Atmospheric Neutrino Oscillations in SK-I

An Updated Analysis

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With much help from
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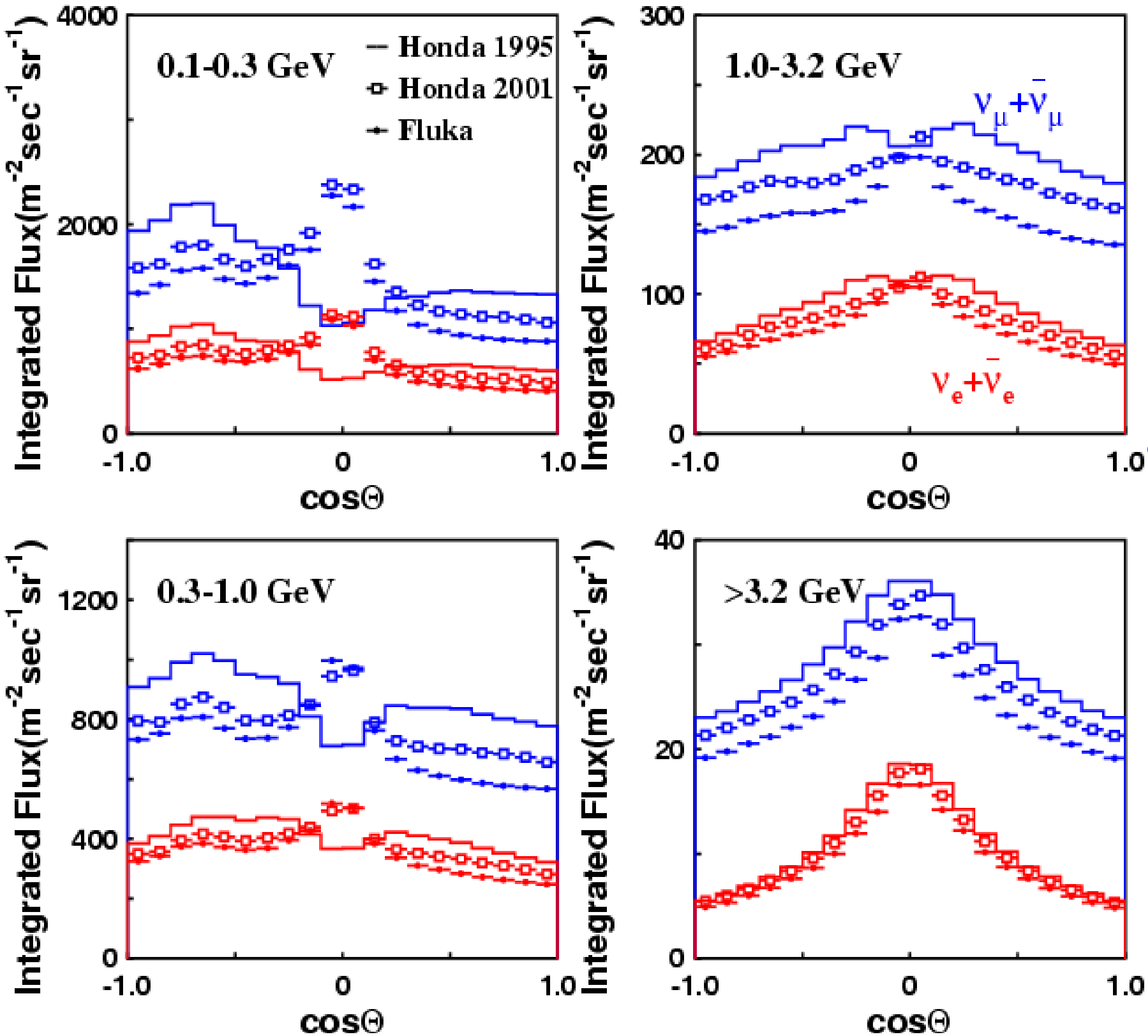
Updated Analysis

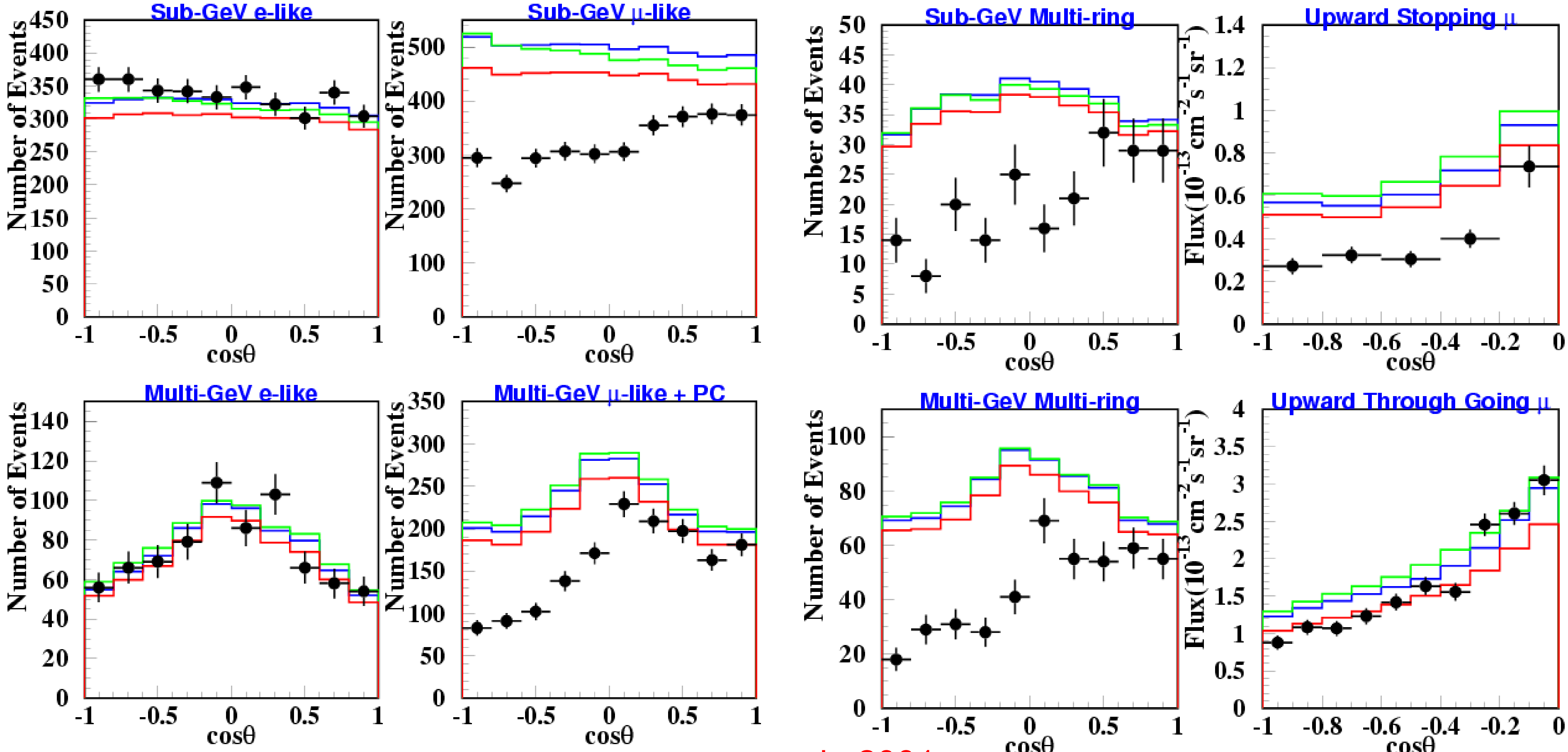
- All "SK-I" data (April 1996-July 2001) reanalyzed (1489 live-days)
  - Ring selection, Particle ID, multi-ring fits improved
  - Up-μ reduction automated and fitting improved (1646 live-days)
- Monte Carlo predictions improved
  - New 2001 Honda 3D ν flux (was Honda 1995)
  - Fermi Momentum, Axial Mass changed to better match K2K near detector ν interaction data
    - (p_F now flat, M_A for QE, single π from 1.0$\rightarrow$1.1)
  - New calibs. improve Outer Detector, H_2O parameters in detector simulation (GEANT 3 based)

