Super-K: High Energy

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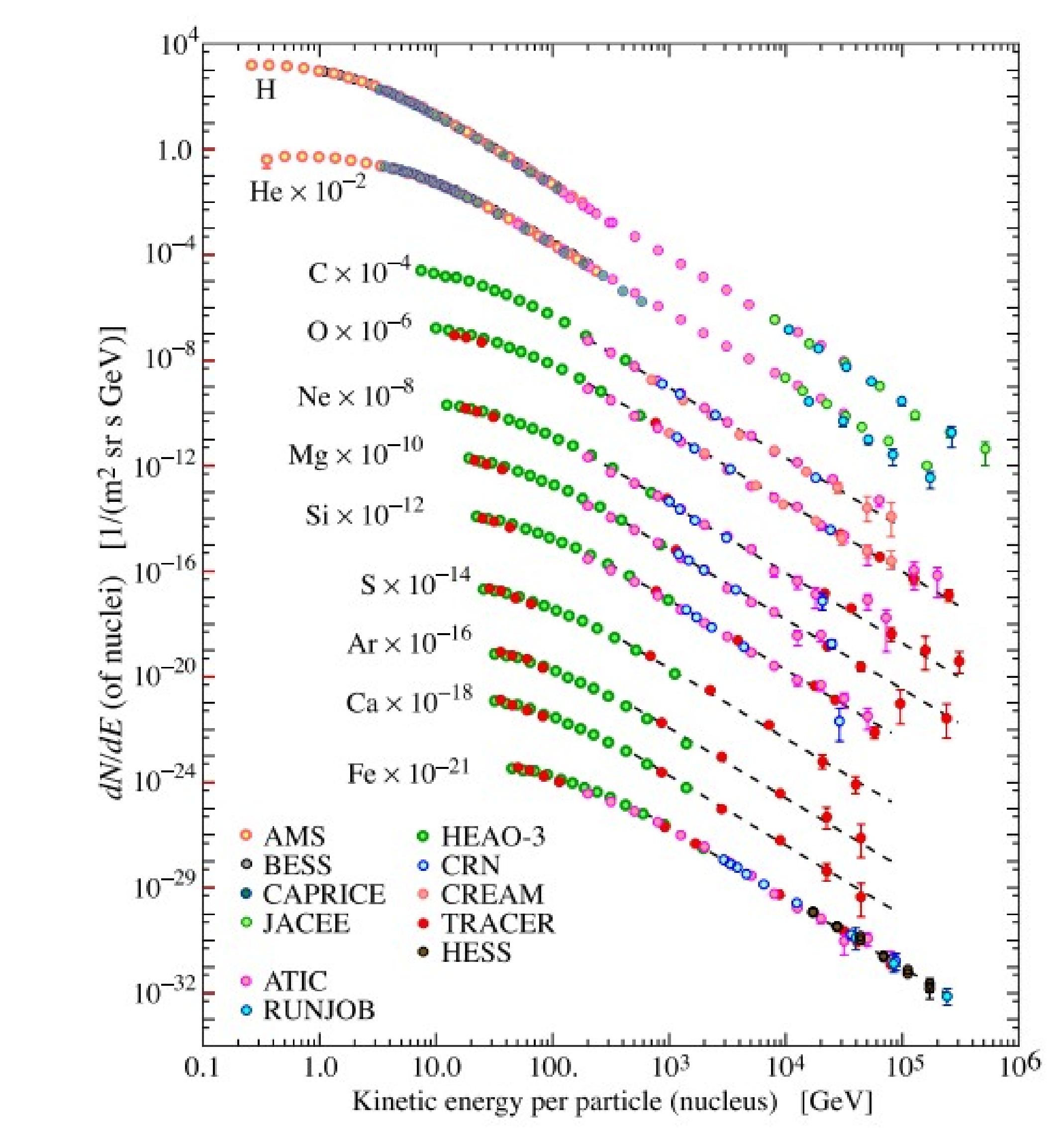
Introduction

- High-energy:
  - Particle interactions with visible energy between ~100 MeV and 100 TeV

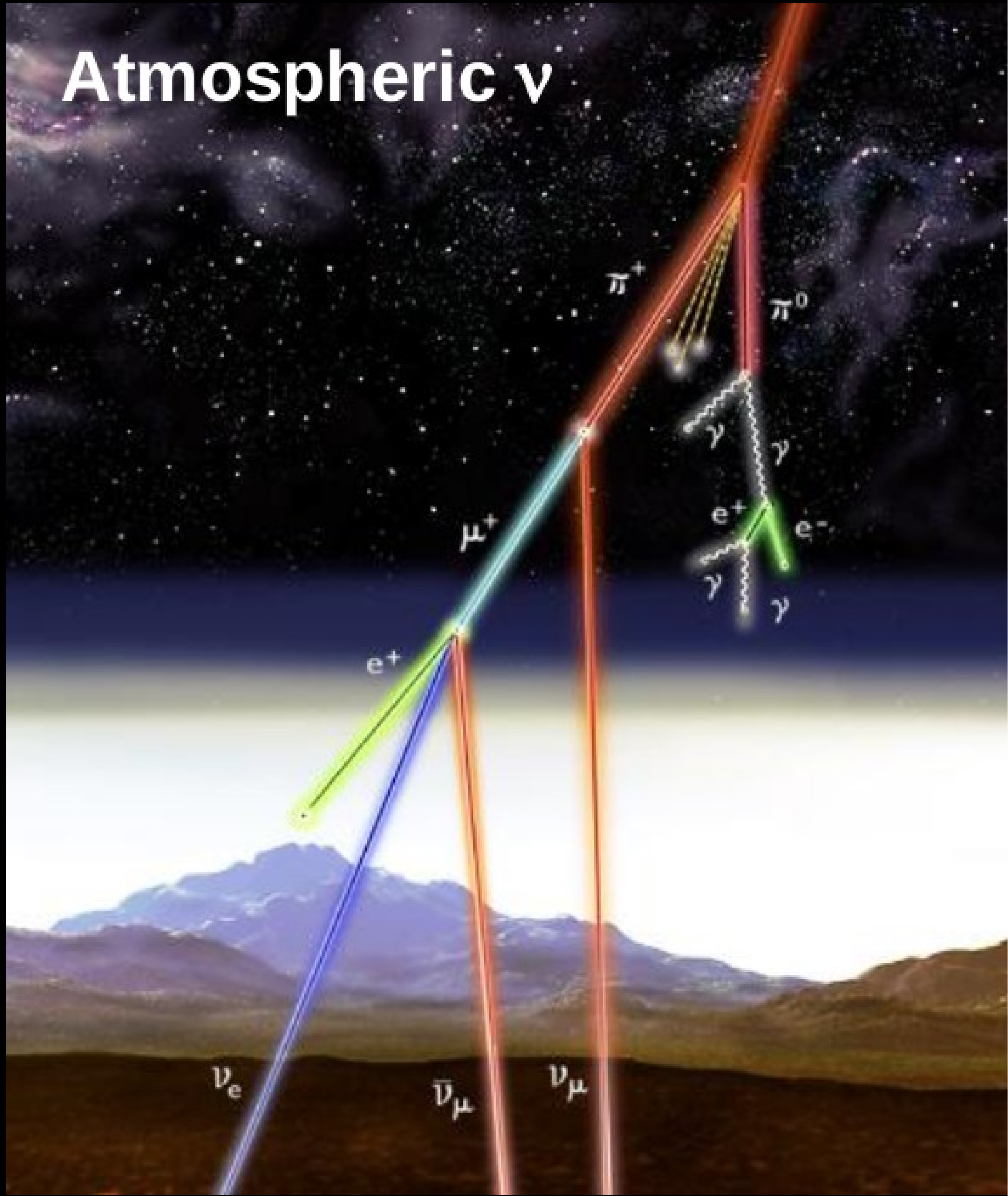
- Today I will mostly focus on ***atmospheric neutrino*** related physics at Super-Kamiokande but the high-energy working group studies several topics
  - Atmospheric neutrino flux
  - Atmospheric neutrino oscillations
  - Neutrinos with the T2K beam (See M. Hartz)
  - Nucleon Decay
  - Astrophysical Neutrinos

- This talk will highlight a few recent results
  - Neutrino Oscillations
  - Indirect WIMP Searches

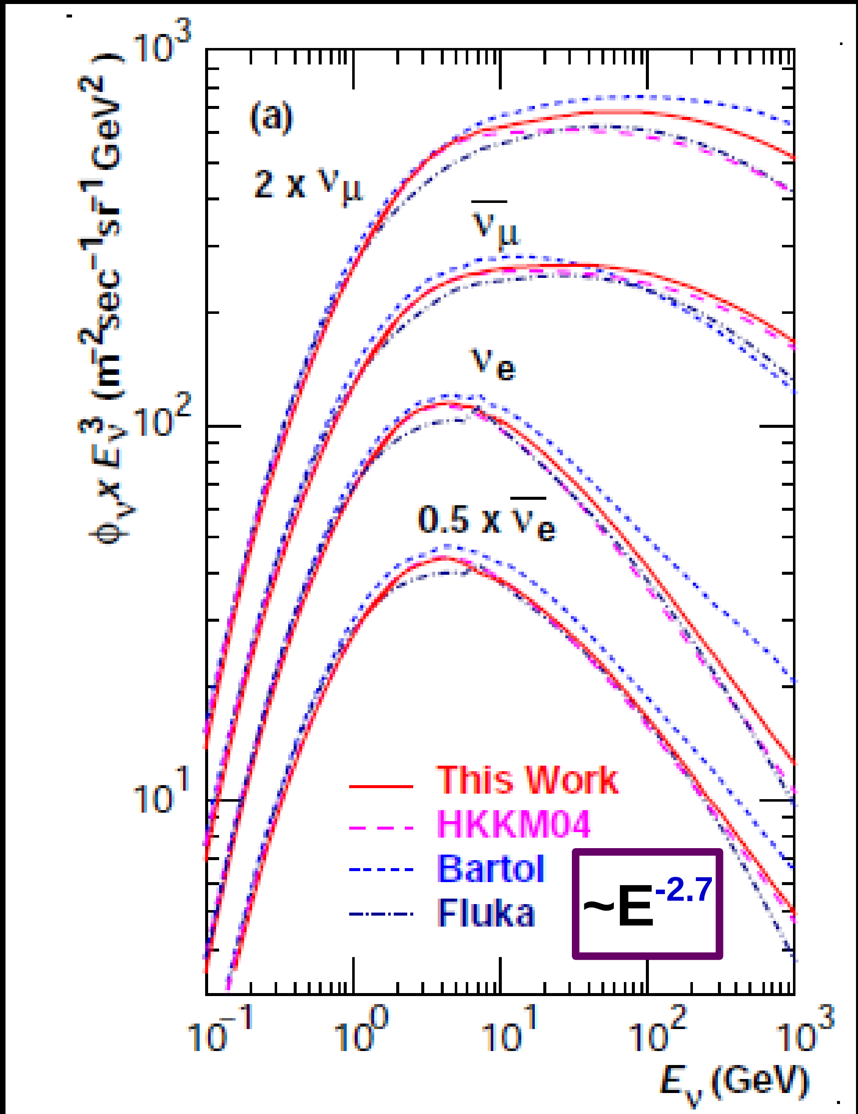
Primary Cosmic Ray Flux



Atmospheric ν



Atmospheric Neutrino Generation



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

$$P + A \rightarrow N + \pi^+ + x$$

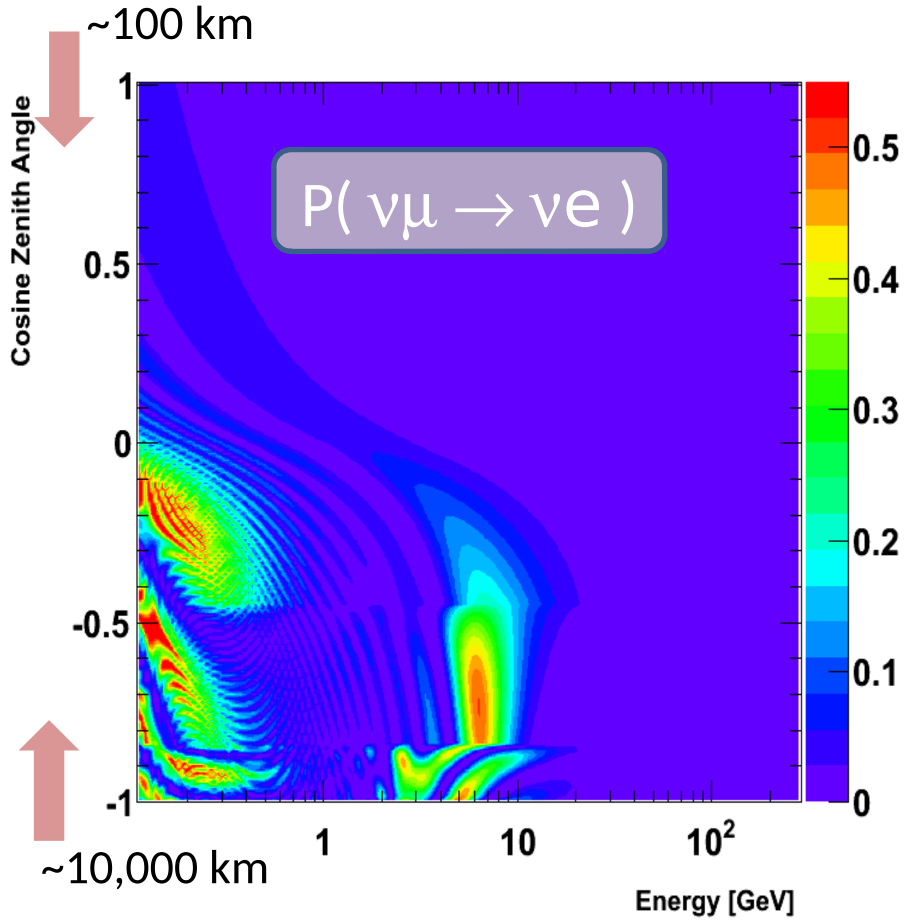
$$\hookrightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km
  - Unlike beam experiment we don't know the true direction of ATM nus
- 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

