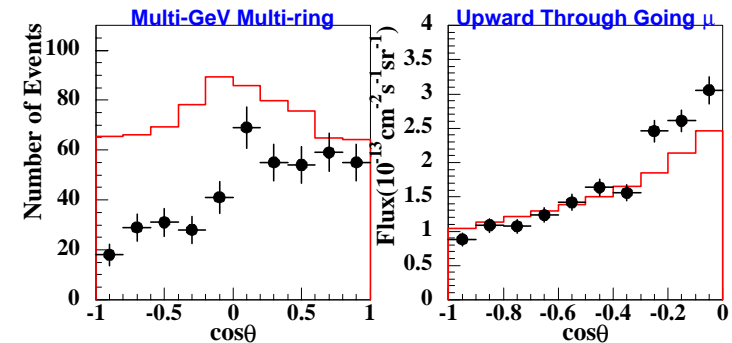
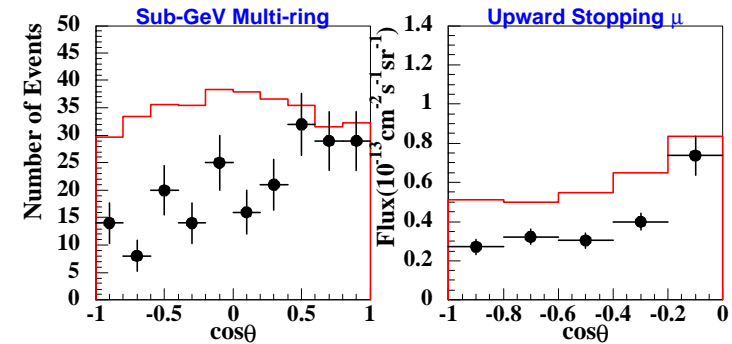
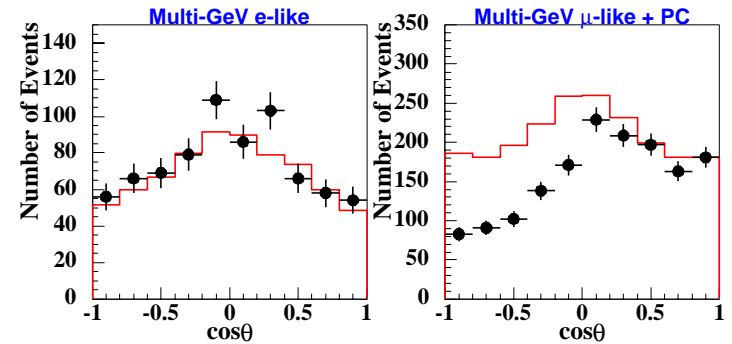
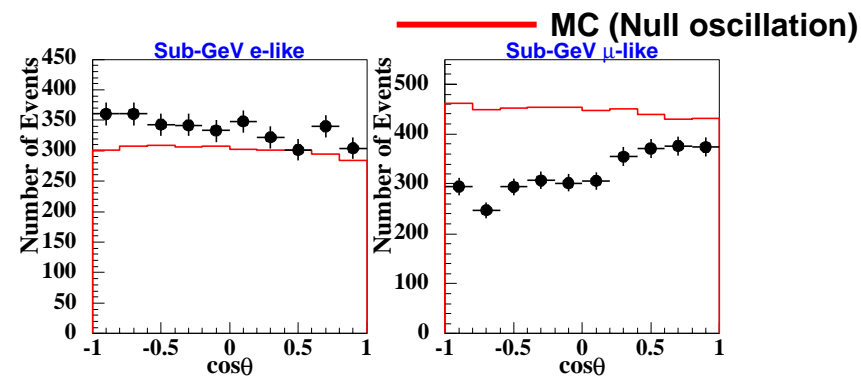
Multi-GeV (Evis>1.33GeV), PC

	Data	MC
1-R e-like	746	700.4
FC 1-R μ -like	651	948.2
≥ 2 -R μ -like	439	739.4
PC	911	1149.8

Up thru & stop μ 1646 days

($\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$)

Stop	measured	$0.41 \pm 0.02 \pm 0.02 \times 10^{-13}$
	theoretical	$0.61 \pm 0.14 \times 10^{-13}$
Thru	measured	$1.70 \pm 0.02 \pm 0.04 \times 10^{-13}$
	theoretical	$1.57 \pm 0.35 \times 10^{-13}$

