Latest Super-K Atmospheric Neutrino Oscillation Analysis

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2012.09.12
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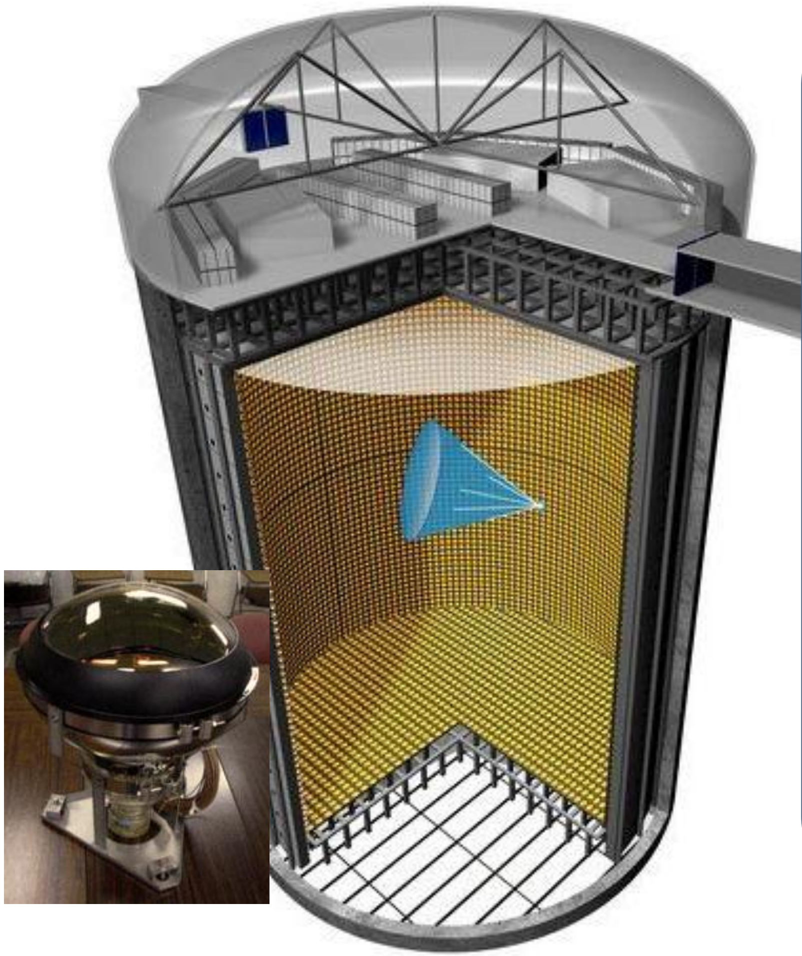
Introduction

- Atmospheric neutrinos are a good tool for studying L/E-style oscillations in a broad sense
  - They can also provide information on sub-leading effects

- Now that θ_{13} is known to be large the goals of atmospheric neutrino measurements become more focused:
  - Can we determine **Mass Hierarchy ?**
  - Can we determine the **θ_{23} octant ?**
  - Can we constrain the allowed values of δ_{cp} **?**

- Several atmospheric neutrino analyses :
  - **Three-flavor oscillation analysis** $\rightarrow$ **Today**
  - L/E Analysis
  - Two-flavor Analysis
  - Tau Appearance analysis

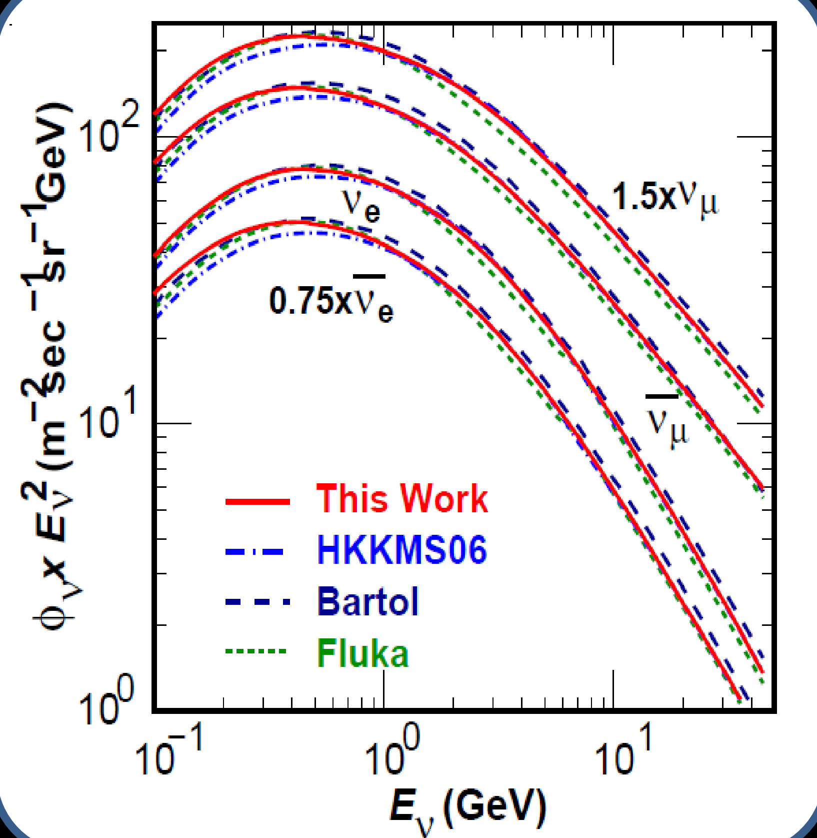
Super-Kamiokande : Introduction



- SK discovered atmospheric neutrino oscillations exploiting the disappearance of upward-going muon events
- Event samples are classified by
  - Number of rings (**Single-** or **Multiple-**)
  - PID of out-going lepton (**e-** or μ-like)
  - Event energy is **fully** or **partially** contained
  - Upward-going muons
- Today: **3903 days of data**
  - ~34,000 Events
- Currently **statistics limited**

- 22.5 kton FV Volume
- Ring Imaging Water Cherenkov detector
- 11,1146 20" Phototubes
- Data taken over four periods since 1996

Atmospheric Neutrino Generation

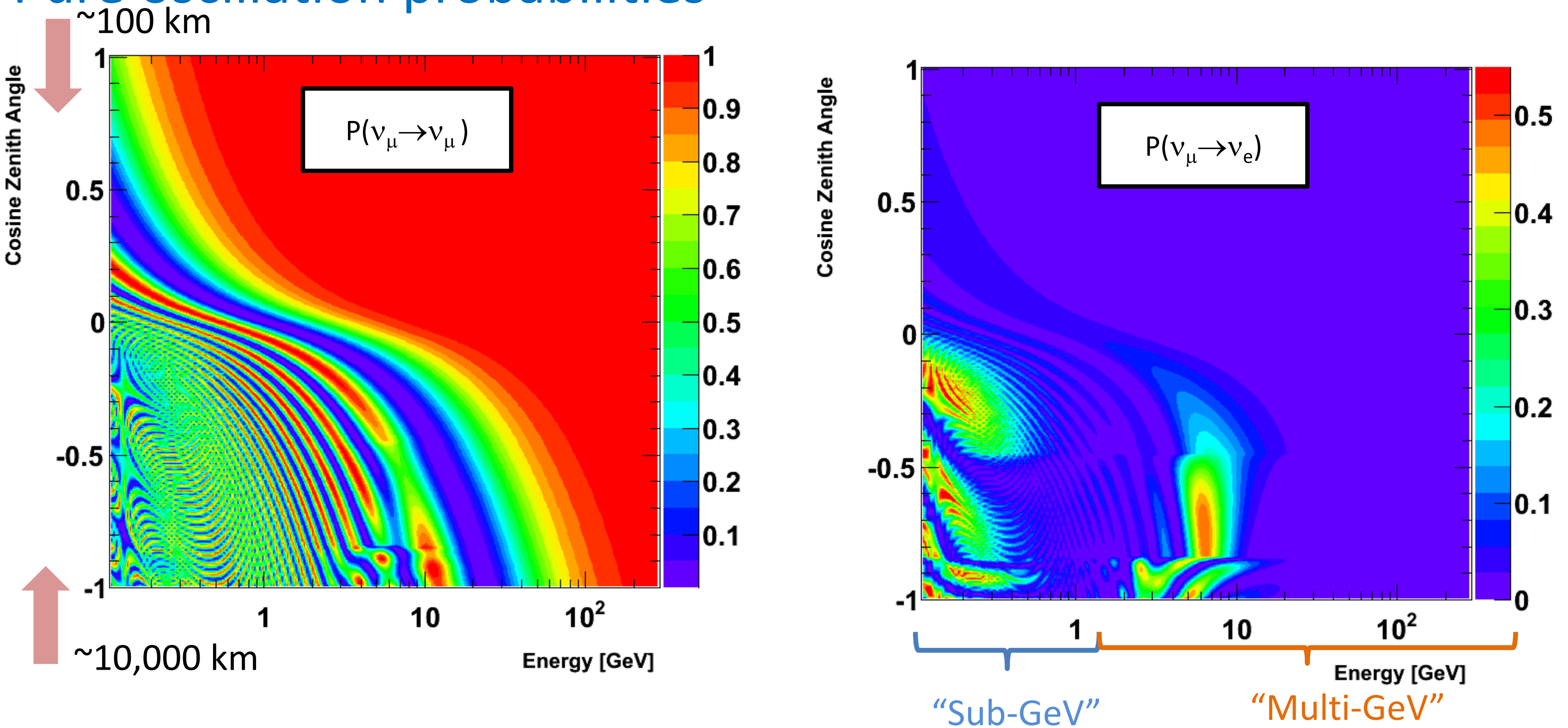


- Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos

$$P + A \rightarrow N + \pi^+ + x$$
$$\hookrightarrow \mu^+ + \boxed{\nu_\mu} \rightarrow e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu}$$

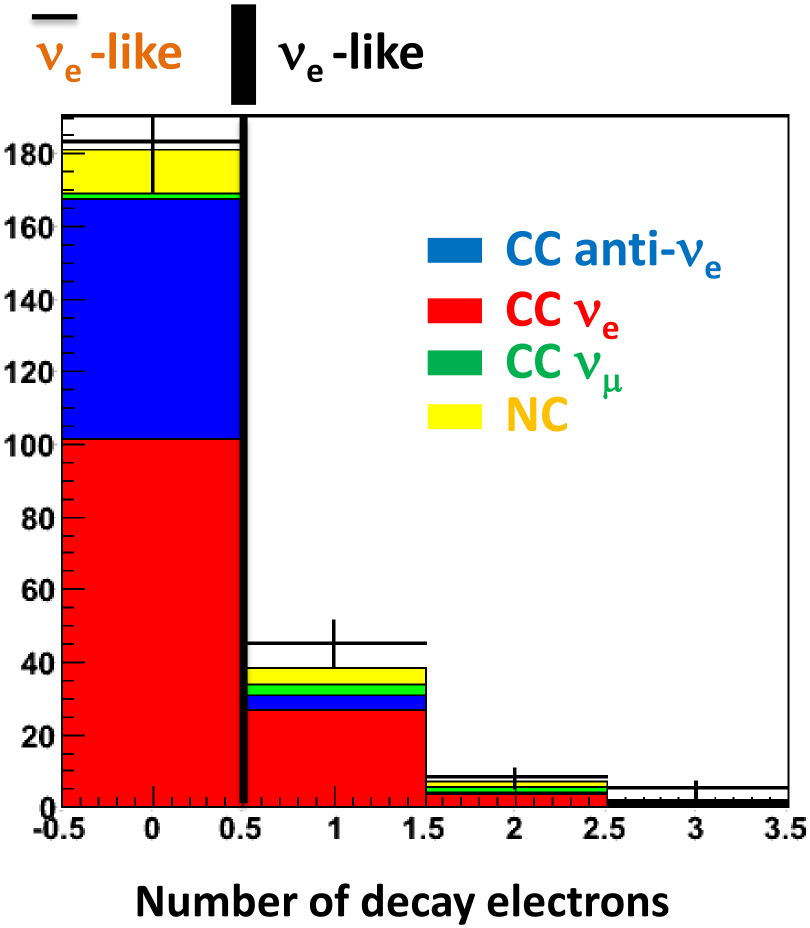
- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km
- Both neutrinos and antineutrinos
  - about 30% of the final samples are antineutrinos
- Spans many decades in energy ~100 MeV – 100TeV$^+$
- Excellent tool for broad studies of neutrino oscillations
  - Access to sub-leading effects with high statistics

Pure oscillation probabilities



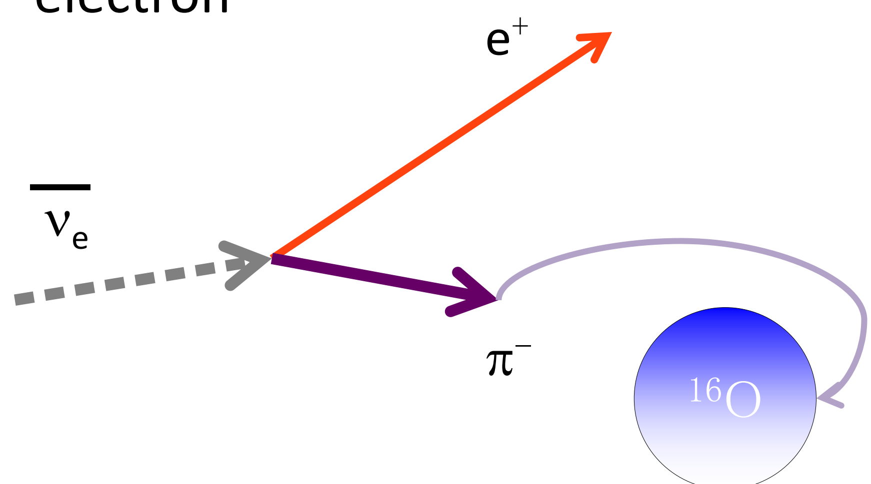
- With large θ_{13} resonant enhancement of the $P(\nu_\mu \rightarrow \nu_e)$ probability occurs in matter
- Resonance occurs only for (anti-)neutrinos under the Normal (Inverted) Hierarchy
  - Size of resonance is a function of θ_{23} octant, θ_{13} , and δ_{cp}
  - "Signal" present in both μ-like and e-like samples
  - Ideally we would like **separate neutrino and antineutrino** samples

Sample Selection : Multi-GeV Single-Ring anti-ν_e and ν_e -like



- Separate neutrinos from anti-neutrinos in the single-ring sample using the number of observed decay electrons

- The outgoing π^- from an anti-neutrino CC-1 π event can be absorbed on a ^{16}O nuclei before it decays. The lack of an outgoing muon means there is no possibility of a subsequent Michel (decay) electron



(Multi-ring events are in general more complicated separation is done using a likelihood)