Flux Changes



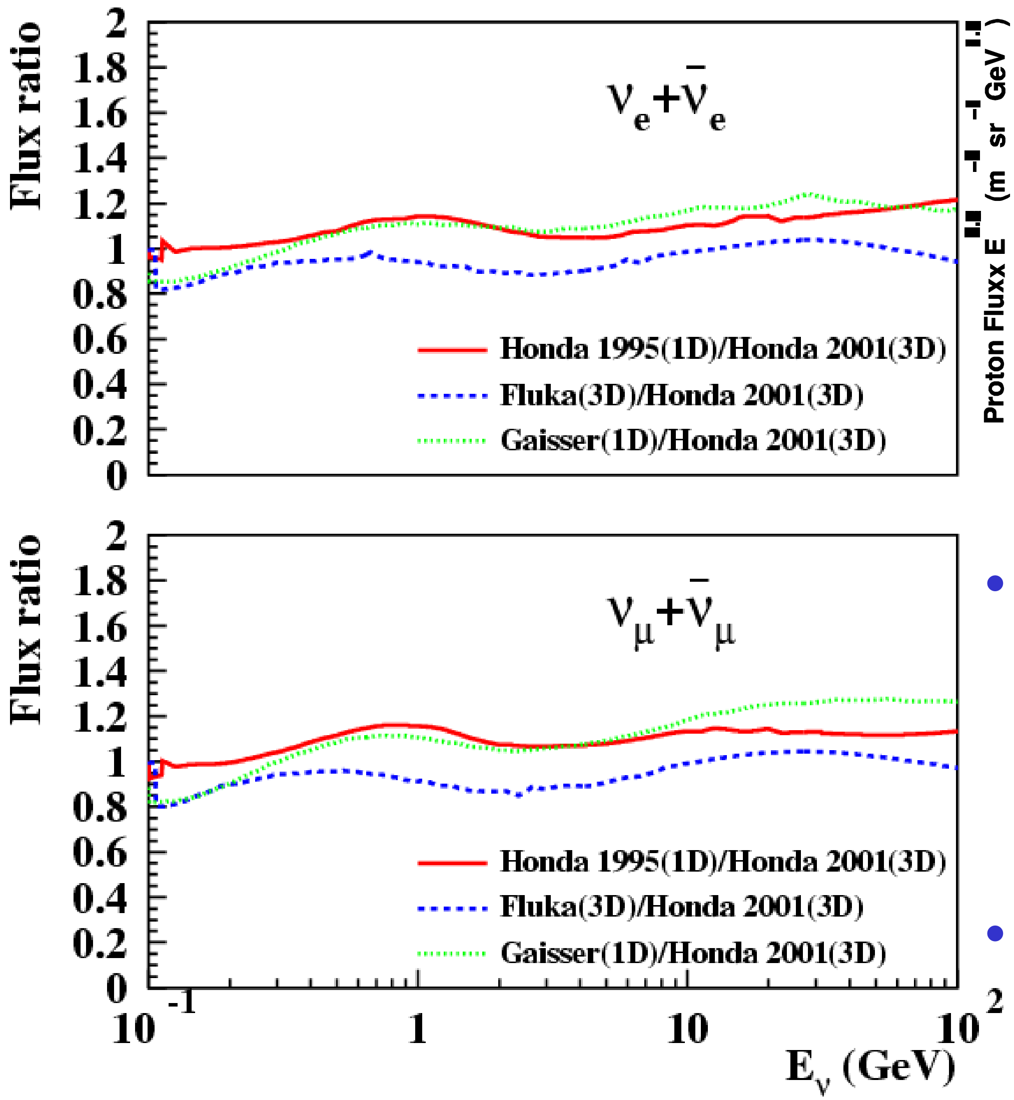
- Honda 1995 1D to Honda 2001 3D
  - Absolute normalization lower
  - "3D" enhancement
    - At low energies
    - Near the horizon
- But at low E, $\nu \rightarrow \mu$ following angle is large
  - Smears out the peak near horizon
  - So 3D-ness changes little for Super-K (see next slide…)