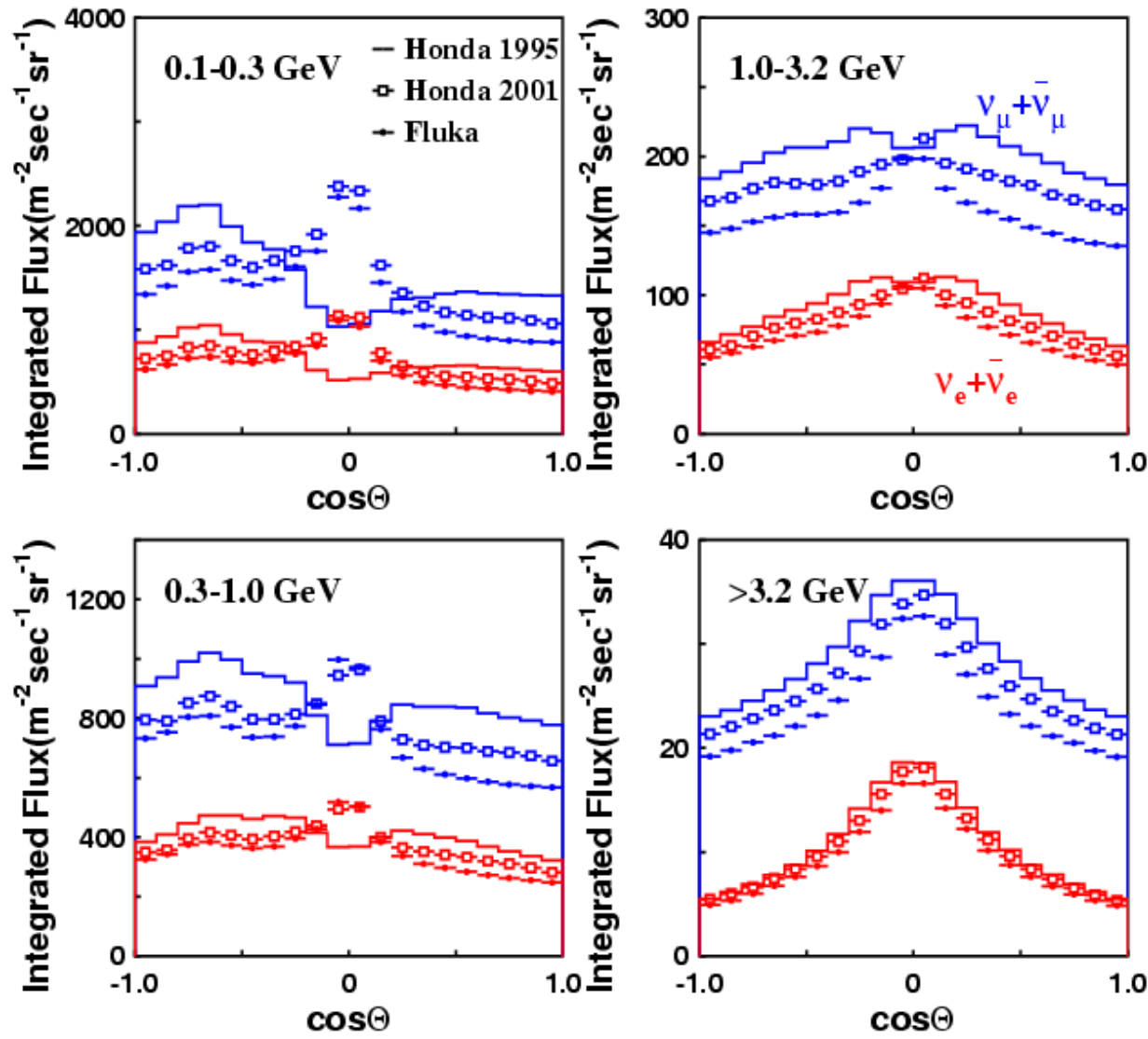
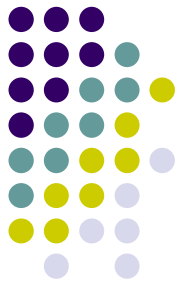


Recent Improvements (from ν 2002)



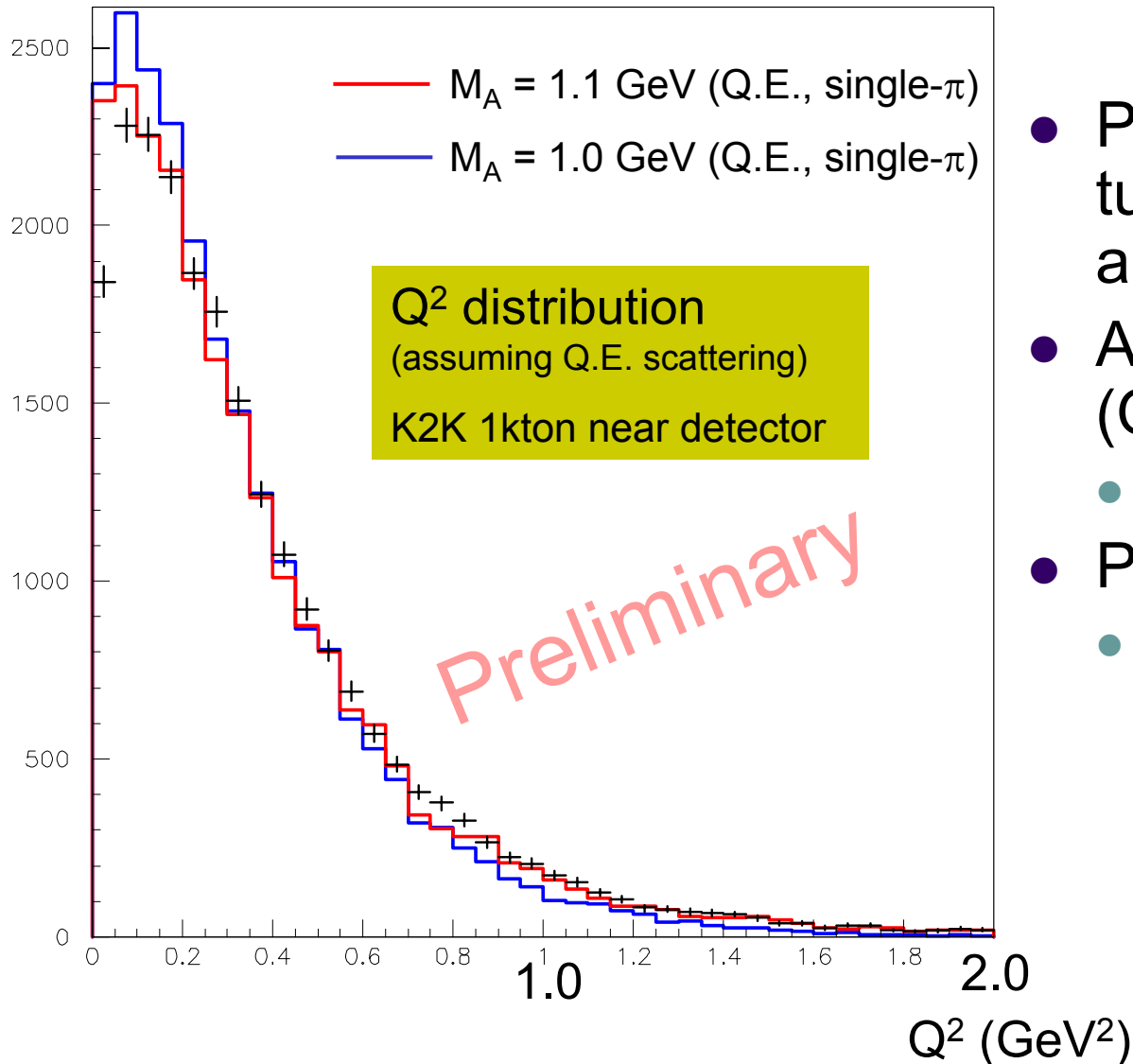
- Three dimensional ν flux calculation
- MC predictions with tuned ν interaction parameters
 - Axial vector mass
 - Fermi-momentum, nuclear potential
- Data analysis
 - Ring selection, Particle ID, multi-ring fits improved
 - Up- μ new automated precise fitter
- New calibs. and improve detector simulation