Atmospheric Neutrinos As Signal

	Large lAr or H20 Cherenkov	Iron Calorimeter	ν Telescope
"Atmospheric" and Neutrino Oscillations			
– $\Delta m2$	■	■	■
– Sin2θ23 , octant	■	■	
– Sin2θ13	■	■	■
– δcp	■		
– Mass Hierarchy	■	■	
– Exotic Scenarios	■	■	■
– τ Appearance	■	■	■
Earth Radiography	■		■
Resolution of Parameter Degeneracy (+ beam)	■	■	■
Measurement of prompt flux			■

- Large lAr or H20 Cherenkov
- Iron Calorimeter
- ν Telescope

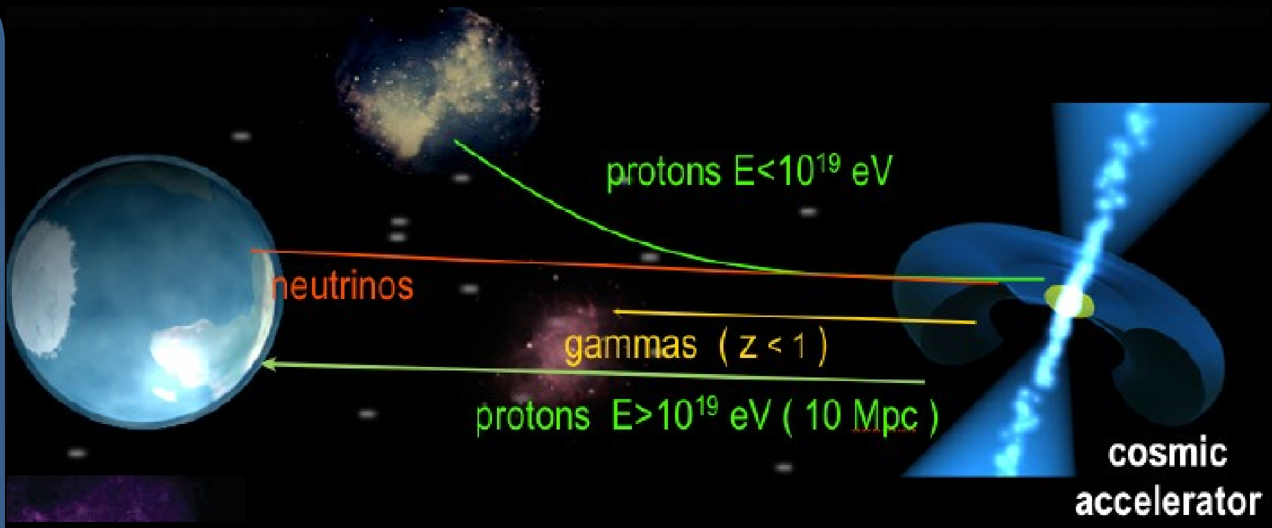


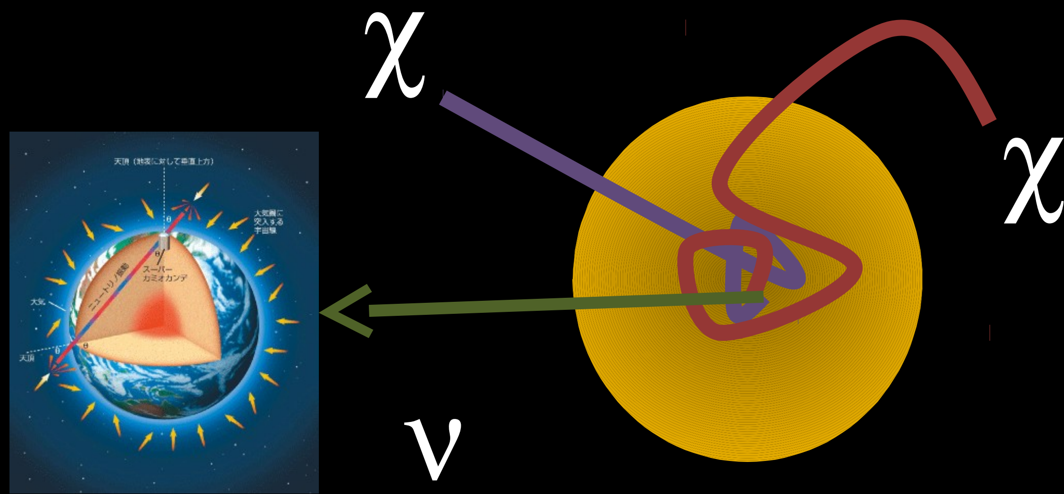
- Sensitivity to three-flavor oscillations via Earth-matter effects
- Resonance exists for either ν or ν bar
  - → hierarchy
  - Strength coupled to θ13

Atmospheric Neutrinos As Background

	Large lAr or H20 Cherenkov	Iron Calorimeter	ν Telescope
☐ Proton Decay	■	■	■
☐ Cosmogenic ν	■	■	■
☐ Point Sources			
☐ AGN			■
☐ GRB			■
☐ Solar Flares	■	■	
☐ Indirect Dark Matter	■	■	■
☐ Exotics			
☐ SUSY			
☐ CHAMPS			

- ☐ Understanding and characterization of these backgrounds is key for future measurements





Neutrino Oscillations

» Definite flavor eigenstates are mixture of eigenstates of hamiltonian

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Flavor Eigenstate **Mass State**

» For two neutrinos in vacuum:

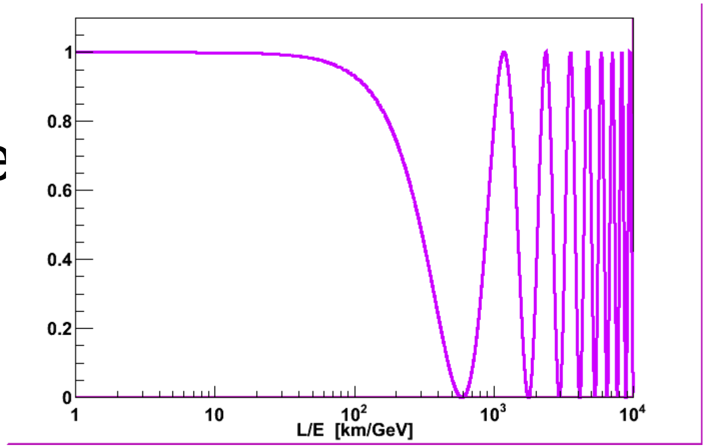
Baseline

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right) \quad \left[\frac{eV^2 km}{GeV}\right] \qquad \Delta m^2 \equiv m_2^2 - m_1^2$$

» Need at least one non-zero mass eigenvalue

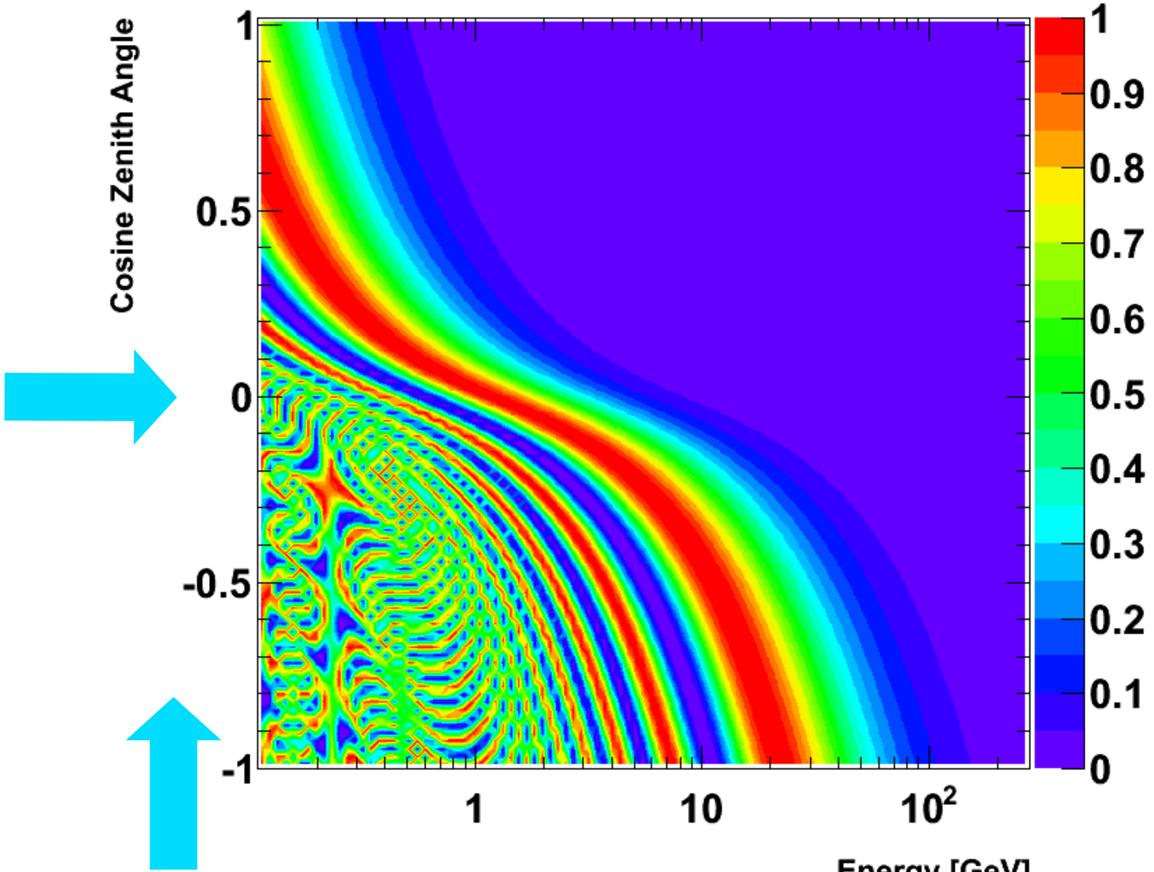
- $\Delta m^2 = m_i^2 - m_j^2 \neq 0$

» Non-zero mixing angle θ



Two-Flavor Atmospheric Oscillations

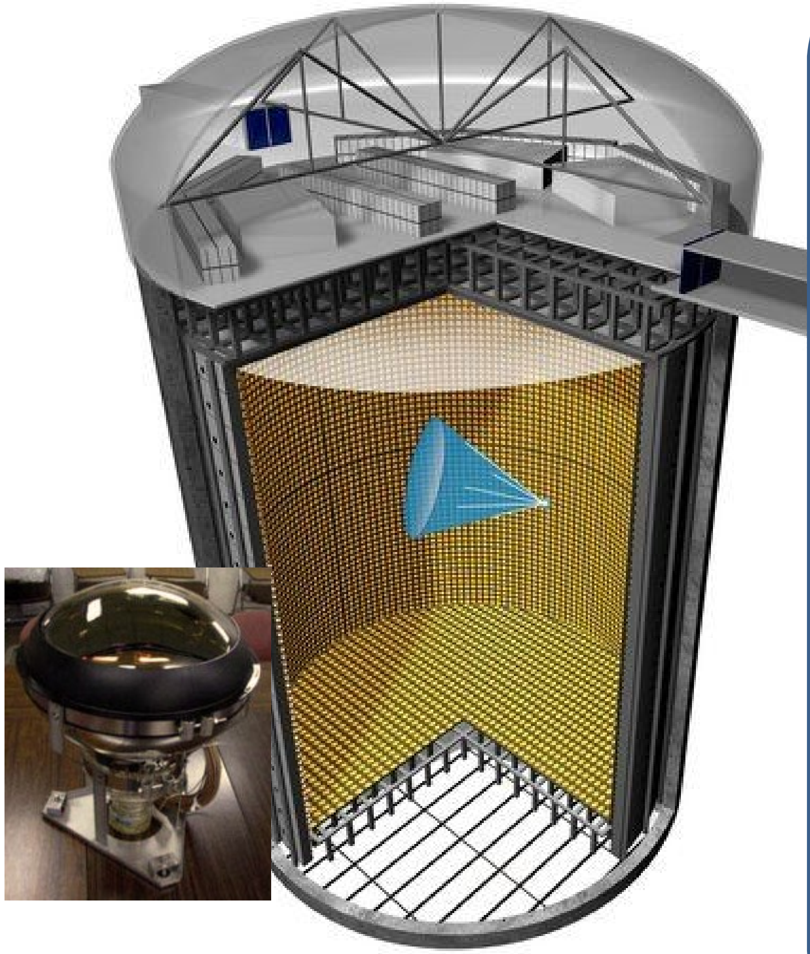
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) \quad \left[\frac{eV^2\, km}{GeV}\right] \quad \Delta m^2 \equiv m_2^2 - m_1^2$$



