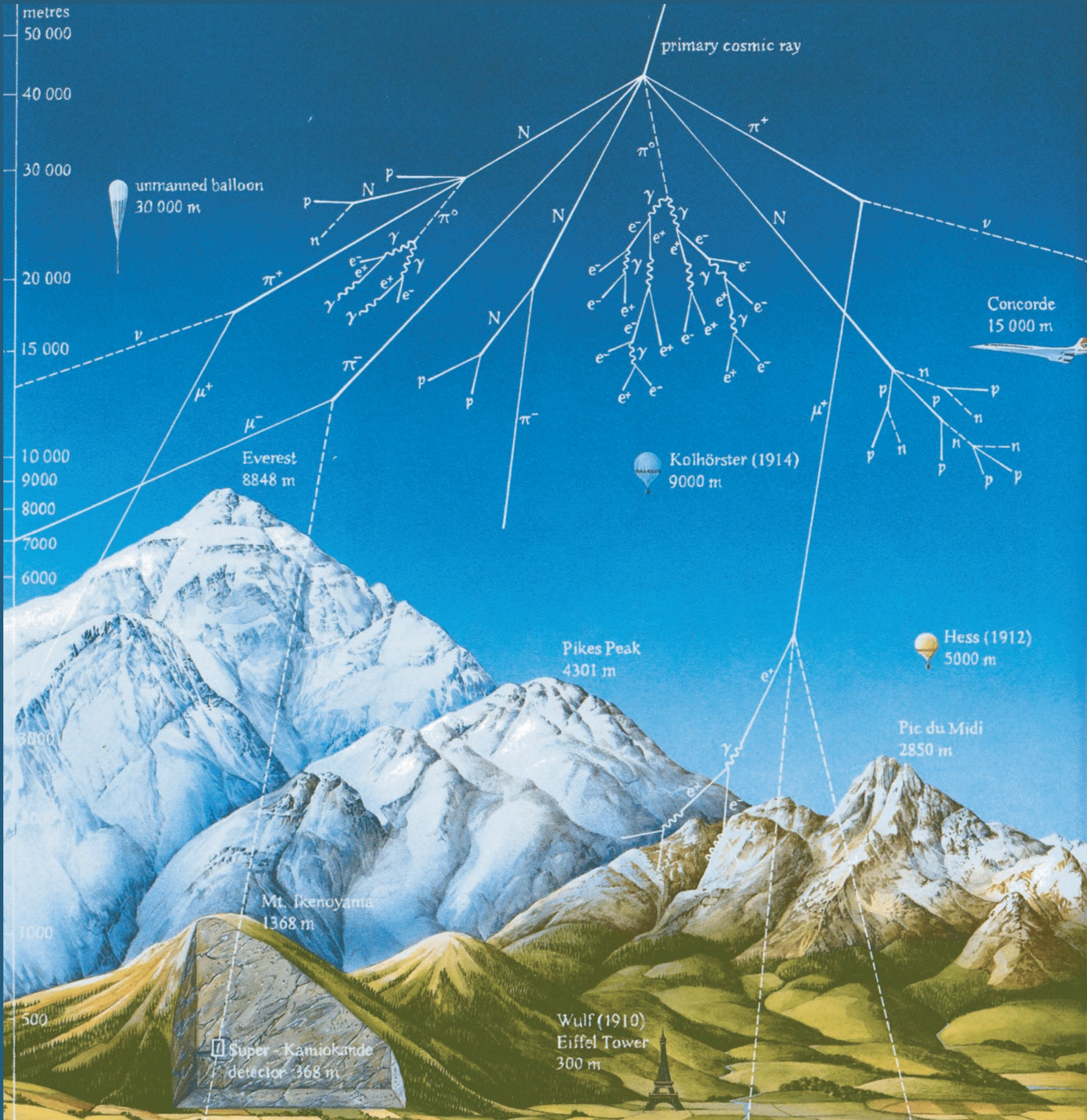

Atmospheric Neutrino Results from Super-K

Ed Kearns
Boston U.

for the Super-Kamiokande collaboration

NEUTRINO 2004
PARIS

Super-Kamiokande Collaboration

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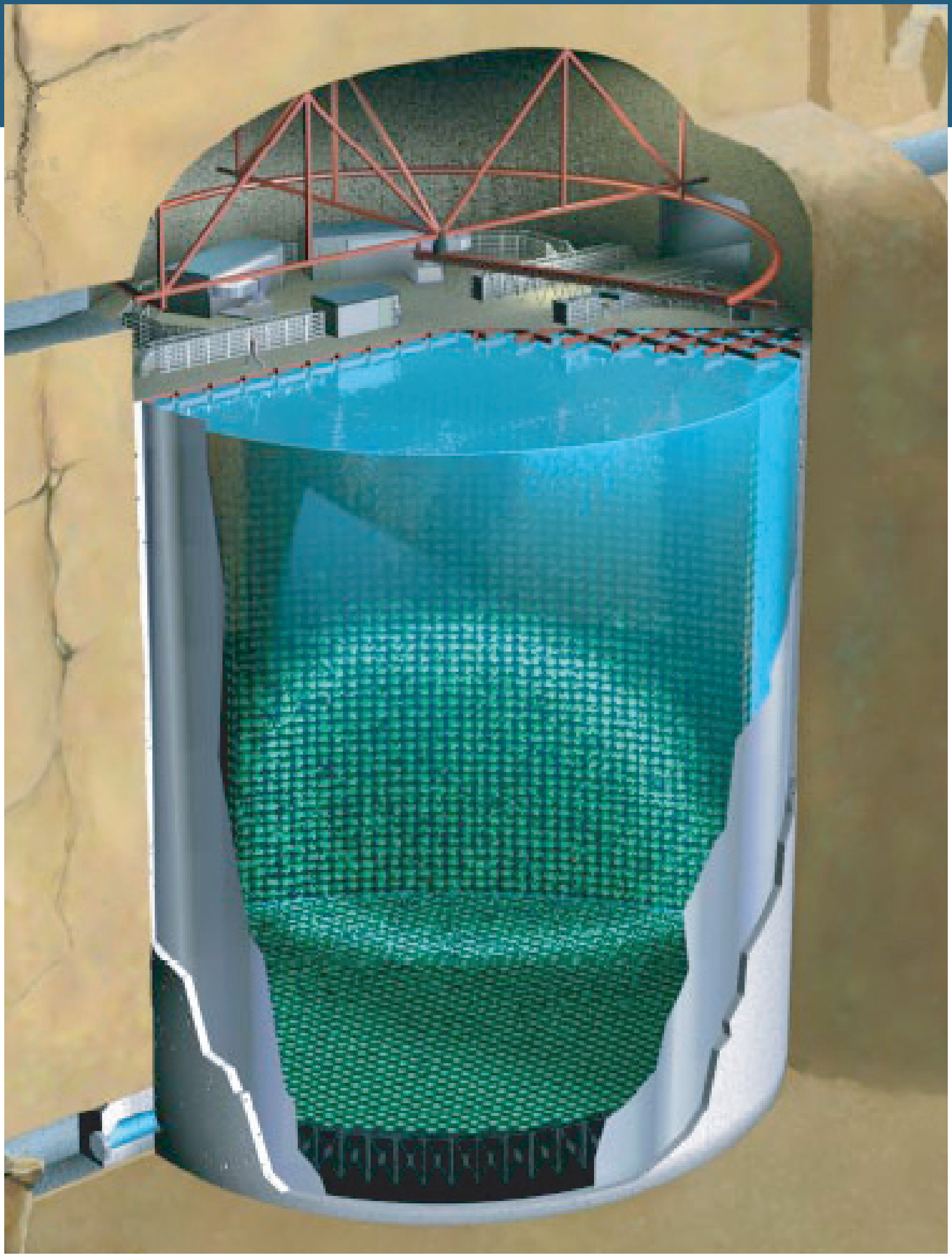
Super-Kamiokande



SK-1 1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

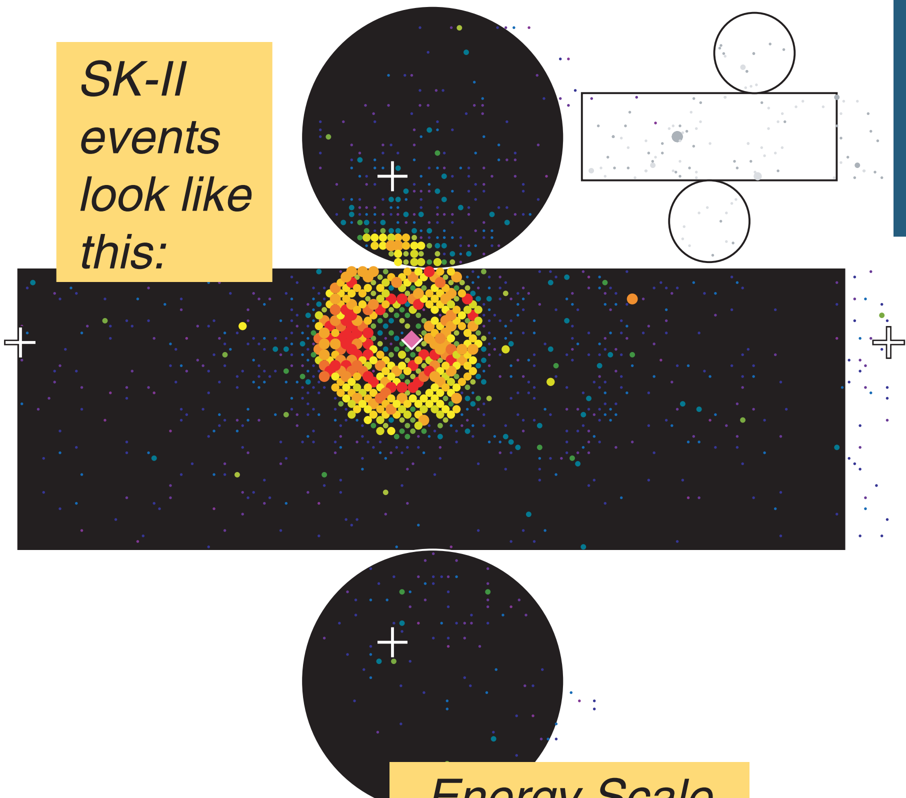
SK-2 January 2003 - October 2005
- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

SK-3 March 2006 +
- original coverage to be restored
- T2K off-axis beam from J-PARC

Super-K II Performance

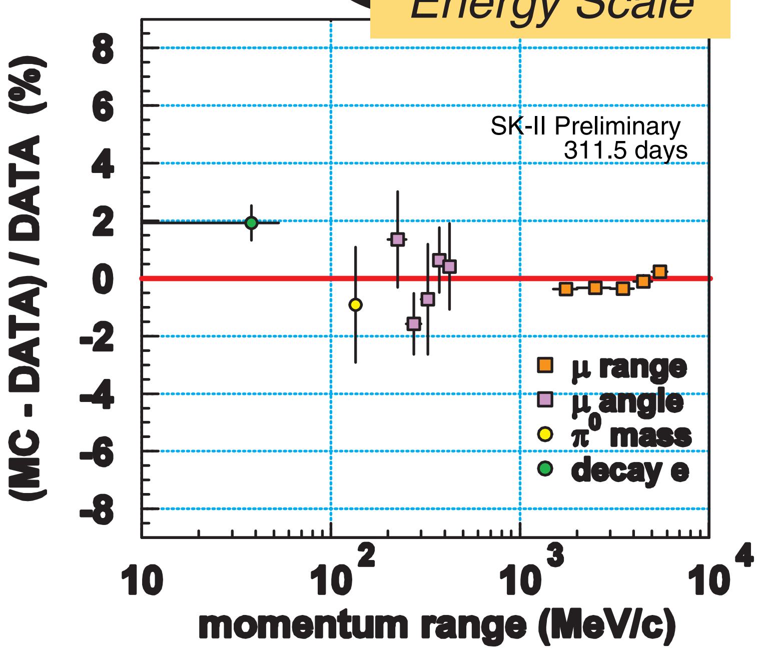
preliminary!