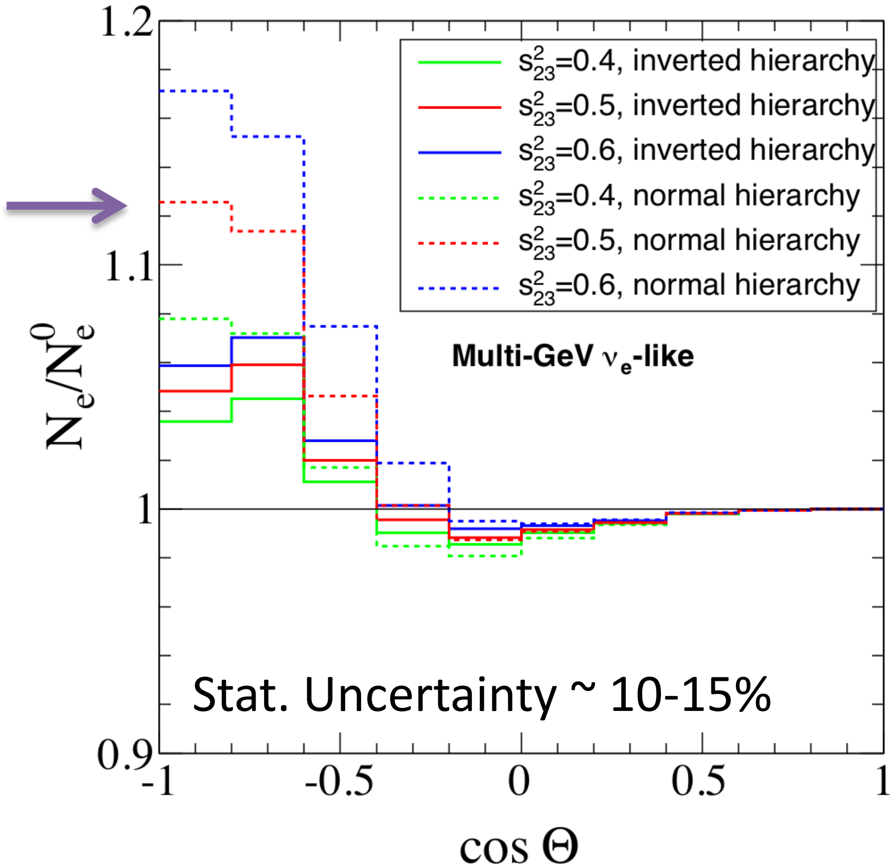
Sample Composition

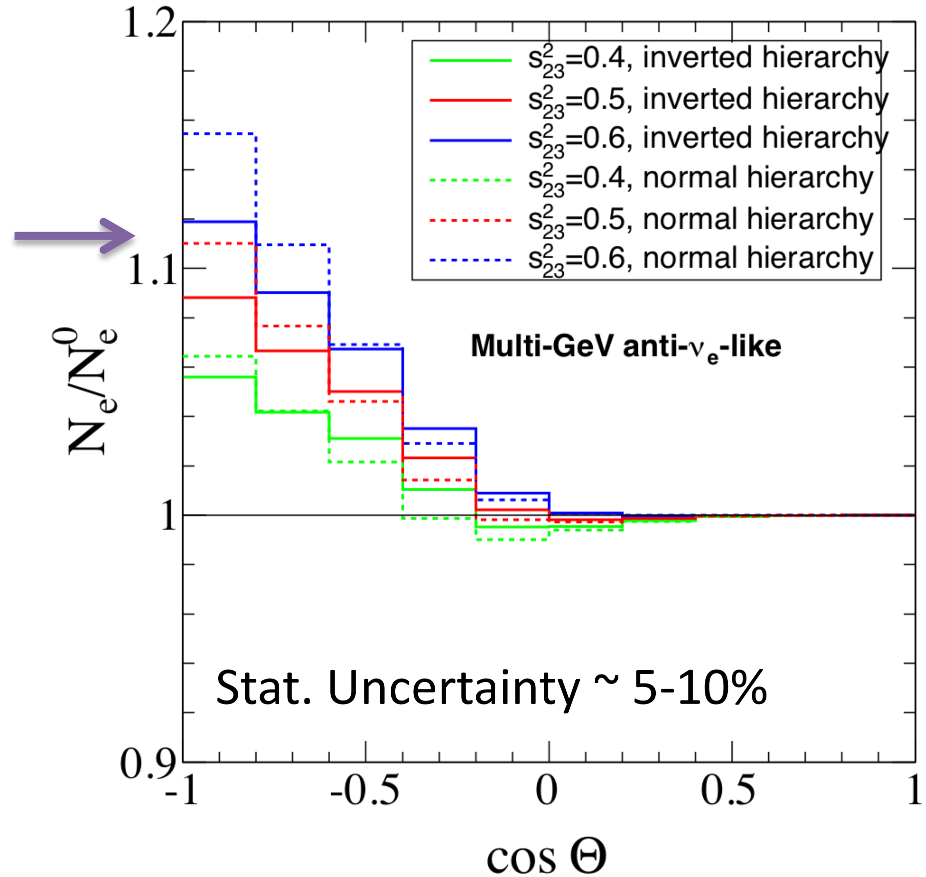
Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_μ like	1R	0.2	0.08	98.8	0.2
	MR	2.5	0.3	91.7	4.4

- Generally the background component of the e-like signal samples is **~20-30%**
- Muon-like samples on the other hand tend have high-purity and reasonable sensitivity to small effects

Expected Effects : Single-Ring e-like and anti-e-like samples

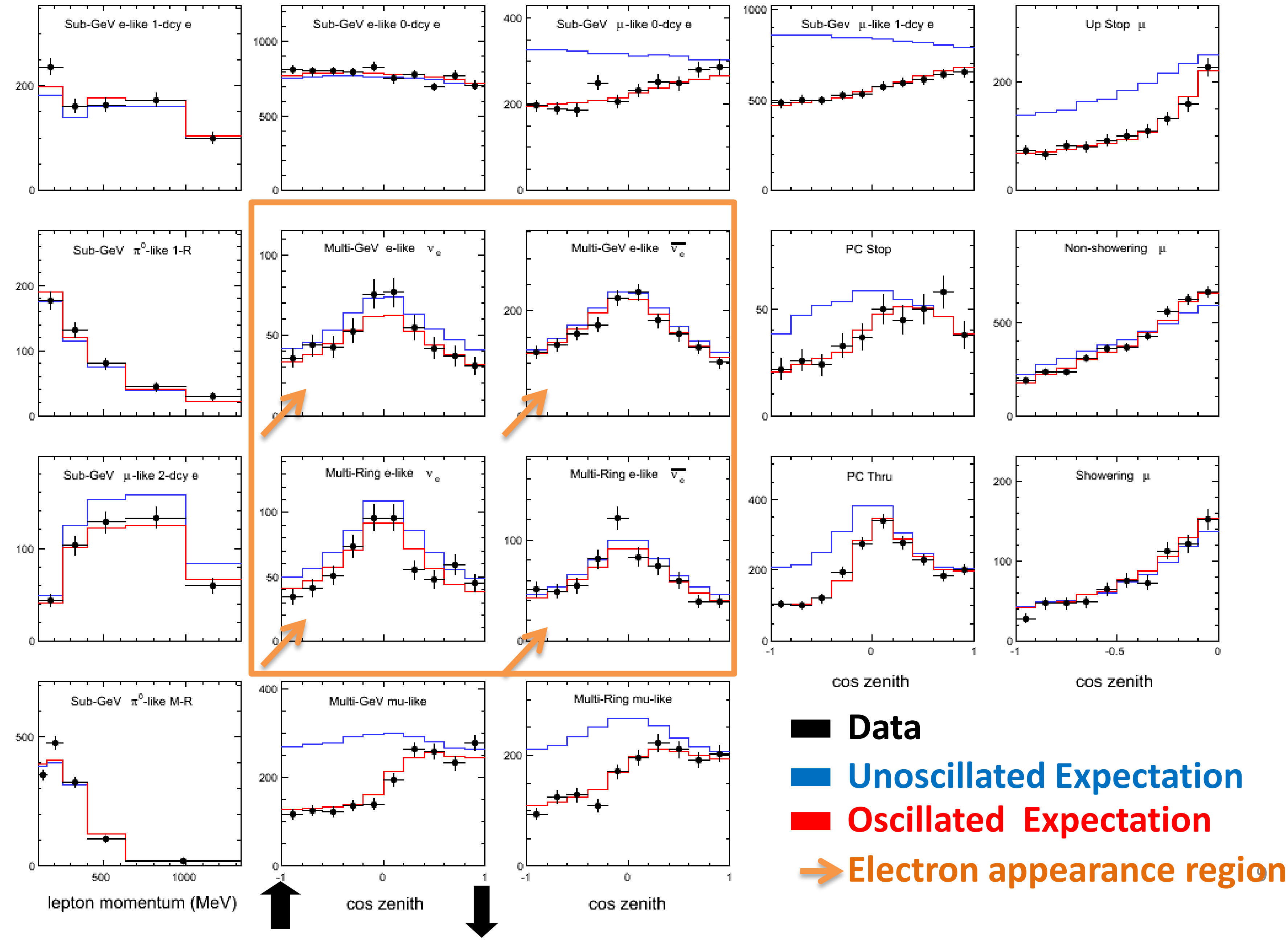




→ Equivalent MC

- Effect of the θ_{23} octant can be large.
- That from δ_{cp} is an additional $\pm$2% on each line
- Statistical uncertainty remains cumbersome

Super-K I+II+III+IV Data – Make Use of All Potential Signals



About Systematics

- Super-K analysis considers 151 sources of systematic uncertainty from the usual cadre of errors
  - Flux, cross-section, detector performance

- This is a partial listing of things relevant to three-flavor issues

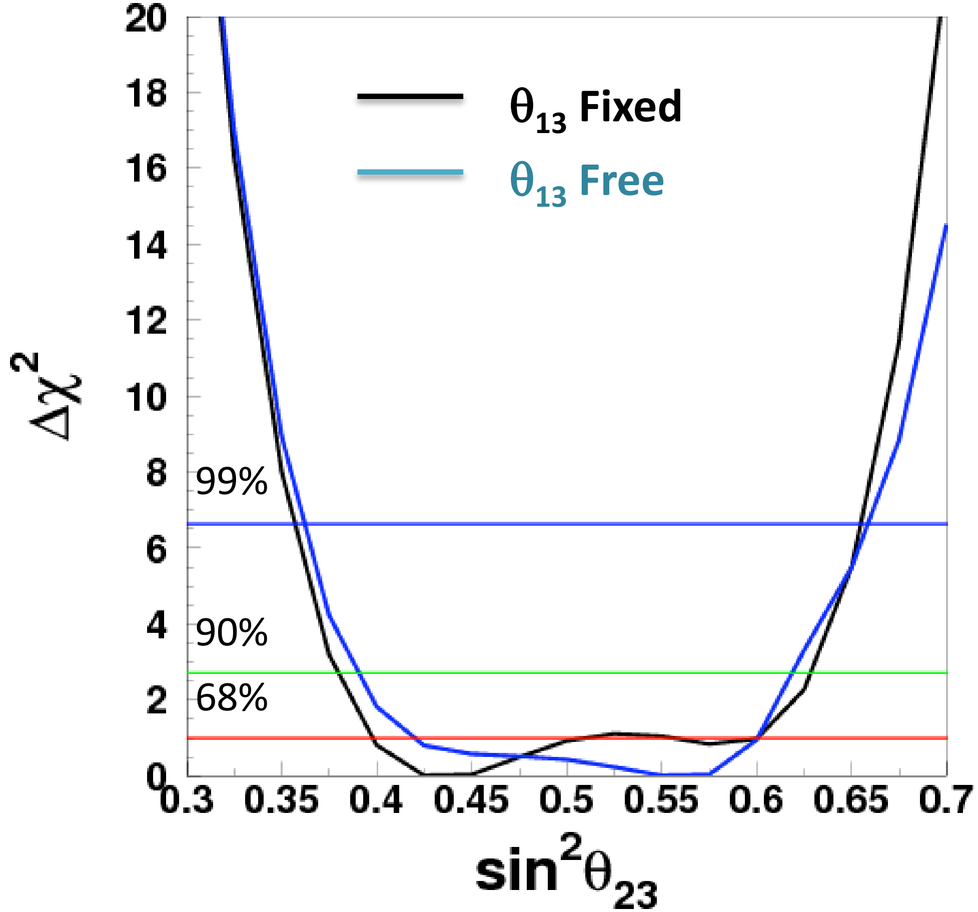
Error Source	Uncertainty
ν_e vs. anti-ν_e sample selection	7%
Charged-Neutral Pion Production	40%
Tau Production Cross section	25%
DIS Cross Section	5-10%
NC / CC Ratio	20%
Single-Pion Production	20%
Flux Normalization above 1 GeV	7%
Flux Ratio ν to ν bar above 1 GeV	5-8%

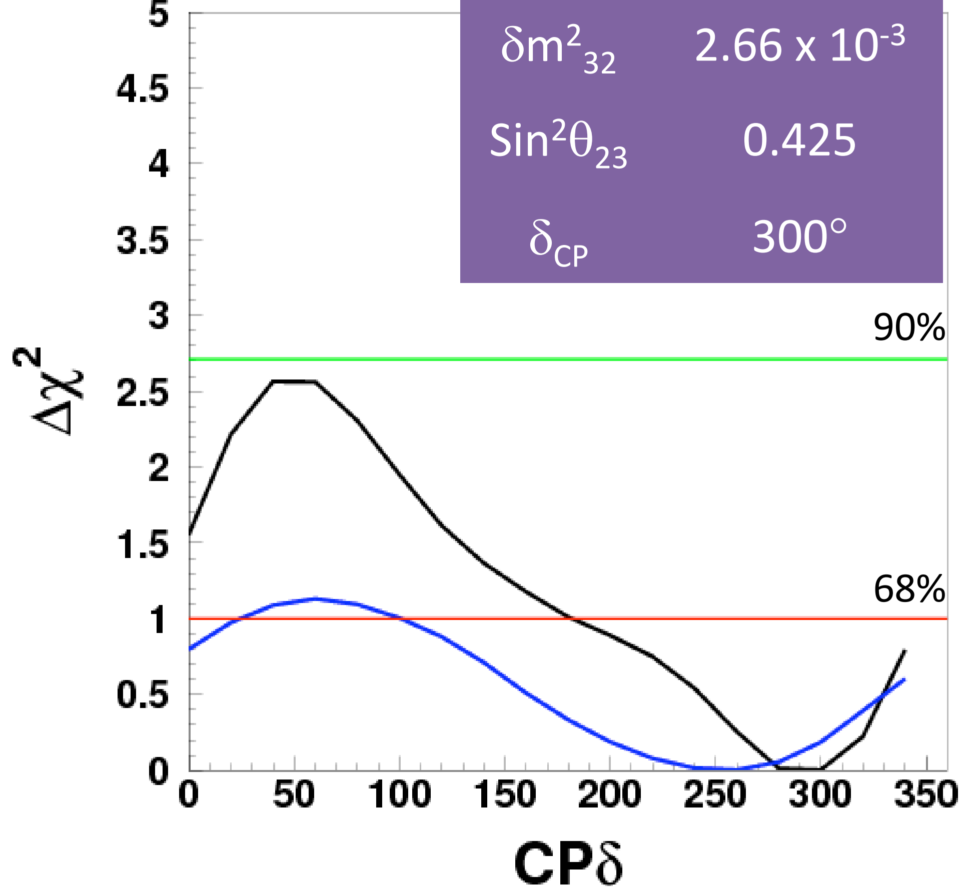
Tau events look similar to e-like events and they are upward-going

Results

+ Simultaneous fitting performed on Δm^2_{32}, θ_{23}, δ_{cp} , θ_{13}
+ Both hierarchies considered
+ Two Analyses : θ_{13} Free / Fixed to reactor value

Normal Hierarchy Results



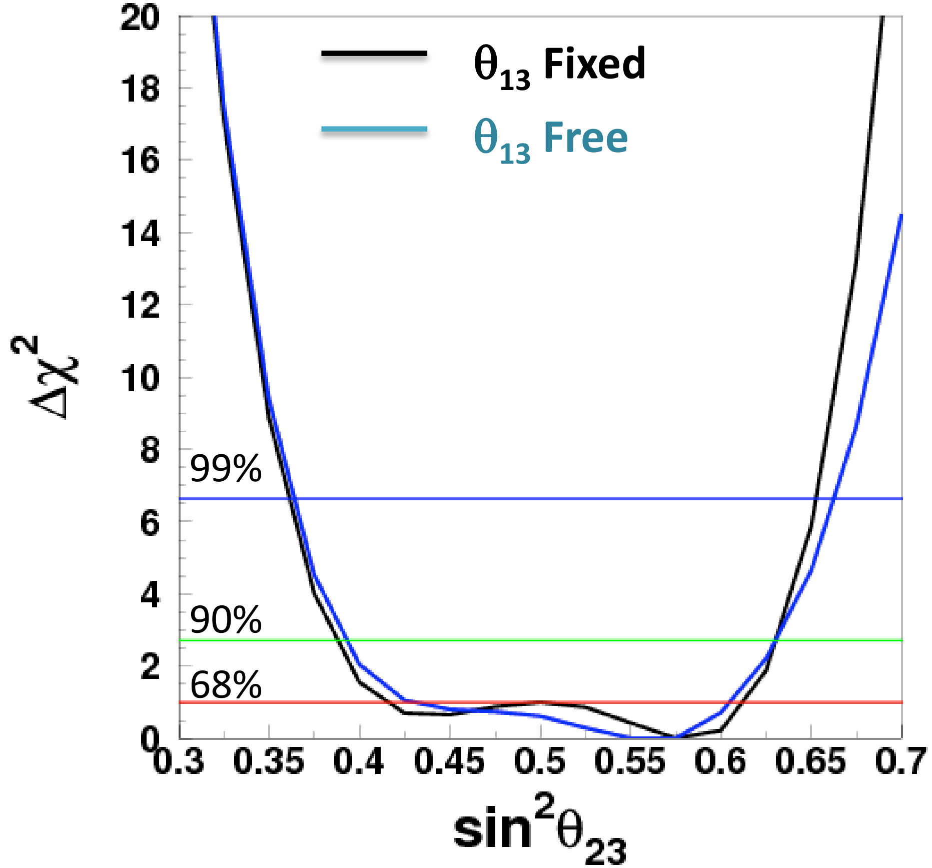


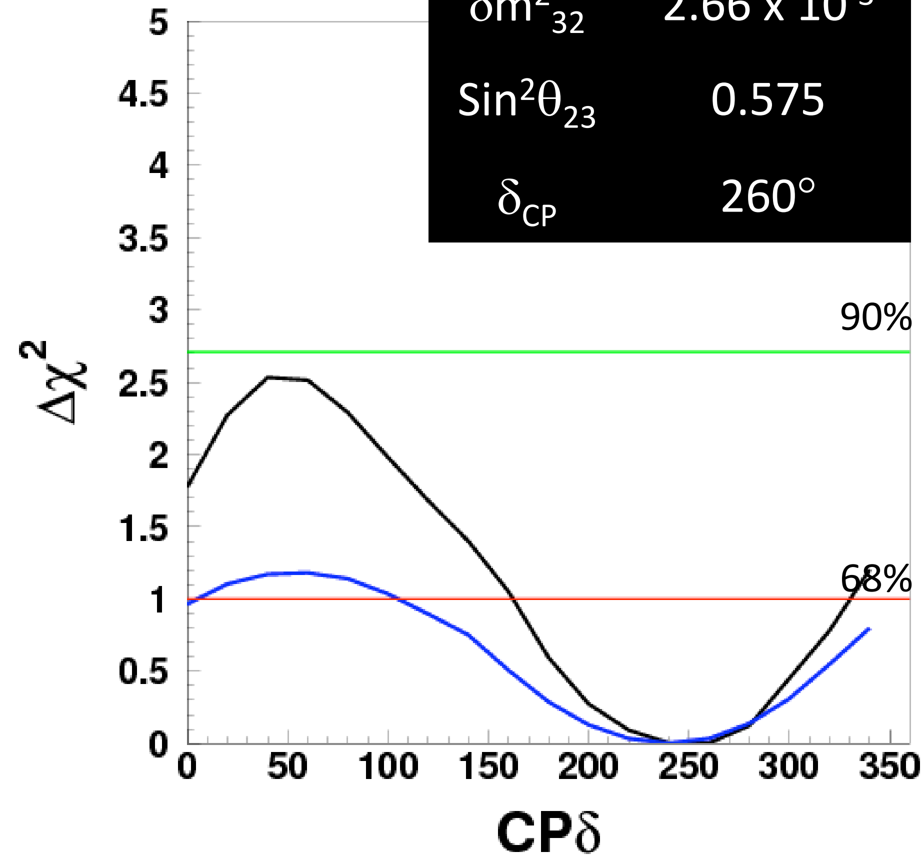
NH	Best -Fixed
δm^2_{32}	2.66×10^{-3}
$\sin^2\theta_{23}$	0.425
δ_{CP}	300°