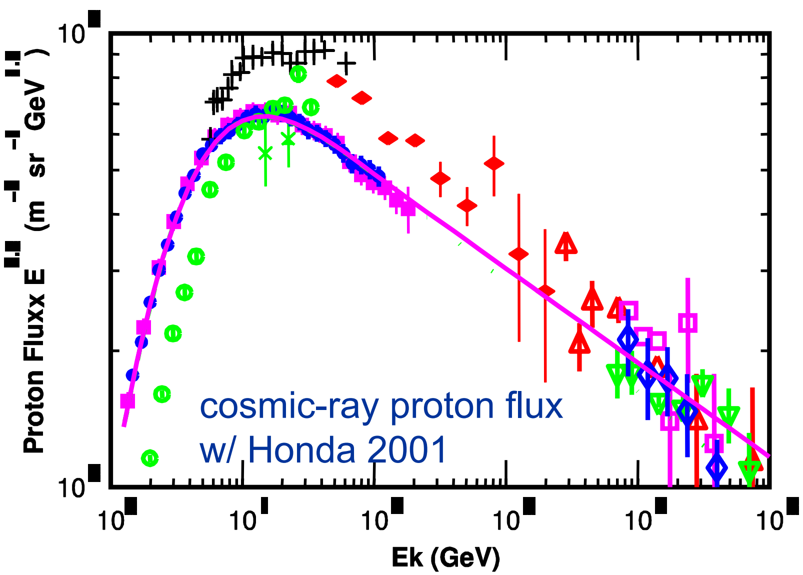
Different Fluxen at Super-K



— Honda 2001
— Honda 1995
— Bartol 1996
+ Data

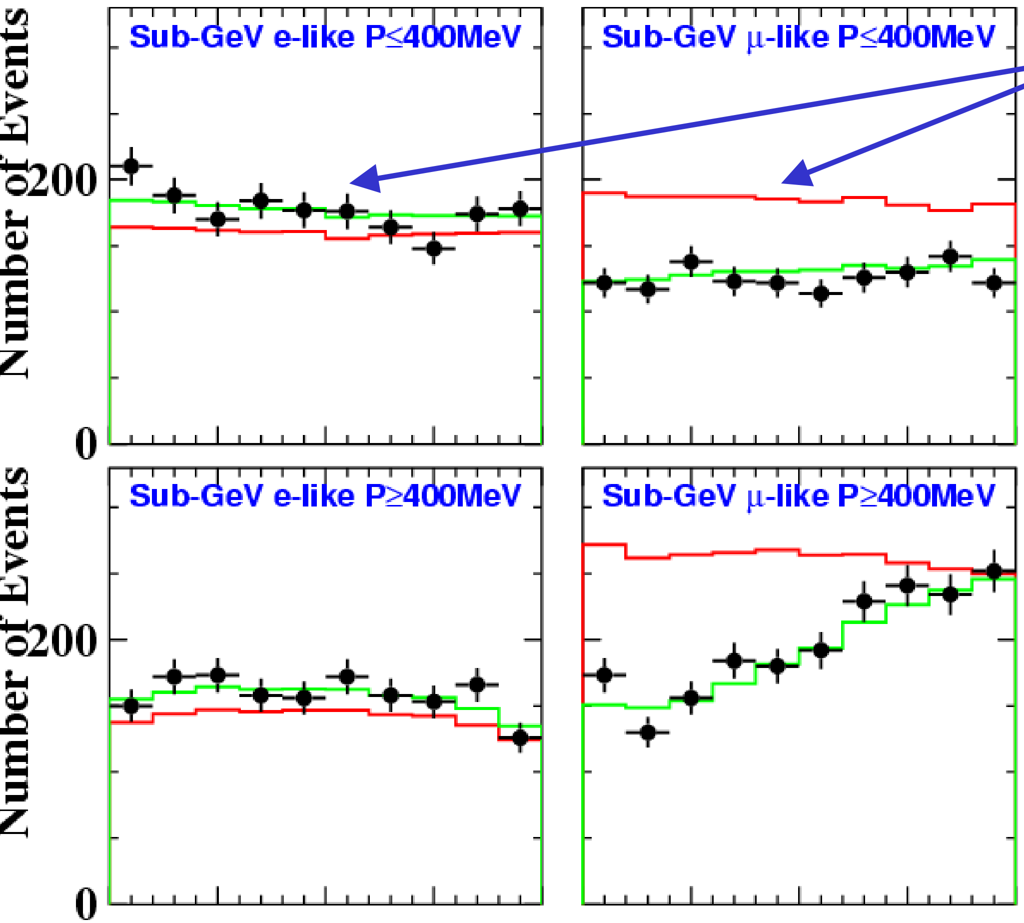
Flux Details





- The Honda 2001 flux uses the newer primary CR fluxes as starting point
  - Results in lower absolute flux
- Spectral differences seen at left

Sub-GeV Data



(note no "3D" horizon peak)

No cos(θ) shape information at the lowest energies, only flavor ratio is useful

	e-like	**μ-like**
Sub-GeV (<1.33 GeV)	3353 (Data) 3013.9 (MC)	3227 (Data) 4466.9 (MC)

Sub-GeV $\frac{(\mu/e)_{data}}{(\mu/e)_{MC}}$

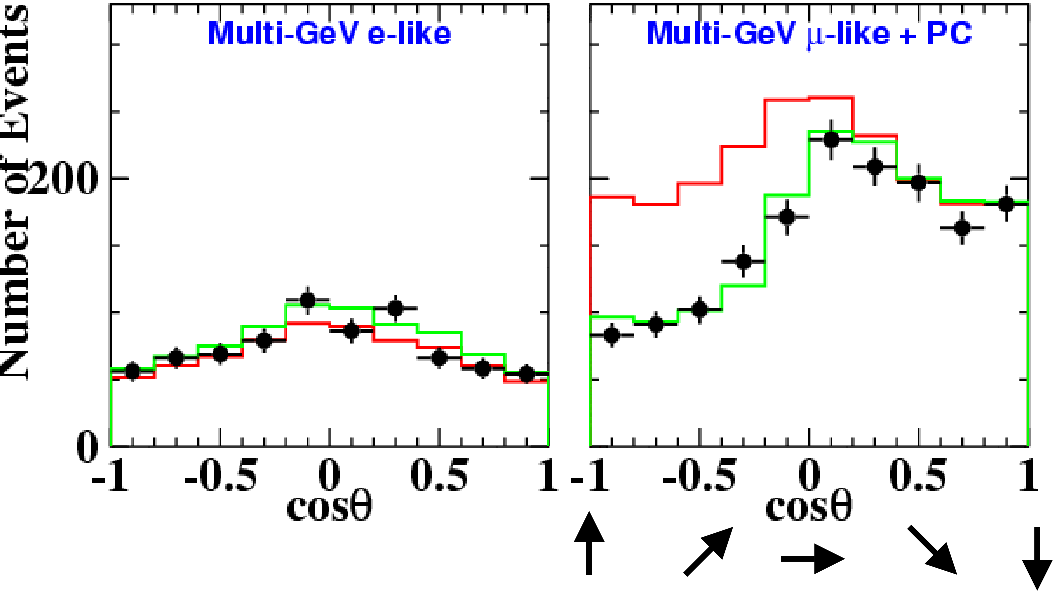
$$= 0.649 \pm 0.016 \pm 0.051$$

(stat.) (syst.)

At higher energies, $\nu \rightarrow \mu$ directionality better preserved plus shorter L ν_μ no longer oscillate: cos(θ) shape information very useful

Key:
+ Data
— MC (no osc.)
— MC (best fit)

Multi-GeV data



ν baseline L: 12800 6200 700 40 15 km

	e-like	μ-like
Multi-GeV + PC	746 (Data) 700.4 (MC)	1562 (Data) 2098.0 (MC)

Multi GeV+PC $\dfrac{(\mu / e)_{data}}{(\mu / e)_{MC}} = 0.699 \pm^{0.032}_{0.030} \pm 0.083$ (stat.) (syst.)

At even higher energies, ν flux up/down symmetric and low-L ν_μ do not have time to disappear.

$$A = \left(\frac{N_{up} - N_{down}}{N_{up} + N_{down}} \right)_{\mu-like} = -0.289 \pm 0.028 \pm 0.004$$