Upward-going events have opportunity to oscillate away

$\nu_\mu \to \nu_\tau$ is the dominant oscillation mode at SK

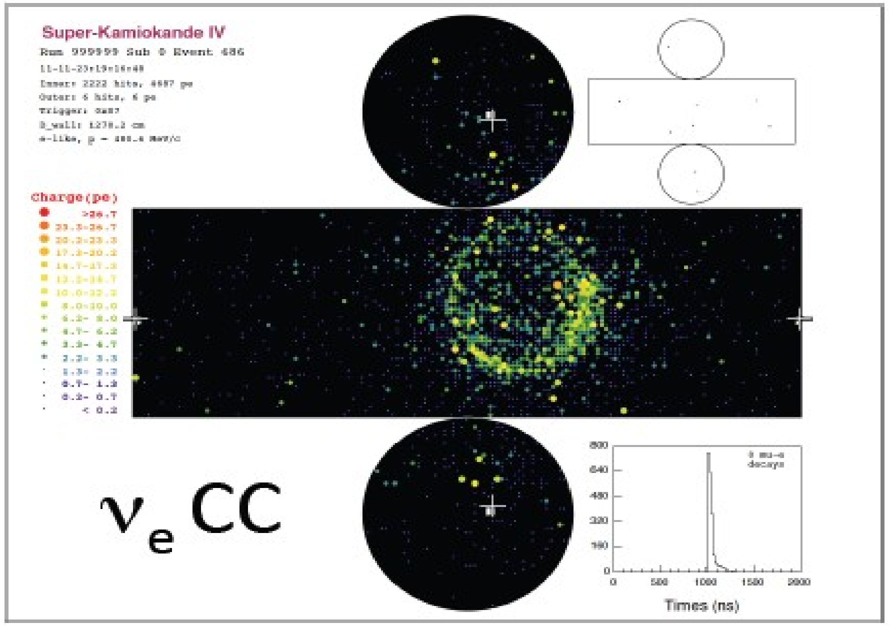
Super-Kamiokande : Introduction

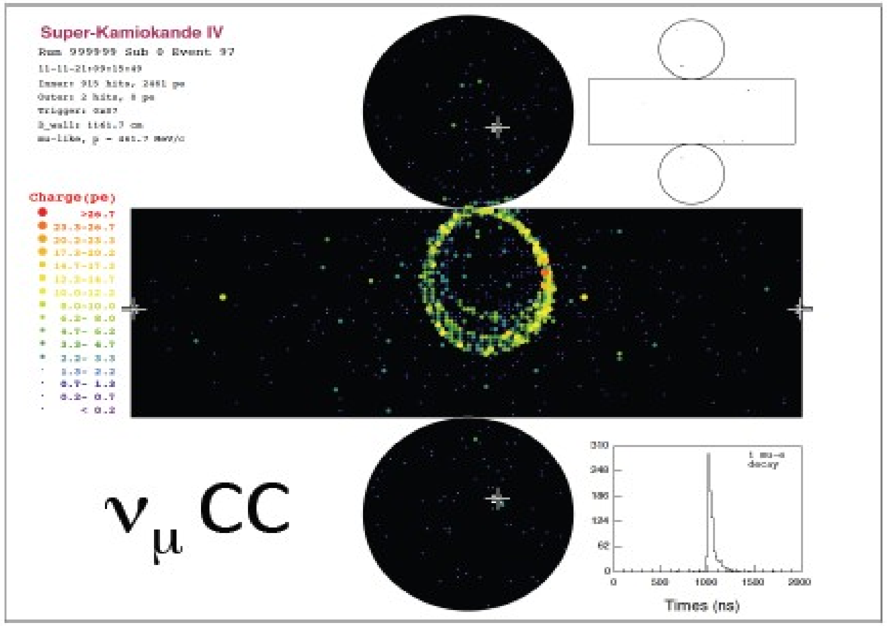


- 22.5 kton FV Volume
- Ring Imaging Water Cherenkov detector
- 11,1146 20” Phototubes
- Data taken over four periods since 1996

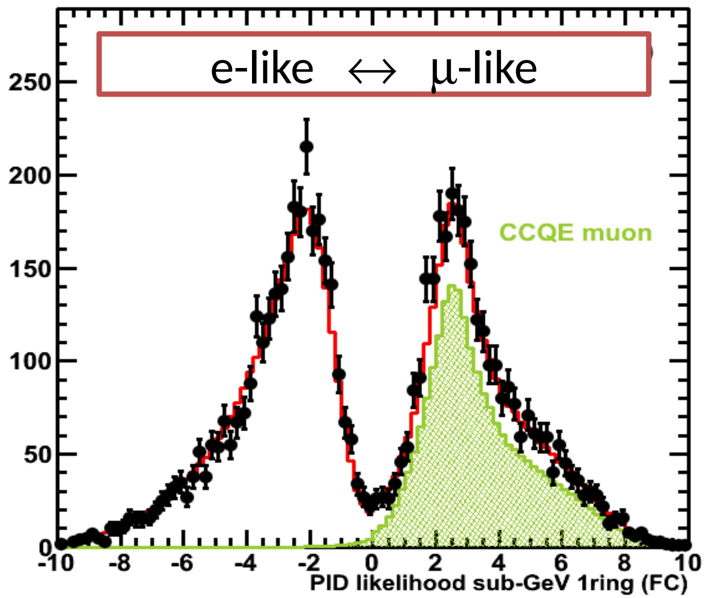
- SK discovered atmospheric neutrino oscillations exploiting the disappearance of upward-going muon events
- Event samples are classified by
  - Number of rings (**Single-** or **Multiple-**)
  - PID of out-going lepton (**e-** or **μ**-like)
  - Event energy is **fully** or **partially** contained
  - Upward-going muons
- Today: **3903 days of atmospheric data**
  - ~34,000 Events
- Currently **statistics limited**
- No net magnetic or electric fields
- Sitting at 2.5 degrees off-axis of the T2K beam

Electron and Muon PID at Super-K

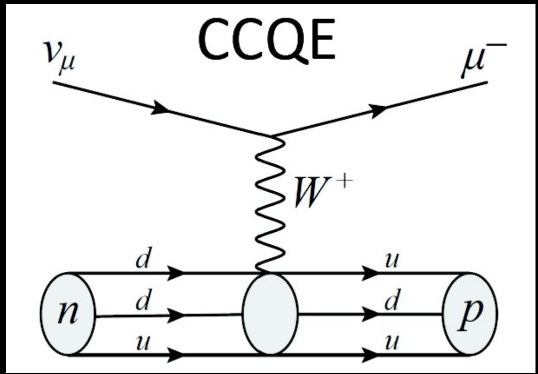


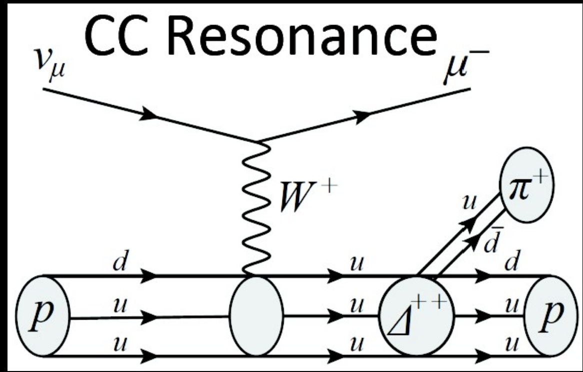


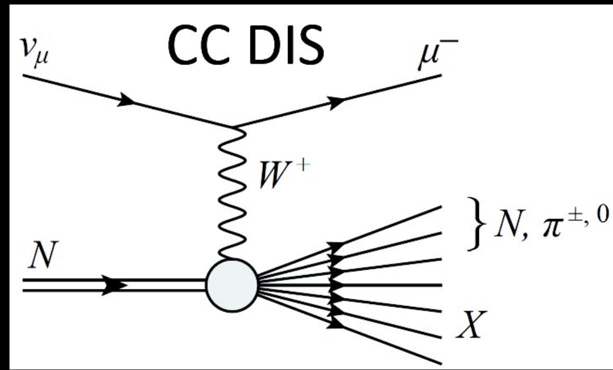
- Particle ID is based on both the cherenkov opening angle and the observed ring pattern
- Probability that a muon is **mis-**reconstructed as an electron is less than 1%
- Expect very low ν_μ contamination in the single-ring e-like samples and vice versa