- Fixing the value of θ_{13} to the reactor experiments value moves the preferred octant from the second to the first (only a very weak preference)
- Weak constraint on δ_{cp} , all values allowed at 90% C.L. in both fits

Inverted Hierarchy Results

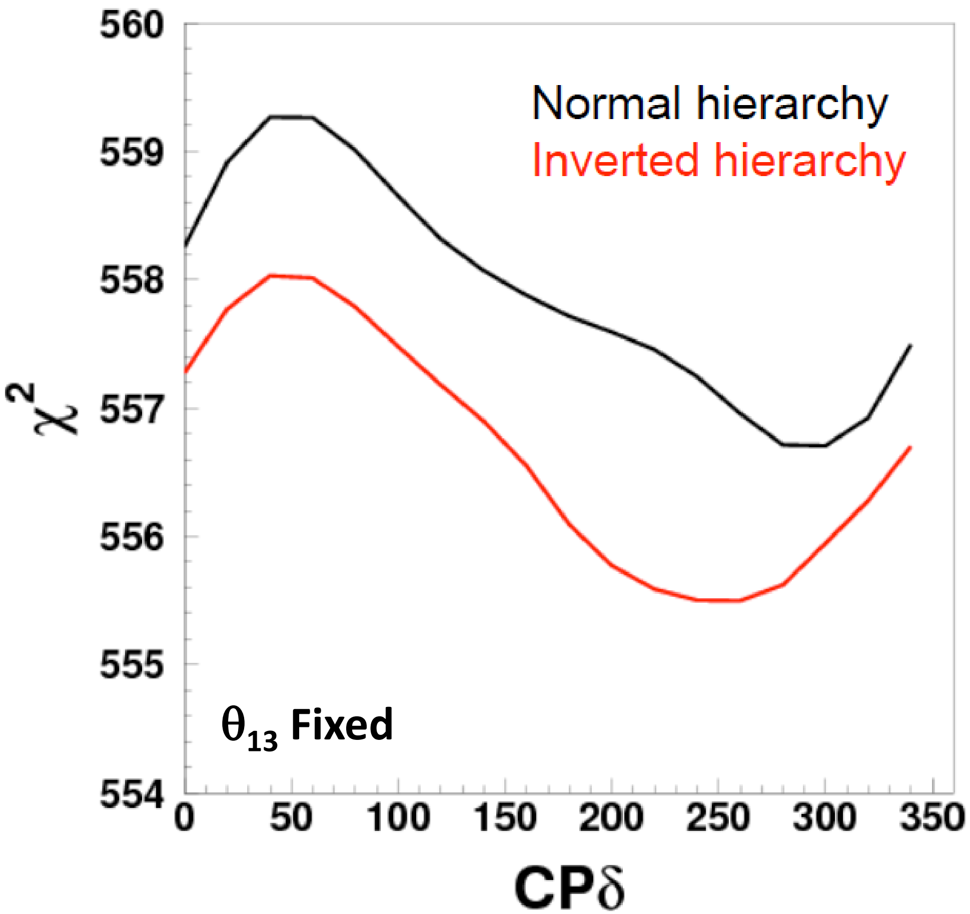
IH	Best -Fixed
δm^2_{32}	2.66×10^{-3}
$\mathrm{Sin}^2\theta_{23}$	0.575
δ_{CP}	260°





- ☐ Both fits find minima in the 2nd octant
- ☐ Weak constraint on δ_{cp} , all values allowed at 90% C.L. in both fits

Hierarchy Comparison

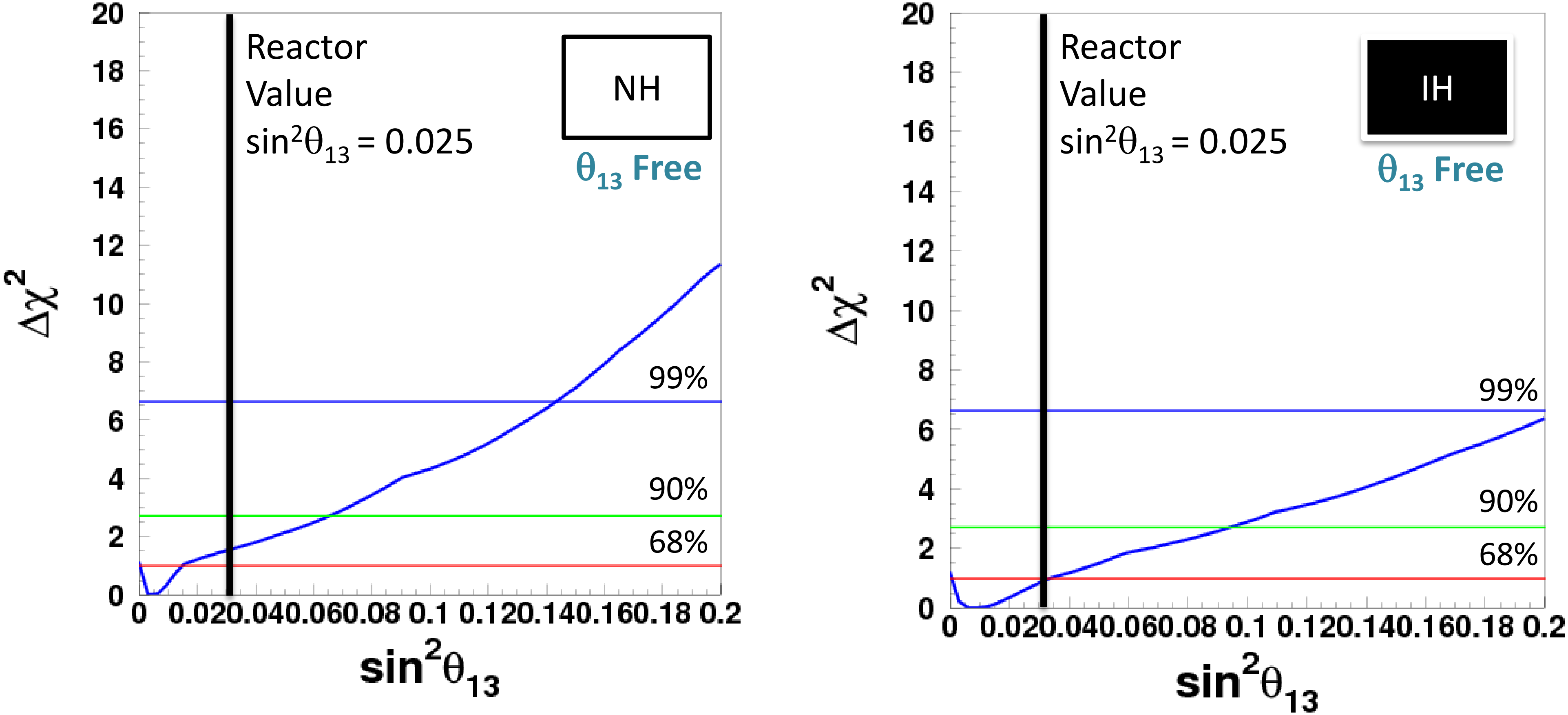


Hierarchy	Fit Result
Normal	556.7 / 477 dof
Inverted	555.5 / 477 dof

$$\chi^2_{min}\,(NH) - \chi^2_{min}\,(IH) = 1.2$$

- Expected sensitivity to the inverted hierarchy is $\Delta\chi^2 = 0.9$
- Data show a 1σ prefence for the inverted hierarchy, not significant

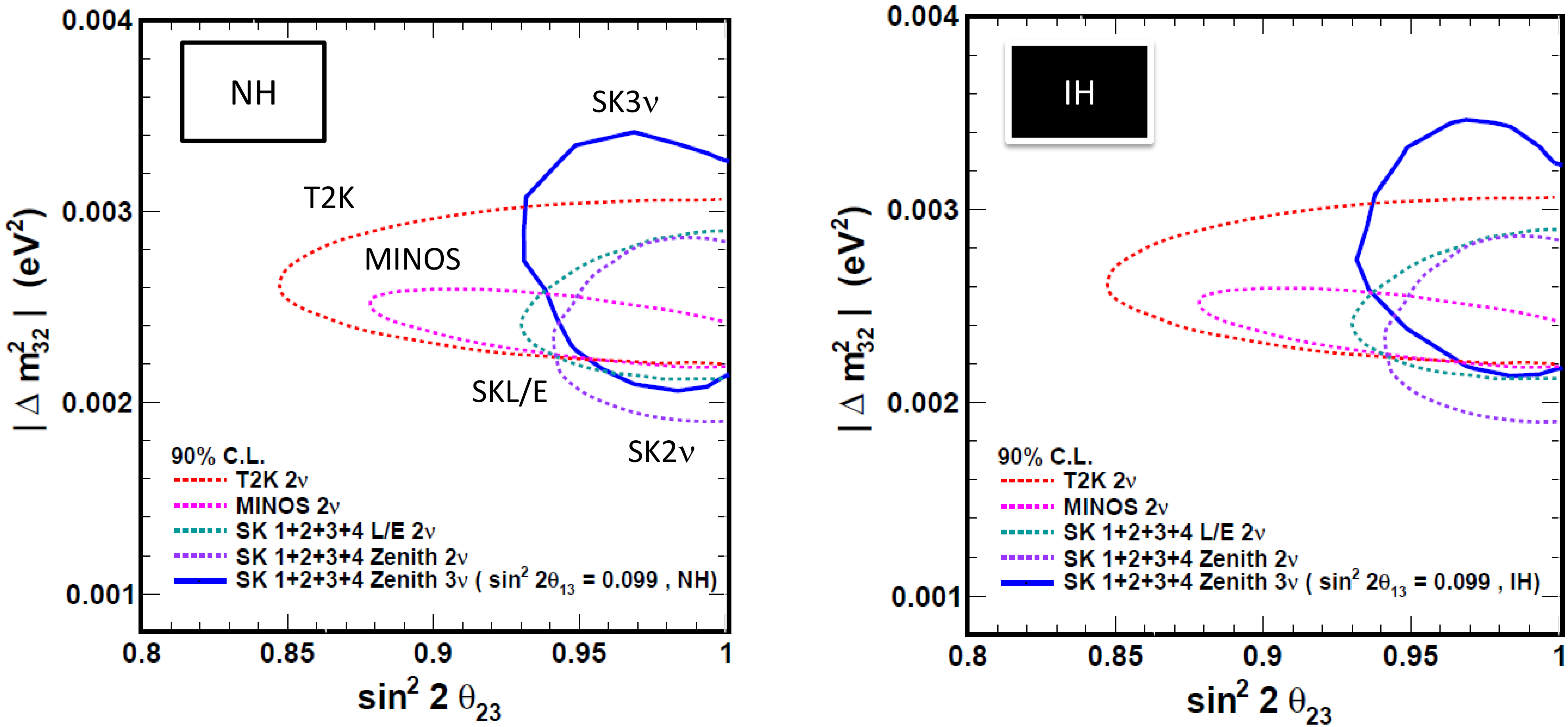
θ_{13} Measurement With Atmospheric Neutrinos



Hiearachy	Best $\sin^2\theta_{13}$	$\sin^2\theta_{13}$ - 90% CL	χ^2
Normal	0.003	0-0.066	555.3 / 476
Inverted	0.006	0-0.094	554.9 / 476

Still a slight preference for the inverted hierachy

Disappearance Parameters Post Neutrino 2012



- Atmospheric neutrinos still provide the strongest constraint on θ_{23}
- Long-baseline experiments have measured Δm^2 more precisely
  - Atmospheric neutrino measurement is consistent

Summary

- Super-K oscillation analysis has been updated to include constraints from global information on θ_{13}
- No decisive indication of the mass hierarchy, θ_{23} octant, or value of δ_{cp} yet …

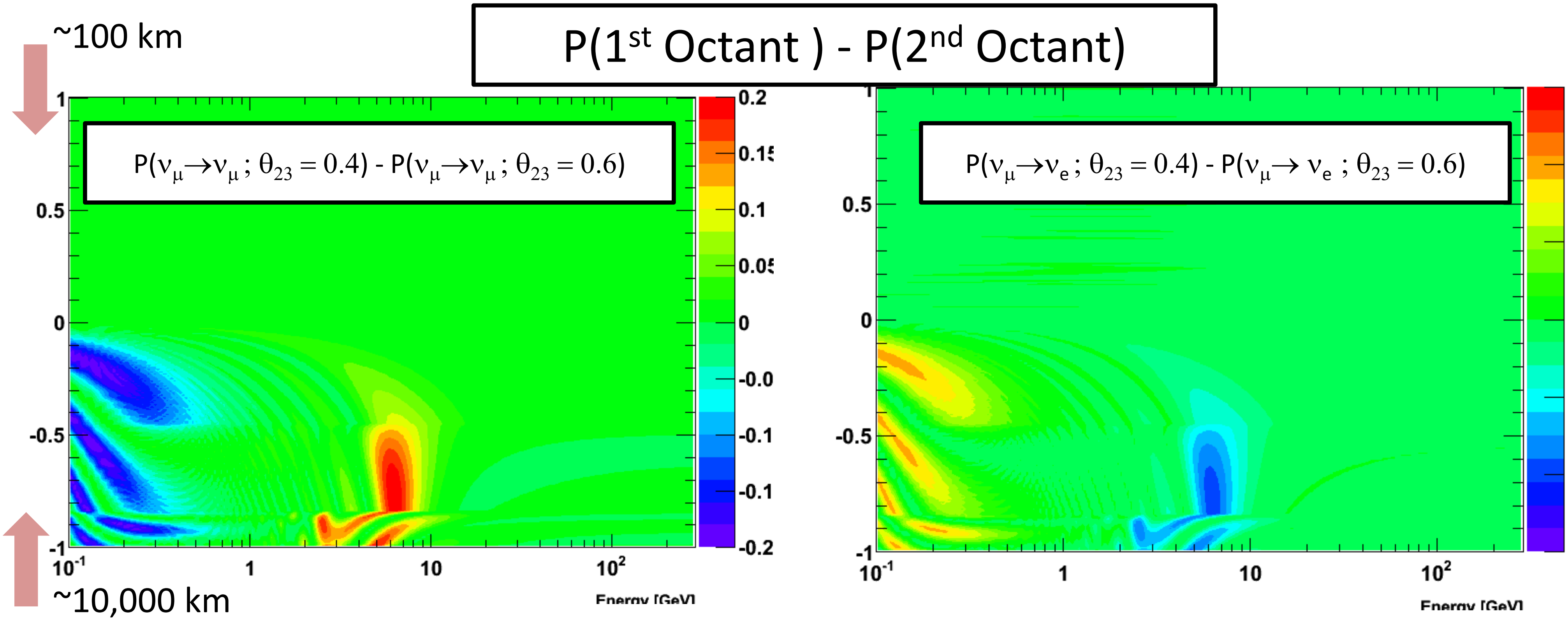
NH	Best fit	90% C.L
Δm^2_{32}	2.66×10^{-3}	$[2.06 - 3.04] \times 10^{-3}$ eV^2
$\sin^2\theta_{23}$	0.425	0.391 - 0.619
δCP	300°	All allowed at 90% C.L.

IH	Best fit	90% C.L.
Δm^2_{32}	2.66×10^{-3}	$[2.14 - 3.04] \times 10^{-3}$ eV^2
$\sin^2\theta_{23}$	0.575	0.393 - 0.630
δCP	240°	All allowed at 90% C.L.