3D Flux Calculation



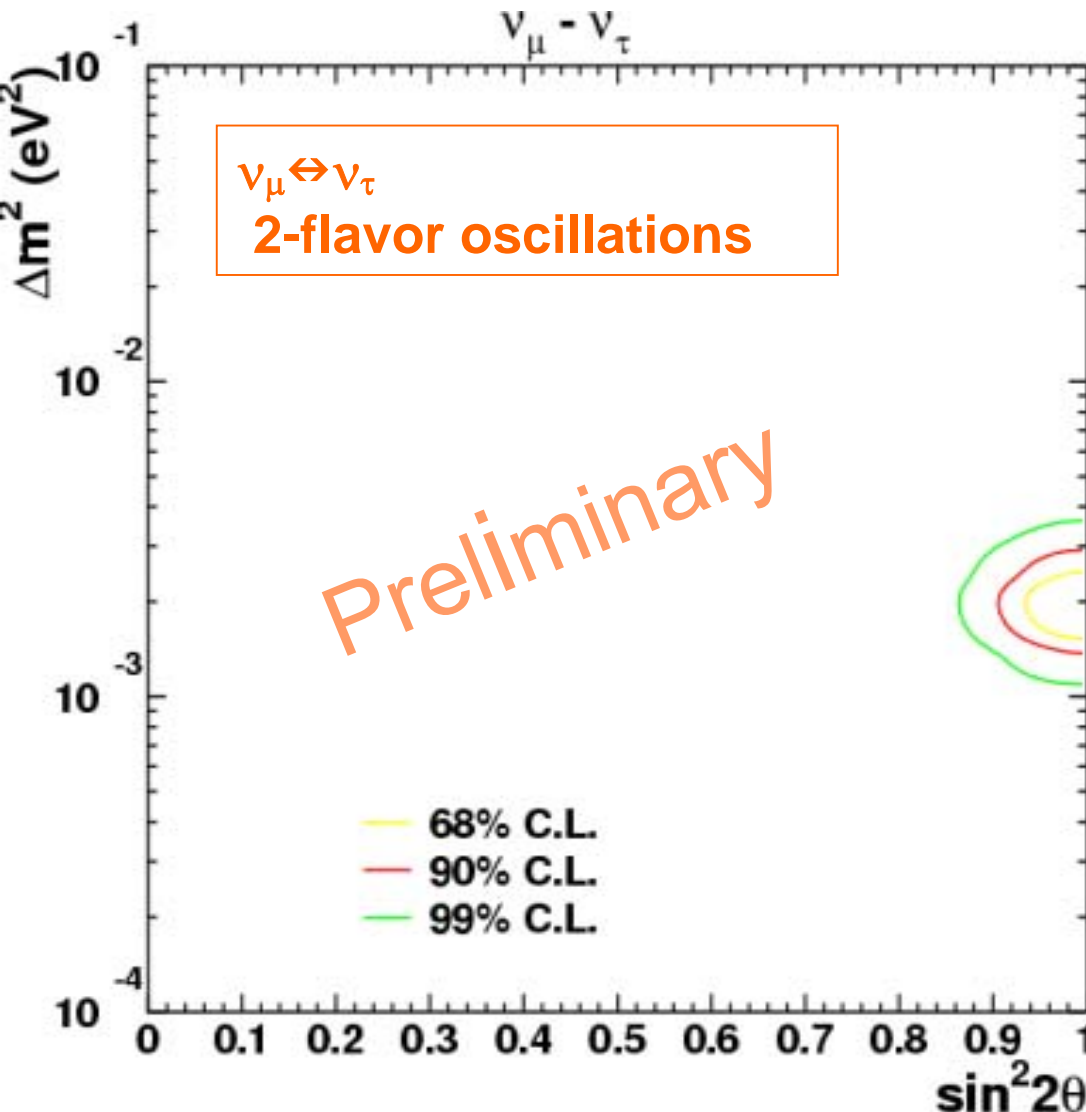
- Honda 2001
 - Absolute normalization lower
 - Enhancement in horizontal direction at low energies
- That peak is smeared out due to large scattering angle of $\nu \rightarrow \mu$

Neutrino Interactions



- Parameters were tuned to reproduce accelerator data
- Axial vector mass (Q.E. 1π)
 - 1.0 \rightarrow 1.1 GeV
- P_F , nuclear potential
 - e-N scattering data

Oscillation Analysis Results



- **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:**
 $\sin^2(2\theta) > 0.90$
 $1.3 < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$