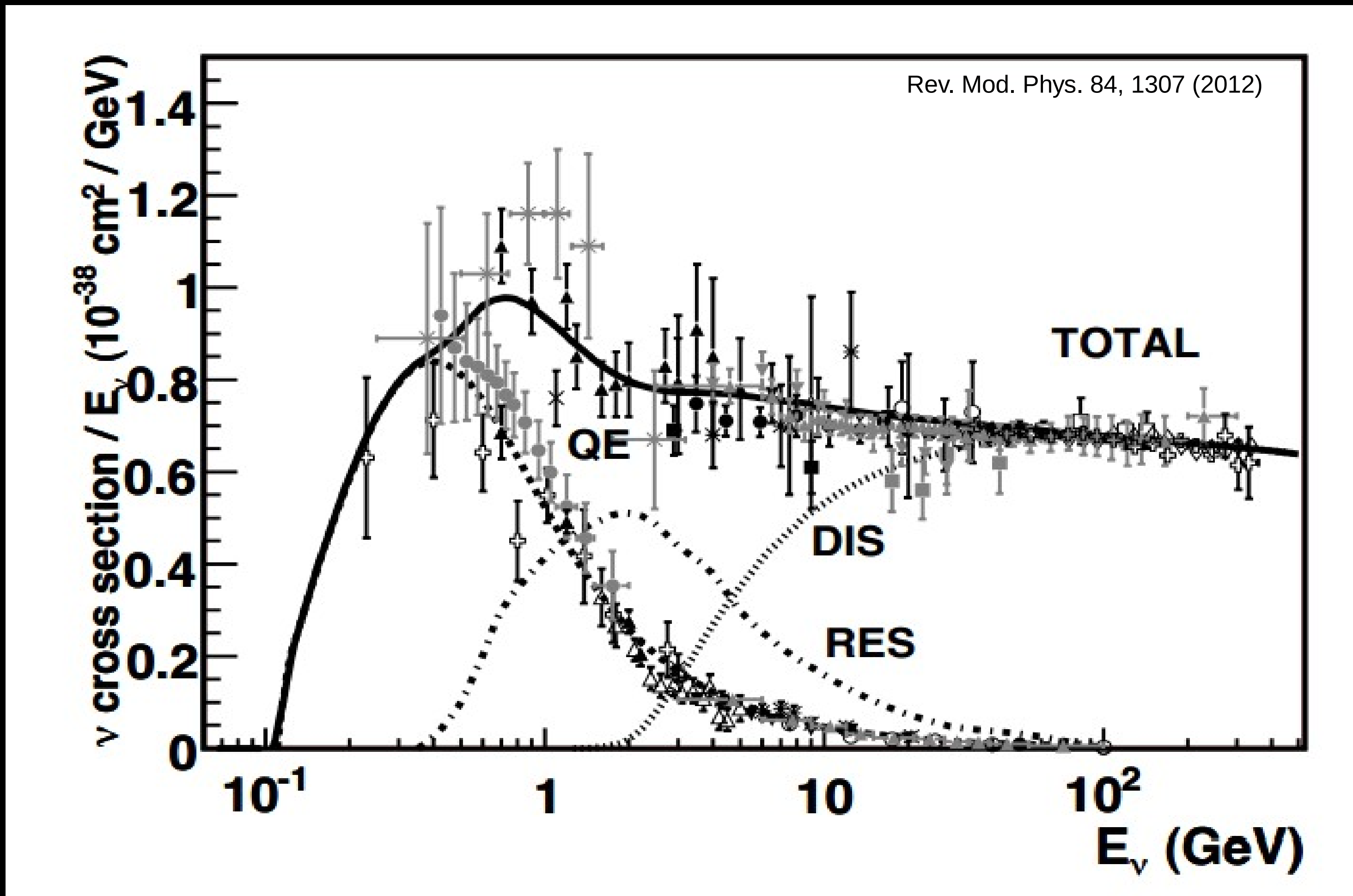


Neutrino Interactions

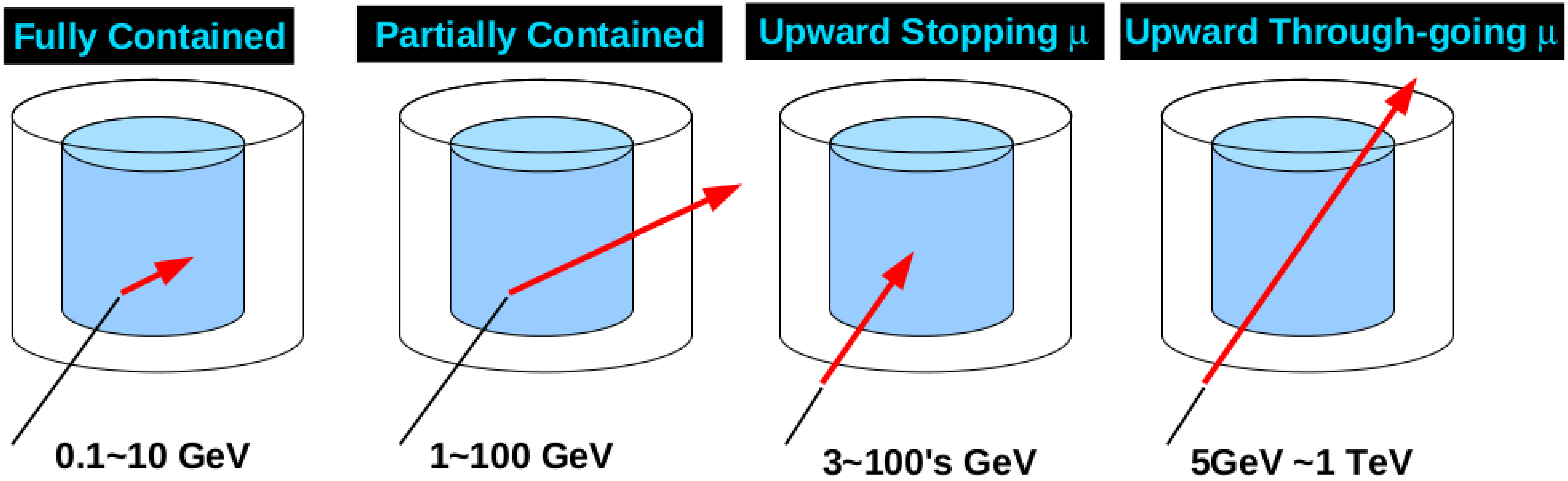






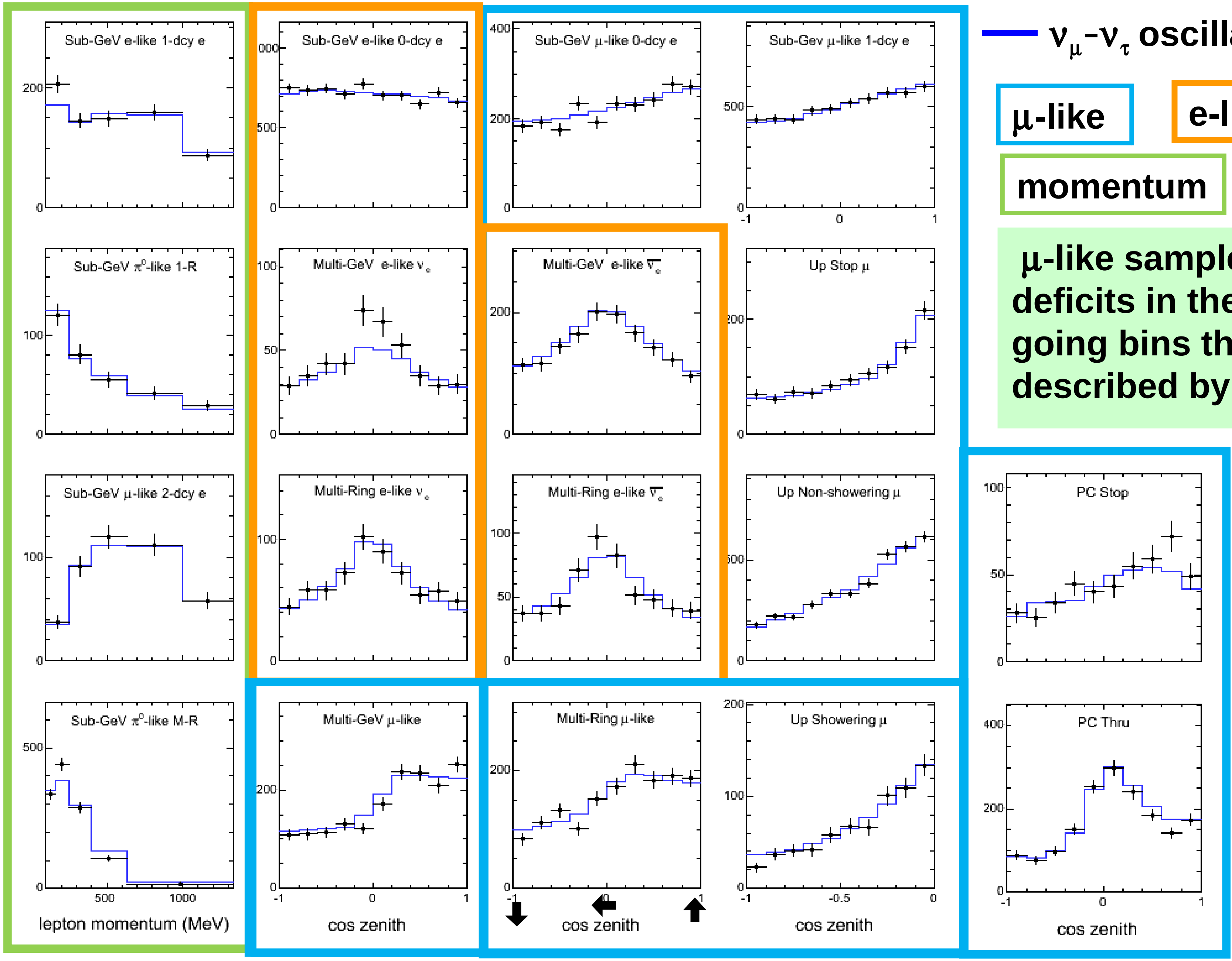


Event Topologies



- Fully Contaned events
  - Average energy ~ 1 GeV , leave no light in the outer detector
  - Divided into several samples based on number of visible rings and their PID
- Partially Contained events
  - Initial vertex is within the SK fiducial volume but with a particle exiting into OD
  - Average Energy ~ 10 GeV
- Upward-going muons
  - Neutrino interaction in the surrounding rock with an entering muon
  - Average Energy ~100 GeV

Zenith angle & lepton momentum distributions : SK-I+II+III+IV



$\nu_\mu - \nu_\tau$ oscillation (best fit)

μ-like

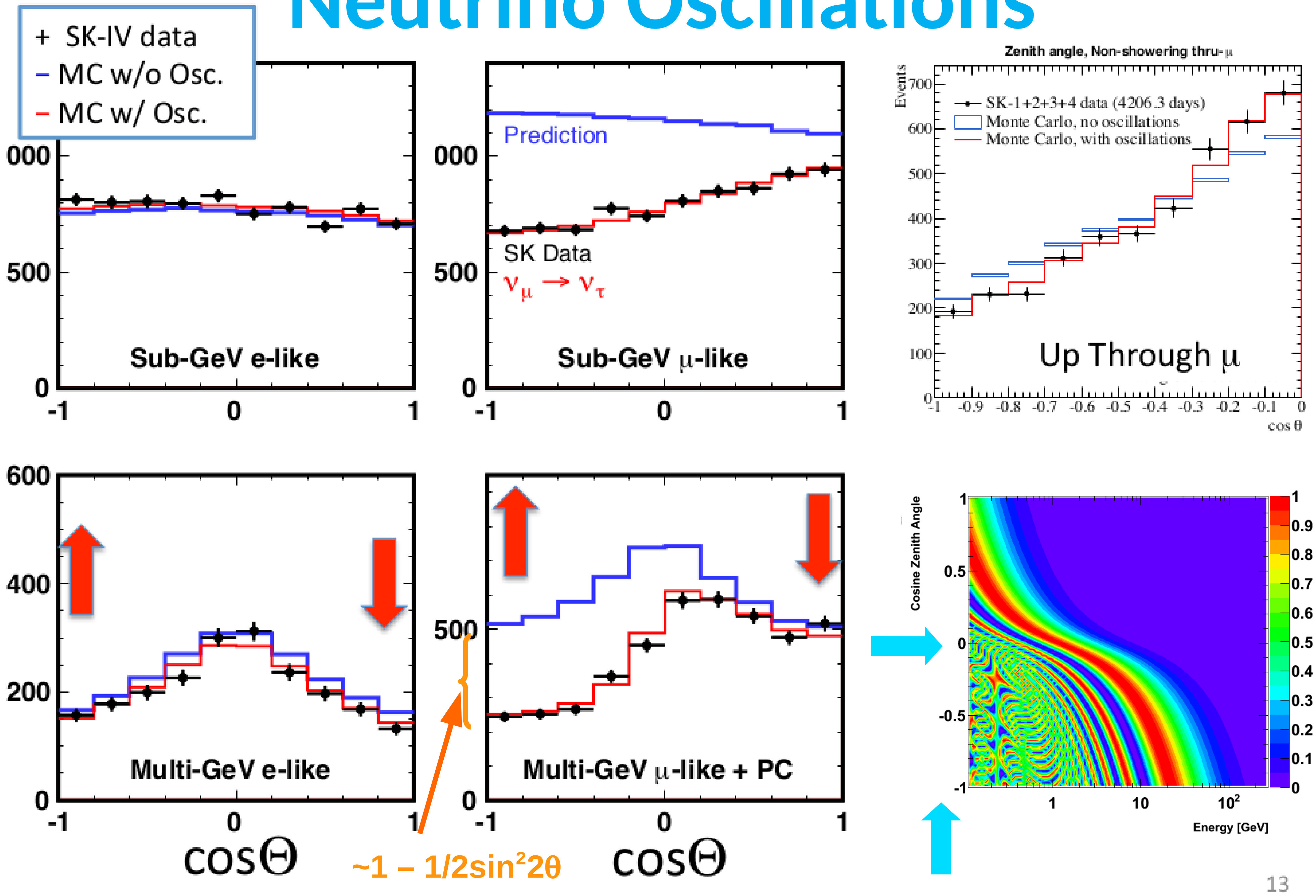
e-like

momentum

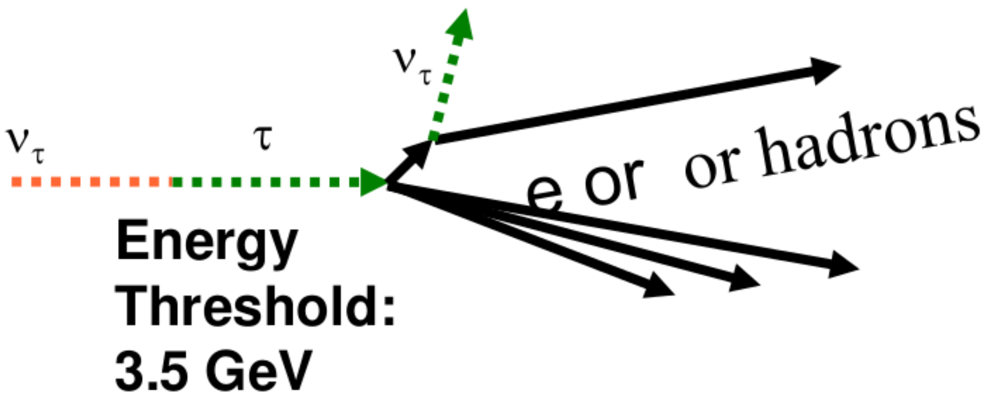
μ-like samples show large deficits in the upward-going bins that are well described by oscillations