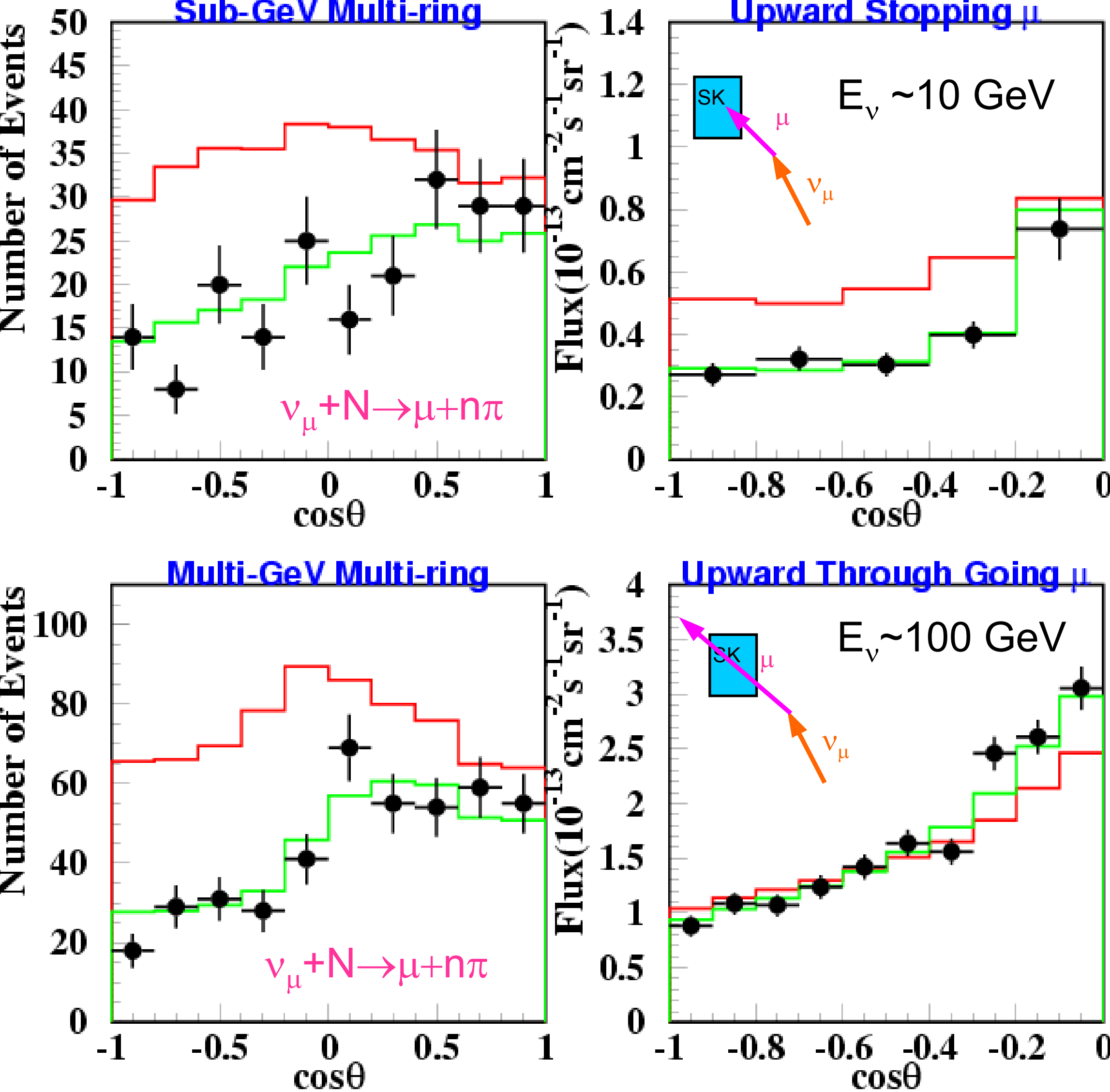
(stat.) (syst.)

Compare to $A_{e\text{-like}} = -0.020 \pm 0.043 \pm 0.005$

MC $A_{\mu\text{-like}} = -0.003 \pm 0.005 \pm 0.009$

Observed $A_{\mu\text{-like}}$ 9.5σ from no-oscillation prediction!

Key:
+ Data
— MC (no osc.)
— MC (best fit)



More Data

Up through going μ –

Measured flux:

$1.70 \pm 0.02 \pm 0.04 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

(stat.) (syst.)

Theoretical calc:

$1.57 \pm 0.35 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

(theo.)

Up stopping μ –

Measured flux:

$0.41 \pm 0.02 \pm 0.02 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

(stat.) (syst.)

Theoretical calc:

$0.61 \pm 0.14 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

(theo.)

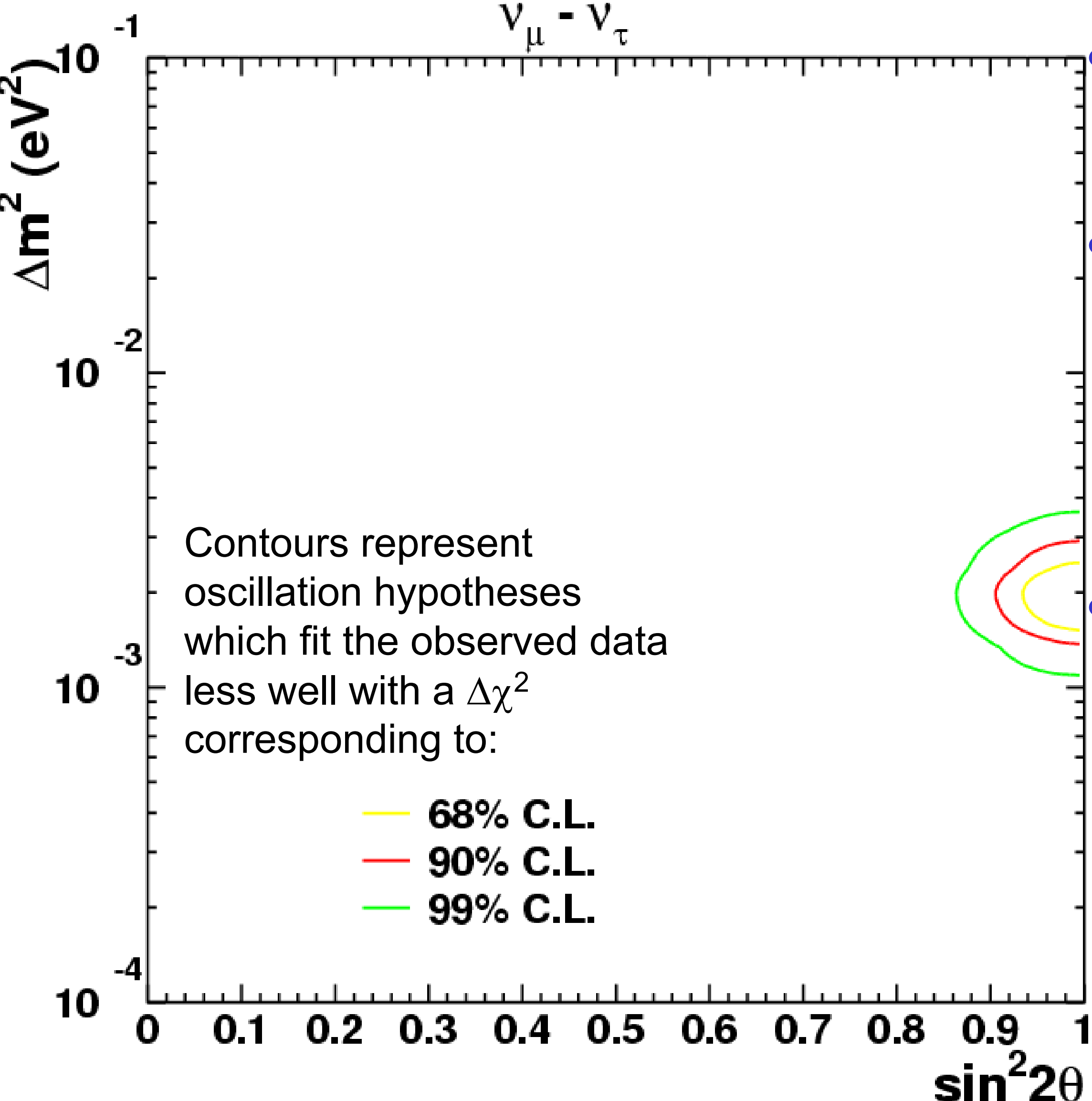
	Data	MC
Sub-GeV Multi-ring μ	208	346.4
Multi-GeV Multi-ring μ	439	739.4

Key:

+ Data
— MC (no osc.)
— MC (best fit)

- More ν_μ, different E_ν and systematics

New Oscillation Results



- For $\nu_\mu \leftrightarrow \nu_\tau$ oscillation:
- Best fit: $\sin^2(2\theta)=1.0$, $\Delta m^2=2.0\times10^{-3}$ eV^2
  - χ^2 = 170.8/170 dof
- 90% c.l. region:
  - $\sin^2(2\theta)>0.9$
  - $1.3 < \Delta m^2 < 3.0\times10^{-3}$ eV^2

Systematics:

- Systematic errors accounted for in fit as extra “bins”, some constrained, others free
  - MC data re-weighted accordingly
  - Gives systematic errors chance to sub for oscillations in explaining observations
- No suspicious pull seen

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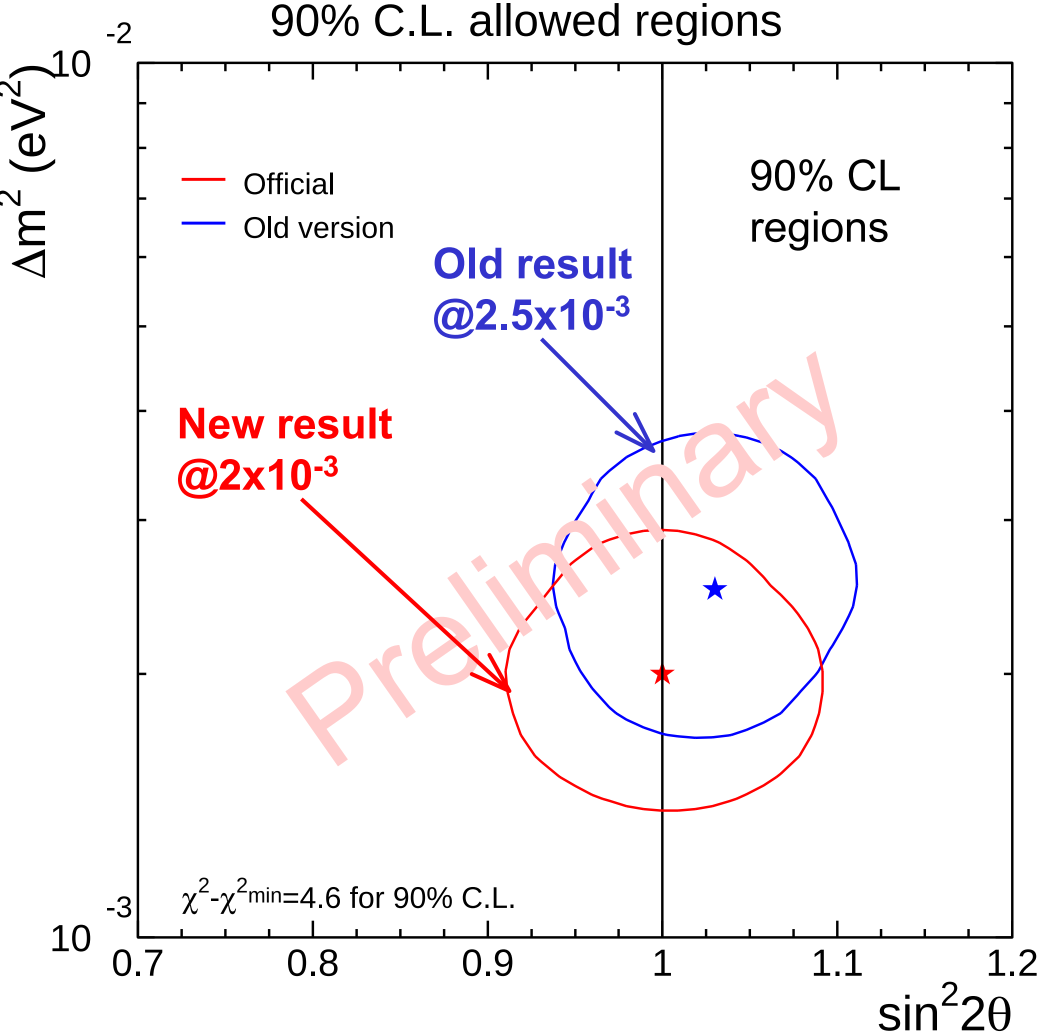
Combined Systematic Errors

		σ_i	best fit
α	**Absolute Normalization Uncertainty**	Free	8.70 %
α_L	**SubGeV Multi-ring Absolute Normalization Uncertainty**	Free	-23.8 %
α_H	**MultiGeV Multi-ring Absolute Normalization Uncertainty**	Free	-26.1 %
δ	**Eν Spectrum Index**	0.05	0.005
β_L	**SubGeV μ/e Ratio**	8 %	-6.1 %
β_H	**MultiGeV μ/e Ratio**	12 %	-12.5 %
ρ	**FC/PC Relative Normalization**	8 %	4.3 %
η_L	**SubGeV Up/Down Asymmetry**	2.4 %	-2.2 %
η_H	**MultiGeV Up/Down Asymmetry**	2.7 %	-1.1 %
β_1	**FC+PC/Stop ↑μ Relative Normalization**	7 %	-2.8 %
β_2	**Through ↑μ/Stop ↑μ Relative Normalization**	7 %	8.2 %
	FC+PC Horizontal/Vertical Uncertainty	4 %	0.2 %
	↑μ Horizontal/Vertical Uncertainty	3 %	1.5 %
	L/E Uncertainty	15 %	-5.8 %