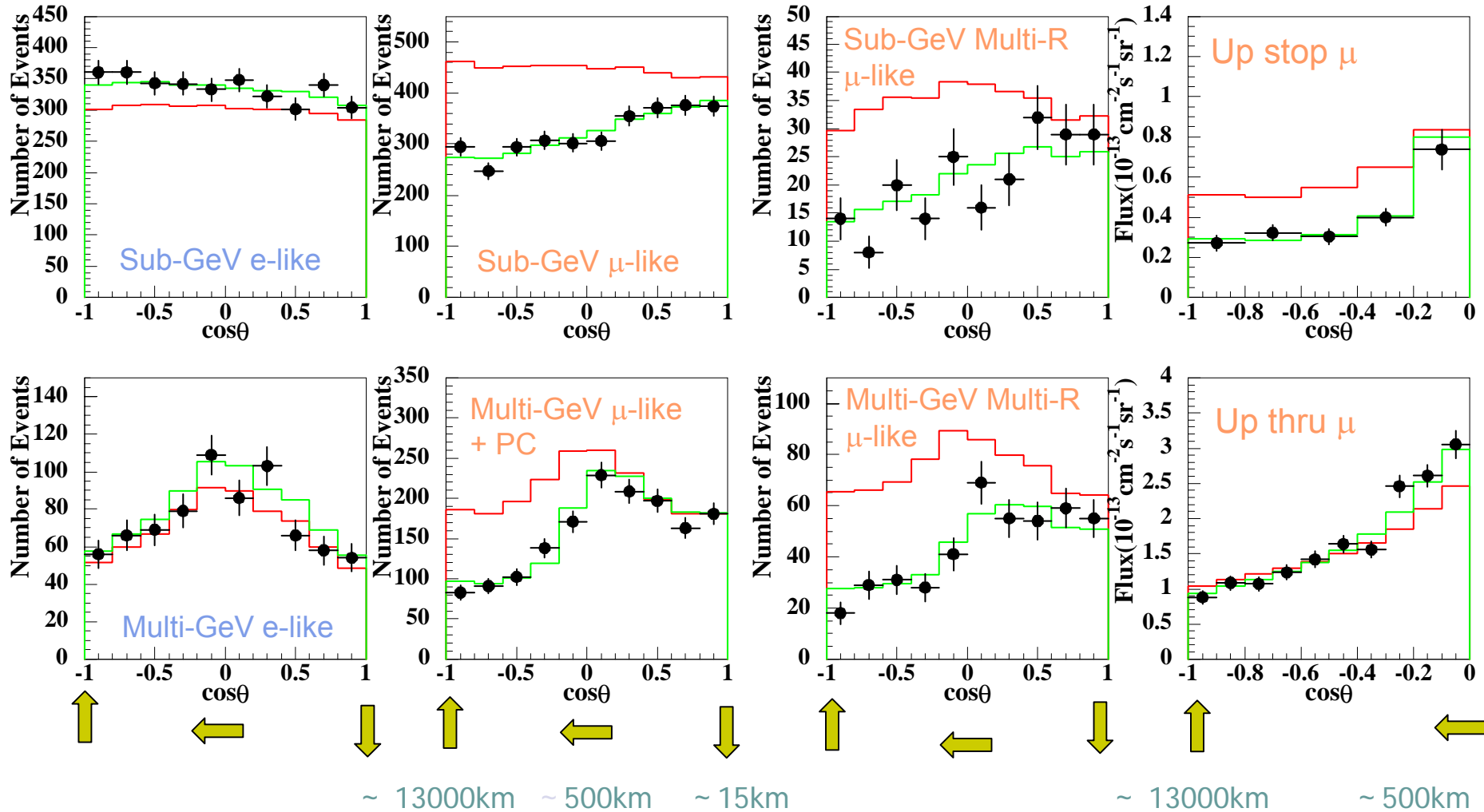
Zenith angle distributions



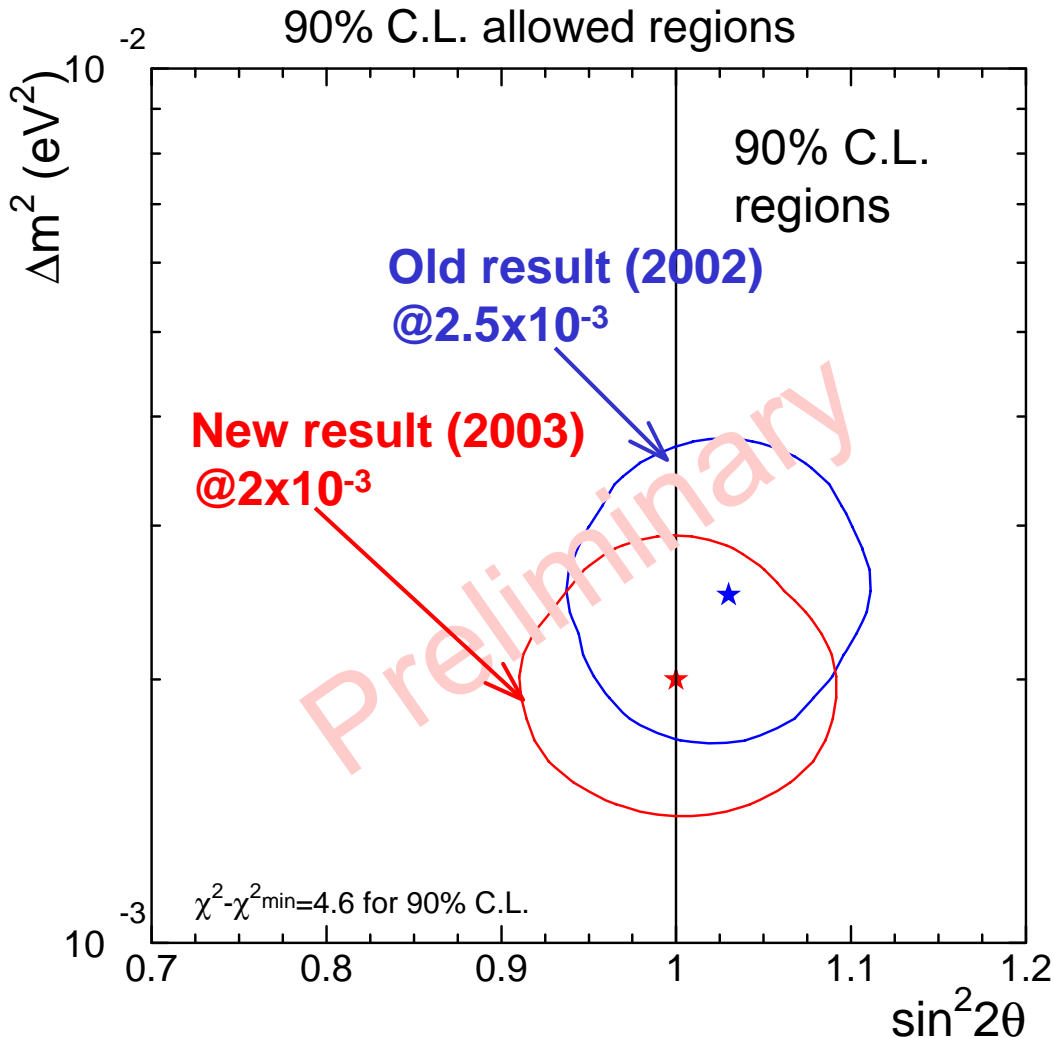
$$\nu_{\mu} \leftrightarrow \nu_{\tau}$$