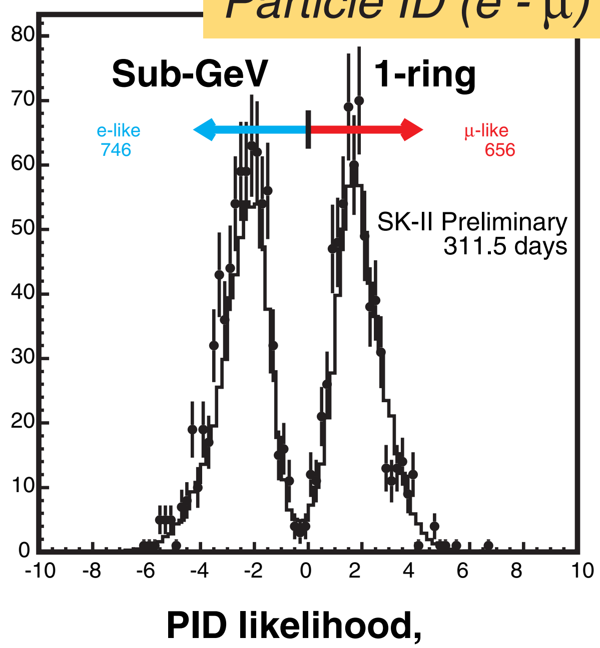
SK-II events look like this:

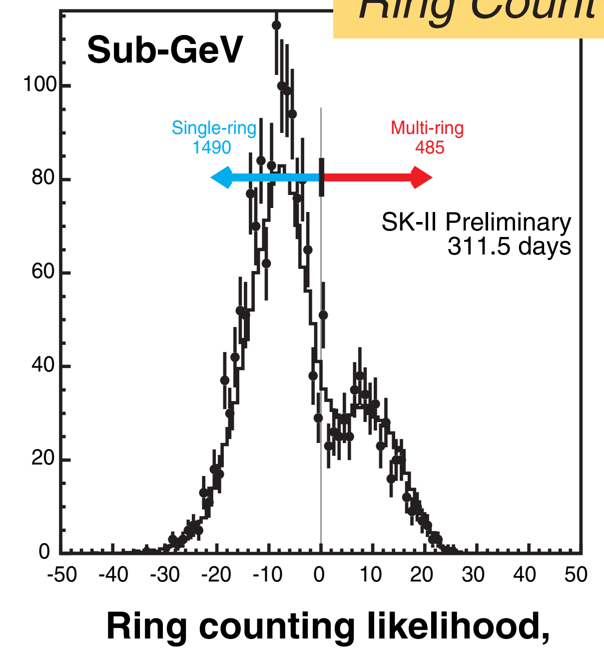


Atmospheric neutrino analysis in early stages - no results yet

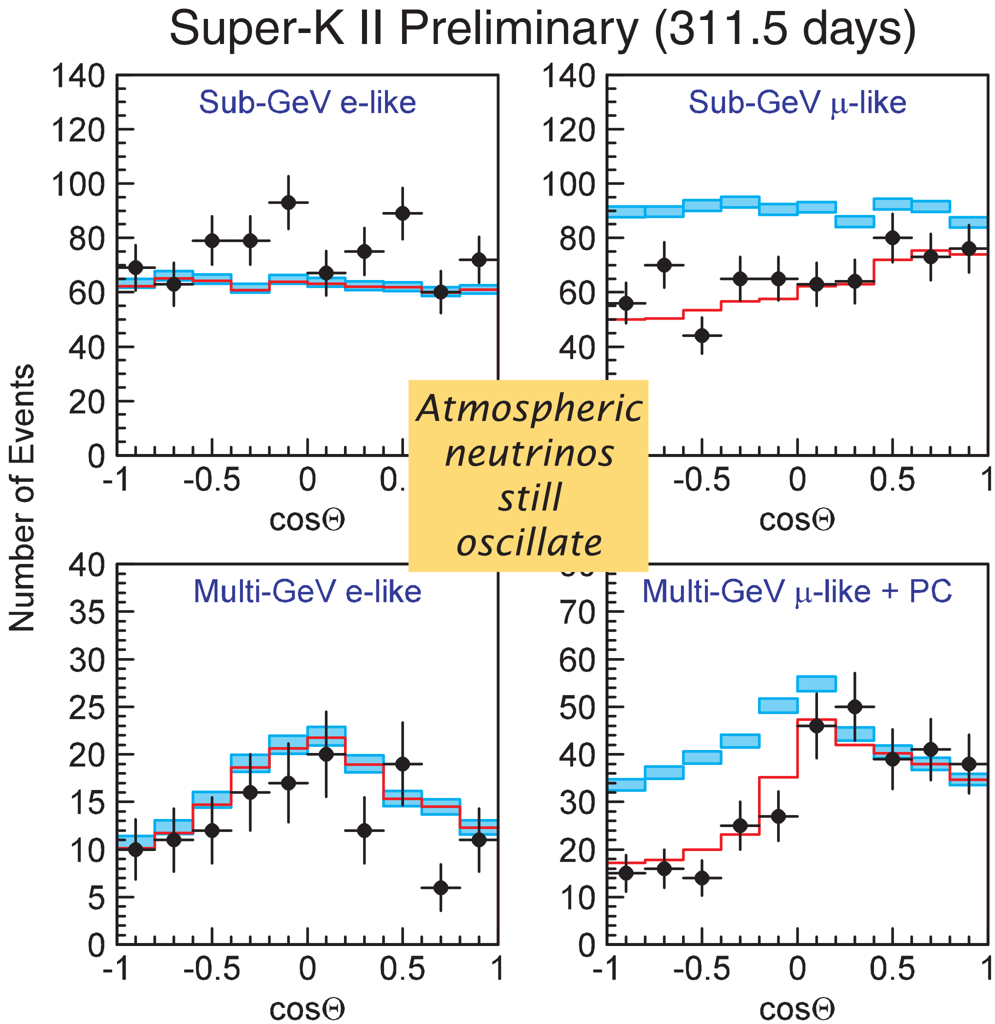
Data is valuable for characterizing performance for K2K







Status of Super-K II Atmospheric Neutrinos

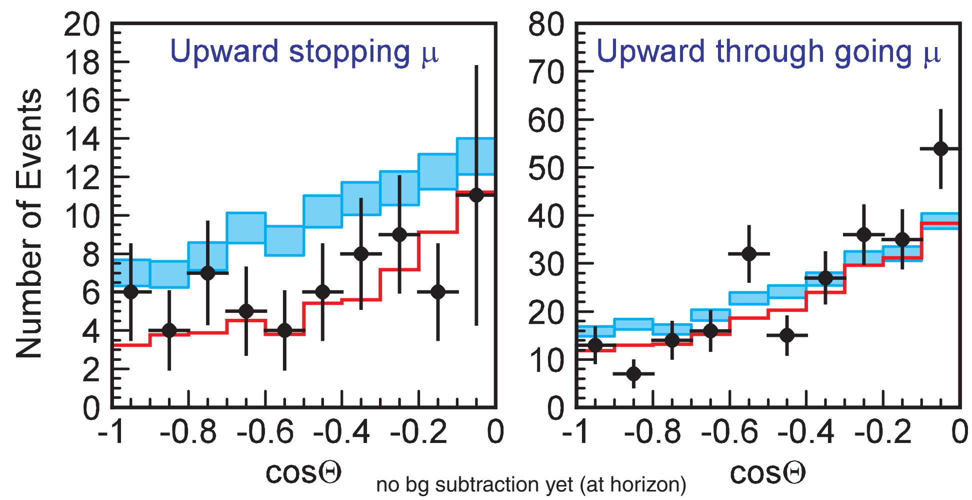


FC data reduction:
8.22 ± 0.16 ev/day (cf. 8.17 SK-I)

PC data reduction:
0.51 ± 0.04 ev/day (cf. 0.61 SK-I)

$R_{\text{sub-GeV}} = 0.61 \pm 0.03 \pm 0.05$

$R_{\text{multi-GeV}} = 0.89 \pm 0.10 \pm 0.16$



SK-II data is consistent with SK-I results. e/μ ID, energy scale look very good.
Current studies emphasize ring counting, PC reduction, OD simulation.

SK-I Atmospheric Neutrino Topics

Exotic scenarios (decay, $L \times E$ etc.)
Sterile admixture
CPT violation
ν astronomy
UHE neutrinos
proton decay

papers in progress

CHARACTERISTICS of NEUTRINO OSCILLATION

ν_τ statistical appearance - under study

➤ full SK-I dataset analysis - paper almost ready (<1mo)

➤ L/E oscillatory signature - published March 2004

➤ 3-flavor analysis - preliminary result (paper < 1 year)

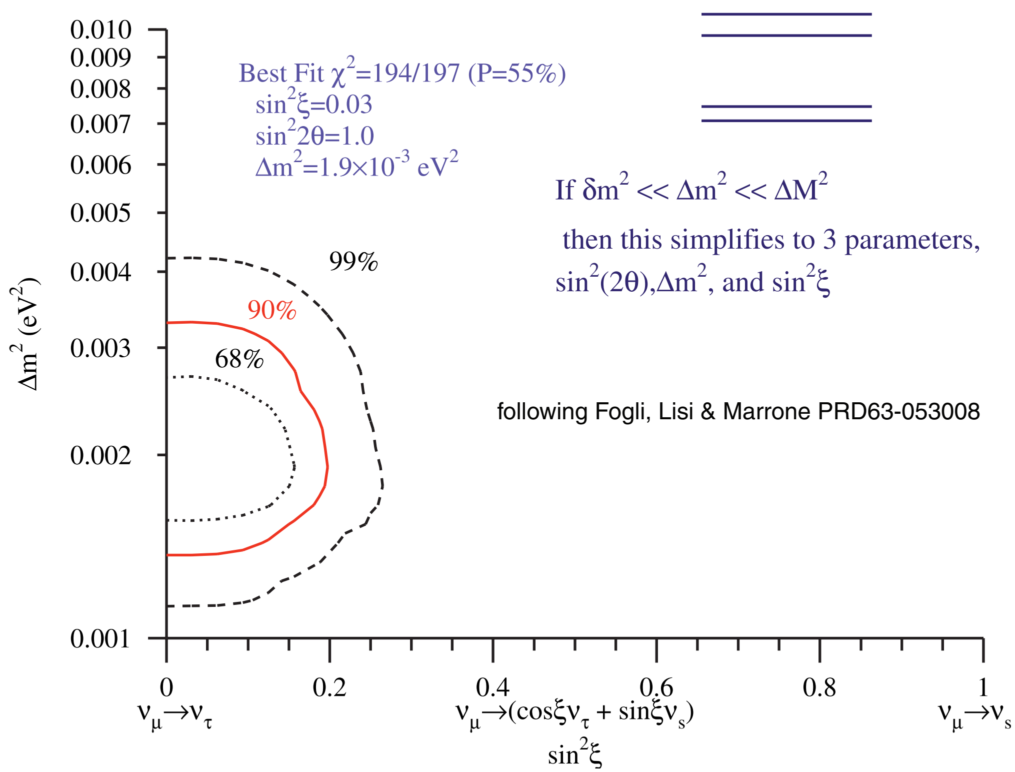
this talk

Exotic Scenarios

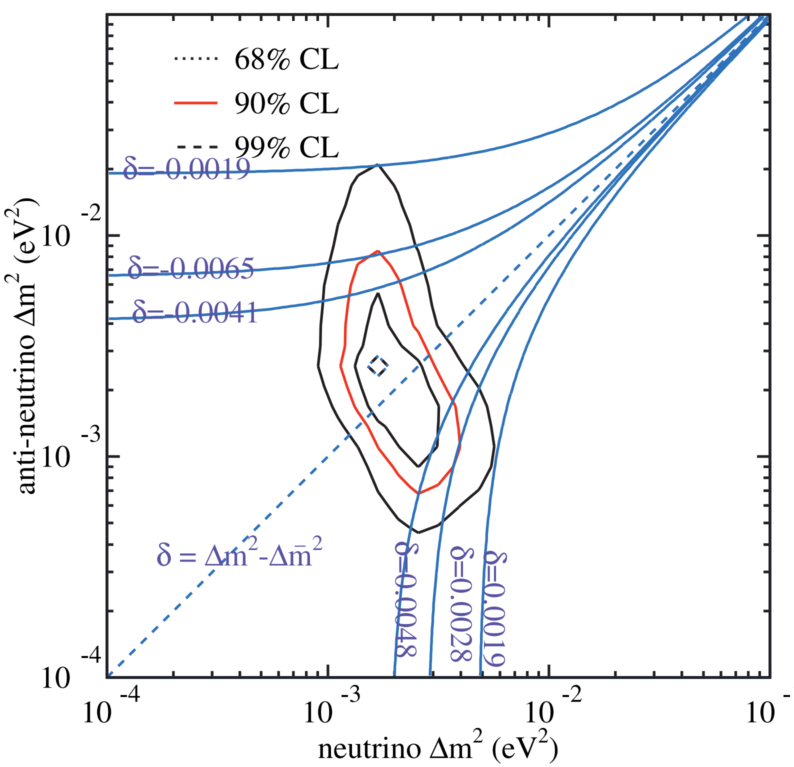
sterile neutrino admixture

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

δm^2 - Solar Neutrinos ($< 10^{-4}$ eV^2)
Δm^2 - Atmosperic Neutrinos ($\approx 10^{-3}$-10^{-2} eV^2)
ΔM^2 - LSND (≈ 1 eV^2)