Difference from Previous Results

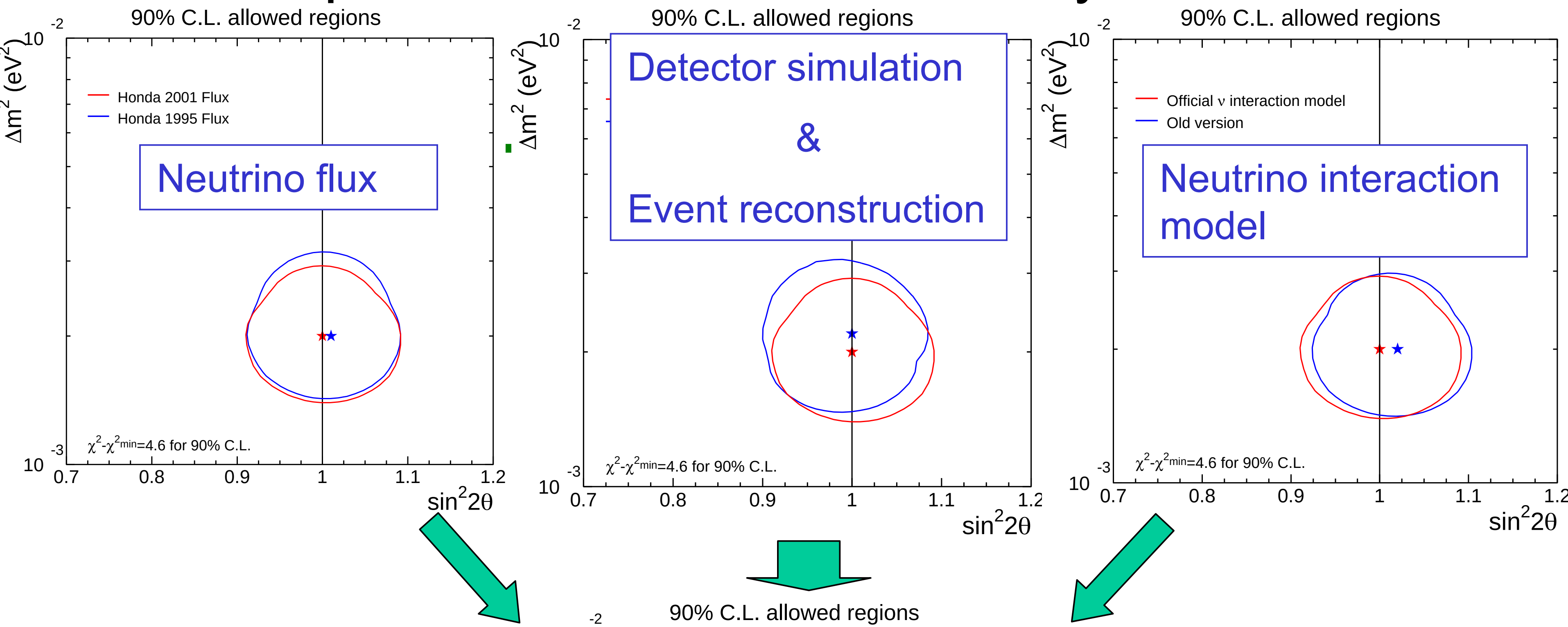


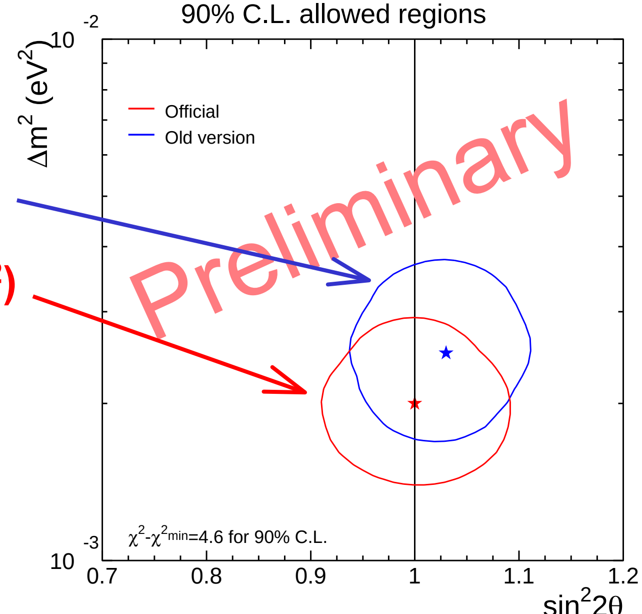
- Small improvements + the same data:
  - but the end result has changed by more than you might expect
- What happened?
  - (*Note this figure is highly zoomed*)

Effects of Improvements on Fit

- Changes each of which caused Δm^2 region to move slightly down:
  - ν flux change (Honda 1995→2001)
  - ν interaction model (p_F flat, M_A 1.0→1.1)
  - Improved detector simulation (OD, H_2O calib.)
  - Improved event reconstruction (Particle ID, ring selection, up-μ fitting)
- Net effect on χ^2 surface of several small changes in same direction is larger

Comparison of old and new analysis results





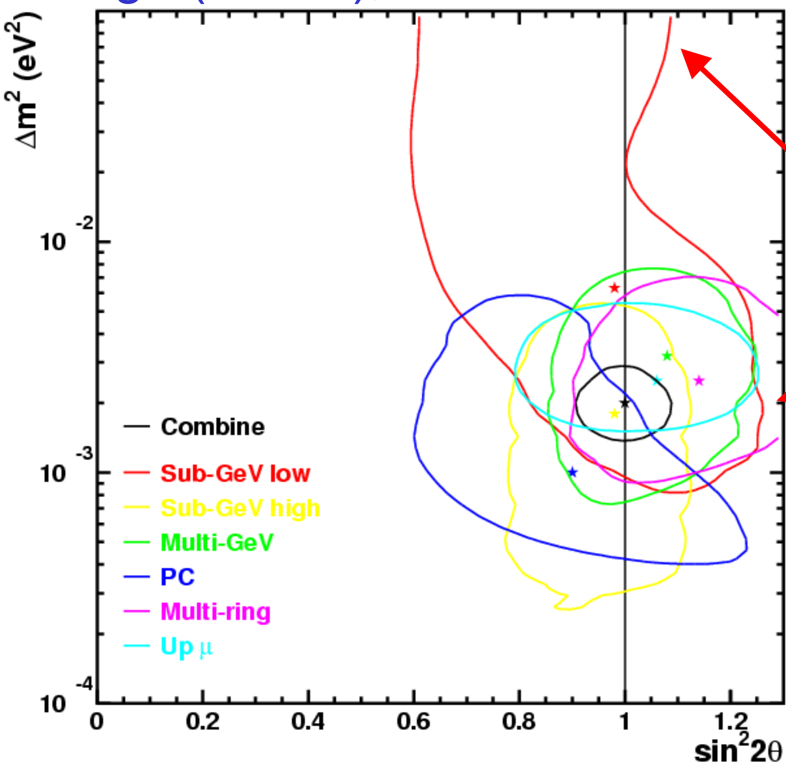
Old (**2.5×10^{-3} eV^2**)

New (**2.0×10^{-3} eV^2**)

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

Sub-Sample Consistency

- Check oscillation fits using different classes of data independently – allowed regions all overlap best fit
- The low energy sub-sample's only handle on oscillations is the μ/e flavor ratio
  - Used to be high (alone!), is now consistent with other sub-samples



Note open-ended "swoosh" shape of a one-parameter flavor ratio fit to two osc. parameters (lowest E event sub-sample)