2-flavor oscillations

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

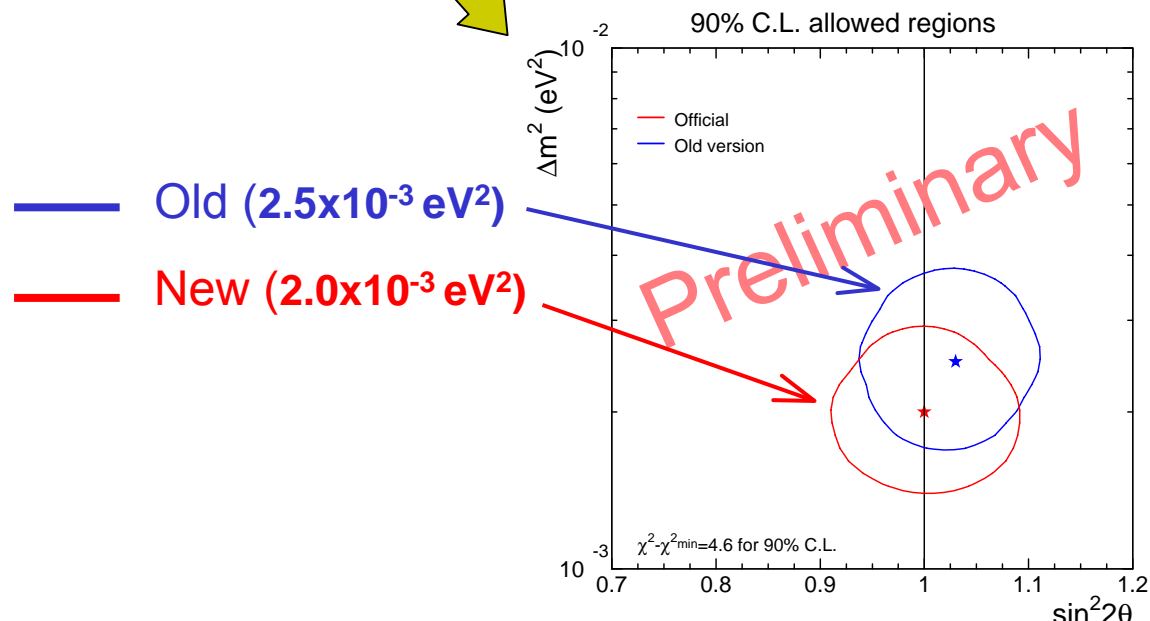
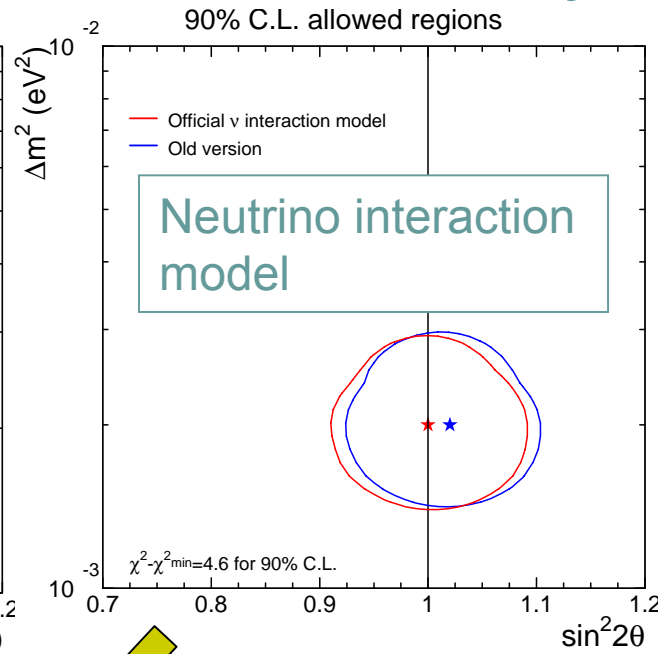
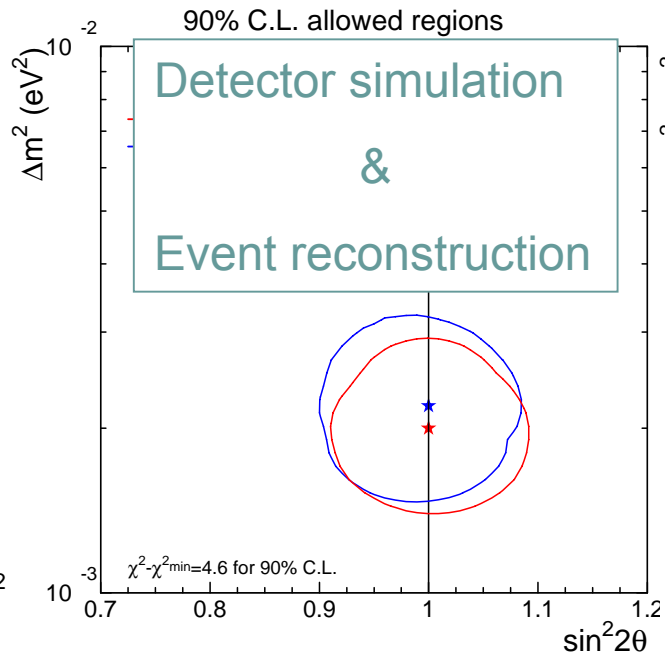
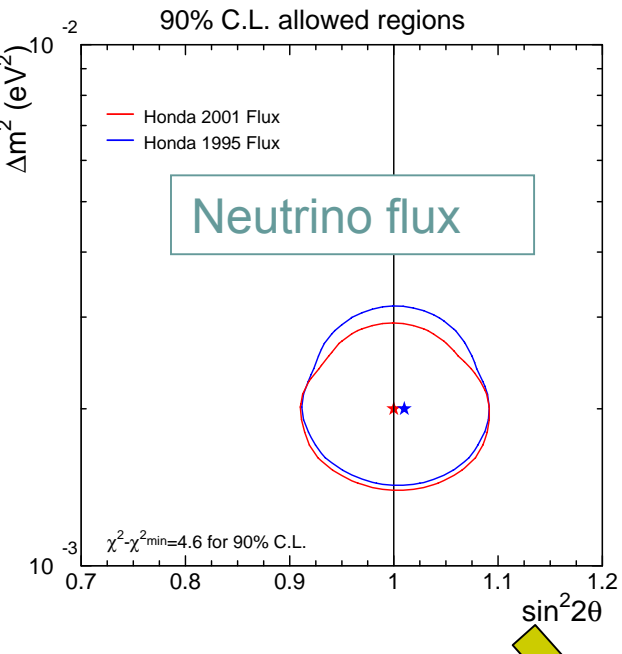