- The Future
  - Still statistics limited
  - Constraints from external data may help focus the sensitivity of atmospheric neutrinos
    - Plans for an analysis incorporating global data underway

Supplements

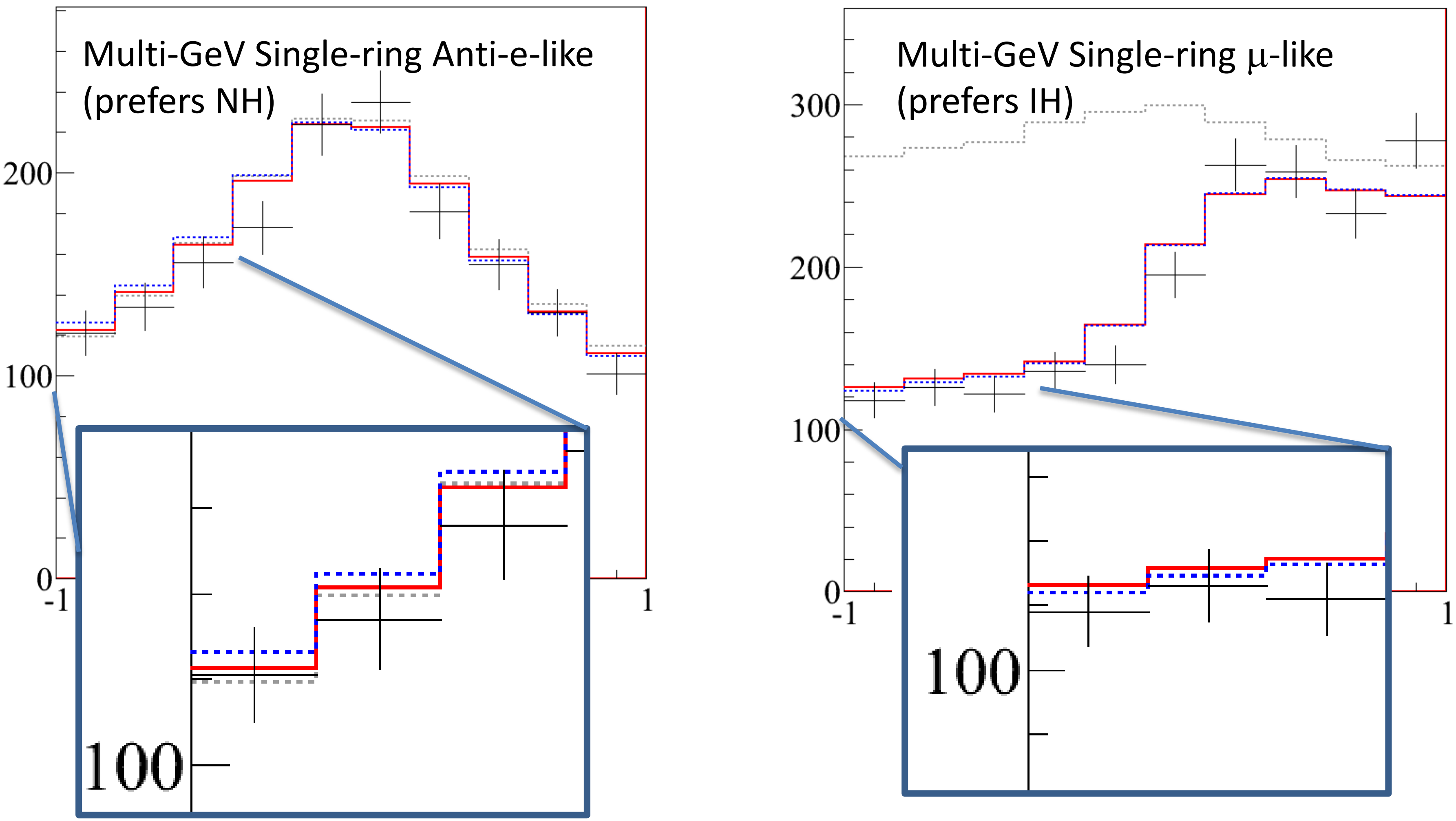
Oscillation probability difference between the θ_{23} octants



- Matter effect gives improved sensitivity
  - Mass hierarchy $\rightarrow$ Asymmetry between neutrinos and antineutrinos
  - size of θ_{13} and δ_{cp} $\rightarrow$ Magnitude of resonance effect
  - Octant of θ_{23} $\rightarrow$ Appearance and disappearance interplay

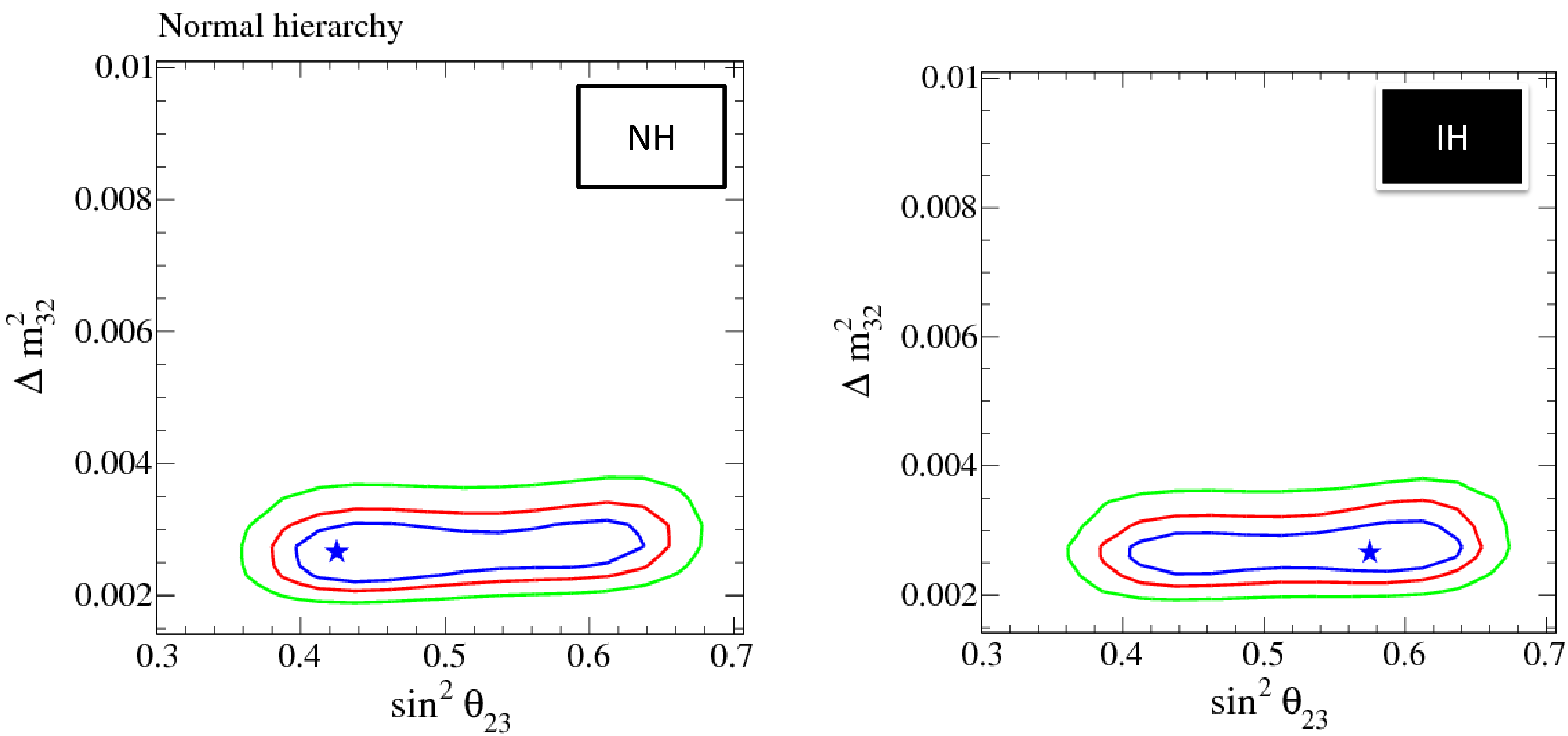
(Trends are Independent of Hierarchy)

Zenith angle distributions of the Data



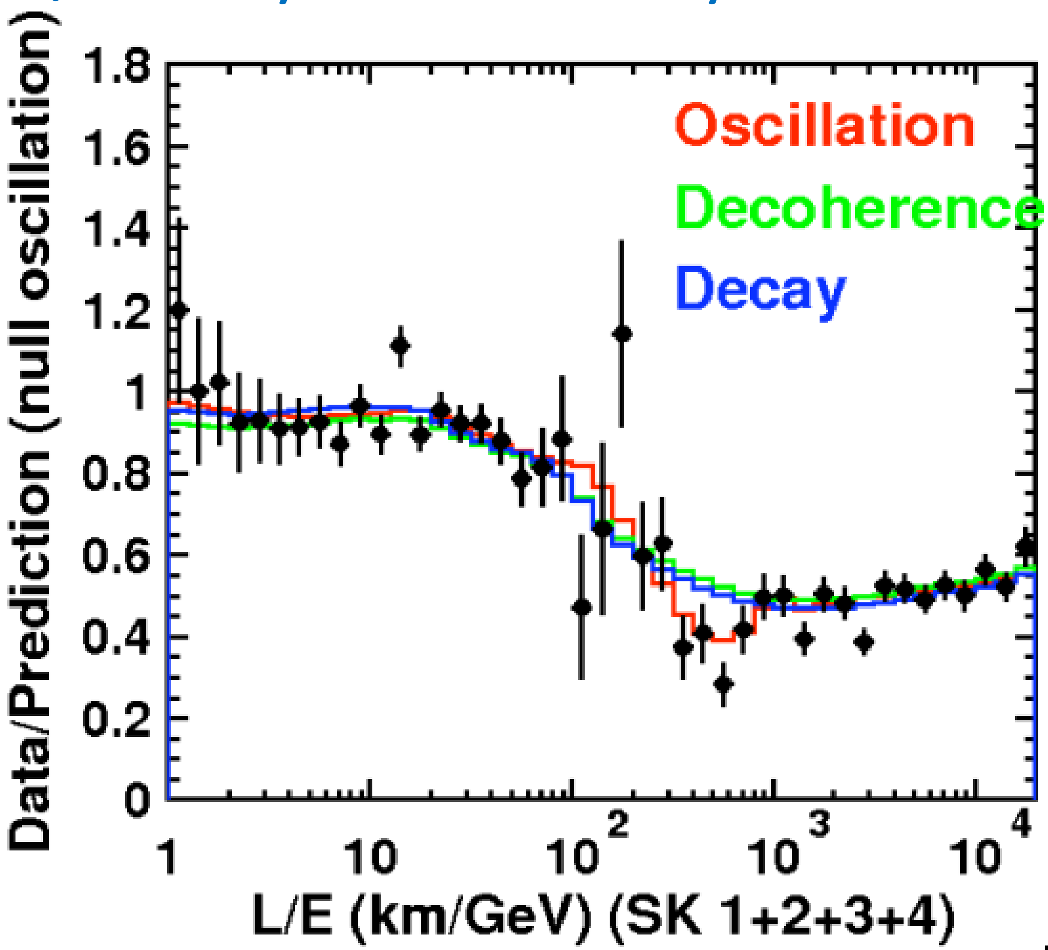
- So far no consistent story has emerged from the data
- Taking more data is a necessity !

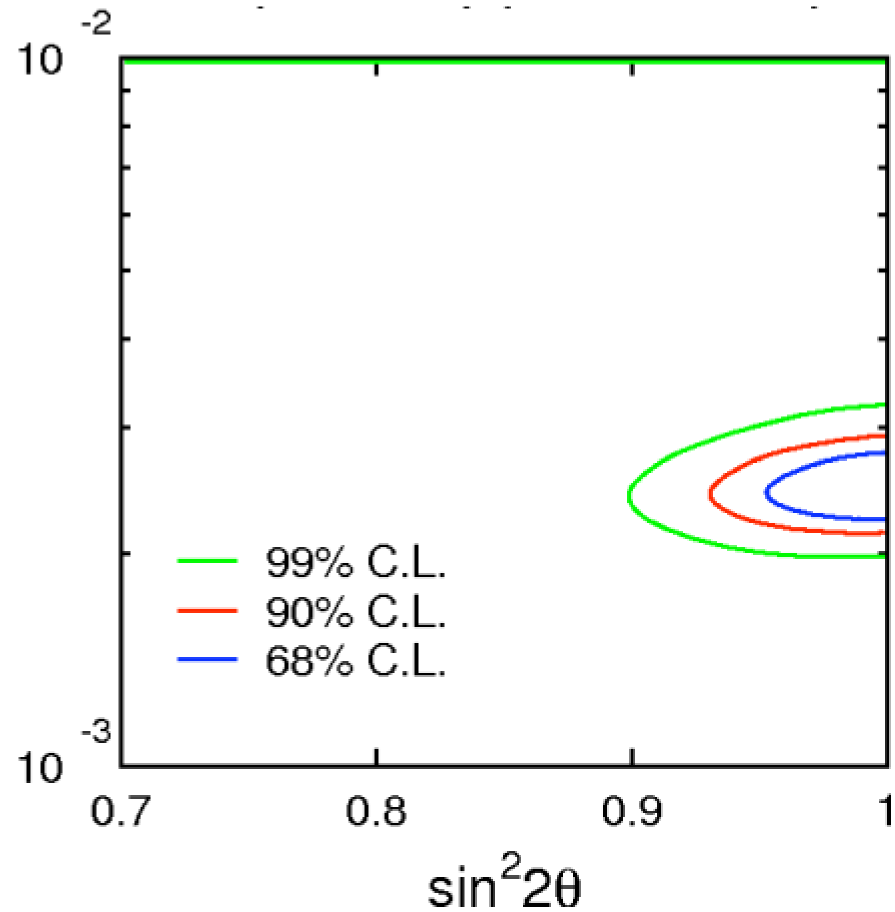
NH Fit
IH Fit



Normal hierarchy
NH
IH
0.01
0.008
0.006
0.004
0.002
0.3
0.4
0.5
0.6
0.7
Δm^2_{32}
$\sin^2\theta_{23}$

L/E Analysis – 3903 Days of Data

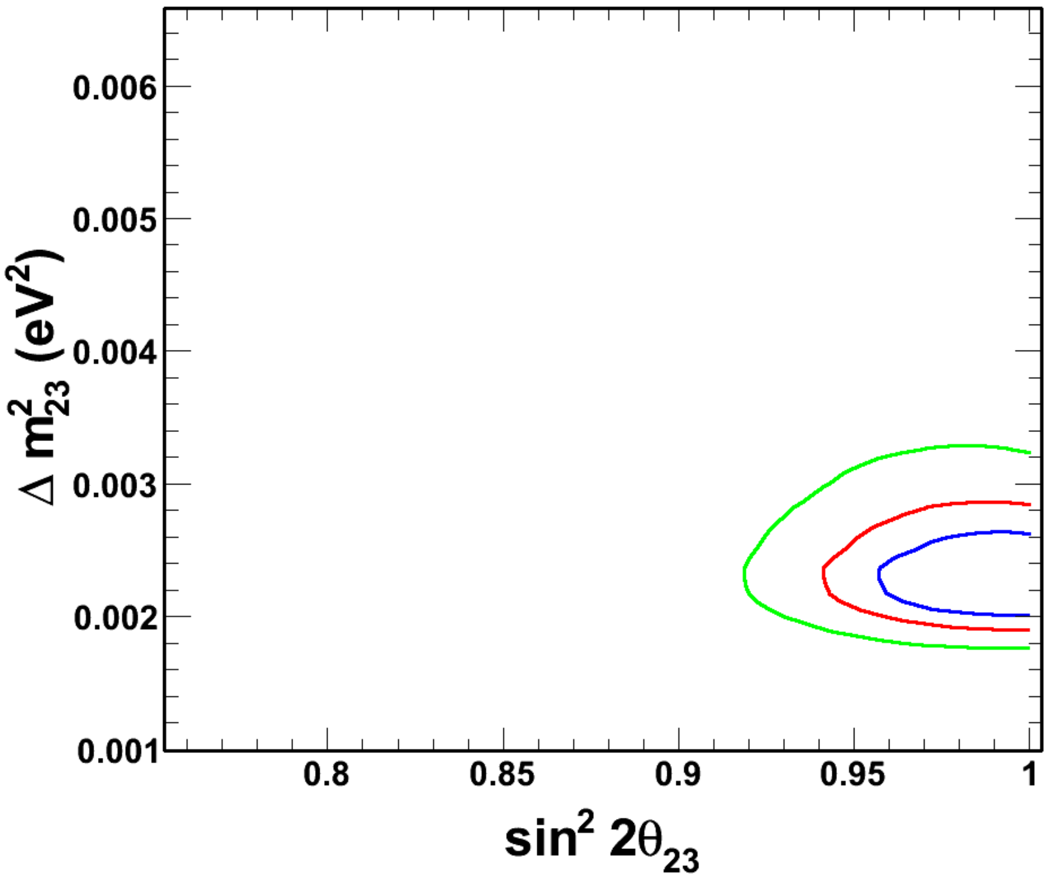




L/E	Best fit	90% C.L
Δm^2_{32}	2.5 x 10^{-3}	[2.13 - 2.91] x 10^{-3} eV^2
$\sin 2^2\theta_{23}$	1.0	> 0.93