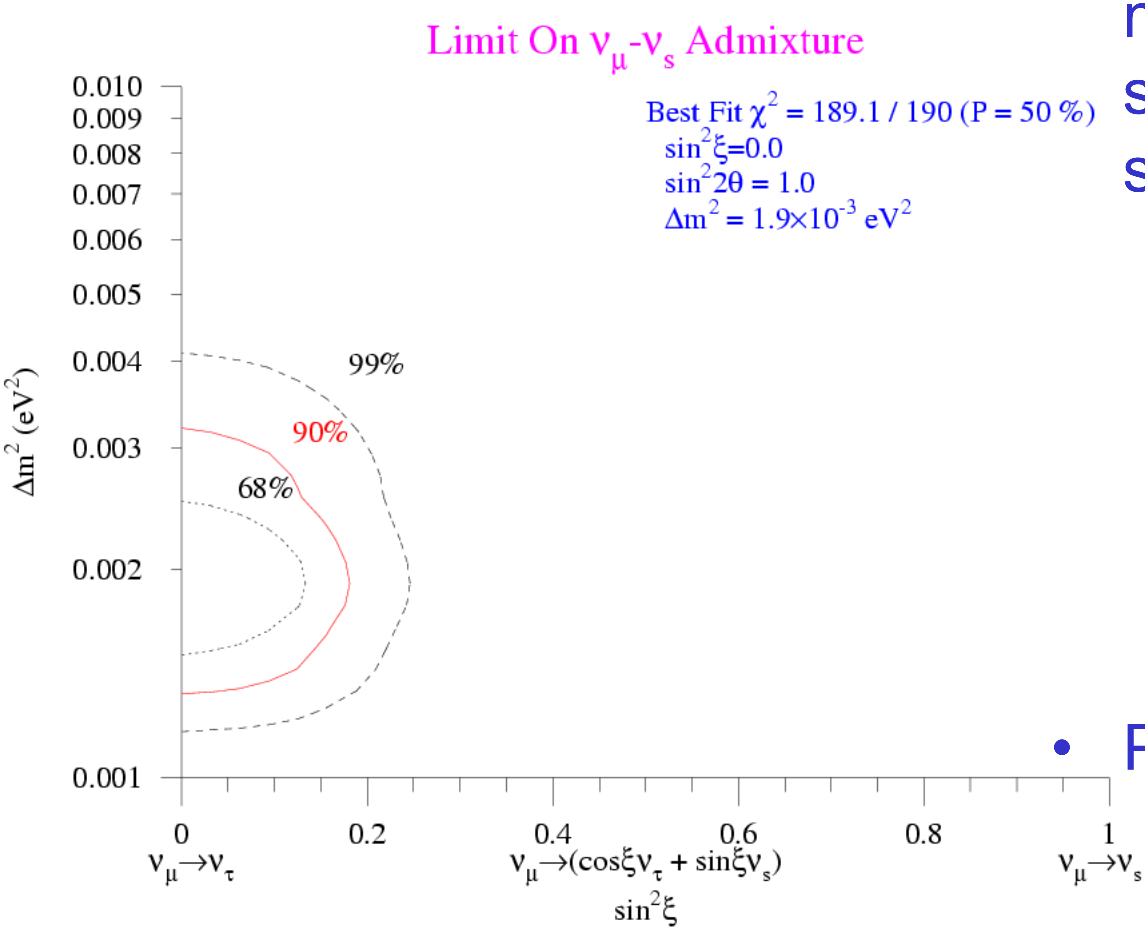
Unusual Models

Mode	Best Fit	χ^2	$P(\chi^2)$	$\Delta\chi^2$	σ
ν_μ-ν_τ $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta=1.00$ $\Delta m^2=1.9\times10^{-3}$ eV^2	189	50%	0.0	0σ
ν_μ-ν_e $\sim\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta=0.98$ $\Delta m^2=4.2\times10^{-3}$ eV^2	304	0%	111	10.5σ
ν_μ-ν_s $\sim\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta=0.93$ $\Delta m^2=2.5\times10^{-3}$ eV^2	231	2%	42.2	6.5σ
LxE (L.I. violation) $\sin^2 2\theta \sin^2(\alpha L \times E)$	$\sin^2 2\theta=0.89$ $\alpha=5.1\times10^{-4}$ GeV/km	329	0%	103	10.1σ
ν_μ decay (short τ) $\sin^4\theta+\cos^4\theta(1-e^{-\alpha L/E})$	$\cos^2\theta=0.49$ $\alpha=3.2\times10^{-3}$ GeV/km	287	0%	98.1	9.9σ
ν_μ decay (long τ) $(\sin^2\theta+\cos^2\theta\, e^{-\alpha L/2E})^2$	$\cos^2\theta=0.33$ $\alpha=9.8\times10^{-3}$ GeV/km	207	19%	18	4.2σ
ν_μ decoherence $0.5\sin^2 2\theta(1-e^{-\gamma L/E})$	$\sin^2 2\theta=0.98$ $\gamma=6.6\times10^{-3}$ GeV/km	198	33%	9.4	3.1σ
Null Hypothesis		469	0%	280	16.7σ

Data Used: (diff. from std.) (FC+PC (cut into 2 samples @E_{vis} = 5 GeV)+NC+multiring+up-μ, 195 bins, 190 d.o.f.)

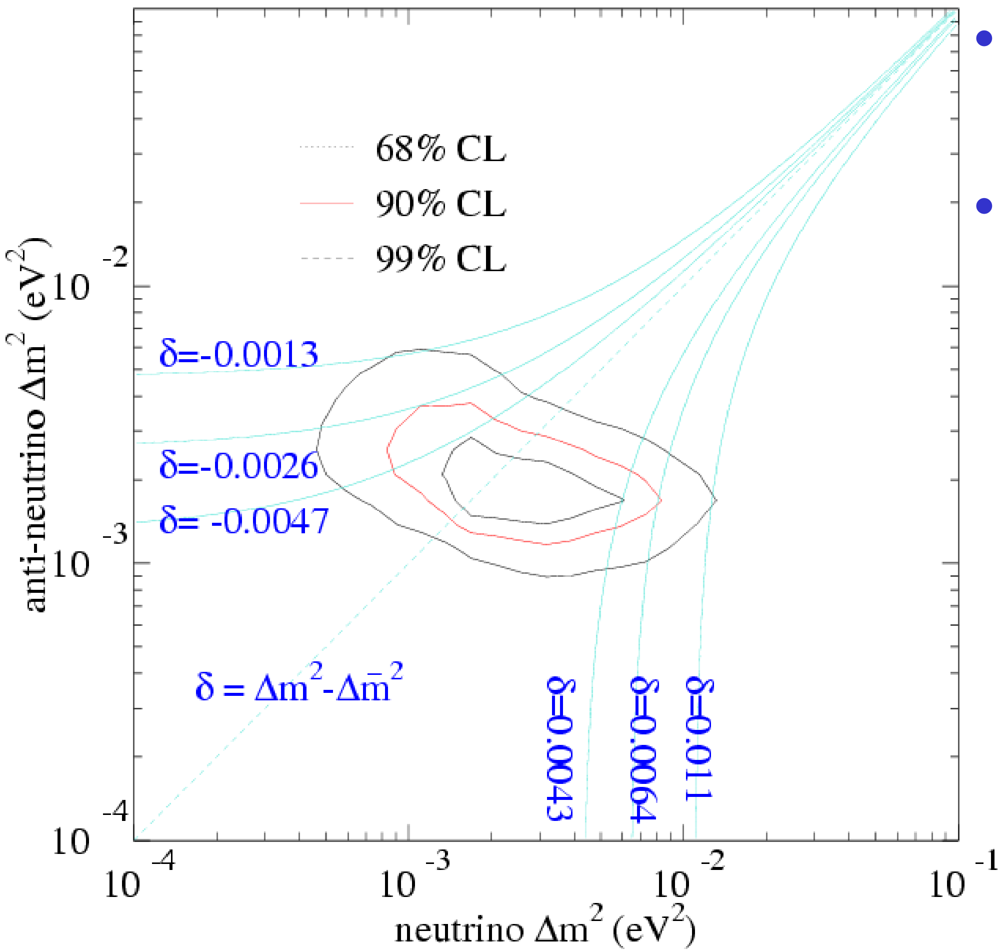
- Ways to make ν_μ disappear without ν_μ,ν_τ flavor oscillations include:
  - Lorentz inv. violation
  - ν decay, decoherence
- Fits using all available SK ν data strongly constrain many such models
  - Hard for model to get good fit over 5 orders of mag. in E and 4 in L
  - Long τ ν_μ decay and ν_μ decoherence disfavored but not eliminated

ν_μ to $\nu_{sterile}$?