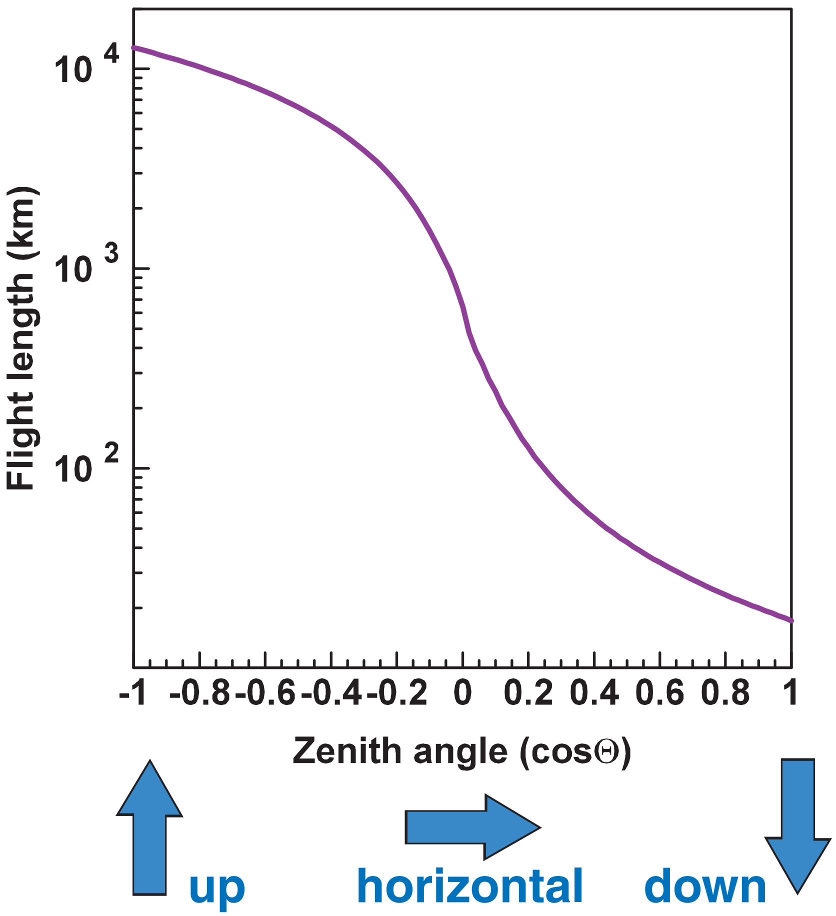
CPT violation



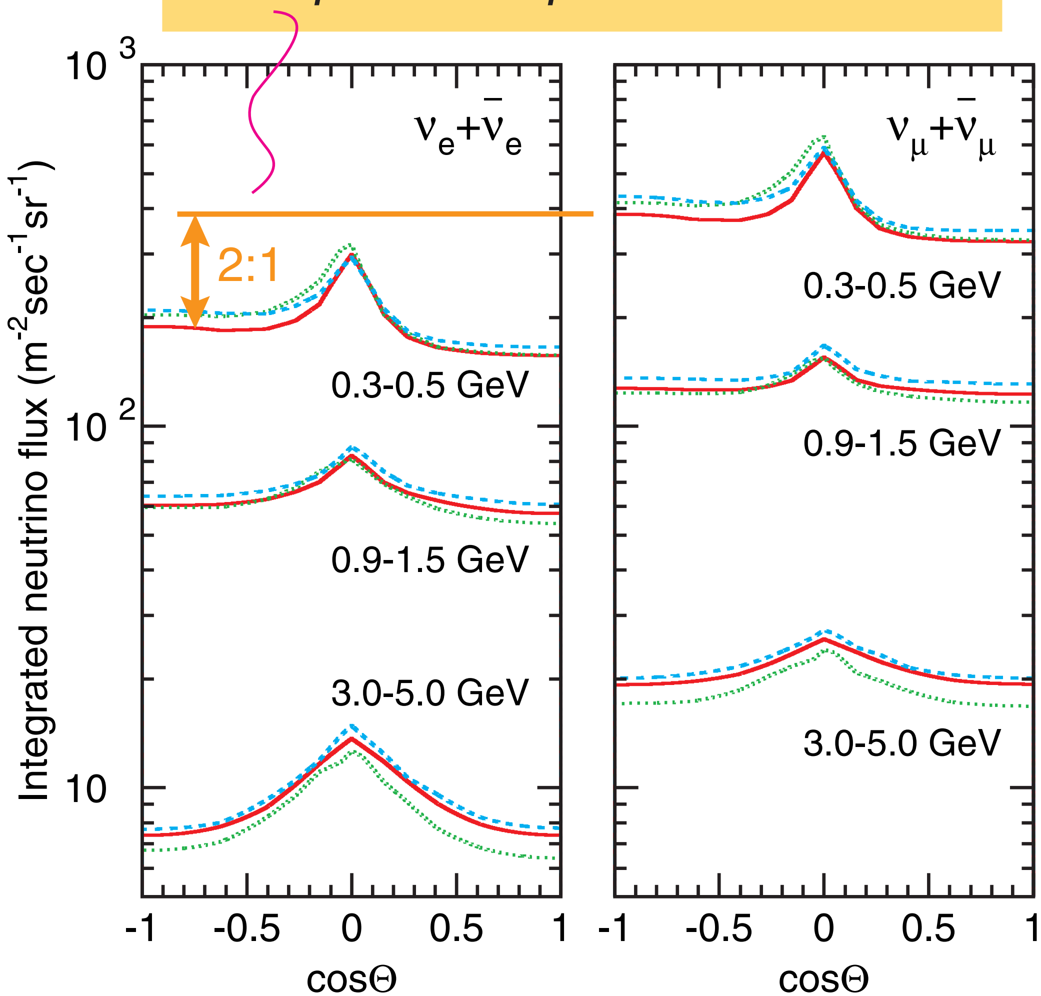
atmospheric neutrino dynamic range very powerful in limiting neutrino exotica

Features of the Atmospheric Neutrino Flux

Three decades of pathlength



Mixed beam of ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$
Well predicted flux ratio

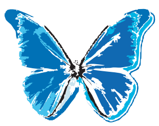


up-down symmetry at high energy

Aspects of Current Super-K Analysis

Improved primary cosmic ray data
3D treatment of secondary particles
[New flux calculations: see G. Barr talk]

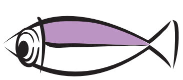
could use further data by AMS, BESS, + HARP, MIPP



Improved treatment of neutrino interactions:
use results from K2K near detector (M_A=1.1)

could use data from MINERνA

Improved experimental tools:
data reduction, reconstruction algorithms, Monte Carlo tuning

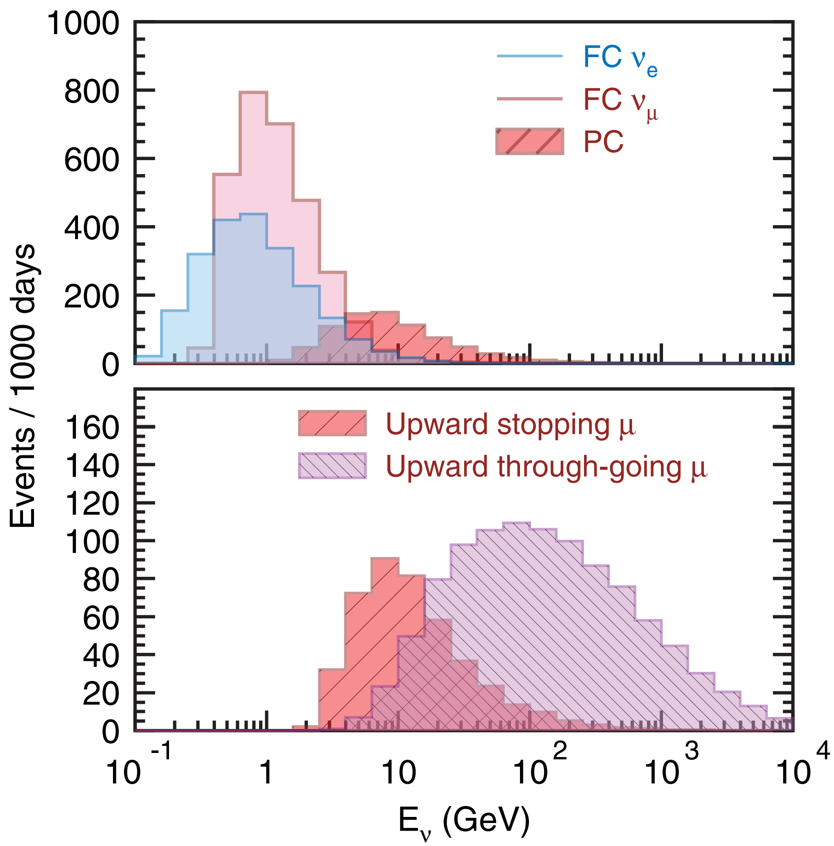


New fitting procedure with improved
treatment of systematic uncertainties

SK-I Atmospheric Neutrino Event Sample

~14000 events total from data reduction

5 decades of neutrino energy



	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%

11530 events used (80%) in oscillation analysis

Ratios

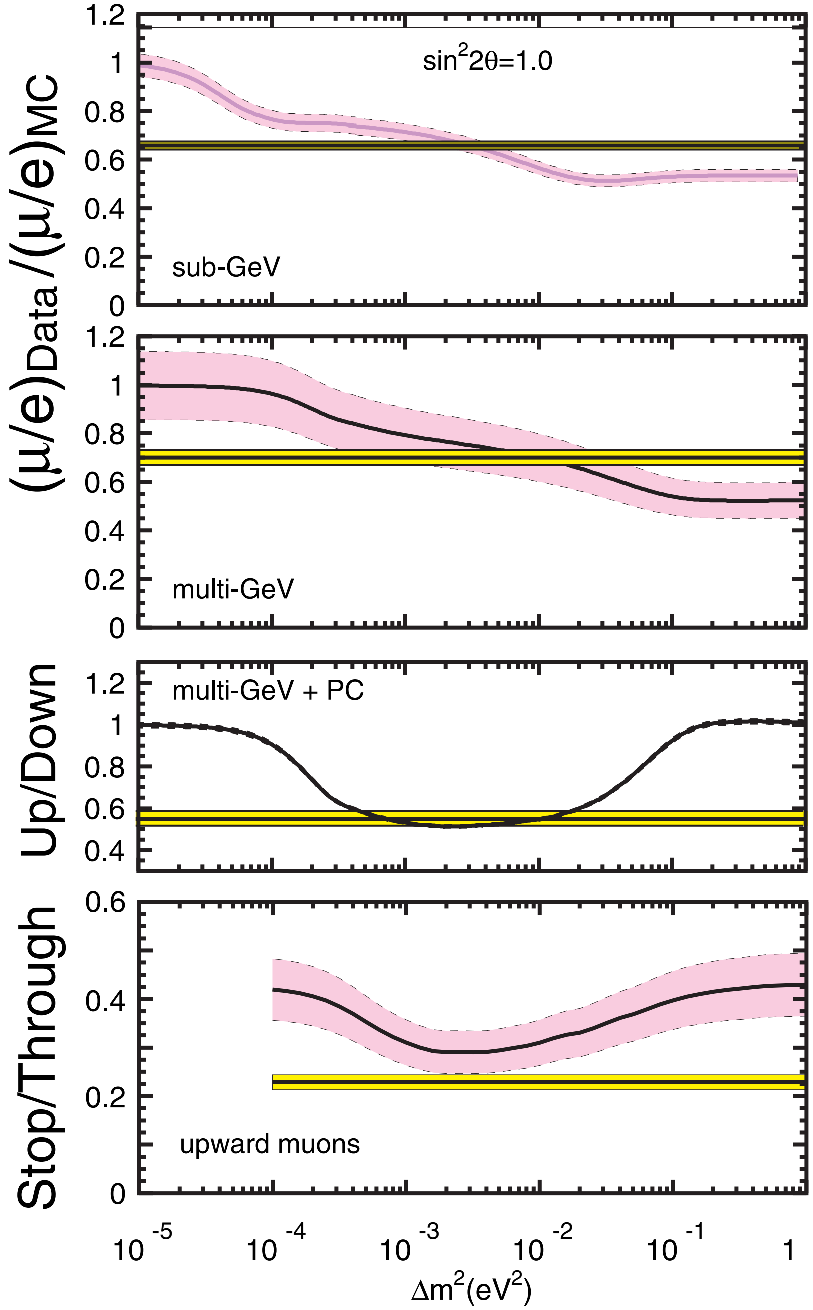
$$R_{sub-GeV} = 0.658 \pm 0.016(stat) \pm 0.032(sys)$$