Preliminary

Neutrino Oscillations

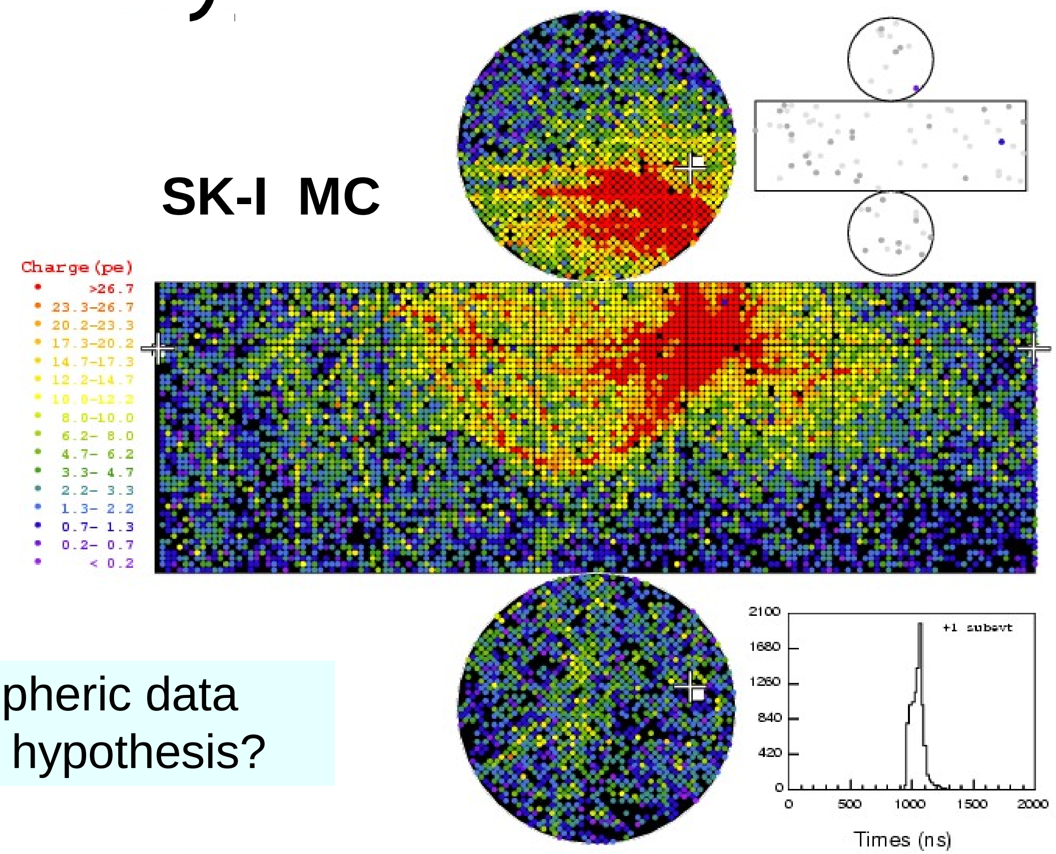


ν_τ Events at Super-K



- 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

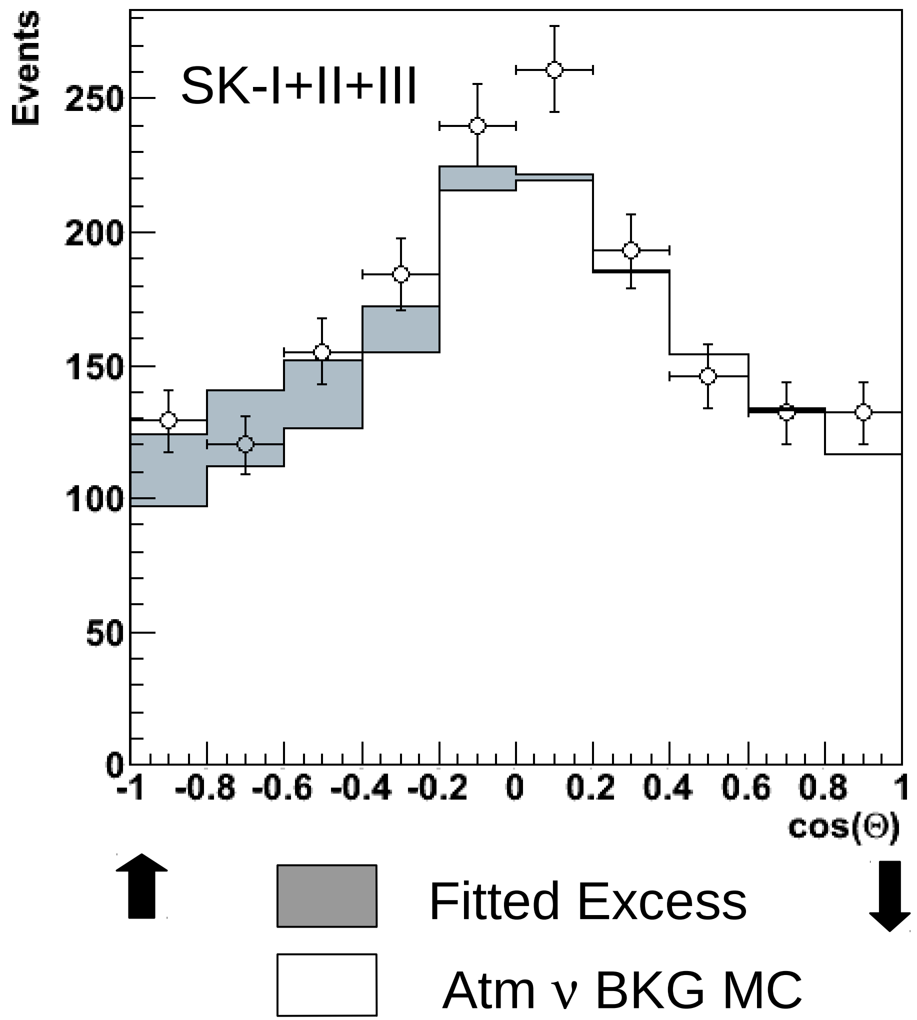


GOAL : Observe $\nu\tau$ events in the atmospheric data
How inconsistent is the "no appearance" hypothesis?

Fit Results, 2806 days

If no ντ appearance , β = 0

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

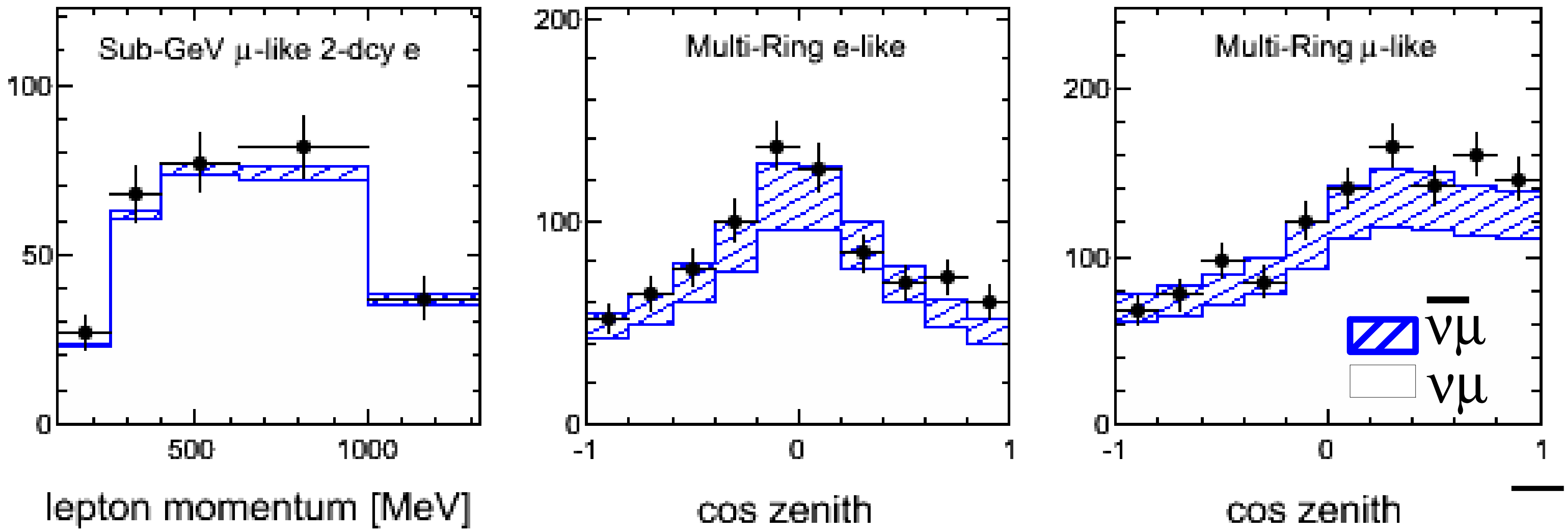


Result	Background	Signal
SK-I	0.95	1.27
SK-II	0.96	1.47
SK-III	0.94	2.16
SK-I+II+III	0.94 ± 0.02	**1.42 ± 0.35**
DIS γ	1.10 ± 0.05	

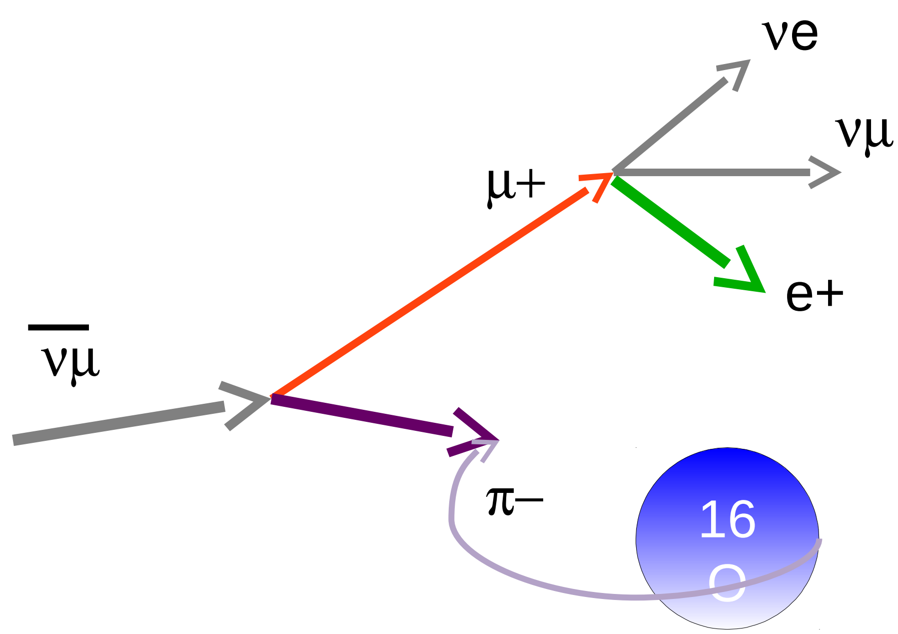
- Tau signal clearly appears in upward-going region
- Tau normalization fits to $1.42 \times$ expectation

This corresponds to **180.1** ± 44.3 (stat) +17.8-15.2 (sys) events a **3.8 σ** excess
(Expected 2.7 σ significance)

Neutrino and Anti-neutrino events at Super-K

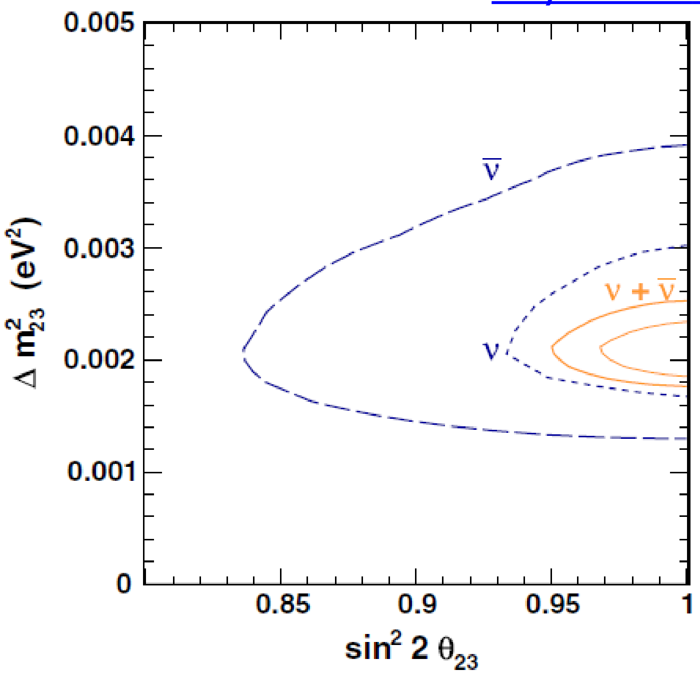


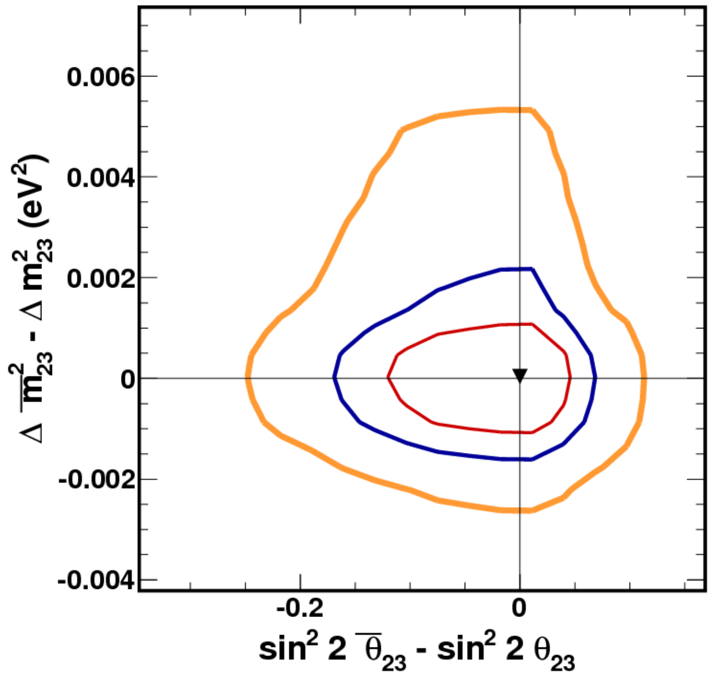
- In principal SK cannot distinguish between neutrino and anti-neutrino interactions on an event-by-event basis
- However, differences in the fluxes and cross sections (energy depenent) and the effects of pion absorption in water change the relative composition the event samples
- It is possible to study neutrino and antineutrino oscillation separately!



ad hoc CPT Violation Test Results

Phys. Rev. Lett. 107, 241801 (2011)