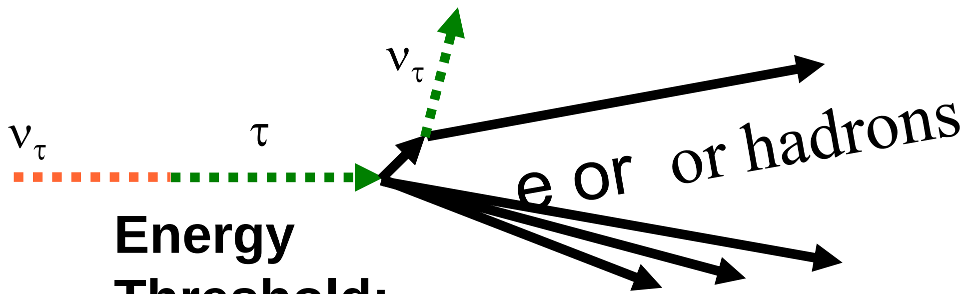
- ☐ Neutrino decay disfavored at 4.0 σ
- ☐ Neutrino decoherence disfavored at 4.8 σ

Two Flavor Analysis



L/E	Best fit	1σ CL
Δm^2_{32}	2.3×10^{-3}	$[2.1 - 2.46] \times 10^{-3}\ eV^2$
$\sin 2^2\theta_{23}$	1.00	> 0.96 (90%)

ν_τ Events at Super-K

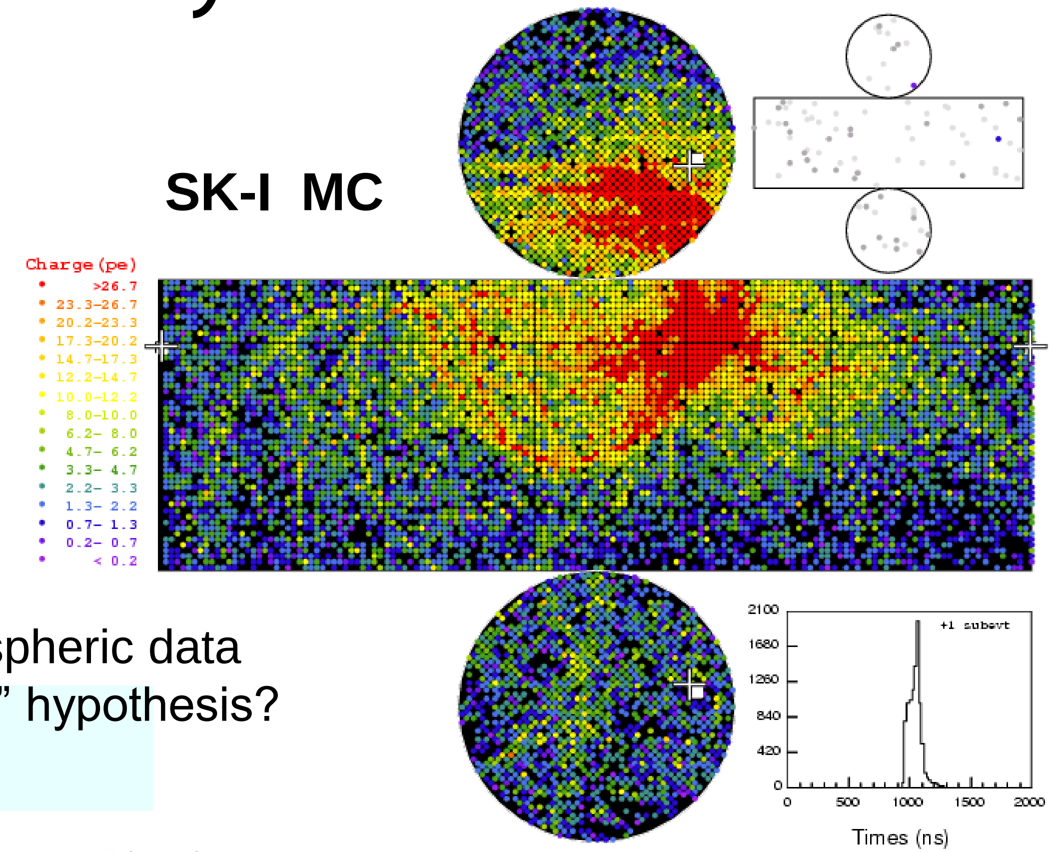


Energy Threshold: 3.5 GeV

- Many light producing particles
- Most events are deep inelastic scattering interactions

- Complicated event topology complicate identification of the leading lepton
  - Use a Neural Network procedure
  - 80% efficient for signal
- Negligible primary flux
  - Observed tau events would be oscillation induced

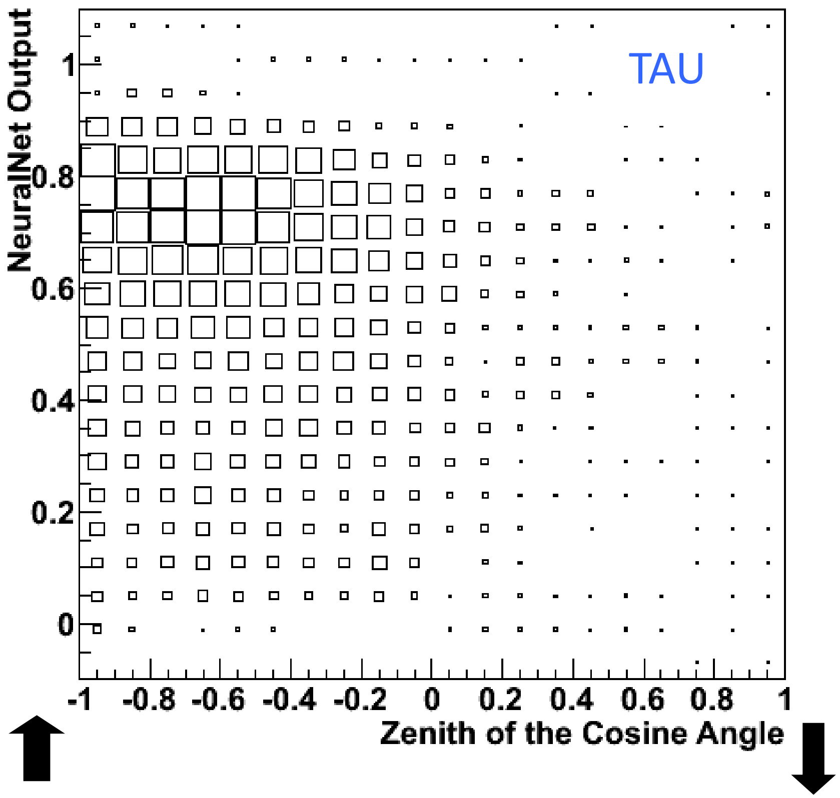
SK-I MC

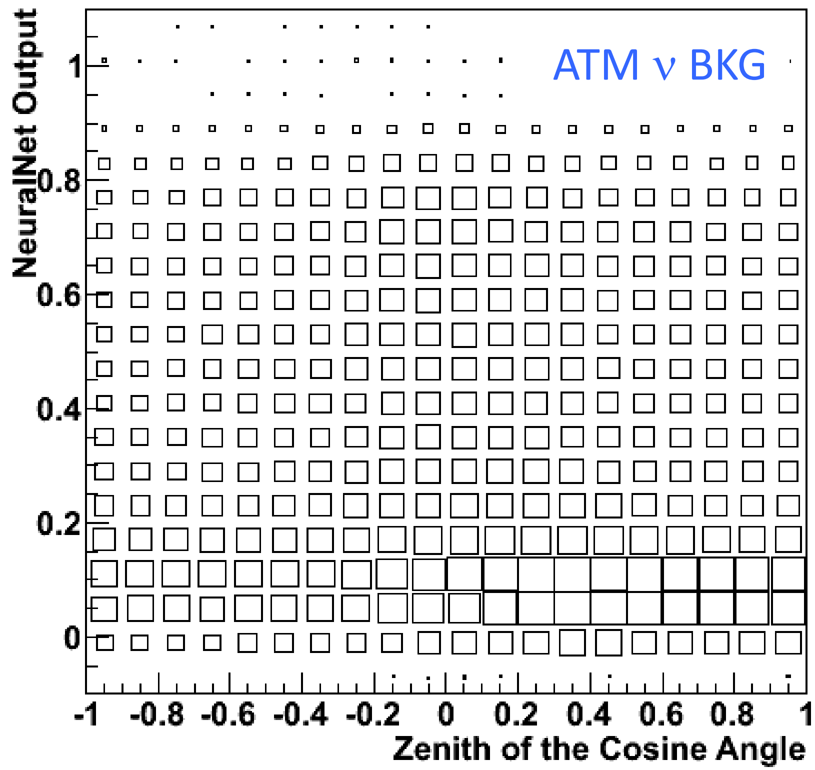


GOAL : Observe ν_τ events in the atmospheric data

How inconsistent is the “no appearance” hypothesis?

Neural Network and Unbinned likelihood fit



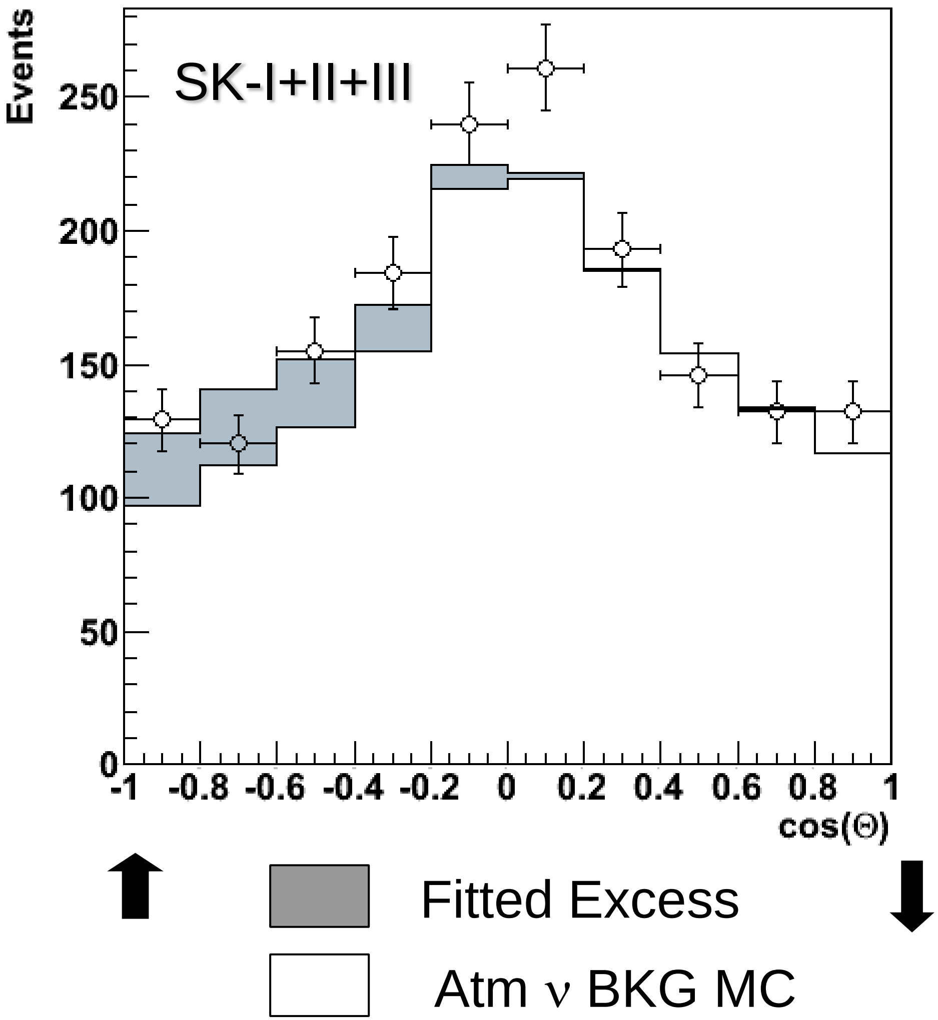


- Neural Network is built to separate tau events
  - Visible Energy, number of decay electrons, maximum distance to a decay electron, number of ring fragments, fraction of momentum in brightest right
- Fit normalization of signal and bacground PDFs as a function of of NN output and Zenith Angle

Fit Results

If no ν_τ appearance , $\beta = 0$

$$Data = \alpha(\gamma) \times bkg + \boxed{\beta}(\gamma) \times signal$$



Result	Background	Signal
SK-I	0.95	1.27
SK-II	0.96	1.47
SK-III	0.94	2.16
SK-I+II+III	0.94 ± 0.02	**1.42 ± 0.35**
DIS γ	1.10 ± 0.05	

Fitting Error only

- Tau signal clearly appears in upward-going region
- DIS fits to 1.10
- Tau normalization fits to 1.42 × expectation

Systematic Errors

	+ %	-%
Flux: Up/Down Ration, Horizontal/ Vertical ratio , K/p **X-sec:** NC/CC ratio **Dectector:** Up/Down Energy cal. Asymmetry	7.9	8.5
Oscillation Parameters: 1 - σ allowed atm.	5.4	1.3

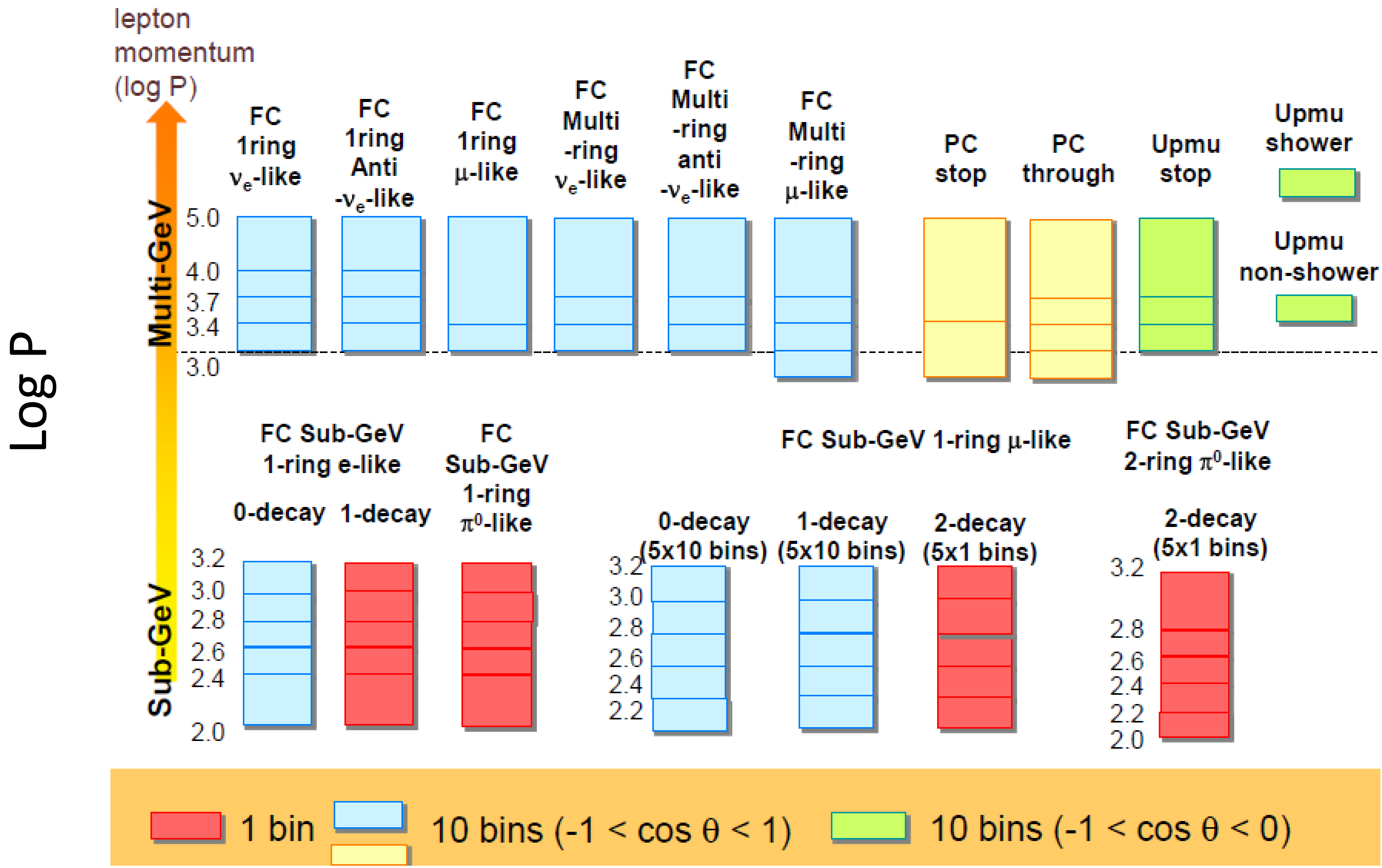
$$\beta = 1.42 \pm 0.35\ (\text{stat})\ ^{+0.14}_{-0.12}\ (\text{sys})$$

This corresponds to 180.1 $\pm$ 44.3 (stat) $^{+17.8}_{-15.2}$ (sys) events a 3.8 σ excess