$$R \equiv \frac{(\mu/e)_{DATA}}{(\mu/e)_{M.C.}}$$

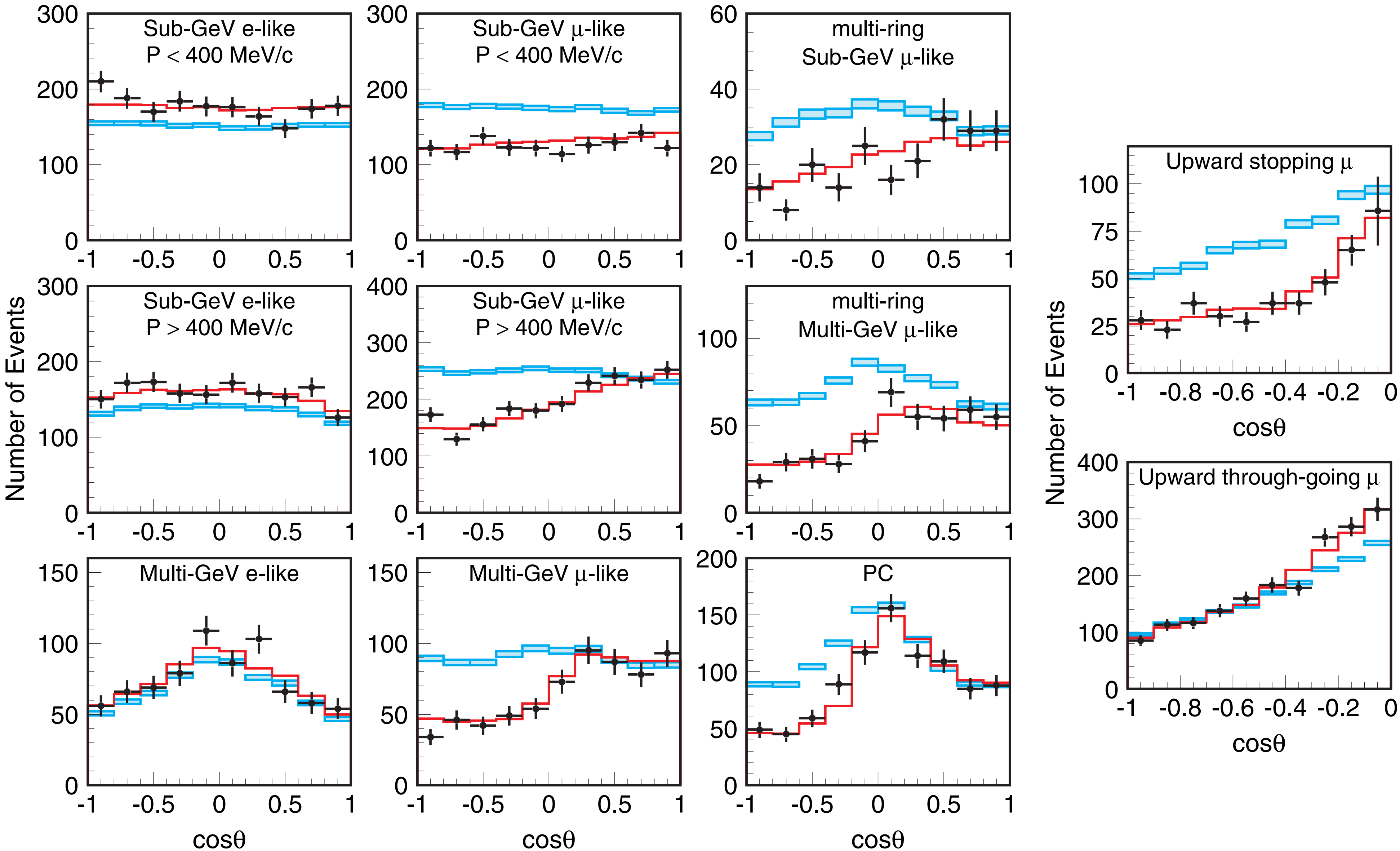
$$R_{multi-GeV} = 0.702^{+0.032}_{-0.030}(stat) \pm 0.099(sys)$$

$$\left(\frac{N_{UP}}{N_{DOWN}}\right)_{Multi-GeV+PC} = 0.55^{+0.035}_{-0.033}(stat) \pm 0.005(sys)$$

$$\frac{\Phi(stop)}{\Phi(through)} = 0.229 \pm 0.015(stat) \pm 0.003(sys)$$



Zenith Angle Distributions



Statistical Treatment of Binned Data

Statistical treatment

eg. G.L. Fogli et al. PRD66 053010 (2002)

- avoid double counting some uncertainties
- treat a much larger number of sources of uncertainty

number of p, Θ bins

number of sys. effects (normalization is free)

$$\chi^2 = \sum_{i=1}^{180} \frac{\left(N_i^{obs} - N_i^{\exp}(1+\sum_{j=1}^{39} f_j^i \cdot \varepsilon_j)\right)^2}{\sigma_i^2} + \sum_{j=1}^{38} \left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

$$N_i^{\exp} = N_i^0 \cdot P(\nu_\alpha \to \nu_\beta) \cdot (1 + \sum_{j=1}^{39} f_j^i \cdot \varepsilon_j)$$

fractional change in predicted event rate due to variation in systematic parameter ε

solve set of linear equations:

$$\sum_{j=1}^{38} \left[\frac{1}{\sigma_j^2} \delta_{jk} + \sum_{i=1}^{180} \left(\frac{N_i^{\exp} \cdot N_i^{\exp} \cdot f_j^i \cdot f_k^i}{\sigma_i^2} \right) \right] \cdot \varepsilon_k = \sum_{i=1}^{180} \frac{\left(N_i^{obs} - N_i^{\exp}\right) \cdot N_i^{\exp} \cdot f_k^i}{\sigma_i^2}$$

Selected Systematic Uncertainties

		error	best fit
	Neutrino Flux		
	Overall absolute normalization	free	14.0%
	FC Multi-GeV sample	5.0%	-5.4%
	PC + stopping upward muon	5.0%	-2.5%
	Energy spectrum $E^{-2.7+\delta}$	0.05	0.61
	K/π ratio	20.0%	-6.4%
	μ/e ratio (< 5GeV)	3.0%	-2.5%
✓	μ/e ratio (> 5GeV)	3.0%	1.4%
✓	zenith shape (various)	(0.3%-2.8%)	
	Neutrino Interaction		
	QE cross section	10.0%	5.0%
	Axial mass parameter (1.1 GeV)	10.0%	-1.0%
	Meson production (various)	(10%-30% + alt. models considered)	
	NC/CC ratio	20.0%	0.6%
	Event Selection		
	PC data reduction efficiency	3.2%	0.7%
	FC/PC events selection (OD hits)	1.8%	0.6%
	FC data reduction	0.2%	0.0%
✓	Non-neutrino BG (various)	(<1%)	
	Event Reconstruction		
✓	Particle ID (μ/e) 1-ring	(<1%)	
	Particle ID (μ/e) multi-ring	(3.4%-4.7%)	
	Energy scale	2.0%	0.5%
	Ring counting (various)	(1.3%-7.2%)	
	Ring counting (multi-GeV e-like)	15.9%	8.1%

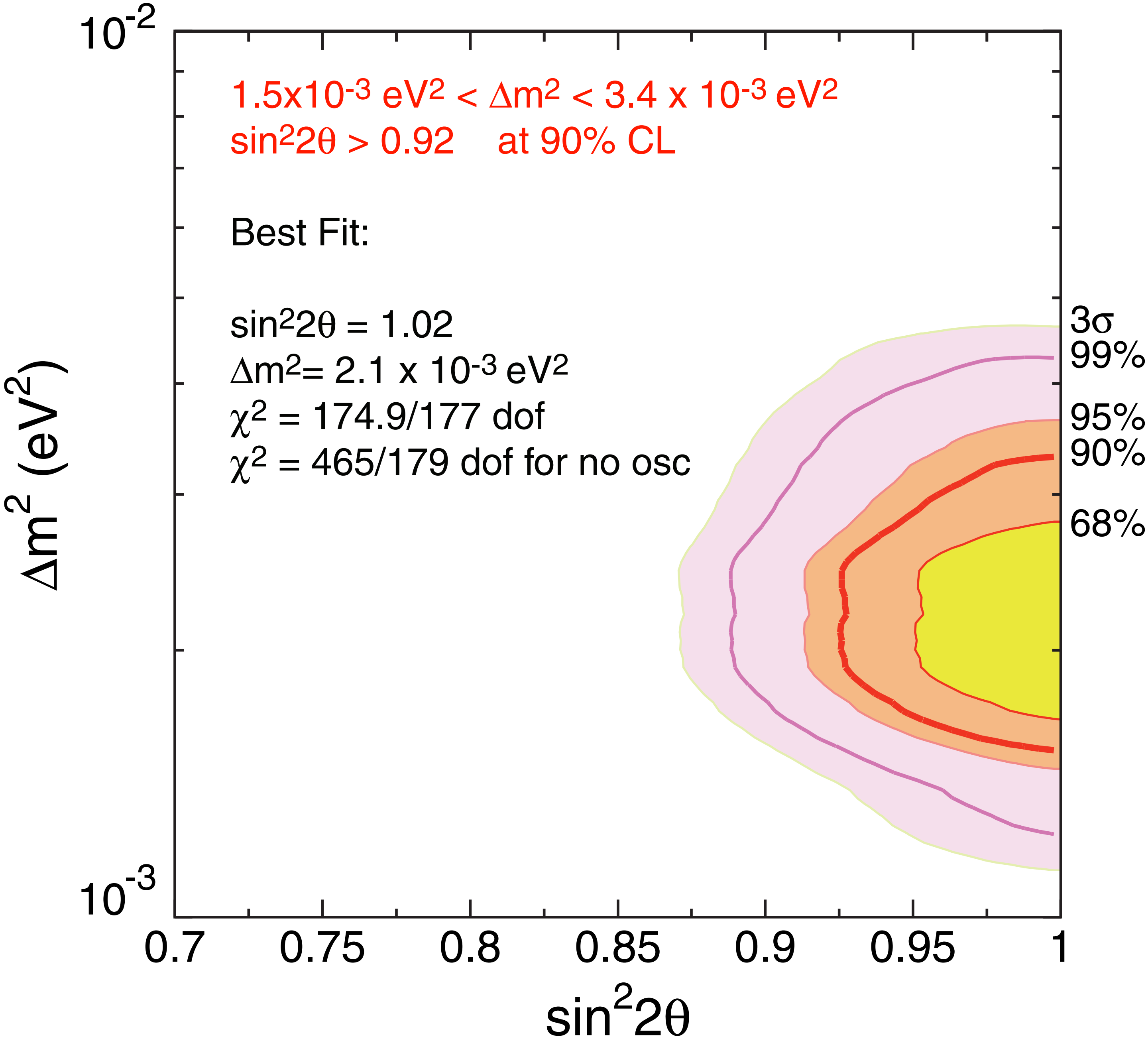
Sample normalizations over 5 decades of E_ν