ν	Best Fit
Δm^2	2.1×10^{-3} eV^2
$\sin^2 2\theta$	1.0

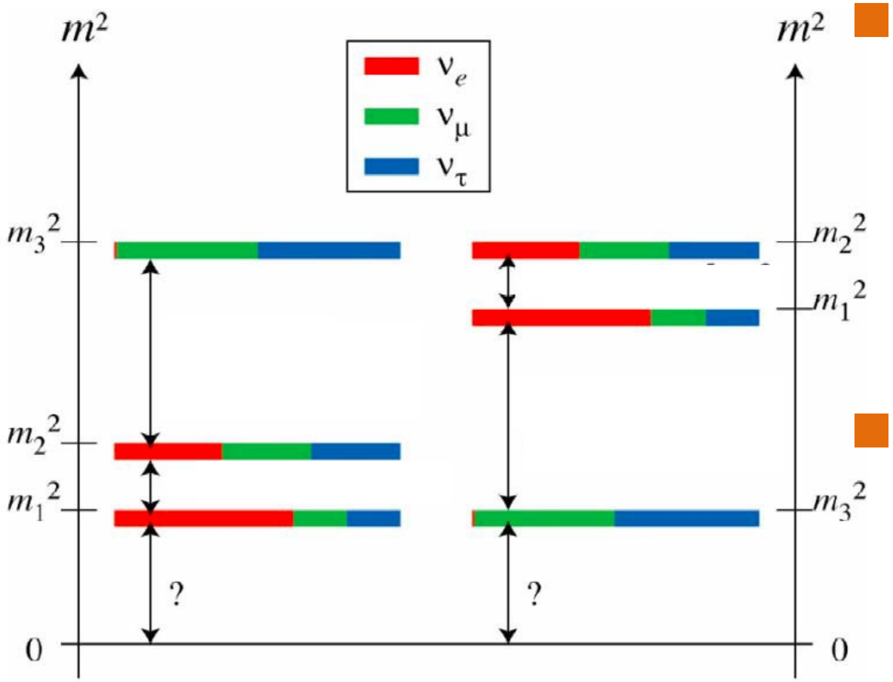
$\bar{\nu}$	Best Fit
$\Delta \bar{m}^2$	2.0×10^{-3} eV^2
$\sin^2 2\bar{\theta}$	1.0

- Essentially the underlying SK MC can be oscillated separately between neutrinos and antinteurinos when fitting the data
  - (Anti-nu)MC^{osc} + (nu) MC^{osc} =? Data
- No evidence seen for a difference in the oscillation of neutrinos and oscillations seen
  - No adhoc CPT violation indicated in SK data

Status of Neutrino Oscillations

Atmospheric | Solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 0 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

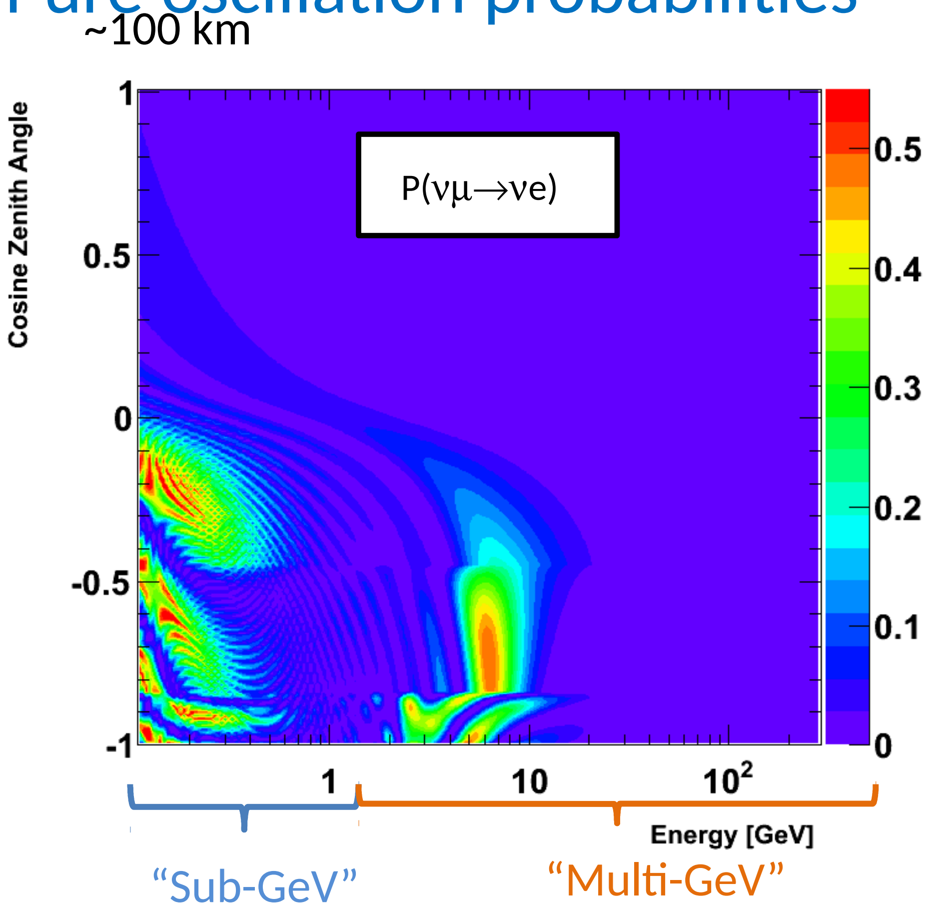


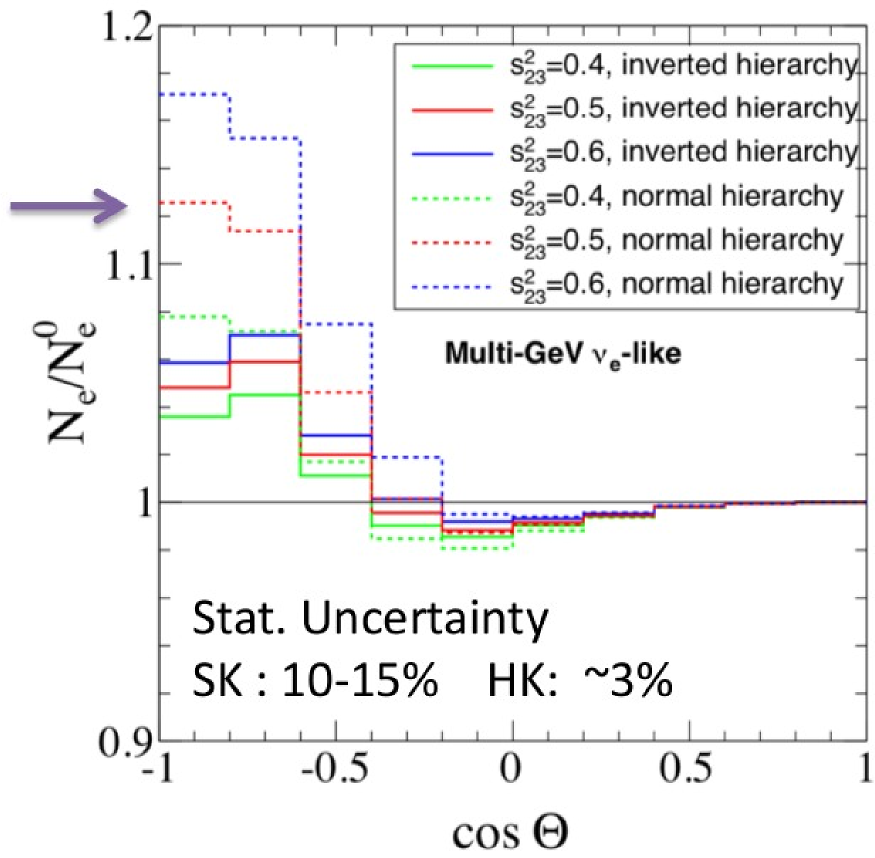
Normal Hierarchy

Inverted Hierarchy

- Mixing between all three neutrino flavors has been observed
  - $\theta_{12} = 33.6 \pm 1.0°$
  - $\theta_{13} = 9.1 \pm 0.6°$
  - $\theta_{23} = 45 \pm 6°$ (octant?)
- Two Mass Differences
  - Δm^2_{12} ~ 7.6e-5 eV^2
  - $|\Delta m^2_{32}|$ ~ 2.4e-3 eV^2 (hierarchy?)
- CP-phase ,δcp remains unkown
- Absolute value of mass states is unknown

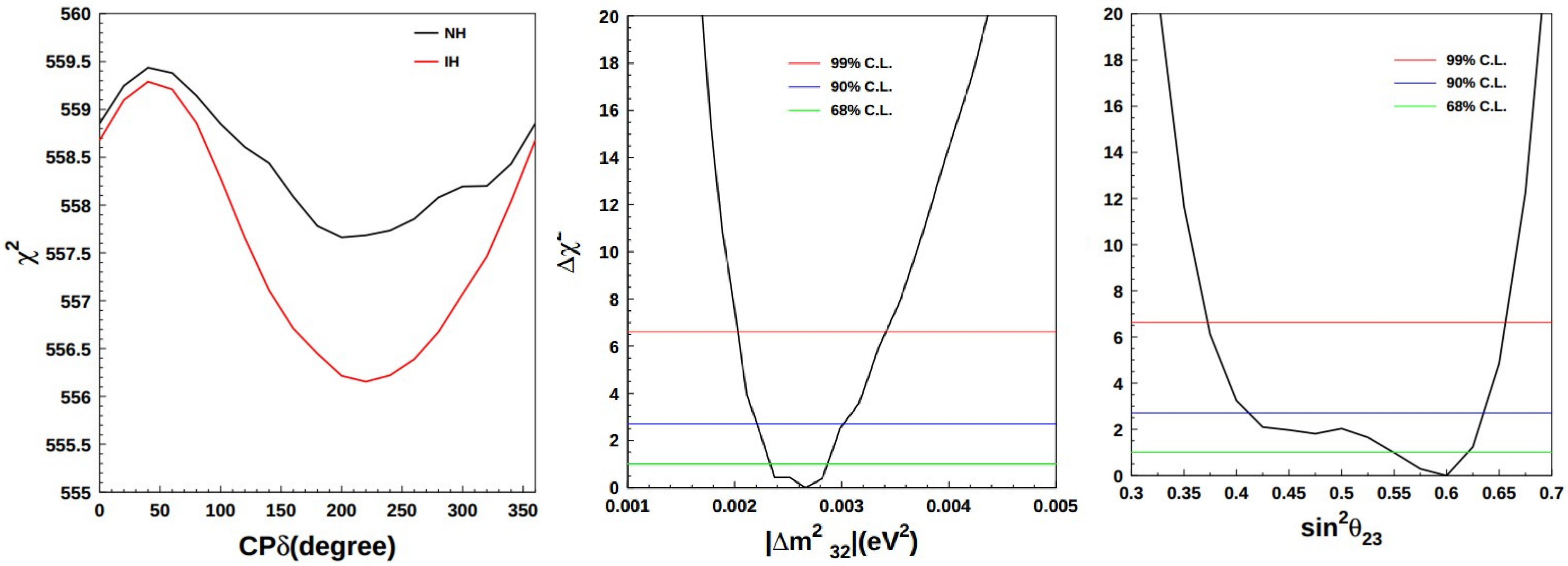
Pure oscillation probabilities





- In the presences of the now large θ_{13} resonant enhancement of the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability occurs via matter interactions
- Resonance occurs only for (anti-)neutrinos under the Normal (Inverted) Hierarchy. Effects on total event rate are roughly halved going to the IH