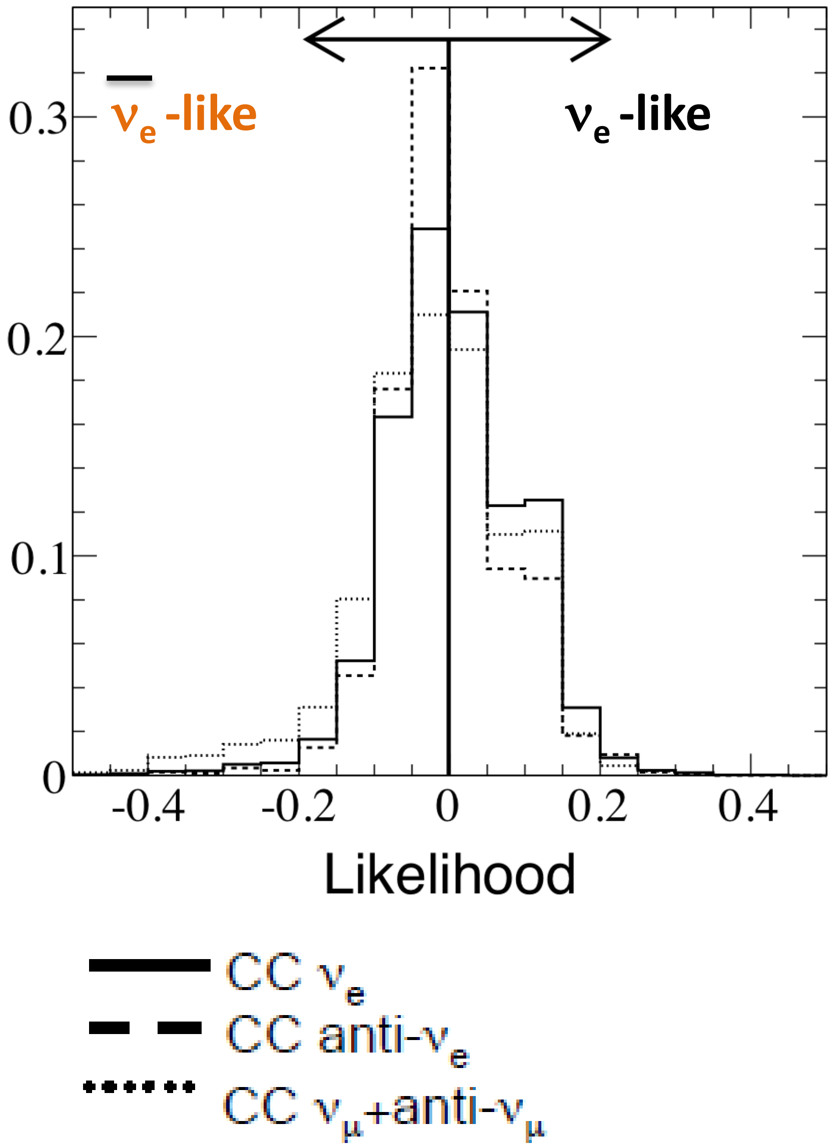
(Expected 2.7 σ significance)

SK Data disfavor 'no tau appearance' at 3.8 σ

Zenith Angle Analysis – 480 Bins in 18 Samples



Sample Selection : Multi-GeV Multi-Ring anti-ν_e and ν_e -like



- Multi-ring events are in general more complicated
  - Many outgoing particles from DIS or multi-π interactions
- Likelihood function built on four variables
  - Number of decay electrons
  - Number of Cherenkov rings found
  - Transverse momentum

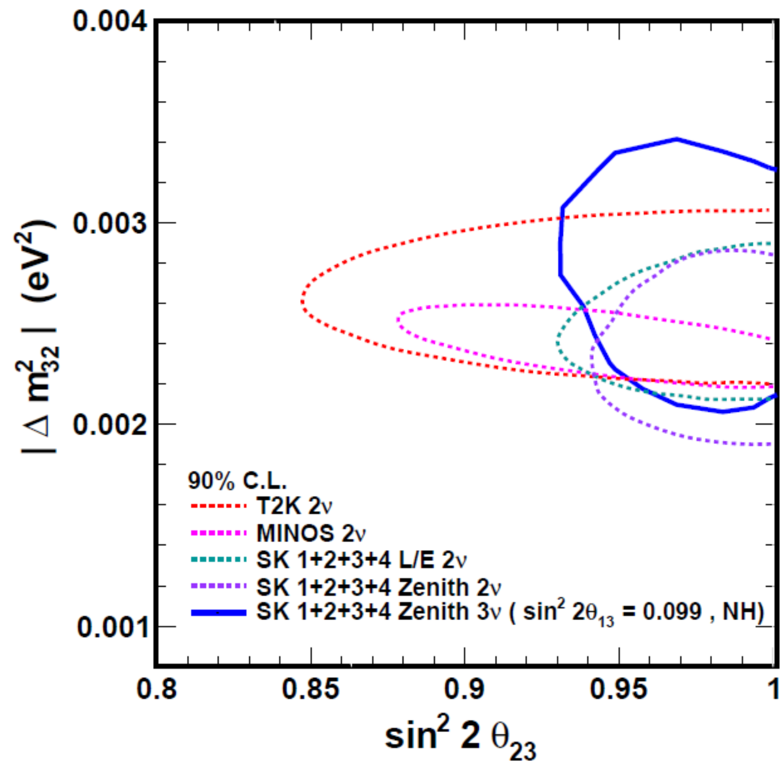
Variable	CC ne	CC anti-ne
N Rings	More	Fewer
N Decay e	More	Fewer
Transverse P	Larger	Smaller

Notes about Parameter Values

- In the studies below, unless specified otherwise the following inputs have been used to compute sensitivities

Parameter	Value	$\sin^2(2x)$	Comment
Δm^2_{32}	2.4×10^{-3} eV^2		Global Fit
$\sin^2\theta_{23}$	0.4-0.6	0.96 - 1.0	**
$\sin^2\theta_{13}$	0.025	0.10	Reactor Data
δ_{cp}	40 degrees		Min.P($\nu_\mu \rightarrow \nu_e$)
$\sin^2\theta_{21}$	0.31	0.85	Global Solar
Δm^2_{21}	7.6×10^{-5} eV^2		Global Solar
Hierarchy	Normal		Assumption

Neutrino 2012



** MINOS central value from Neutrino 2012: $\sin^2(2\theta_{23}) = 0.96$

Systematic Error			fit value	σ
Flux normalization	$E_\nu < 1$ GeV		34.7	25[a]
	$E_\nu > 1$ GeV		8.8	7[b]
ν_μ/ν_e				
	$E_\nu < 1$ GeV		-1.9	2
	$1 < E_\nu < 10$ GeV		-2.5	3
	$E_\nu > 10$ GeV		-3.7	5[c]
$\bar{\nu}_e/\nu_e$				
	$E_\nu < 1$ GeV		5.54	5
	$1 < E_\nu < 10$ GeV		1.13	5
	$E_\nu > 10$ GeV		-0.10	8[d]
$\bar{\nu}_\mu/\nu_\mu$				
	$E_\nu < 1$ GeV		-0.48	2
	$1 < E_\nu < 10$ GeV		-1.35	6
	$E_\nu > 10$ GeV		-1.75	6[e]
Up/down ratio	$<$ 400 MeV	e-like	-0.07	0.1
		μ-like	-0.23	0.3
		0-decay μ-like	-0.84	1.1
	$>$ 400 MeV	e-like	-0.61	0.8
		μ-like	-0.38	0.5
		0-decay μ-like	-1.29	1.7
	Multi-GeV	e-like	-0.53	0.7
		μ-like	-0.15	0.2
	Multi-ring Sub-GeV	μ-like	-0.15	0.2
	Multi-ring Multi-GeV	e-like	-0.23	0.3
		μ-like	-0.15	0.2
	PC		-0.15	0.2

Horizontal/Vertical ratio	< 400 MeV	e-like	-0.01	0.1
		μ-like	-0.01	0.1
		0-decay μ-like	-0.03	0.3
	> 400 MeV	e-like	-0.14	1.4
		μ-like	-0.19	1.9
		0-decay μ-like	-0.14	1.4
	Multi-GeV	e-like	-0.33	3.2
		μ-like	-0.23	2.3
	Multi-ring Sub-GeV	μ-like	-0.13	1.3
	Multi-ring Multi-GeV	e-like	-0.29	2.8
		μ-like	-0.15	1.5
	PC		-0.17	1.7
K/π ratio in flux calculation			-12.9	10^f
Neutrino path length			-8.8	10
Sample-by-sample	FC Multi-GeV		-4.5	5
	PC + Up-stop μ		-7.1	5

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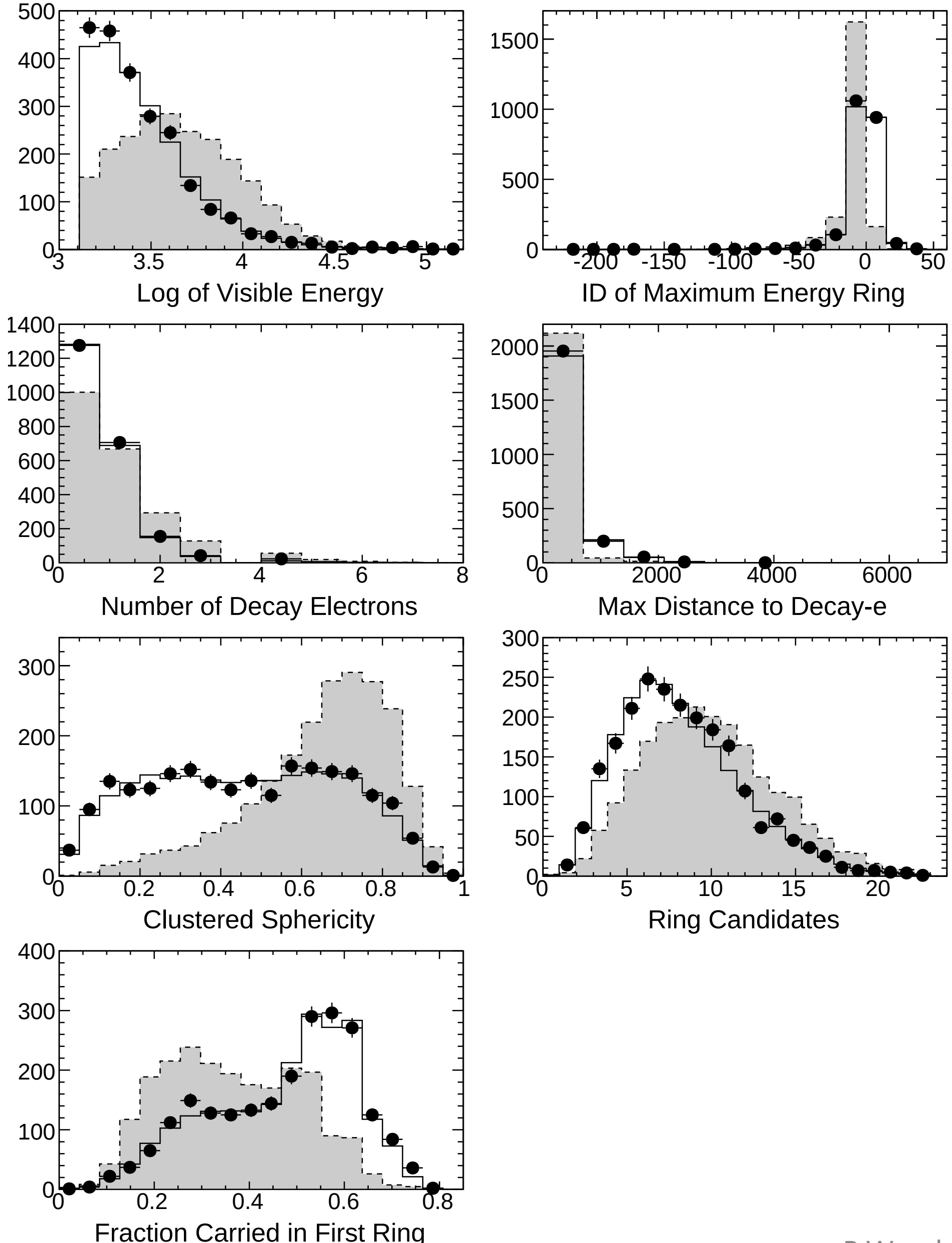
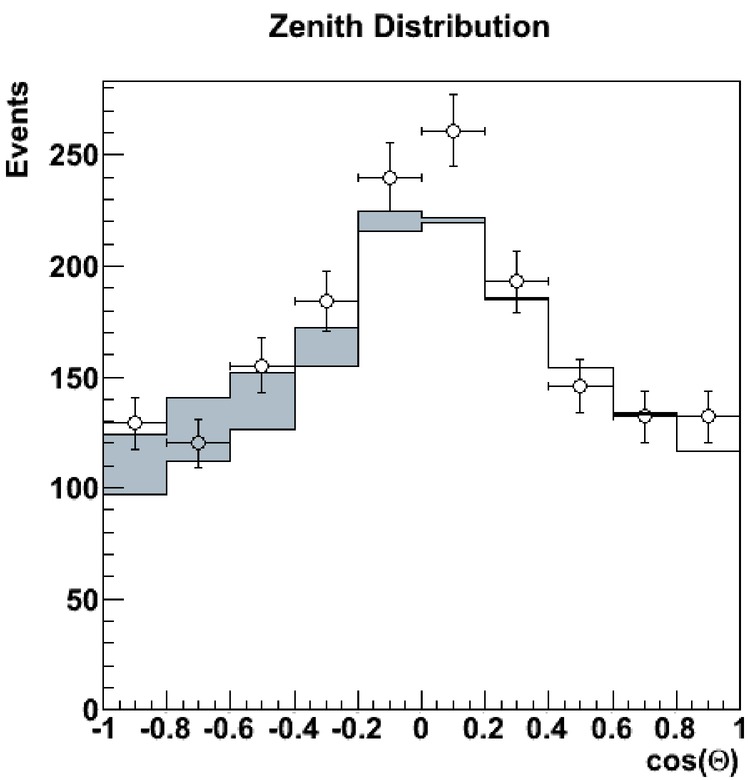
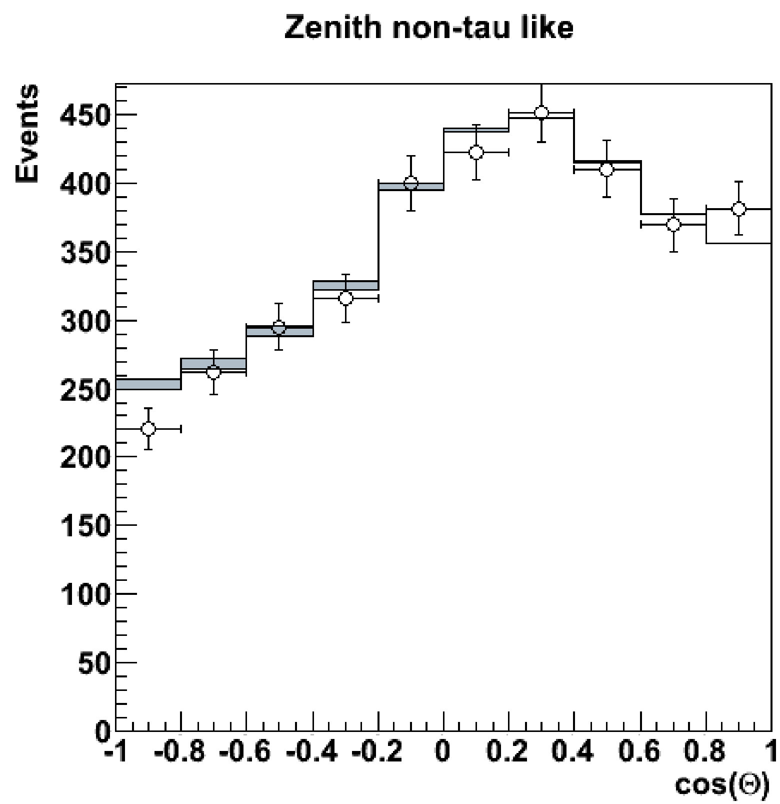

Log of Visible Energy
ID of Maximum Energy Ring
Number of Decay Electrons
Max Distance to Decay-e
Clustered Sphericity
Ring Candidates
Fraction Carried in First Ring