Separate flux table information on parent

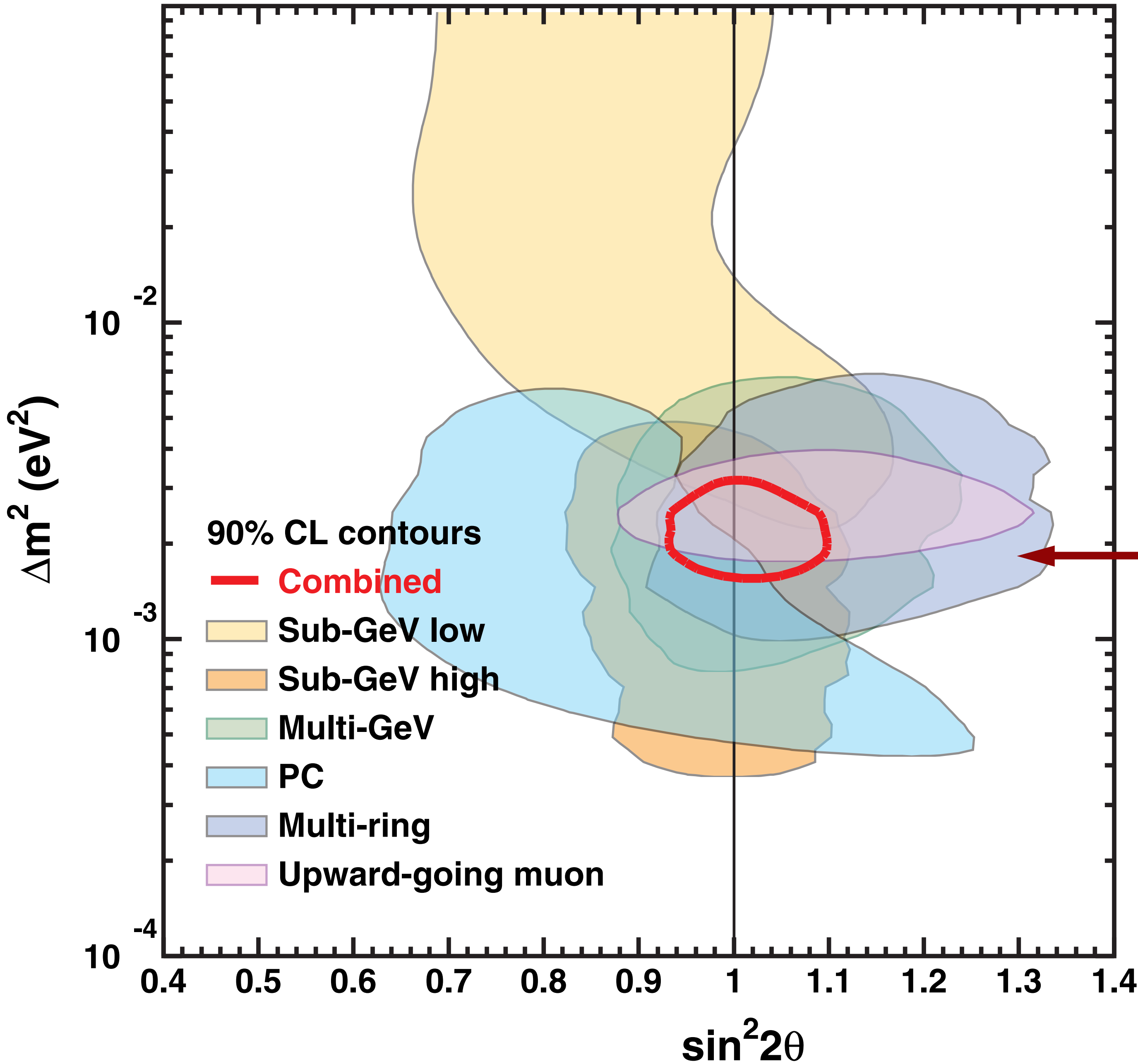
See NuInt series of workshops

largest experimental uncertainties

Best Fit and Contours for SK-I

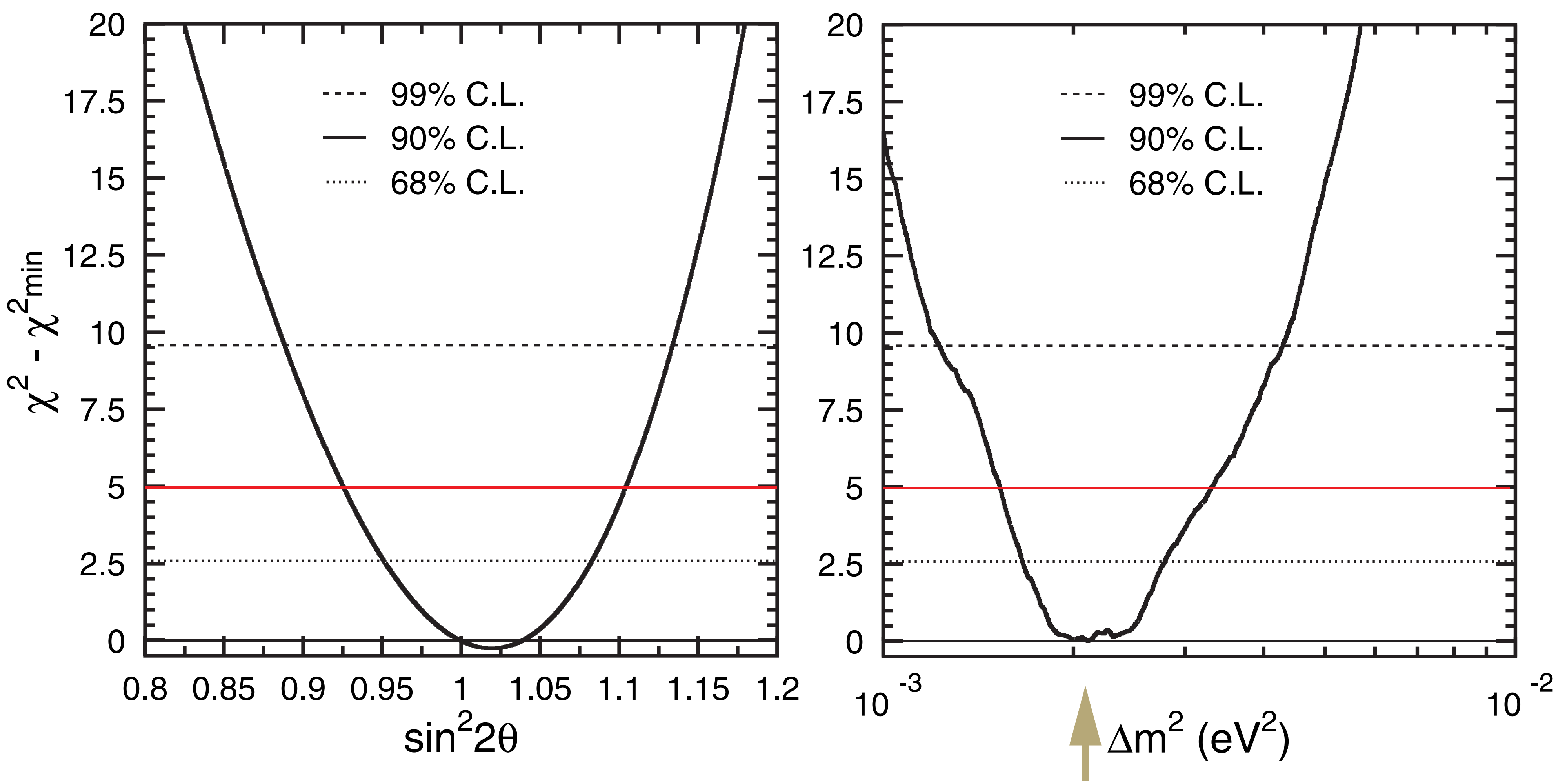


Sub-sample Contours



Upward muons provide strong constraint on minimum Δm^2

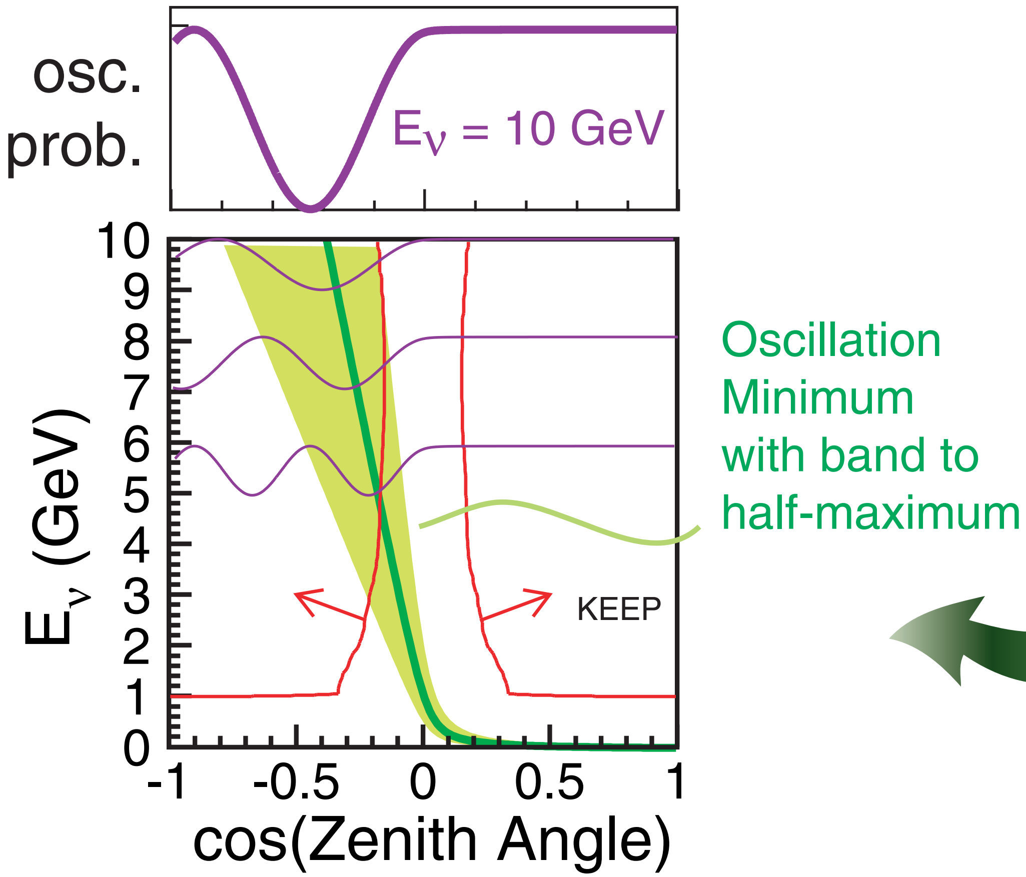
Chi-Squared Shape

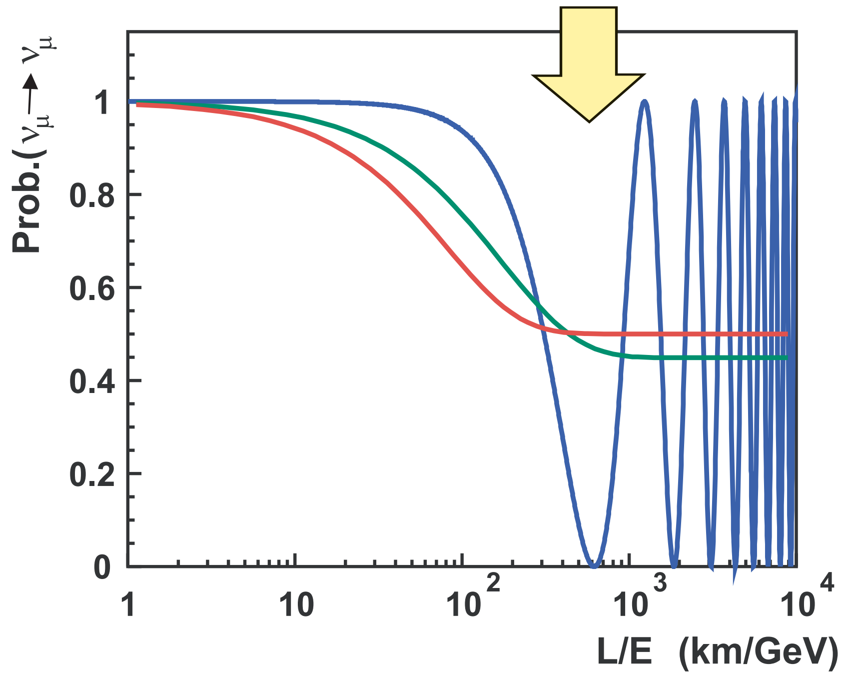


$\Delta\chi^2$ shape is rather flat and uneven between 2.0-2.5 x 10^{-3} eV^2

Separate Analysis - High Resolution L/E

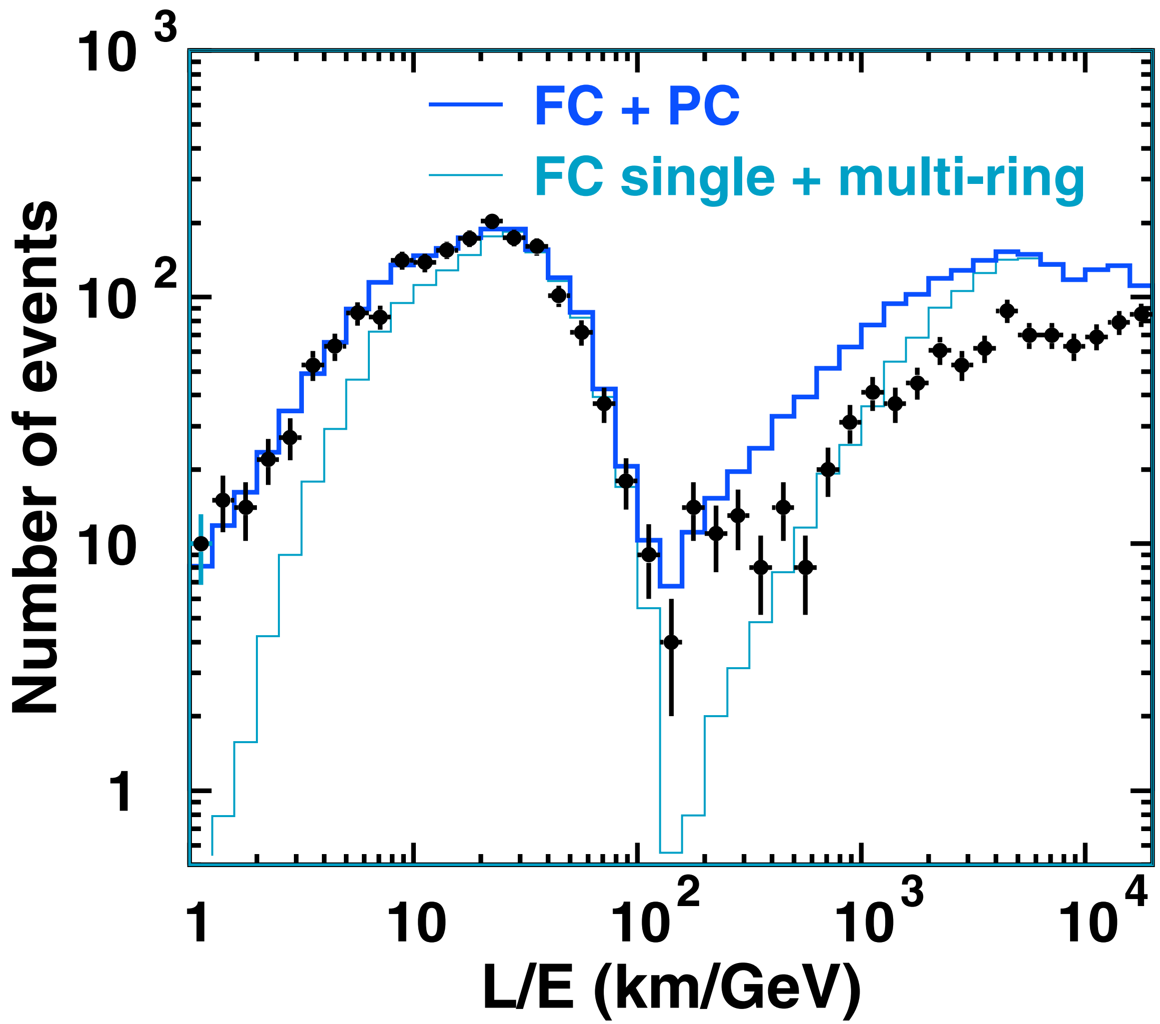
Attempt to observe oscillation pattern
Strong constraint on Δm^2