Putting it all together – ThreeFlavor Oscillations



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

$\chi 2min$ (NH) - $\chi 2min$ (IH) = 1.5

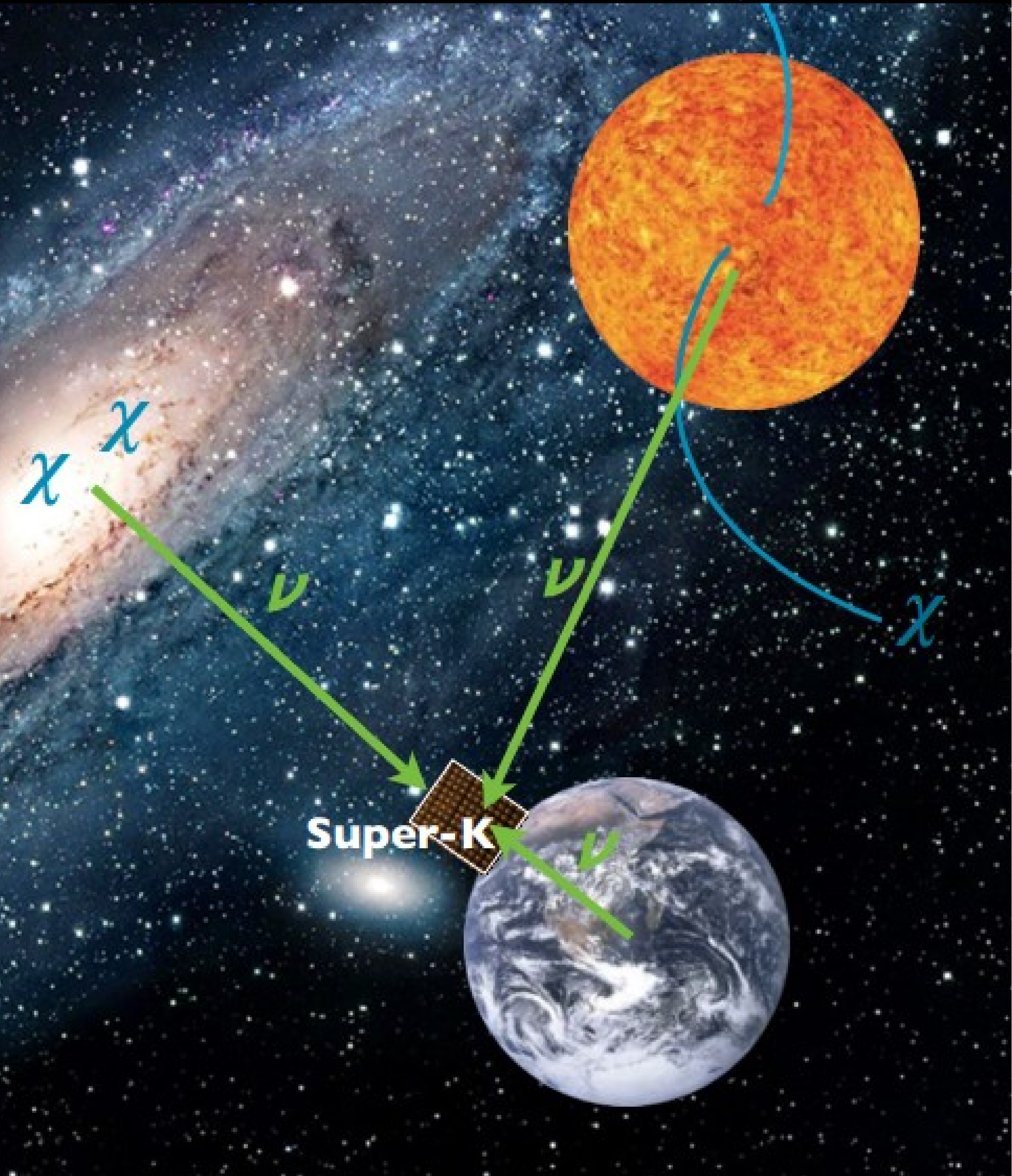
- Weak hints for non-maximal mixing
- Weak preference for the inverted hierarchy
- Slight indication of $\delta_{cp} \sim 3\pi/2$
- Statistics limited!

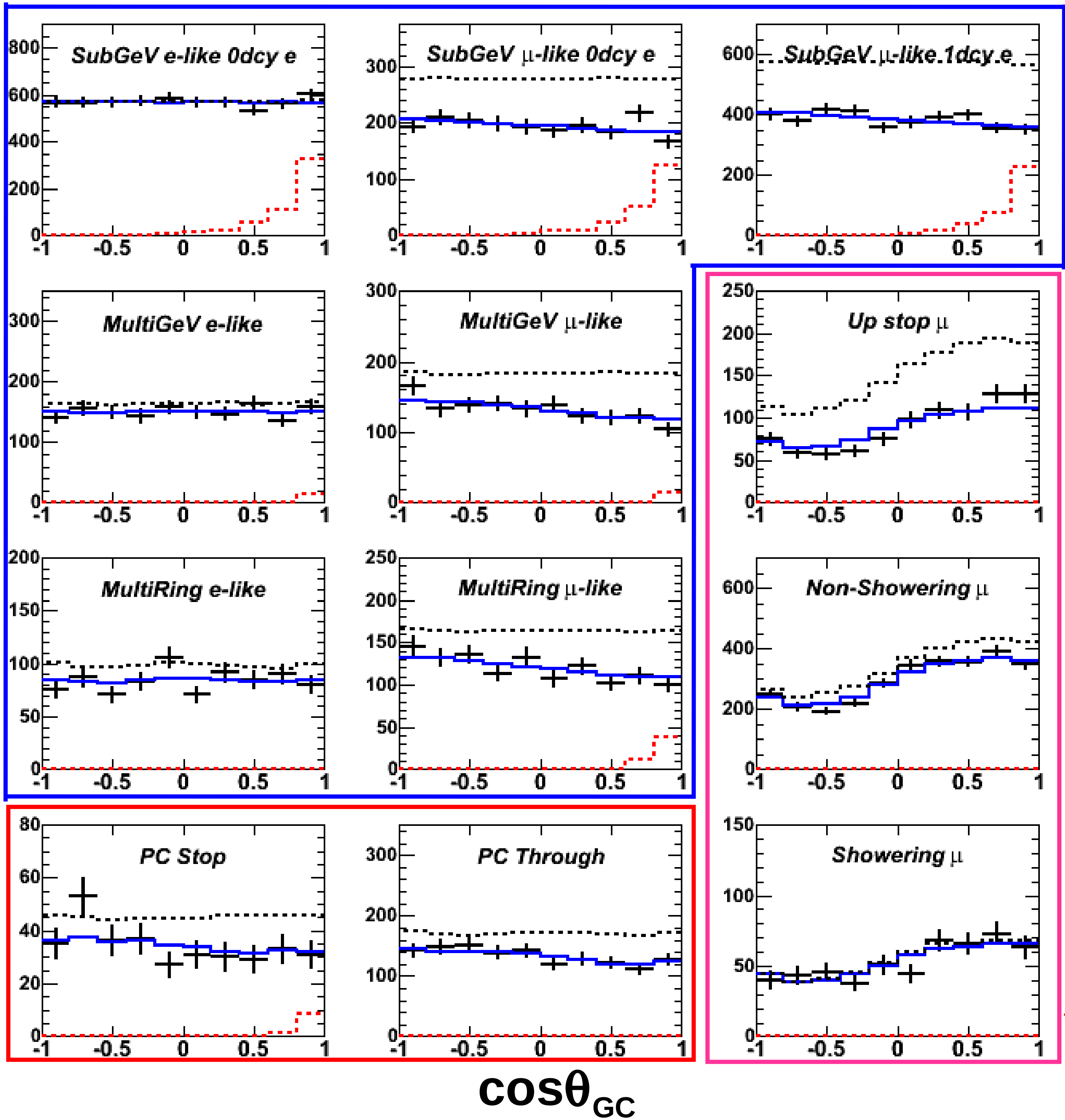
Atmospheric Neutrinos as Background: Indirect WIMP Searches

- Currently looking at the Galactic center, halo, Sun and Earth
- Atmospheric neutrinos(GeV) produced by cosmic rays are back ground.

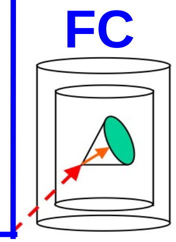
- **Indirect detection allows a sensitive probe of a wide range of dark matter masses**
- ***Assumptions about the source distribution and neutrino production mode are required (annihilation, decay, what channels)**

$$\chi\chi \rightarrow \begin{matrix} q\bar{q}\left(c\bar{c}, b\bar{b}, t\bar{t}, \ldots\right) \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \rightarrow \ldots\ldots \rightarrow \nu\ , \gamma, \bar{e}, \bar{p}, \overline{H}_2,$$