Examine both the tau-like and non-tau like events in zenith

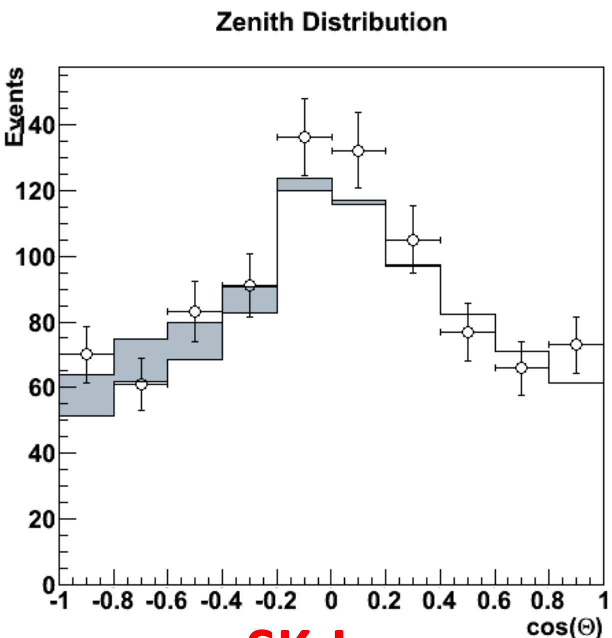
Tau like



Non-Tau Like

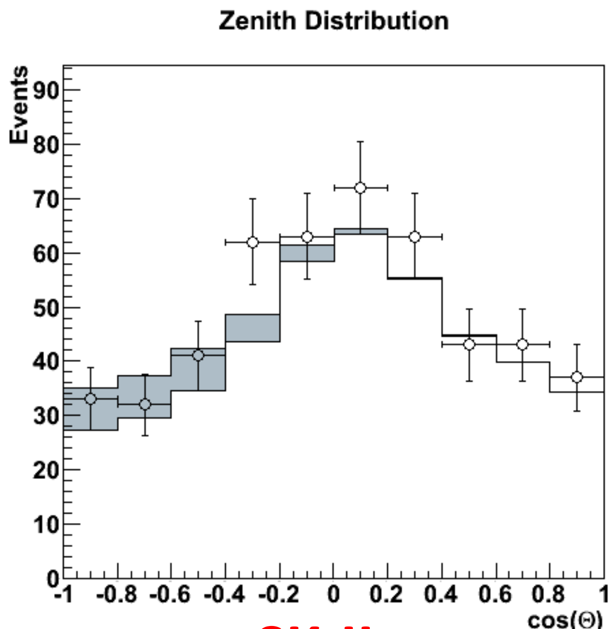


Fit results separately for SK-I, SK-II, SK-III



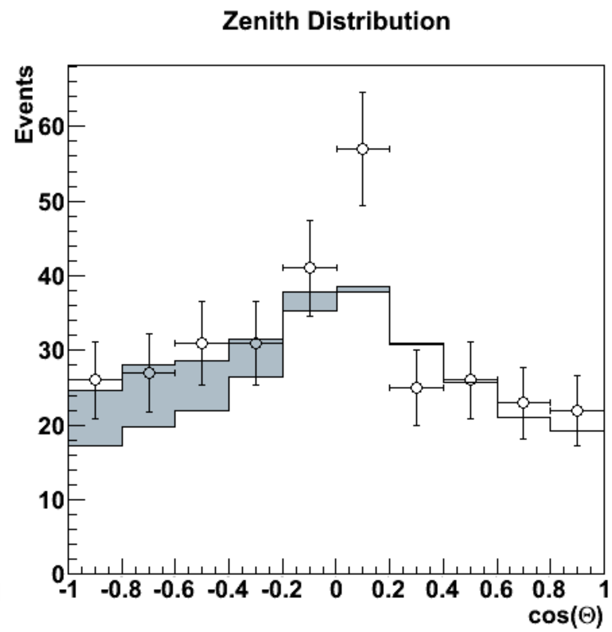
SK-I

B = 1.27 ± 0.49



SK-II

B = 1.47 ± 0.62

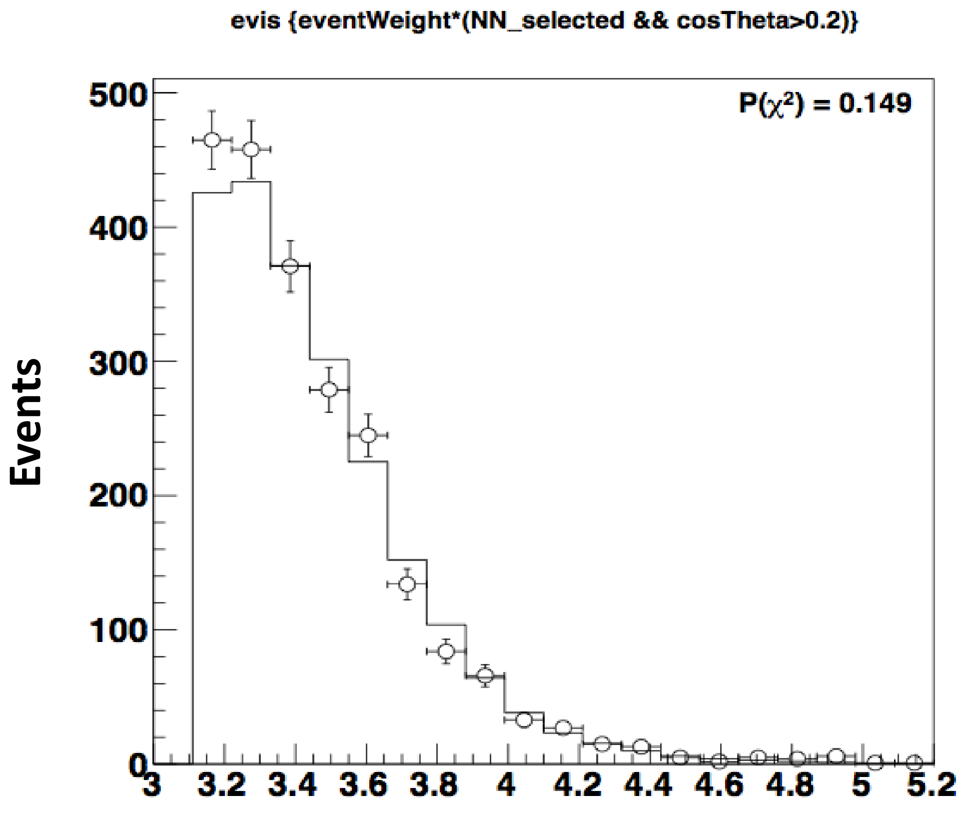


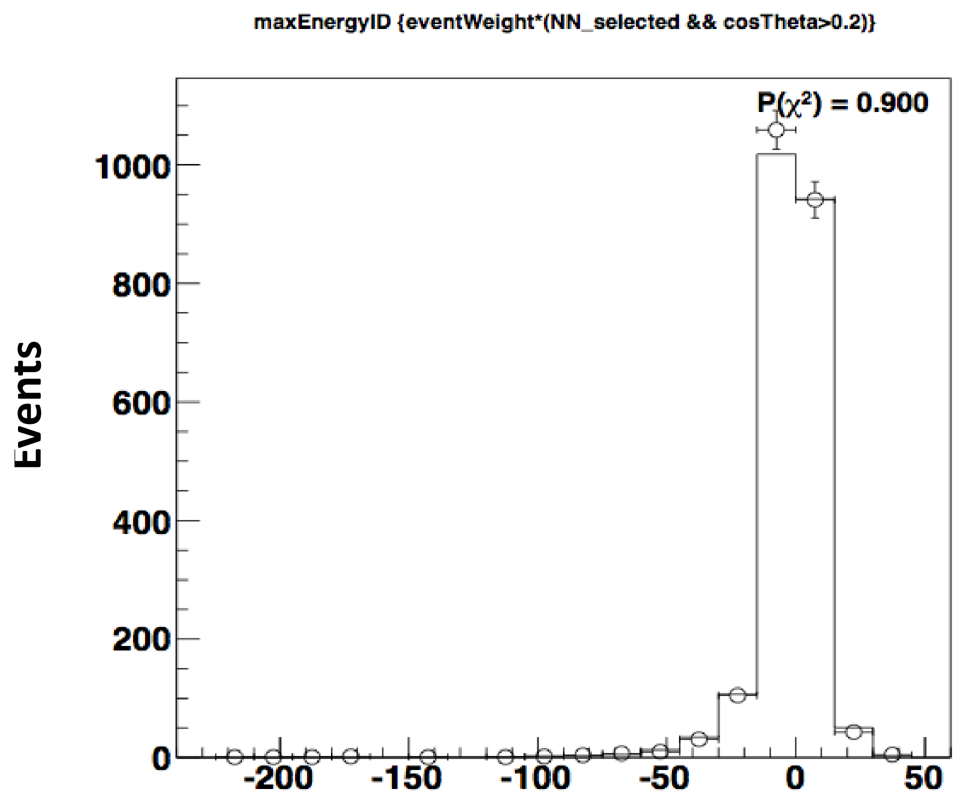
SK-III

B = 2.16 ± 0.78

Now compare Downward going Data/MC

SKI + SKII + SKIII Combined





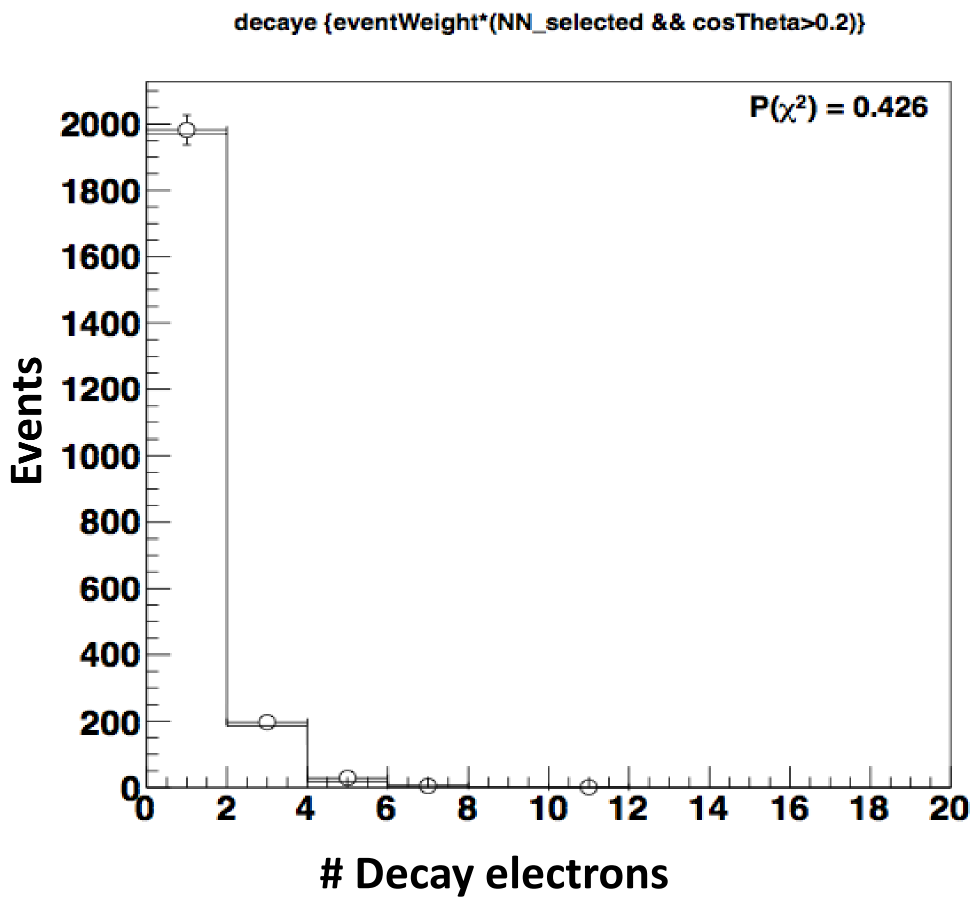
Log10(evis)

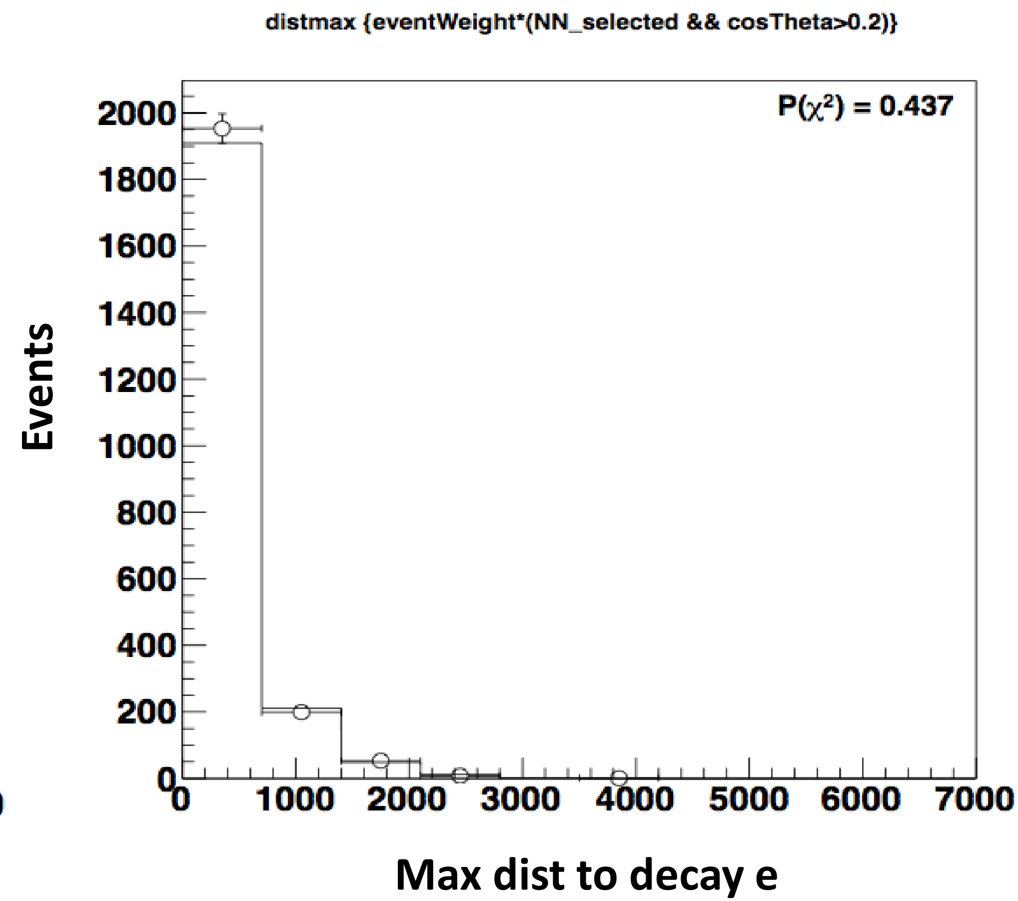
PID of maximum E ring

Note: Adjusted to fit values (DIS, bkg norm)

Data vs MC (downward)

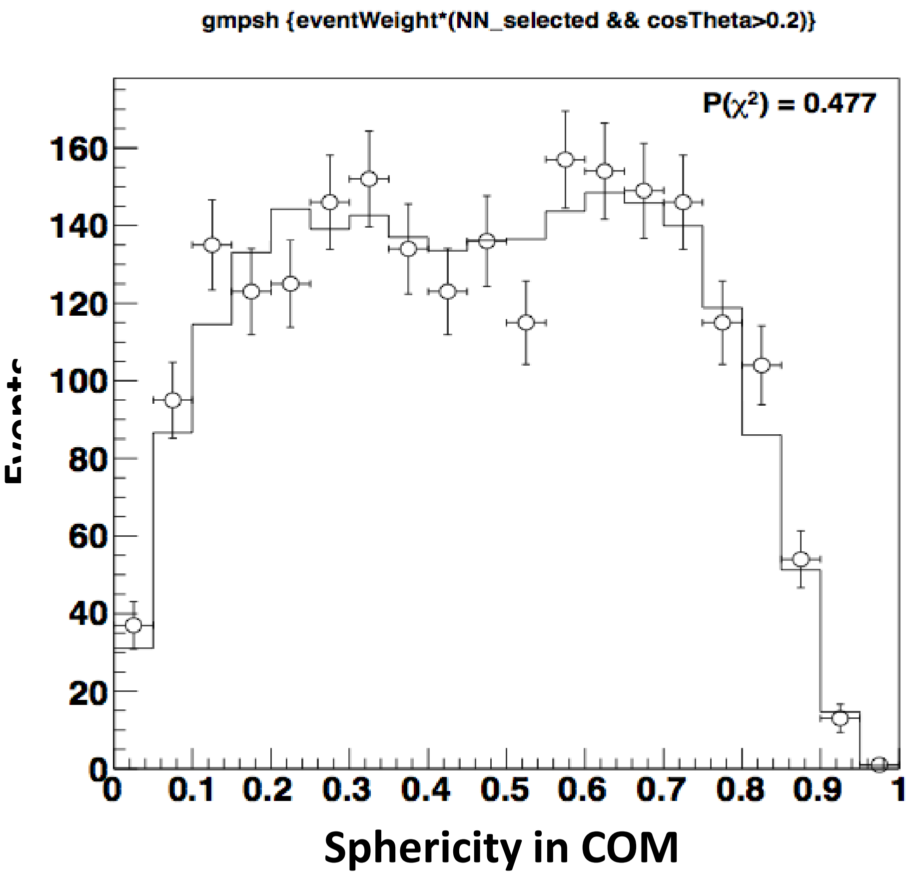
SKI + SKII + SKIII Combined

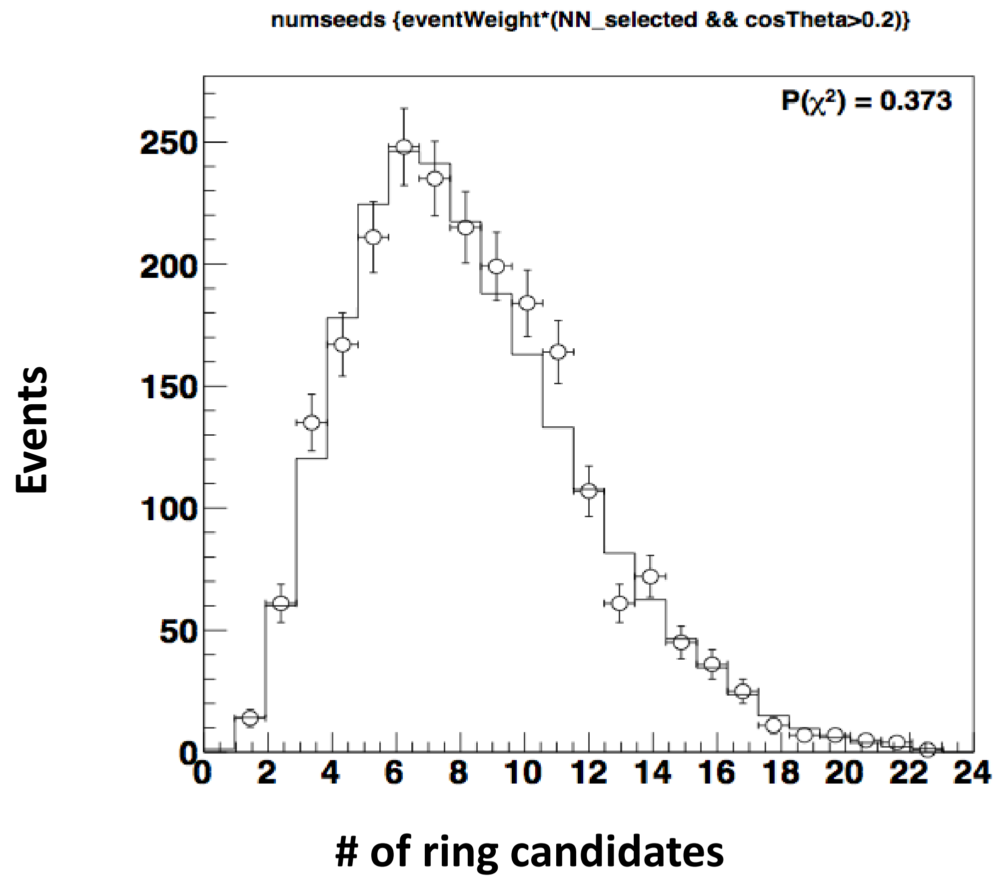




Data/MC (downward)