Help reject some exotic hypothesis





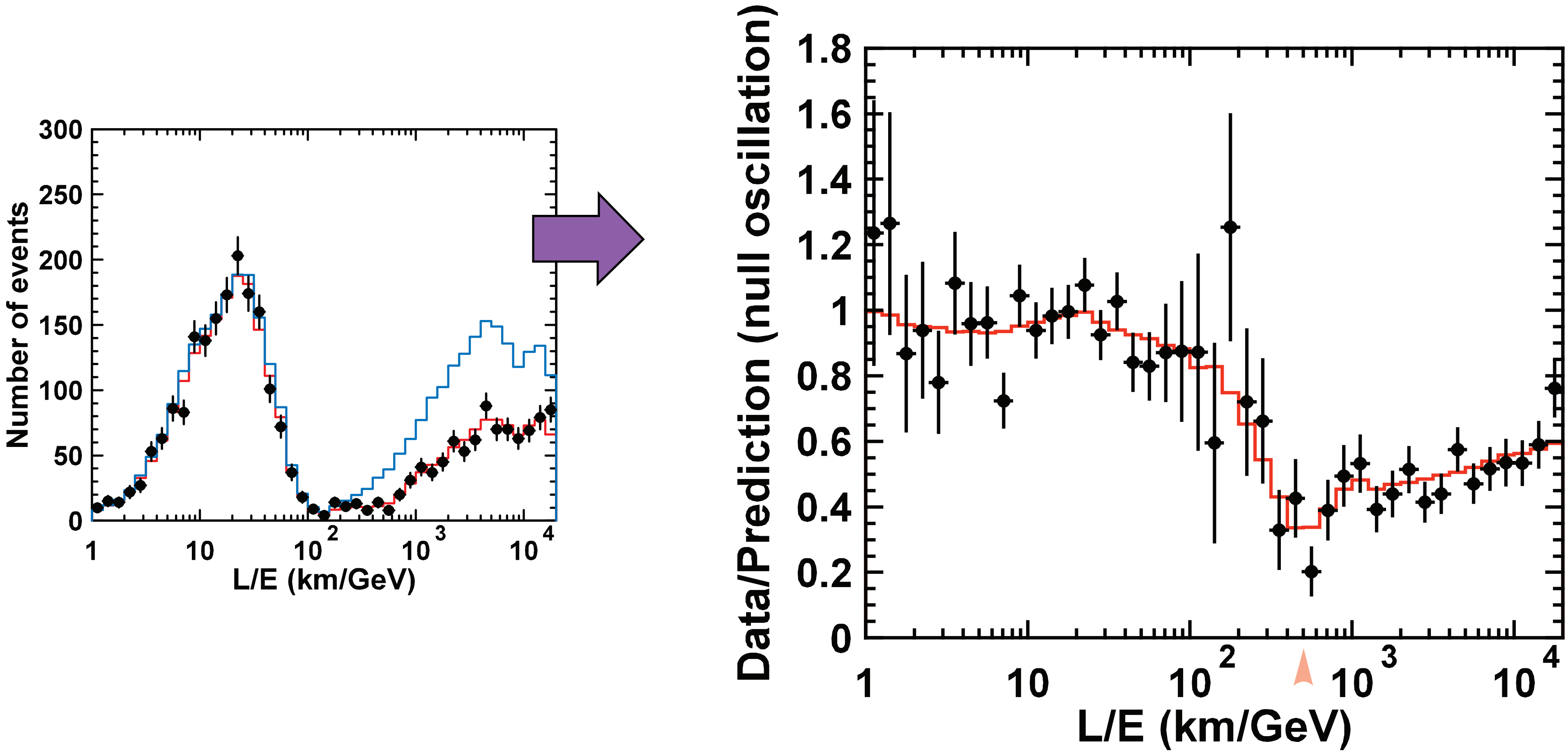
- Expand fiducial volume (26.4 kt)
  - need statistics
  - need to contain muons
- Select events with best L/E resolution
  - isolate PC muons that stop in OD
  - use FC, multi-ring, PC (stop, thru)
  - 2726 events (3725.7 expected)

L/E Event Distribution



Mostly PC through-going

L/E Distribution



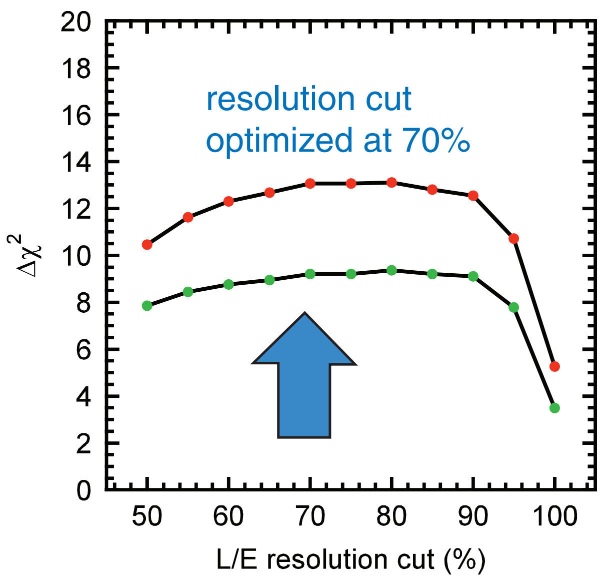
oscillation dip seen at ~500 km/GeV

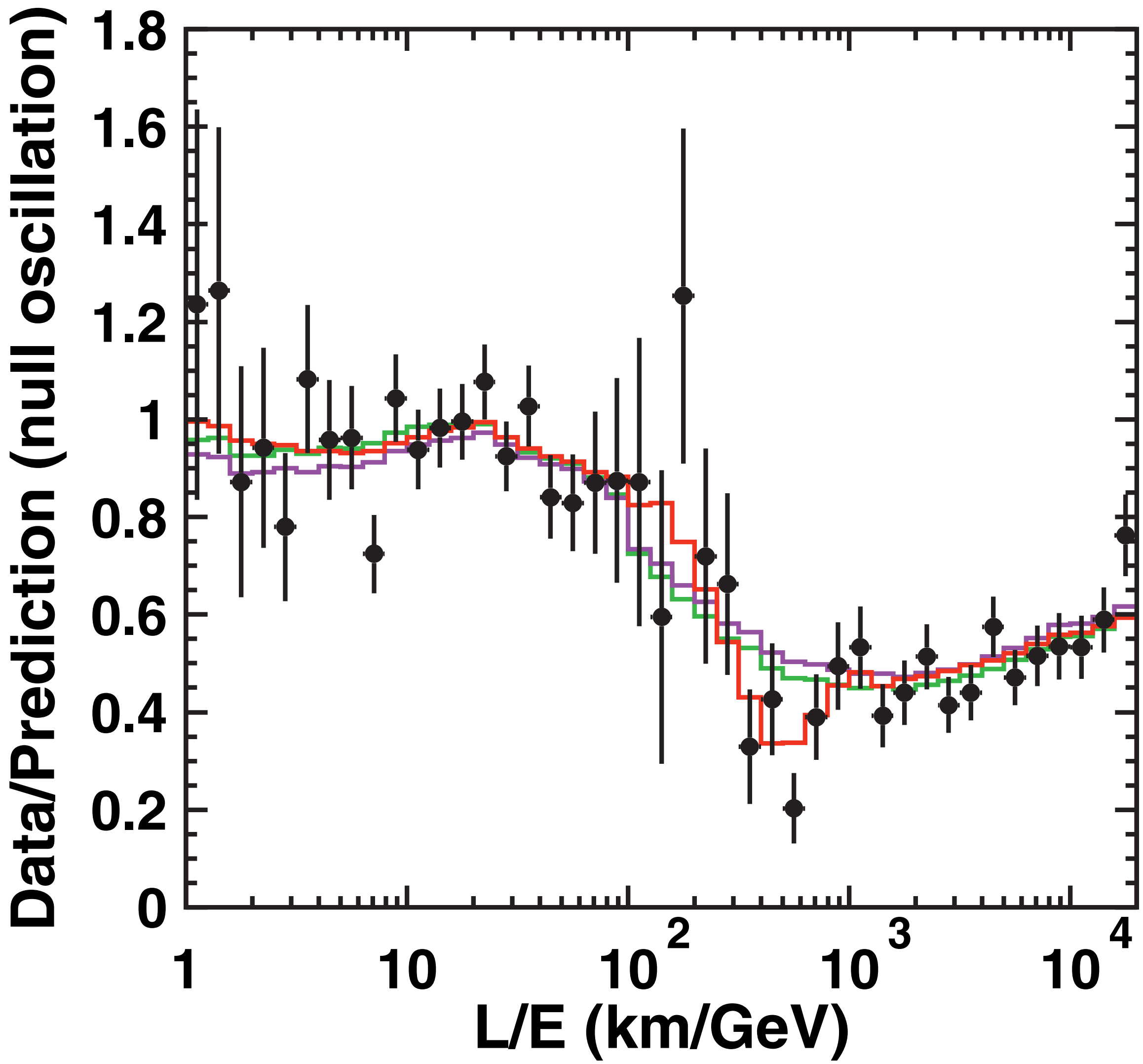
L/E Significance

To evaluate significance of oscillation signature, we need a comparison shape (no oscillations too strongly ruled out by high L/E data)