Difference from Previous Results



- Same data, but small improvements in the analysis
- Allowed region slightly shifted
 - $2.5 \times 10^{-3} \rightarrow 2.0 \times 10^{-3}$ eV²

Comparison of old and new analysis results

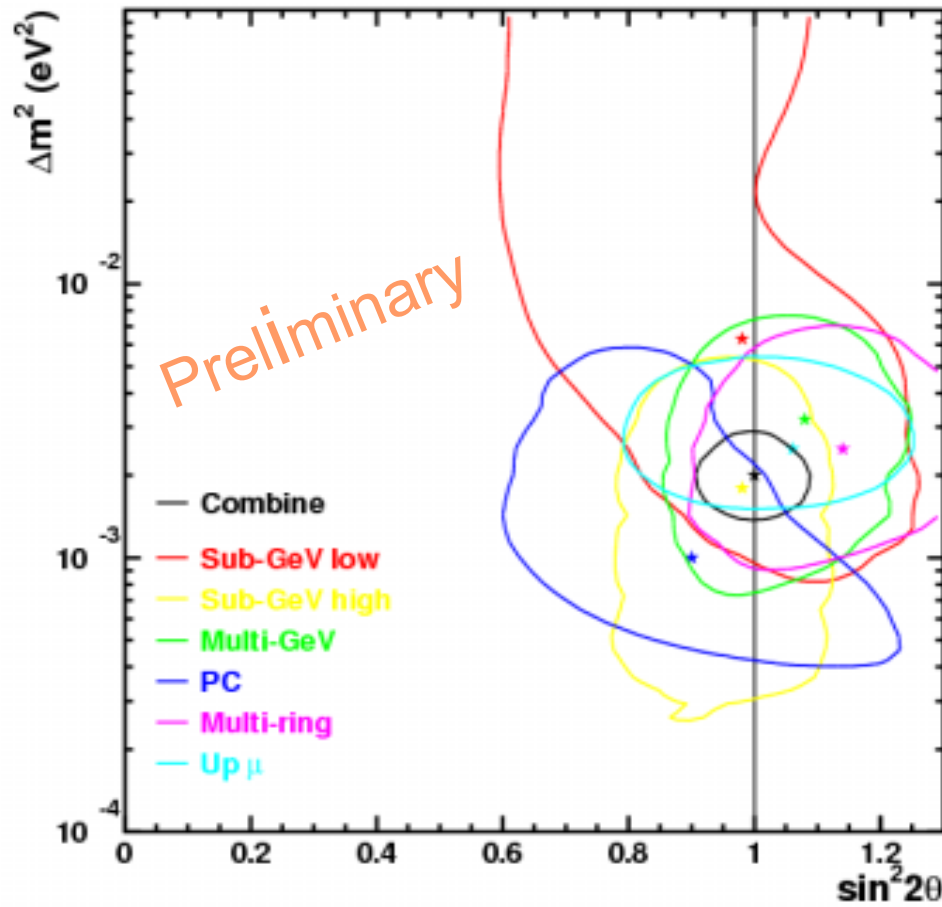


Each change contributes to the shift in the allowed (Δm^2) region.

Sub-Sample Consistency

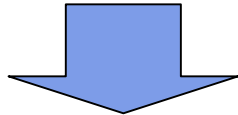


- Check oscillation fit using different samples of data independently
 - each allowed region overlaps with best fit point

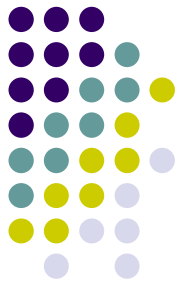


Toward SK-I Final Results



- Re-estimate of systematic errors are in progress
 - Better handling of systematic error terms
 - Re-estimate systematic errors and estimate additional errors
 - Improved ν_{μ} flux predictions
 - analytical calculation \rightarrow full detector simulation
 - New 3D flux calculation
 - Dipole approximation \rightarrow Multi-pole for geomagnetic field
- 
- To be finalized in near future
 - full paper (including $\nu_{\mu} \leftrightarrow \nu_{\tau}$ oscillation analysis) in preparation

Test of Alternative Models



Mode	Best Fit	χ^2	$P(\chi^2)$	$\Delta\chi^2$	σ
$\nu_\mu - \nu_\tau$ $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 1.00$ $\Delta m^2 = 1.9 \times 10^{-3} \text{ eV}^2$	189	50%	0.0	0σ
$\nu_\mu - \nu_e$ $\sim \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 0.98$ $\Delta m^2 = 4.2 \times 10^{-3} \text{ eV}^2$	304	0%	111	10.5σ
$\nu_\mu - \nu_s$ $\sim \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 0.93$ $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$	231	2%	42.2	6.5σ
LxE (L.I. violation) $\sin^2 2\theta \sin^2(\alpha LxE)$	$\sin^2 2\theta = 0.89$ $\alpha = 5.1 \times 10^{-4} \text{ GeV/km}$	329	0%	103	10.1σ
ν_μ decay (short τ) $\sin^4 \theta + \cos^4 \theta (1 - e^{-\alpha L/E})$	$\cos^2 \theta = 0.49$ $\alpha = 3.2 \times 10^{-3} \text{ GeV/km}$	287	0%	98.1	9.9σ
ν_μ decay (long τ) $(\sin^2 \theta + \cos^2 \theta e^{-\alpha L/2E})^2$	$\cos^2 \theta = 0.33$ $\alpha = 9.8 \times 10^{-3} \text{ GeV/km}$	207	19%	18	4.2σ
ν_μ decoherence $0.5 \sin^2 2\theta (1 - e^{-\gamma L/E})$	$\sin^2 2\theta = 0.98$ $\gamma = 6.6 \times 10^{-3} \text{ GeV/km}$	198	33%	9.4	3.1σ
Null Hypothesis		469	0%	280	16.7σ

(FC+PC +NC+multi-ring+up- μ , 195 bins, 190 d.o.f.)