SKI + SKII + SKIII Combined

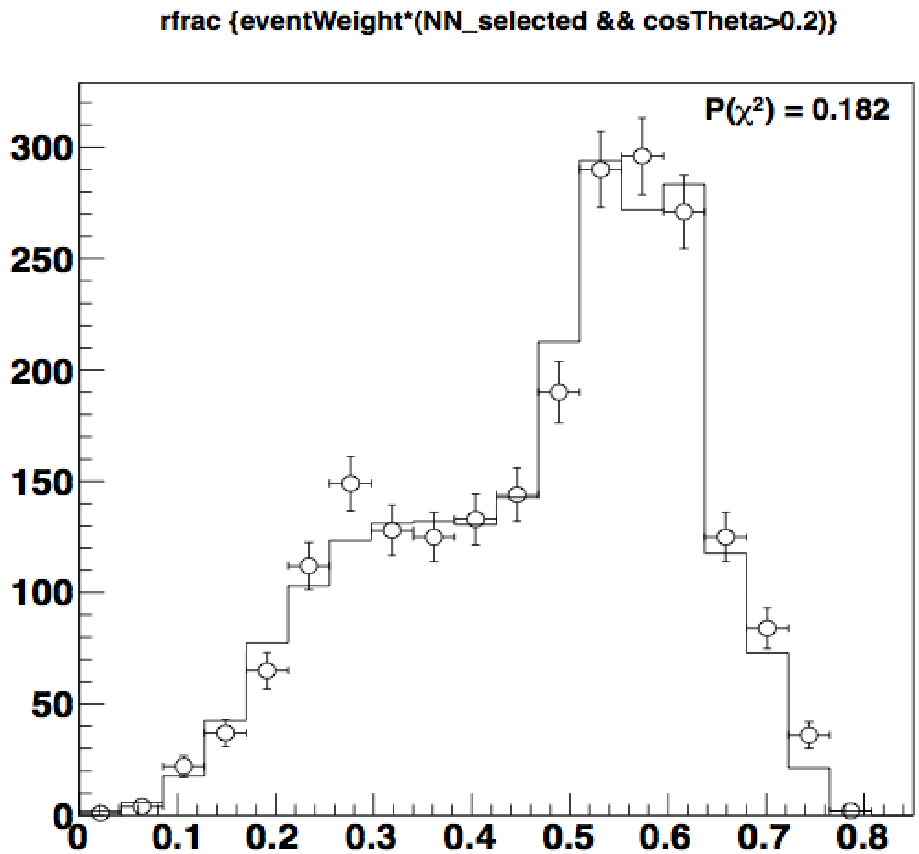




Data/MC (downward)

SKI + SKII + SKIII Combined

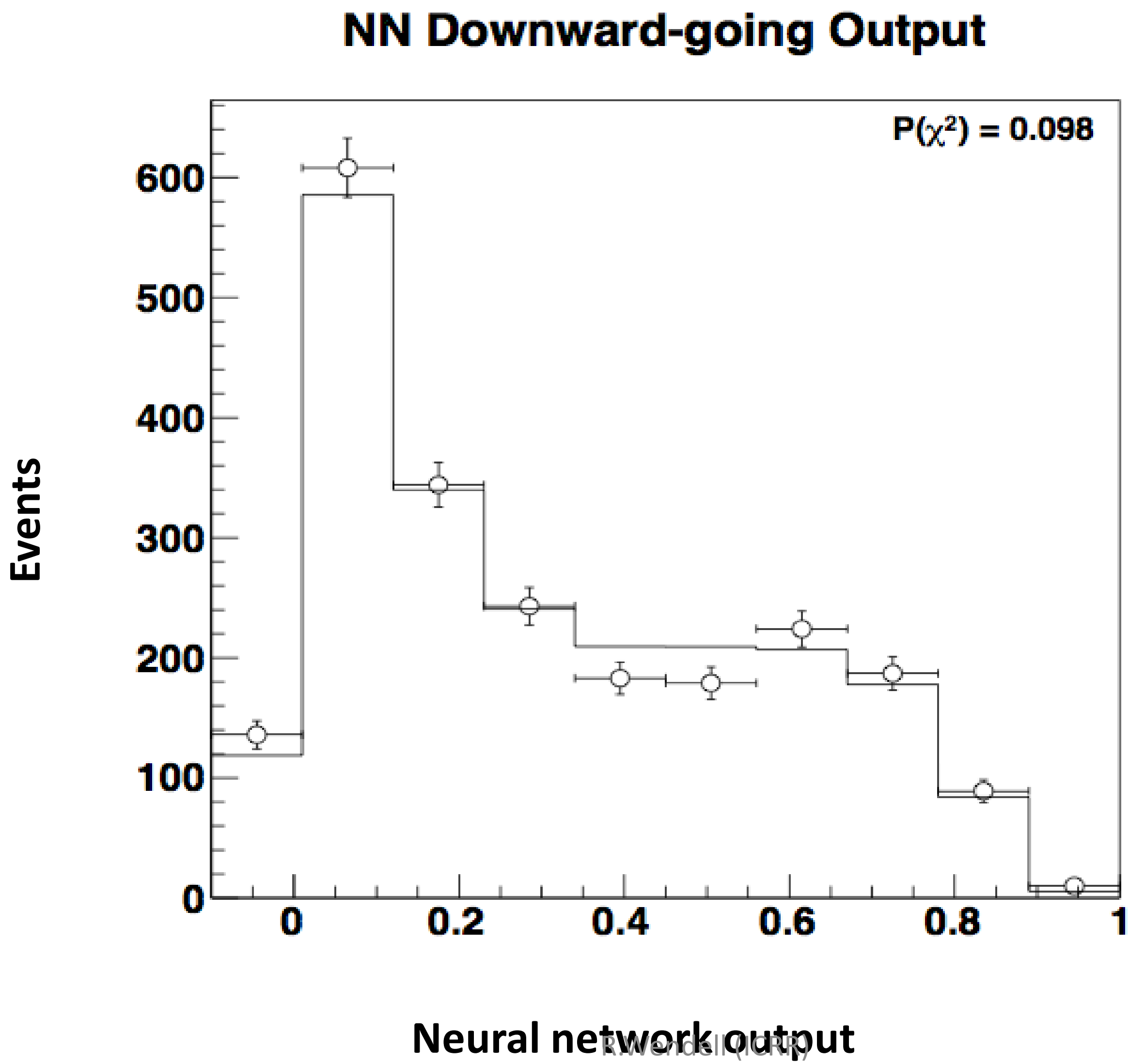
Events



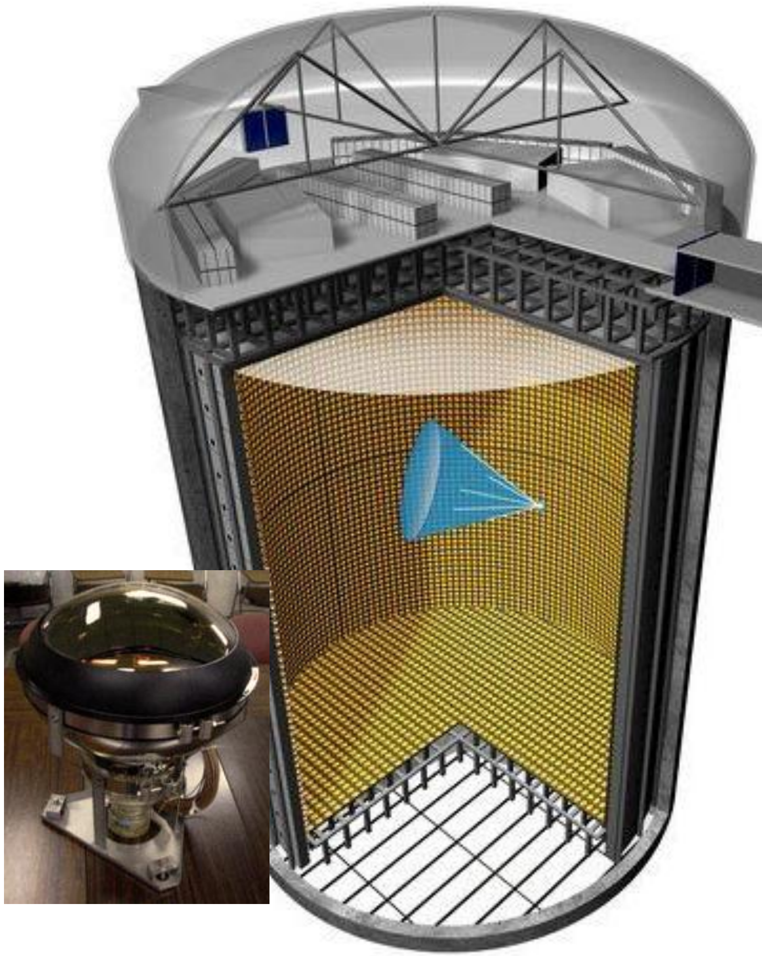
Fraction of photo electrons in leading ring

NN Output Data/MC (downward)

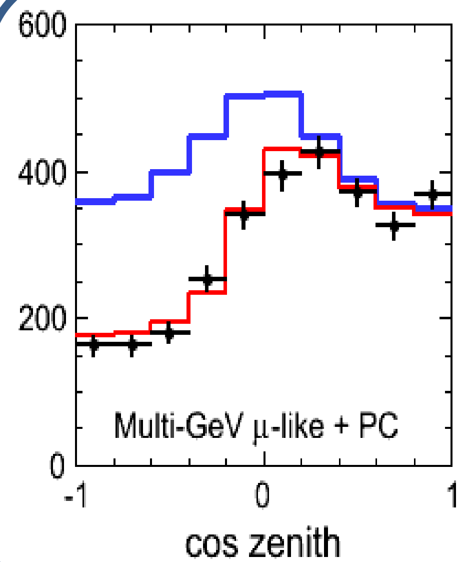
SKI + SKII + SKIII Combined

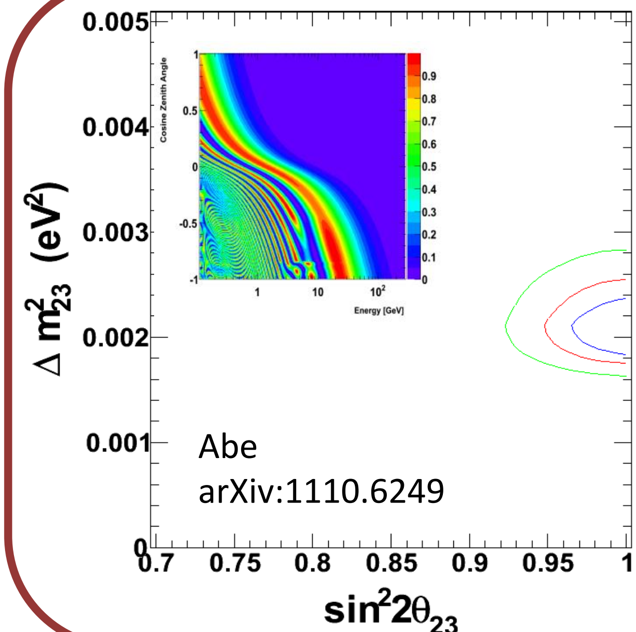


Super-Kamiokande : Introduction



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\, \Delta m^2_{23}\, L/E)$$

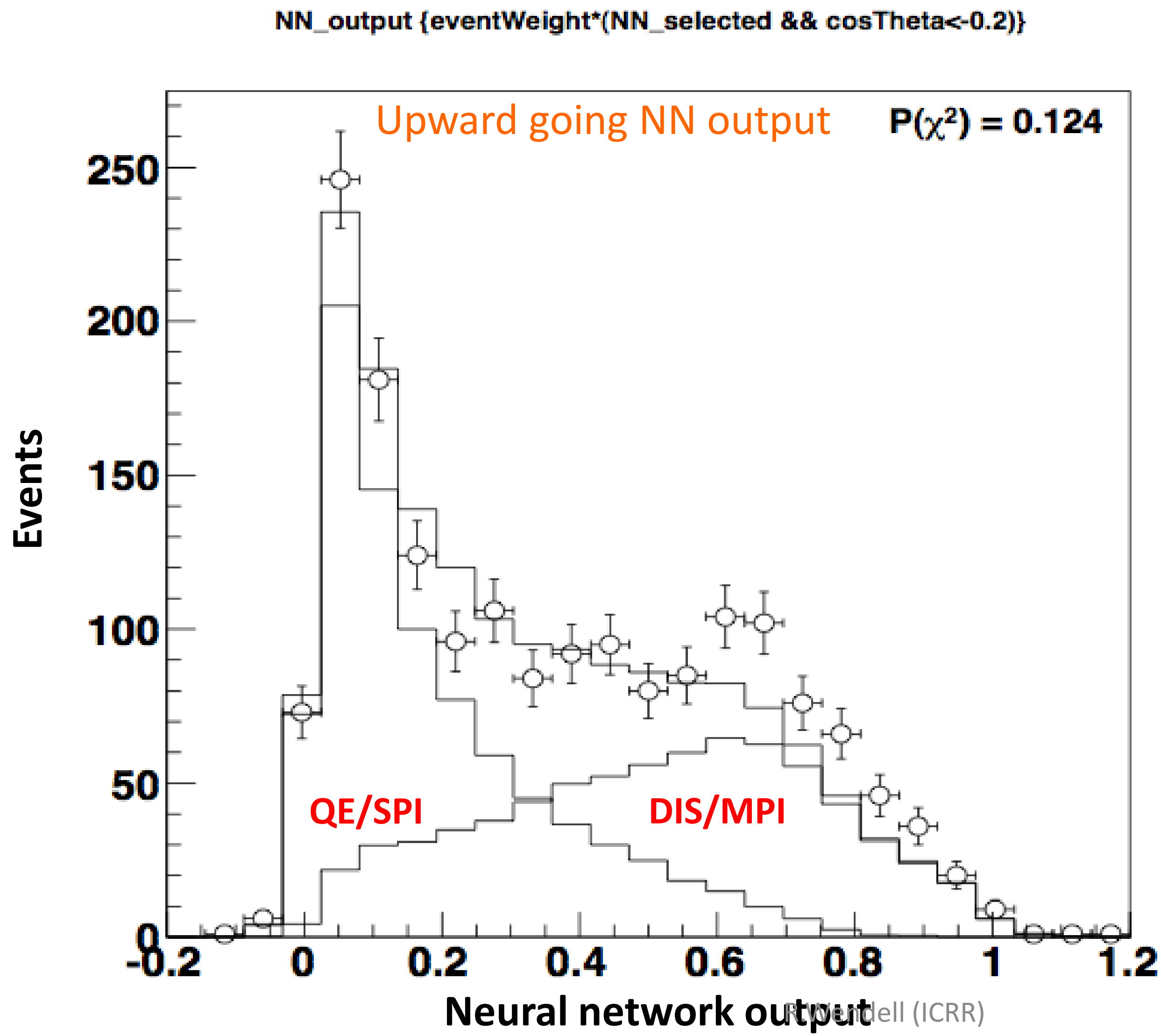




- 22.5 kton FV Volume
- Ring Imaging Water Cherenkov detector
- 11,1146 20” Phototubes
- Data taken over four periods since 1996

- SK discovered atmospheric neutrino oscillations exploiting the disappearance of upward-going muon events
- Currently **statistics limited**
  - Today: **3903 days of data**

Why we need to treat DIS separately



The neural net clearly separates
The bkg into DIS and non-DIS.
DIS events look more like taus.

The relative signal/bkg "slope" changes by increasing the amount of DIS events. So we Need to adjust the central value in the fit.