Fit against: neutrino decay
neutrino decoherence

Barger et al: PRD54 (1996) 1
Barger et al: PLB462 (1999) 462
Grossman and Worah: hep-ph/9807511
Lisi et al: PRL85 (2000) 1166

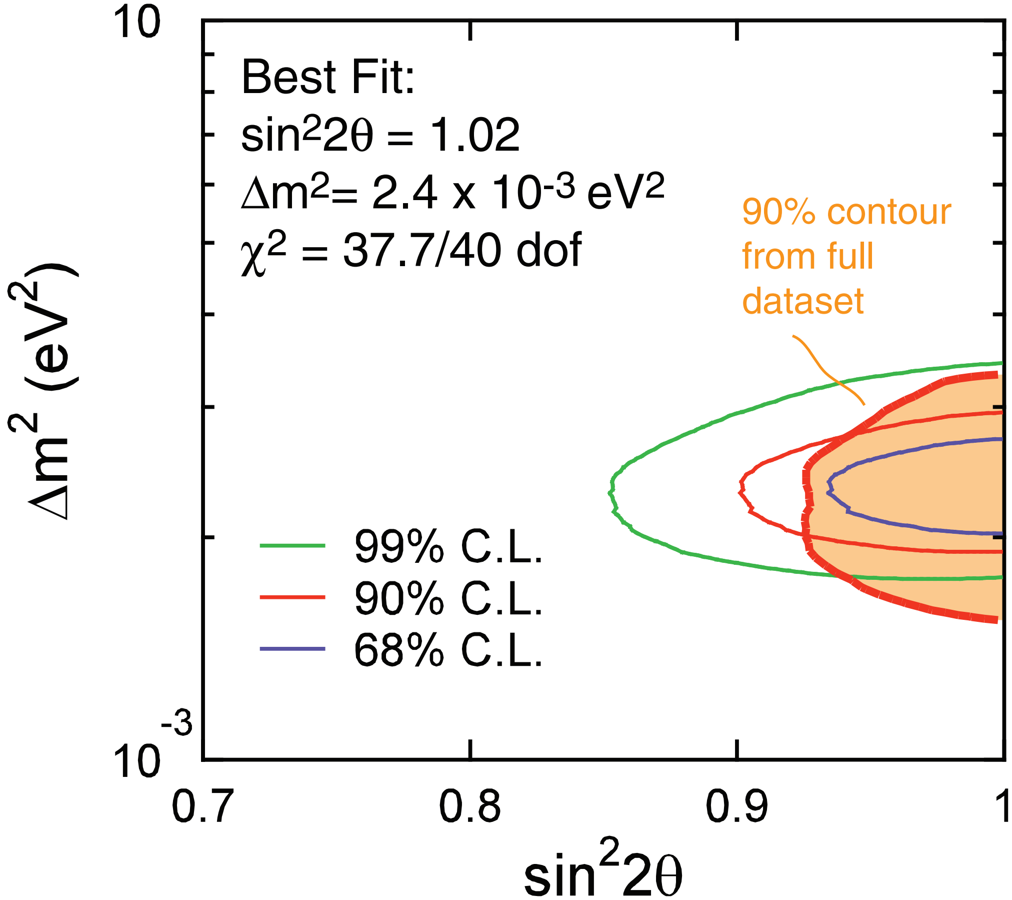


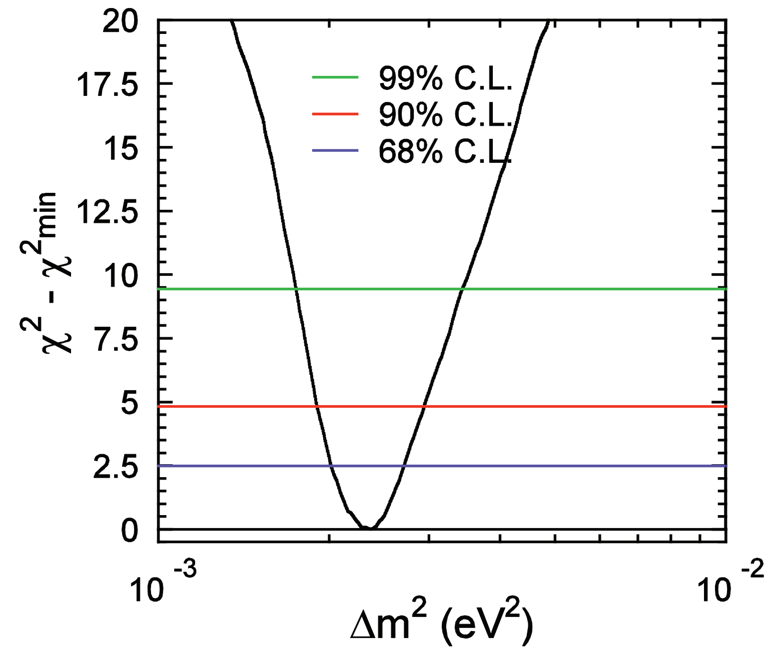


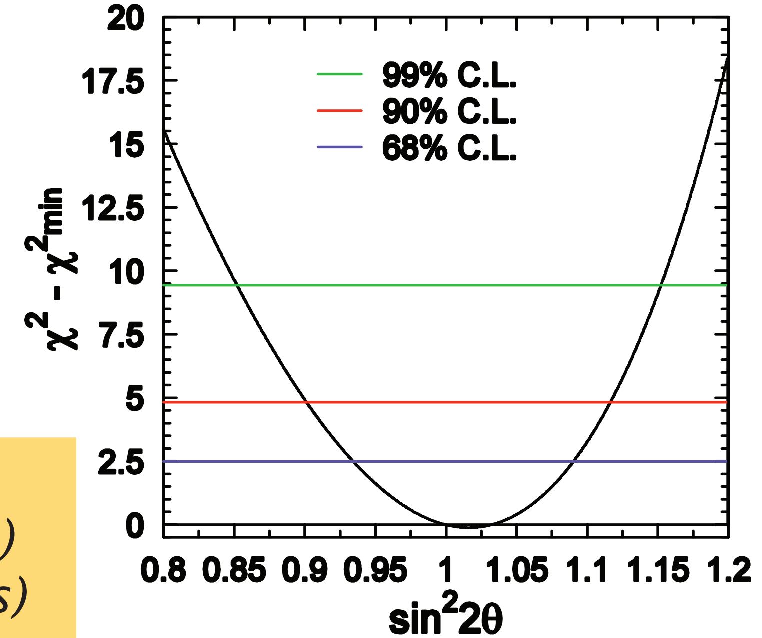
Decay rejected at 3.4σ
Decoherence rejected at 3.8σ

L/E Analysis Oscillation Fit

1.9×10^{-3} eV^2 < Δm^2 < 3.0×10^{-3} eV^2
$\sin^2 2\theta > 0.90$ at 90% CL

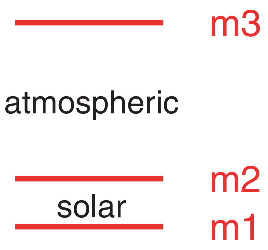






Strong constraint on minimum value of Δm2 with data sub-sample (not independent of course) no use of upward muons (cf. full dataset analysis)

Active 3-Flavor Oscillation ($\nu_e - \nu_\mu - \nu_\tau$)



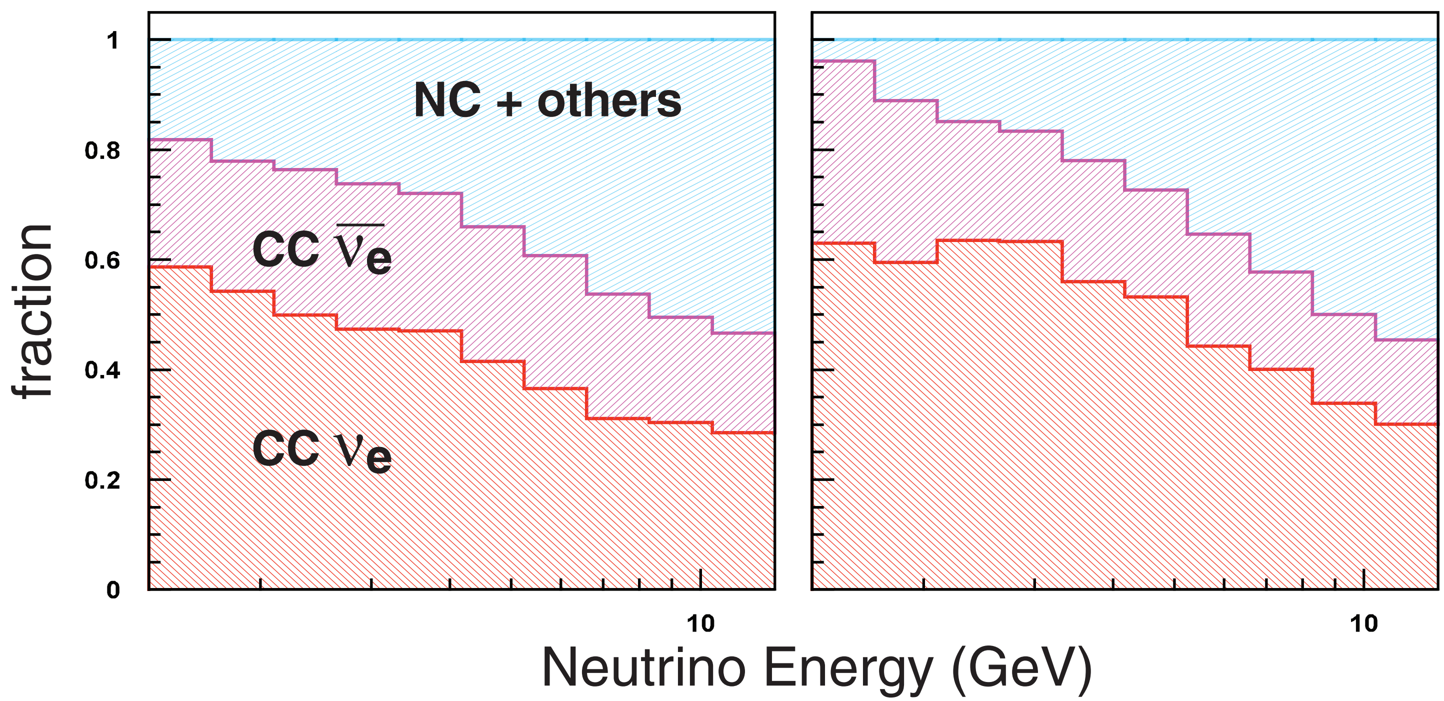
$$P_{e\mu} = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 1.27\, \Delta m^2\, L/E$$

$$P_{\mu\tau} = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 1.27\, \Delta m^2\, L/E$$

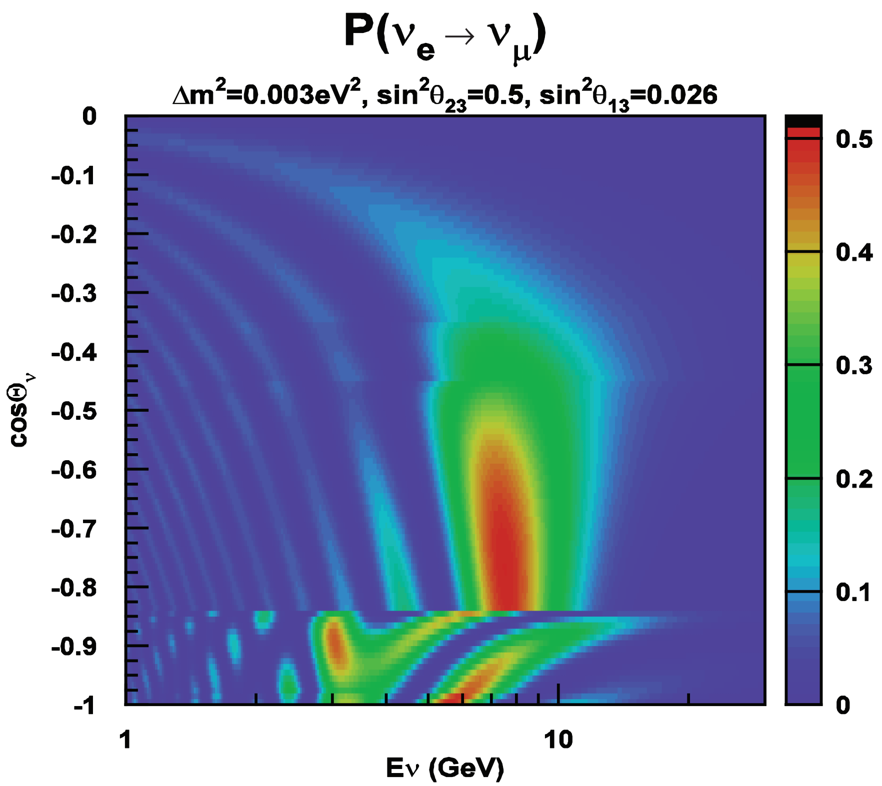
$$P_{\tau e} = \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2 1.27\, \Delta m^2\, L/E$$

only
3 parameters

Separately consider normal and inverted heirarchy: "sign" of matter resonance
Differing fraction distribution of ν_e and ν_e, different σ and $d\sigma/dy$