- Test with non-standard hypothesis except $\nu_\mu \leftrightarrow \nu_\tau$
 - Lorentz inv. violation
 - ν decay, decoherence
- SK ν data strongly constrain many such models
 - Long τ ν_μ decay and ν_μ decoherence $\Delta\chi^2 > 9$



Limit on Sterile Admixture

If $\nu_\mu \rightarrow \nu_{\text{sterile}}$

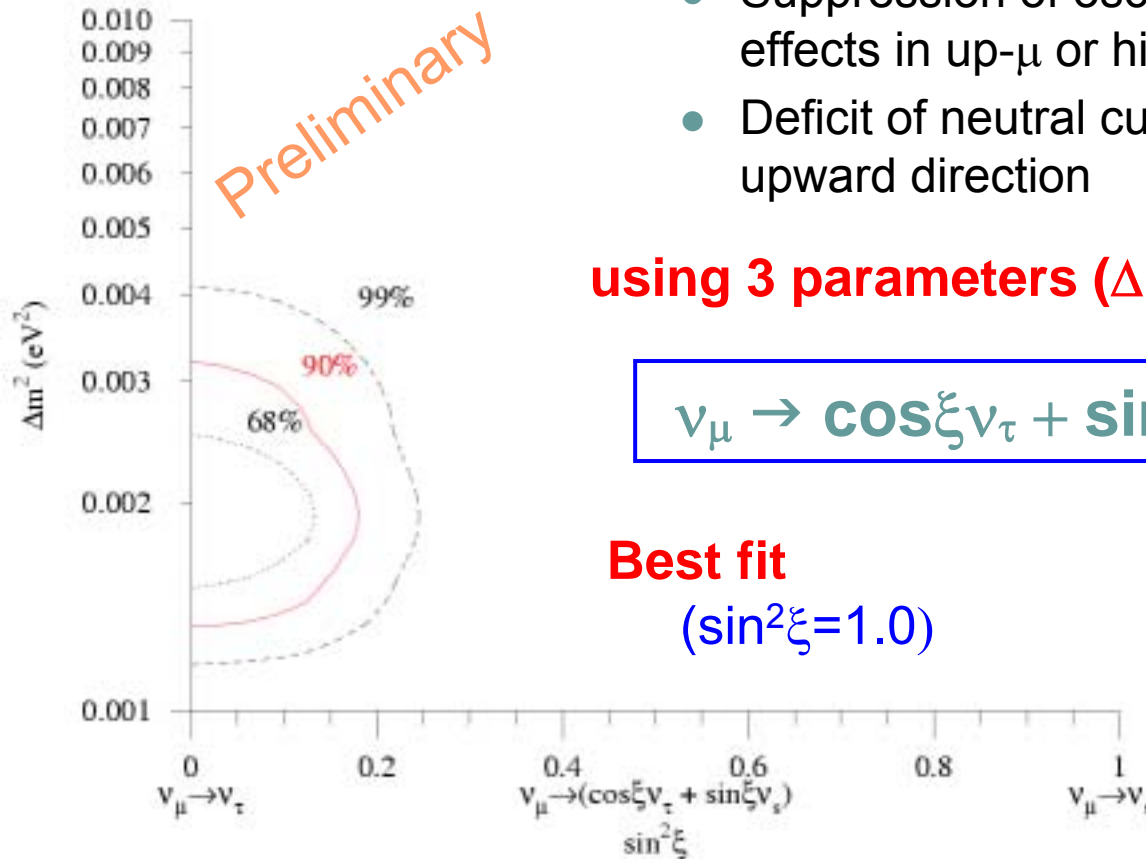
- Suppression of oscillation due to matter effects in up- μ or high-energy PC
- Deficit of neutral current interactions in upward direction

using 3 parameters (Δm^2 , $\sin^2 2\theta$, $\sin^2 \xi$)

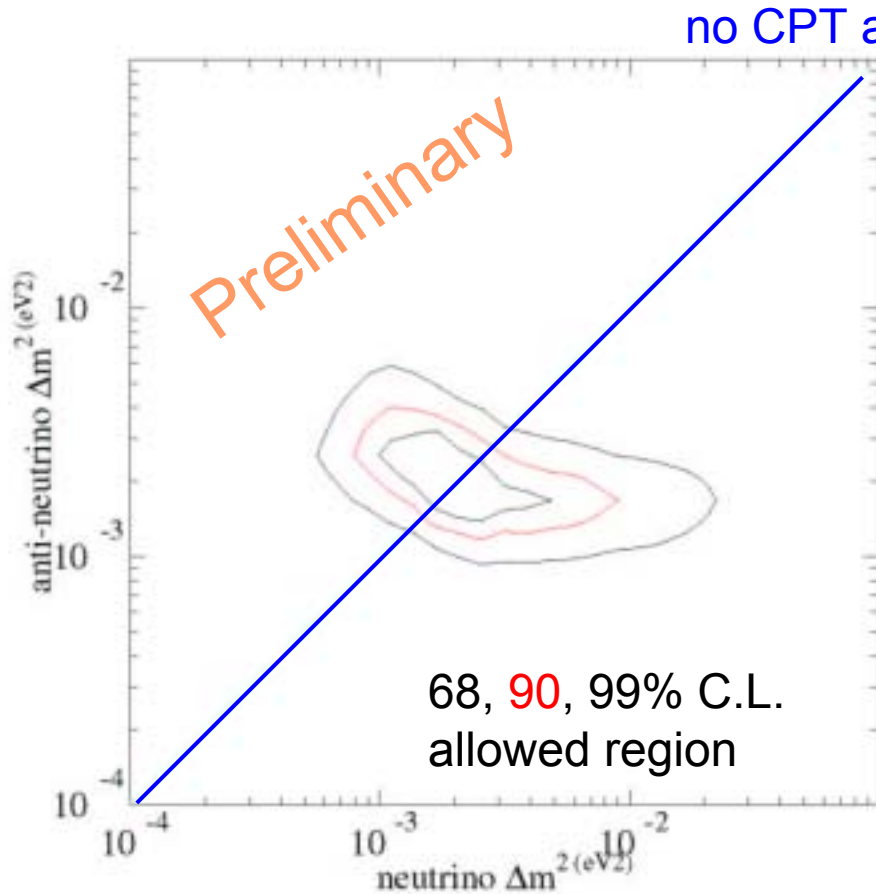
$$\nu_\mu \rightarrow \cos \xi \nu_\tau + \sin \xi \nu_s$$