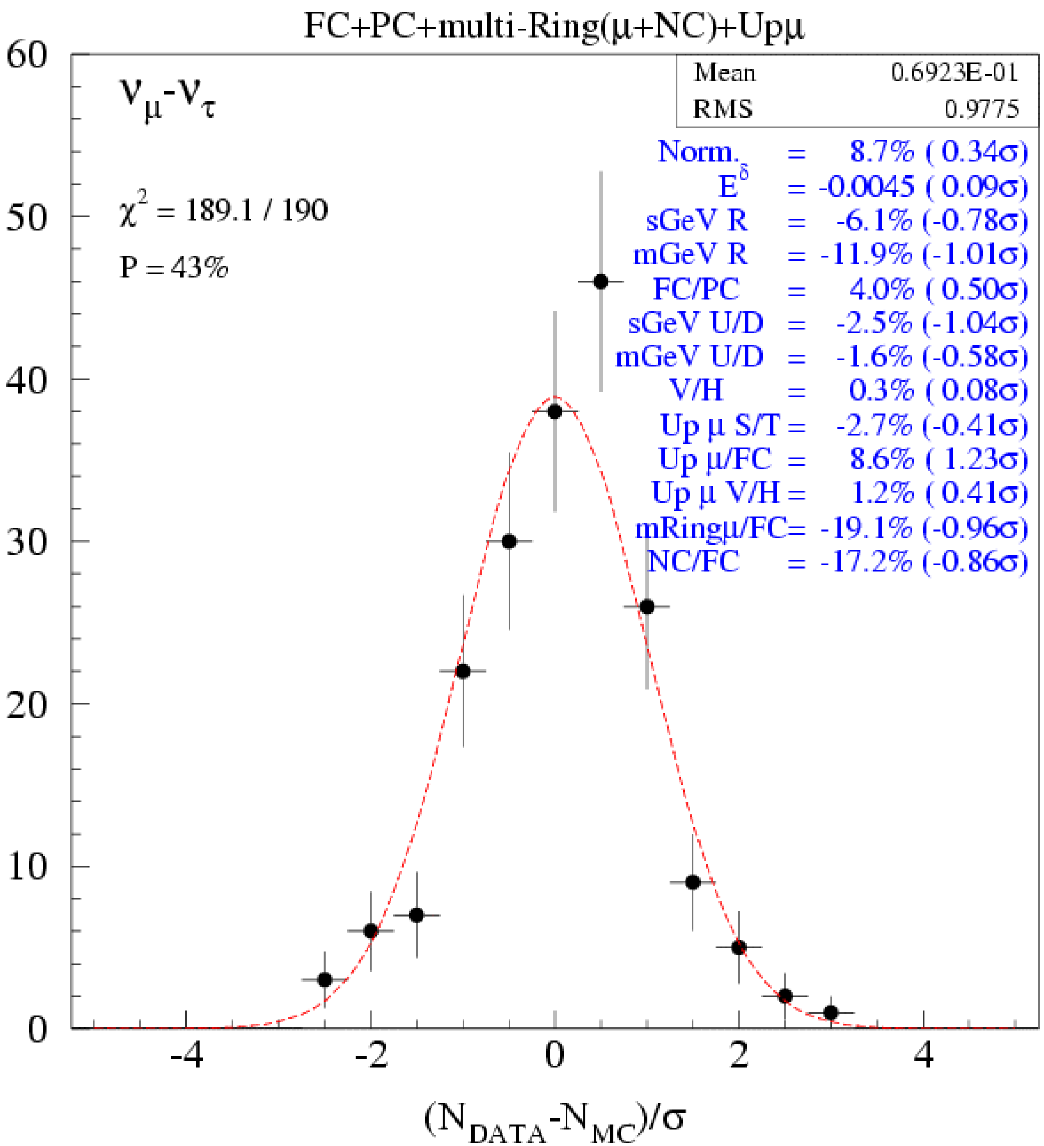
- High energy ν experience matter effects which suppress oscillations to sterile ν
  - Matter effects not seen in up-μ or high-energy PC data
  - Reduction in neutral current interactions also not seen
  - constrains ν_s component of ν_μ disappearance oscillations
- Pure $\nu_\mu\leftrightarrow\nu_s$ disfavored
  - ν_s fraction < 20% at 90% c.l.

CPT Violation



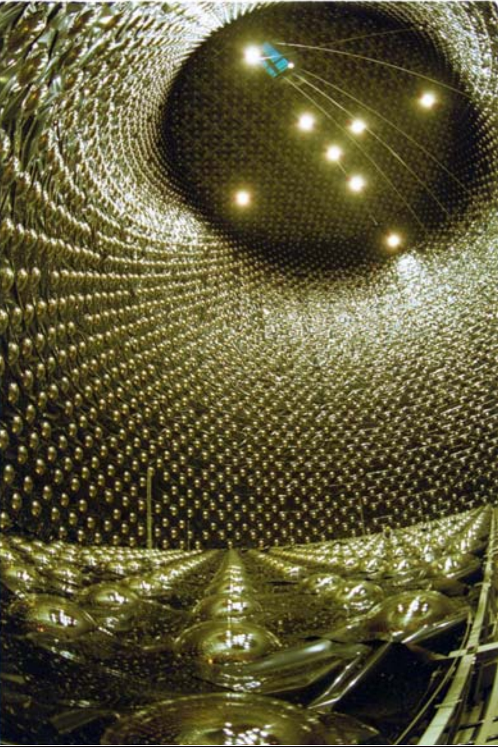
- Do ν_μ oscillate differently than $\overline{\nu}_\mu$?
- SK cannot tell the difference between ν_μ and $\overline{\nu}_\mu$ event-by-event
  - But we see the sum of the two
  - One behaving very differently would show up in the total

Residuals



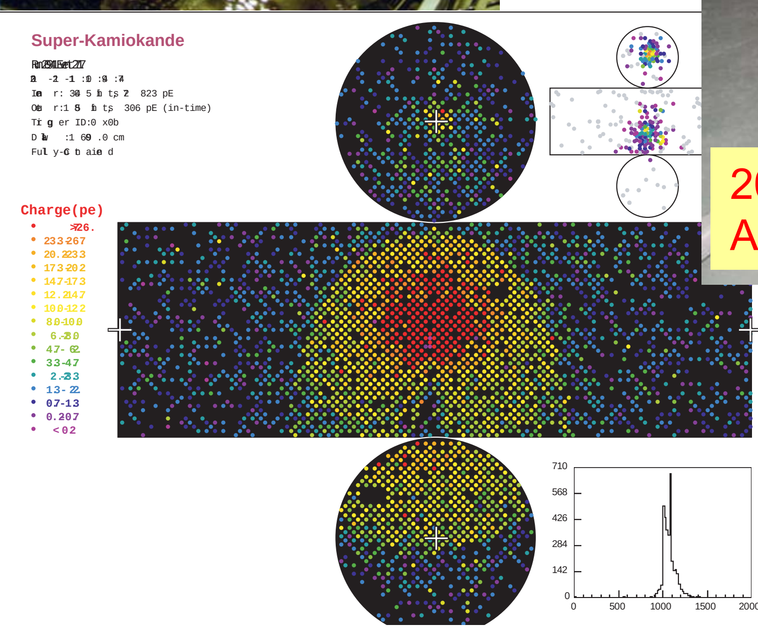
- Sanity check:
- If this MC prediction and the data match well within statistics, the residuals on all those bins should form a Gaussian of mean zero and width one
- They do!
  - Including systematic error terms

SK-II Back in Action!



- Experiment rebuilt in summer 2002
  - Has 47% of original ID 20” PMTs (~5200)
  - 20” PMTs in acrylic shells to prevent future chain implosions
  - OD at full complement (1885) of 8” PMTs
  - Lower PMT count has little effect on reconstruction of high-energy events
- Taking data since 12/02

20inch PMT with Acrylic + FRP vessel



SK-II Cosmic ray muon sample

Summary

- $\nu_\mu \leftrightarrow \nu_\tau$ oscillations fit the data better than other means of making ν_μ disappear
  - Best fit value is ($\Delta m^2 = 2.0\text{x}10^{-3}$ eV^2, $\sin^2(2\theta) = 1.0$)
  - $1.3 < \Delta m^2 < 3.0\text{x}10^{-3}$ eV^2, $\sin^2(2\theta) > 0.9$ @ 90% c.l.
- Analysis improvements to
  - ν interaction & flux models
  - Detector simulation
  - Event reconstruction
- No one improvement drove the changes to the final fit
  - Each contributed a little in the same direction
  - All data sub-samples now individually consistent with the overall fit

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