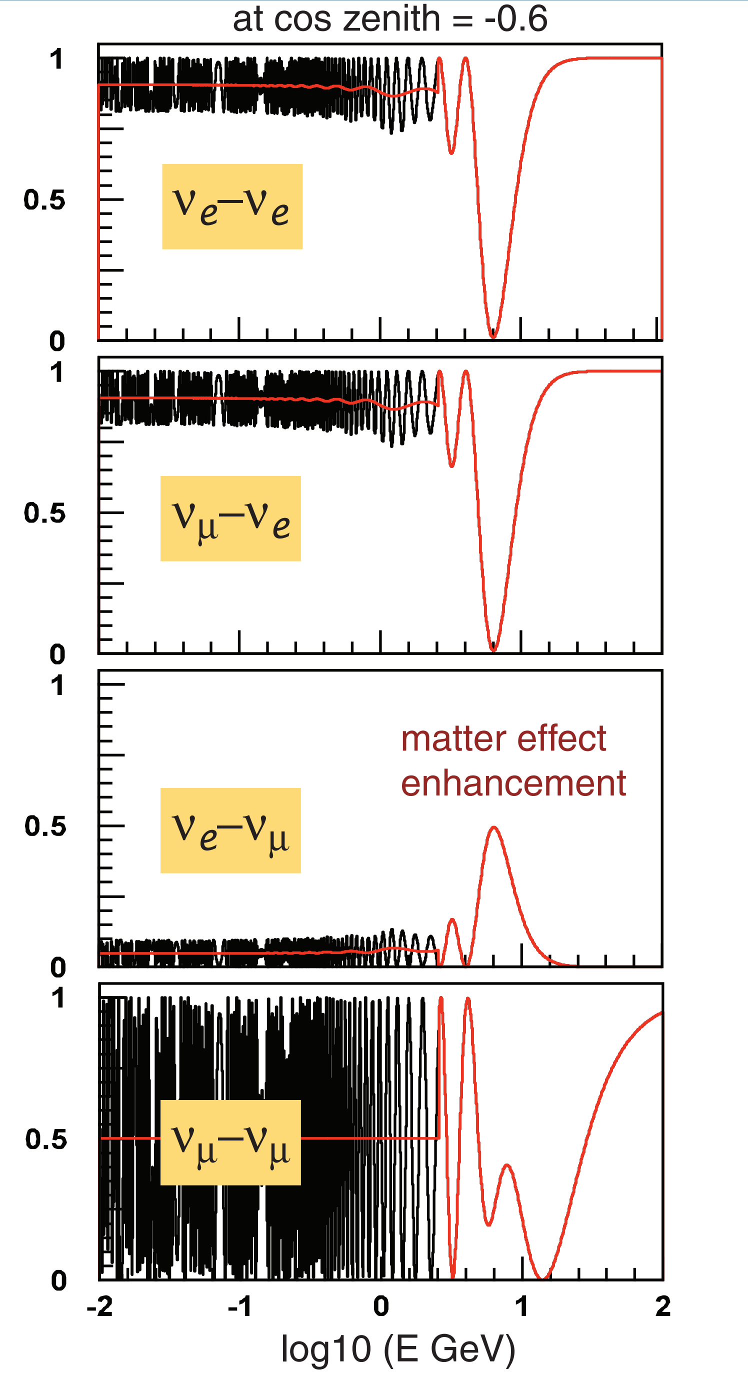


Three Flavor Analysis Strategy

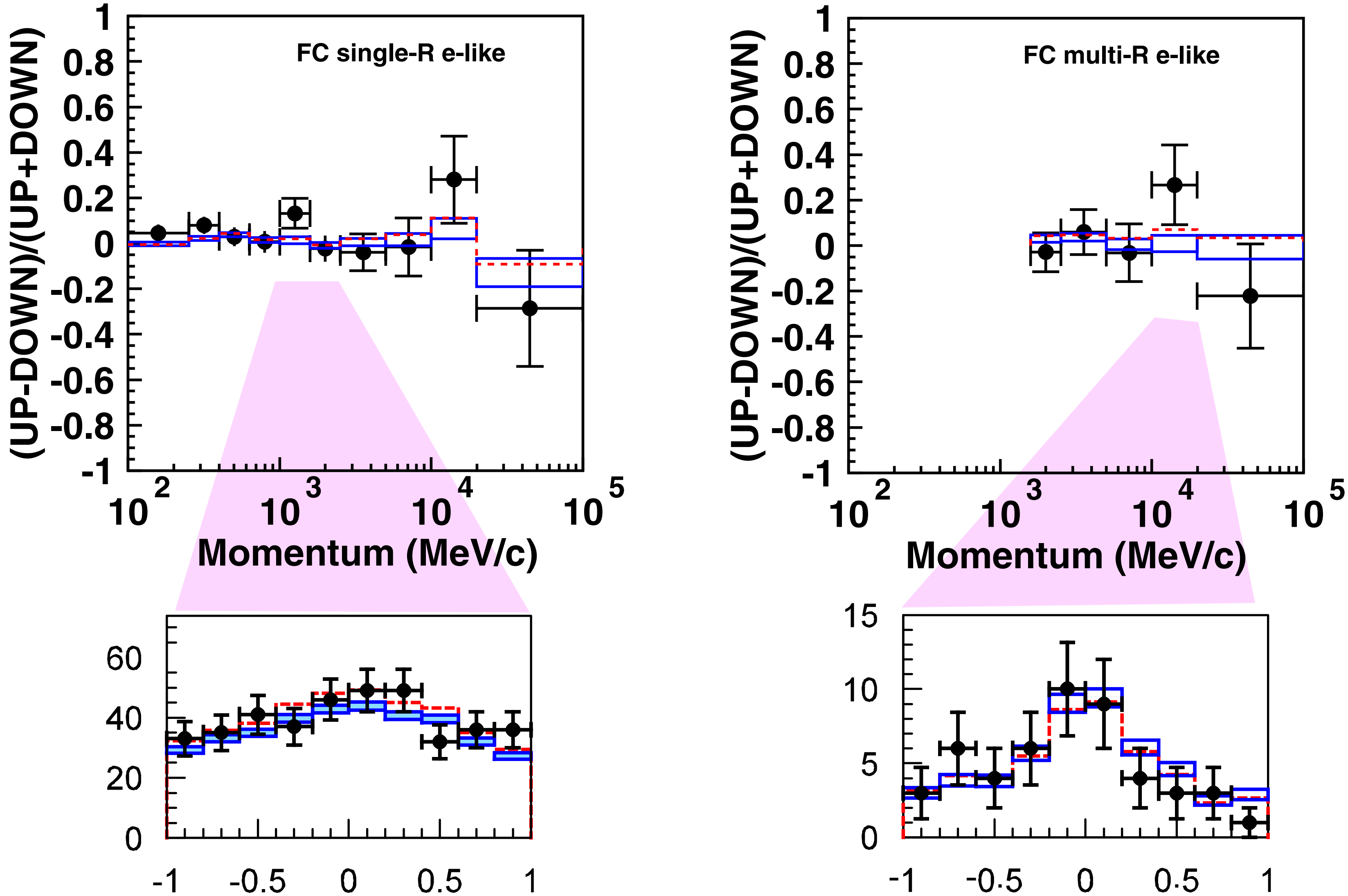


Strategy: bin data very finely and look for enhancement at certain energies and angles due to electron neutrino resonance in earth

- Add multi-ring electrons (brightest ring)
- Use PC stop/through selection
- 370 bins total including upward muons



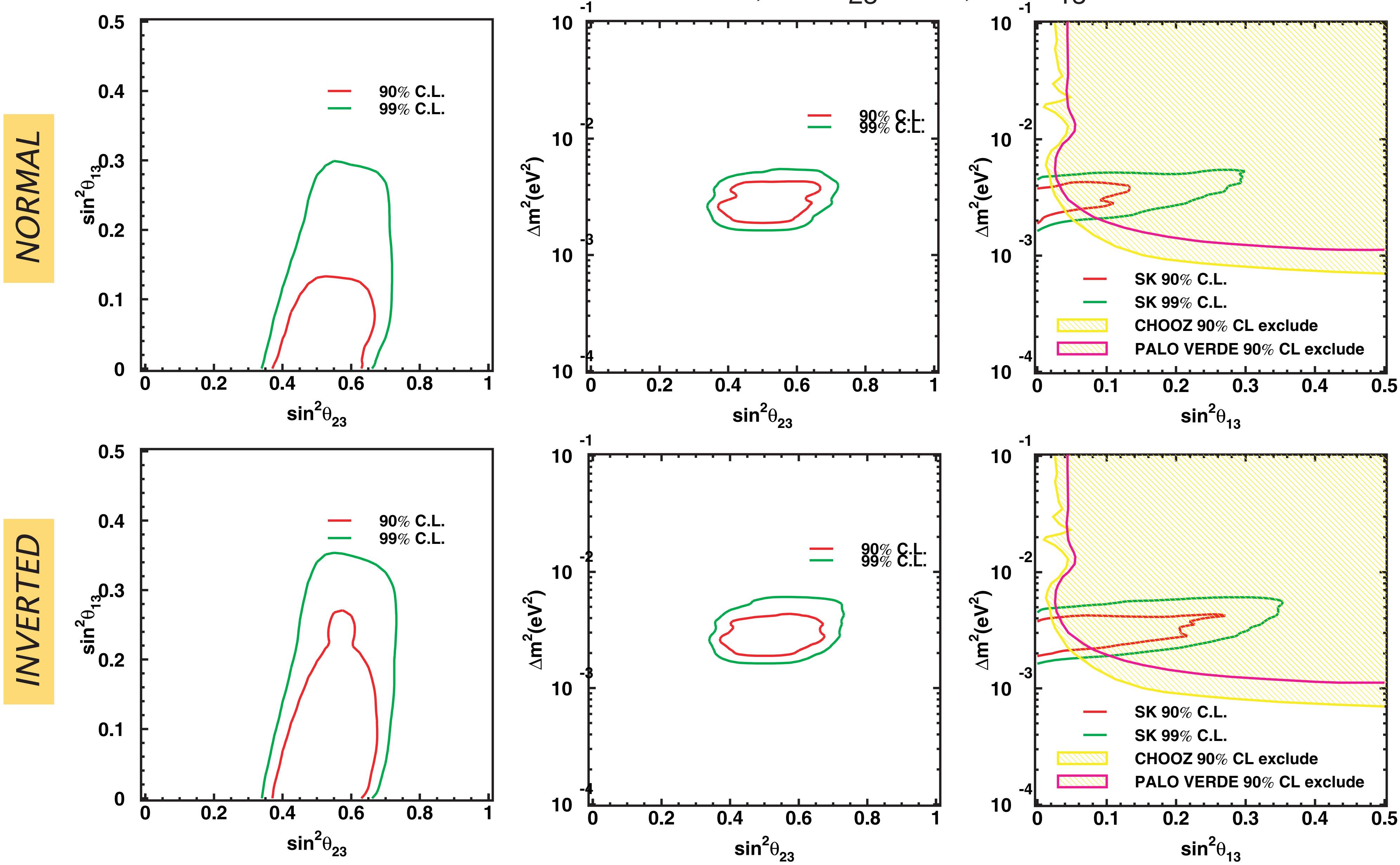
Example of e-like Data



no signs of enhancement in this or other data samples: set limit...

Confidence Intervals for 3-Flavor Analysis

Best fit: $\Delta m^2 = 2.7 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.0$



Conclusion

Preliminary look at SK-II atmospheric neutrinos: neutrino oscillation
Reduction and reconstruction in good shape for K2K analysis

Final SK-I papers in progress
Characteristics of neutrino oscillation favor $\nu_\mu - \nu_\tau$ with parameters as described by several (non-independent) analyses