$\sin^2 \xi = 0$; pure $\nu_\mu \rightarrow \nu_\tau$
 $\sin^2 \xi = 1$; pure $\nu_\mu \rightarrow \nu_s$

Best fit
 $(\sin^2 \xi = 1.0)$

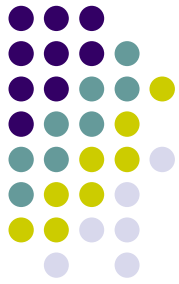


CPT Violation Test

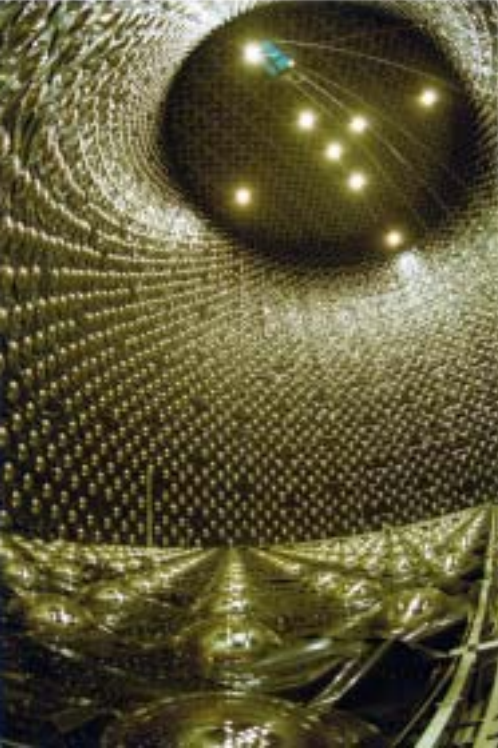


4 parameters fitted independently
(Δm^2 , $\sin^2 2\theta$) for ν and $\bar{\nu}$

consistent with no CPT asymmetry

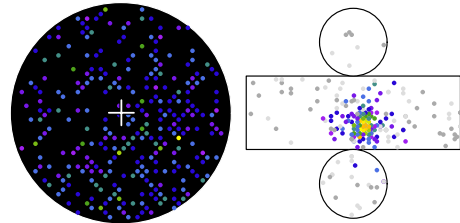


SK-II in operation!



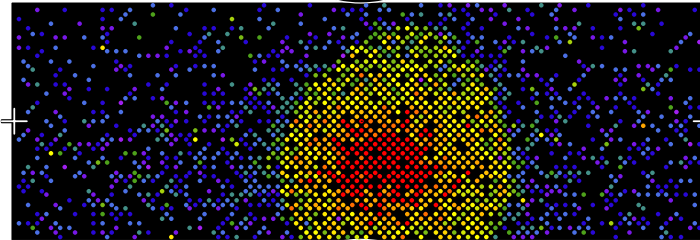
Super-Kamiokande

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 wall: 1690.0 cm
Fully-Contained Mode

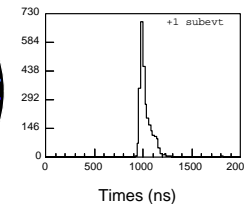
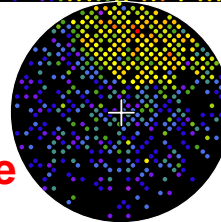


Charge (pE)

- >26.7
- 23.3-26.7
- 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



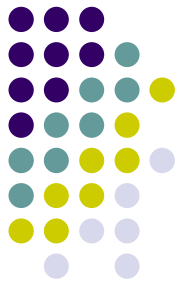
SK-II partially-contained sample



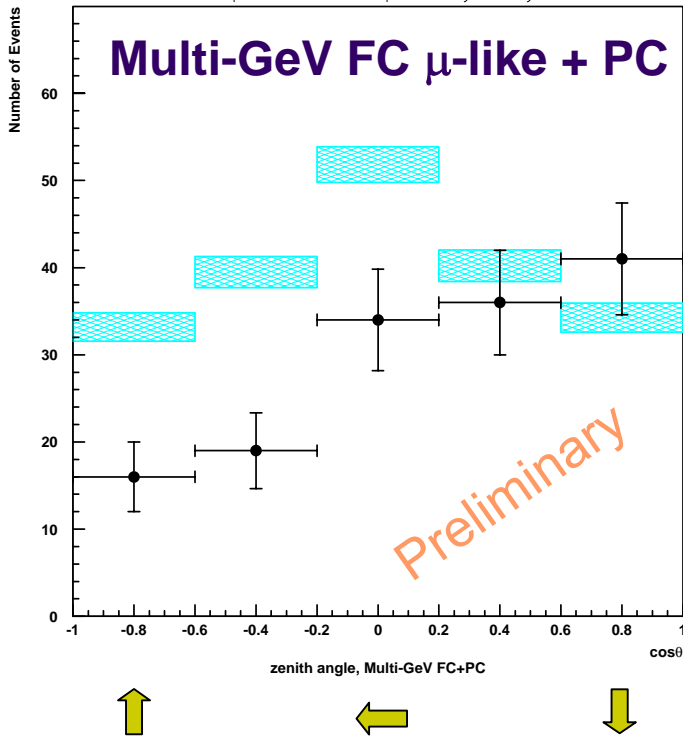
20inch PMT with
Acrylic + FRP
vessel

- Rebuilt in summer 2002
 - Has 47% of original ID 20" PMTs (~5200)
 - 20" PMTs in acrylic shells to prevent future chain implosions
- Taking data since Dec 2002

Status of SK-II Analysis



Super-Kamiokande II preliminary 149days



- 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)

Summary



SK-I analysis is about to be finalized

- SK-I full data set (FC,PC 1489days, up- μ 1646 days)
- Improved data analysis and MC predictions
- Best fit value $\nu_{\mu} \leftrightarrow \nu_{\tau}$ is ($\Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta = 1.0$)
 - $1.3 < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$, $\sin^2(2\theta) > 0.90$ @ 90% c.l.
- Analysis will be completed soon with further systematic error estimates

SK-II analysis has started