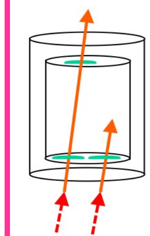


DM signal illustration



M_χ = 1.3 GeV

- Assume annihilation into **nu-nubar**



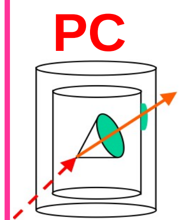
- Bin in angle to the galactic center

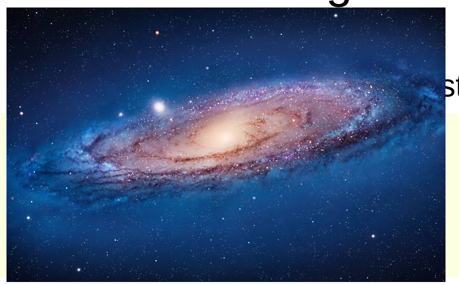
DATA
SK1,2,3

OSC ATM MC

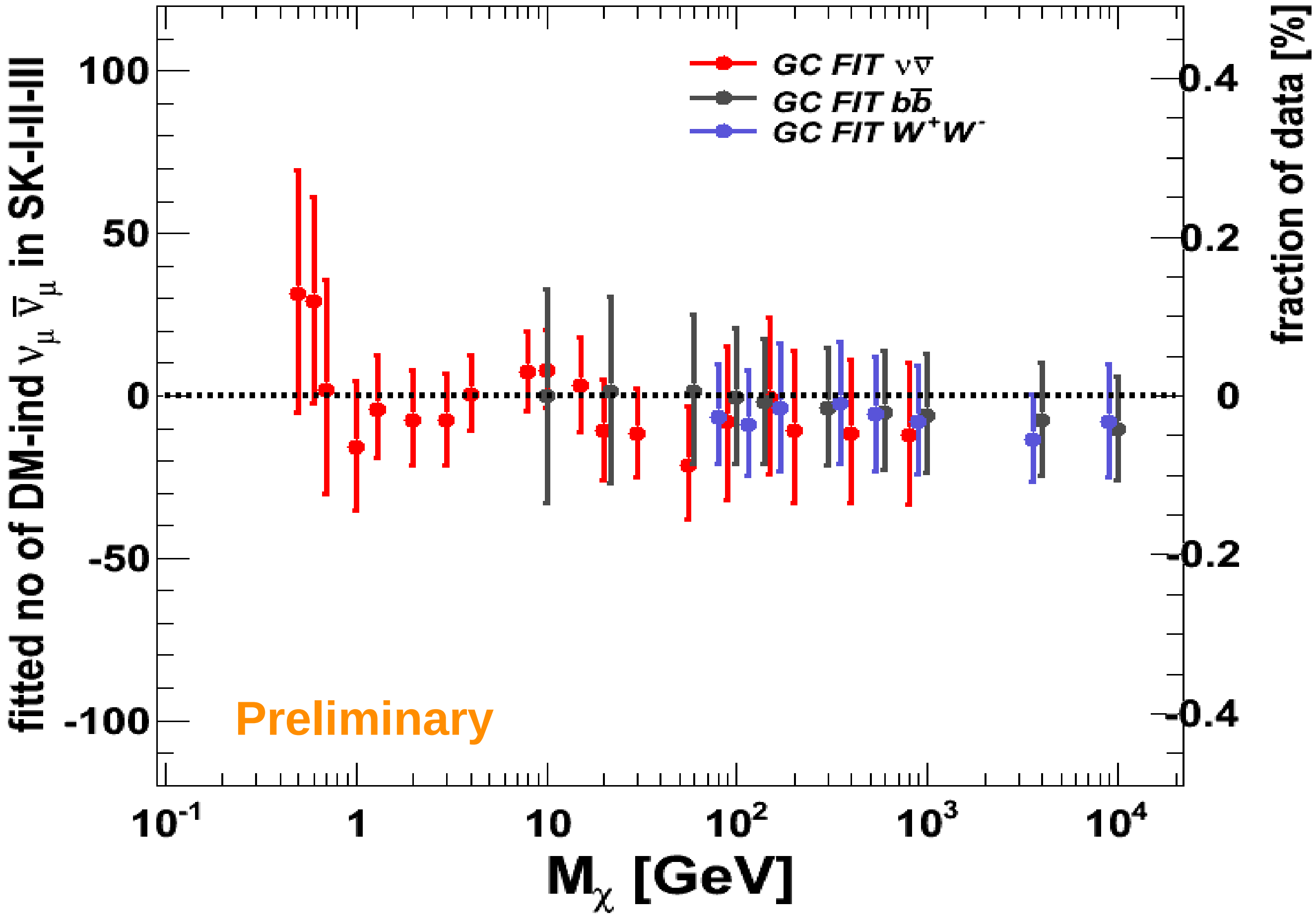
NON-OSC ATM MC

DM signal



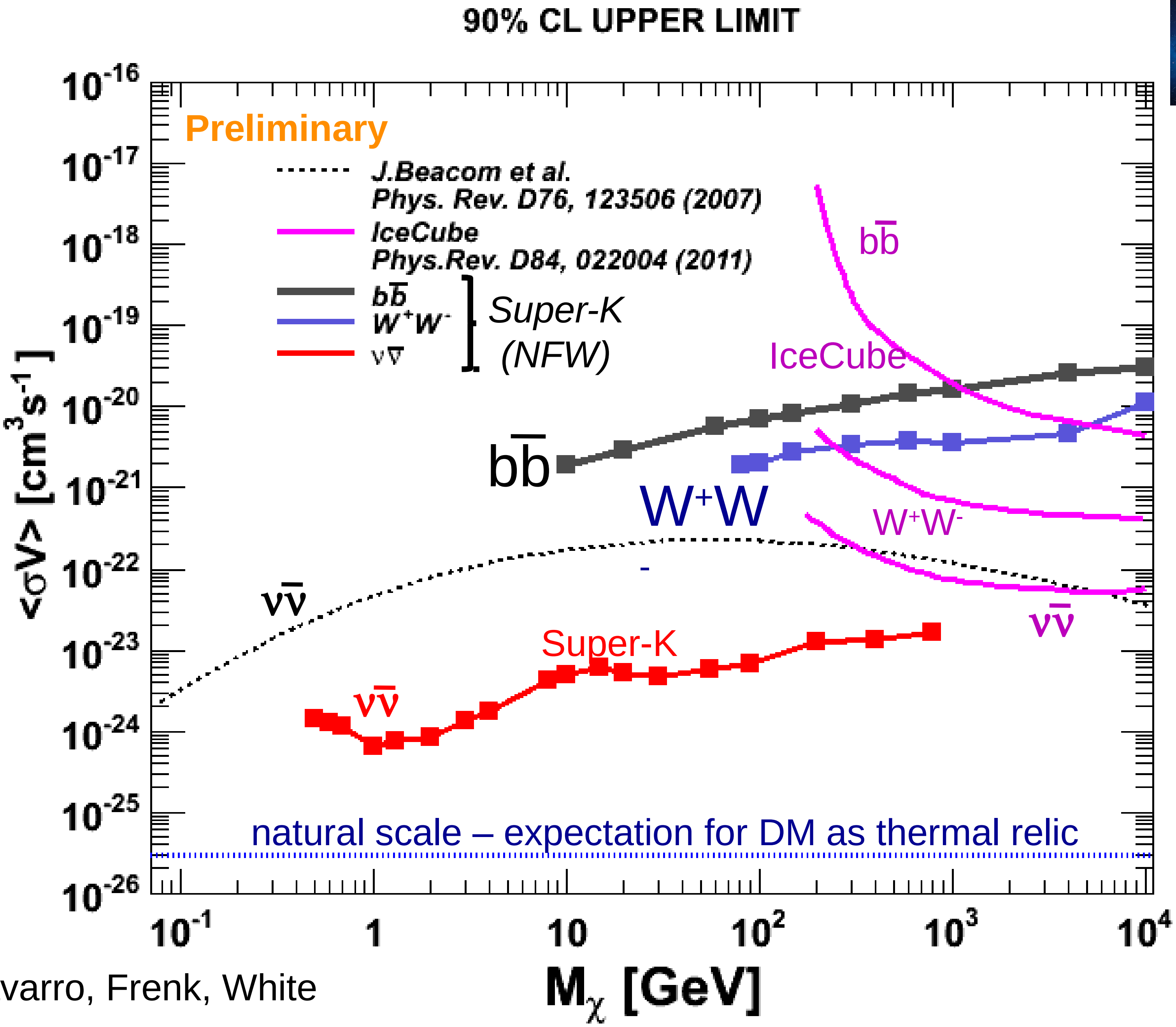


Repeat this process for many masses and annihilation scenarios



- No indication of an allowed WIMP excess of neutrinos between for WIMP masses between 500 MeV and 800 GeV
- This can be converted into a limit on the DM self annihilation cross-section (averaged over an assumed velocity distribution)

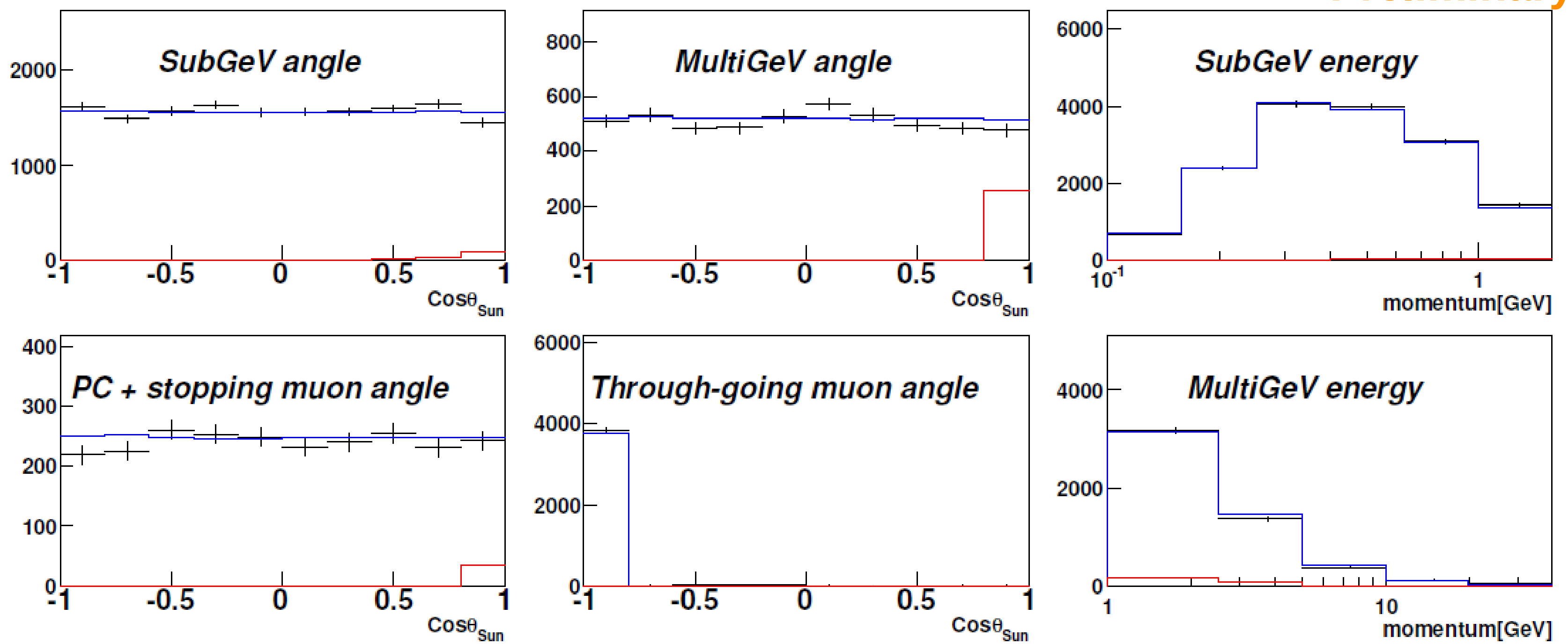
Limits for the Search for a Neutrino excess from the GC



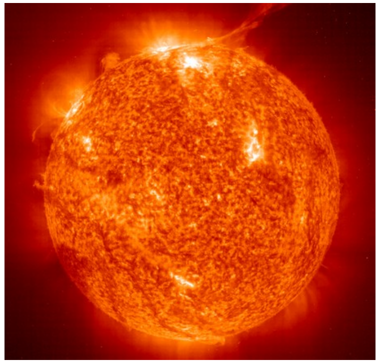
NFW – Navarro, Frenk, White

WIMP-Induced Neutrino Events from the Sun

Preliminary

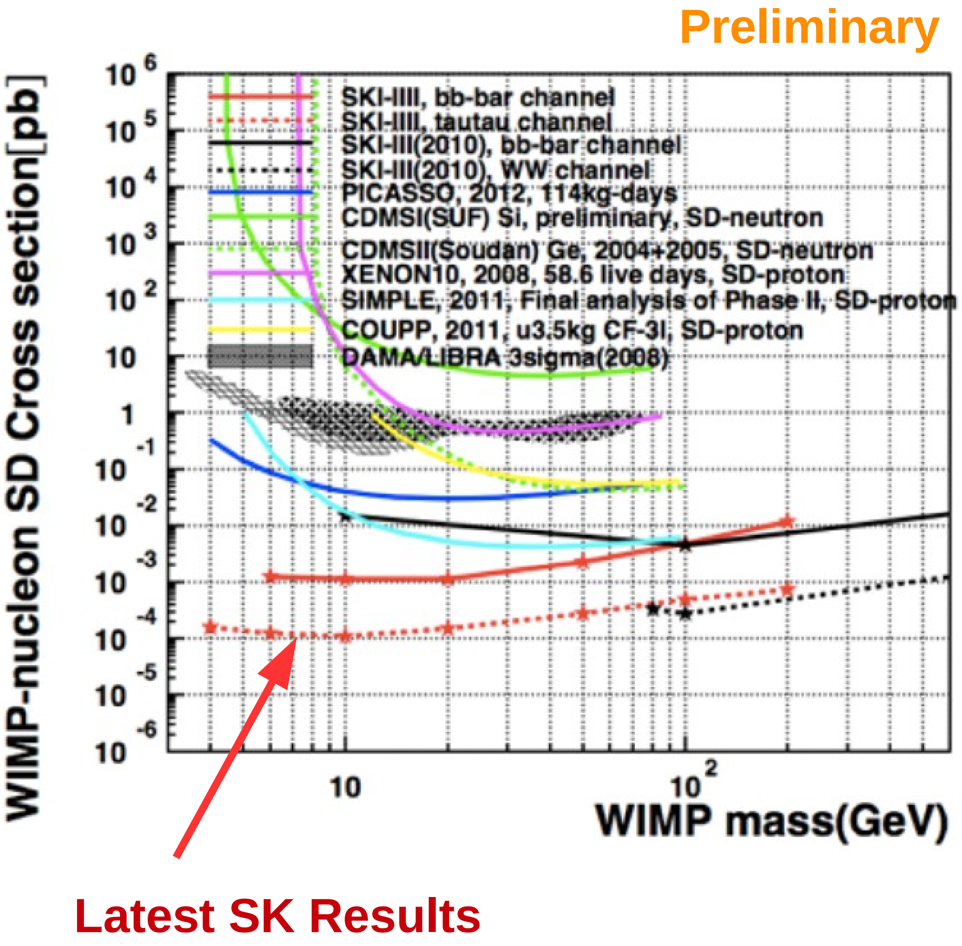


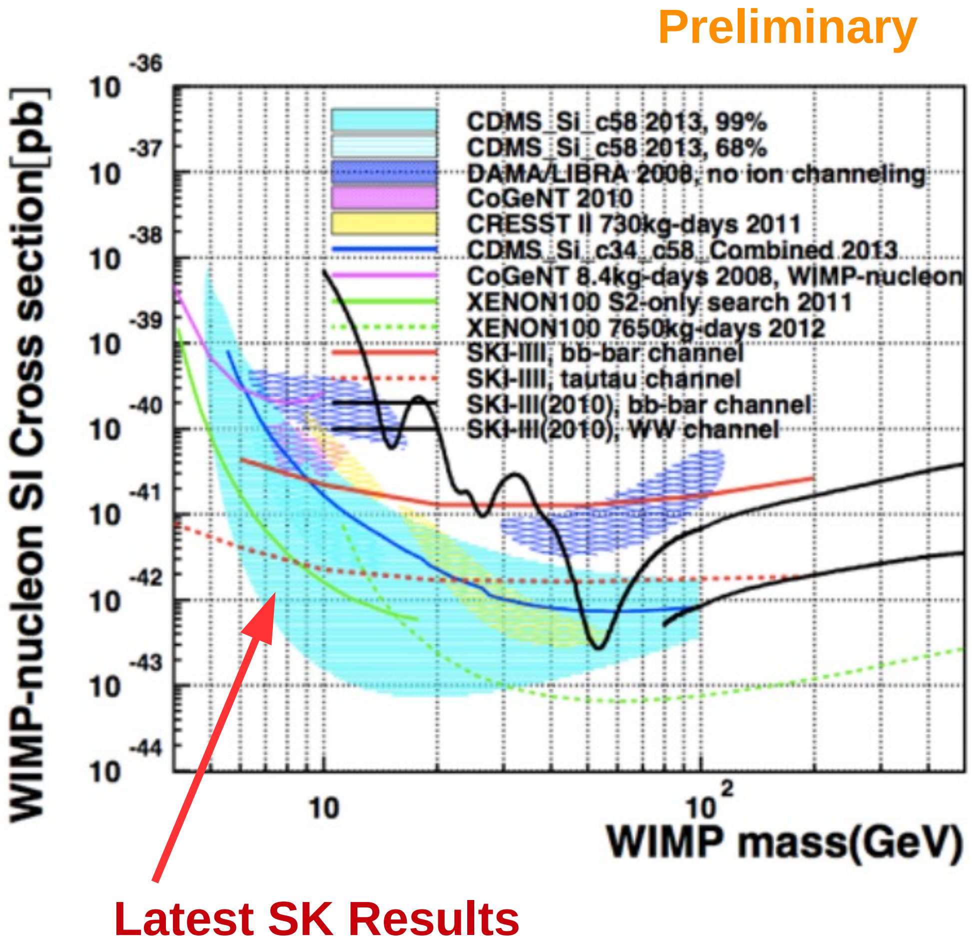
10 GeV Annihilation signal int b-bbar from the sun



- The same kind of search can be done assuming DM annihilation in the sun
  - Fit atmospheric neutrino data in bins of the direction to the sun
- Focus on lower mass WIMPS
- No evidence for an excess of neutrino events coming from the sun

WIMP Nucleon Cross-section results





- Assumes standard dark matter halo profile, local density of 0.3 GeV/cm3
- Maxewellian velocity distribution v ~ 270 km/s
- Assumption of equilibrium between dark matter capture and annihilation within the sun needed to relate excess neutrinos to WIMP-Nucleon σ

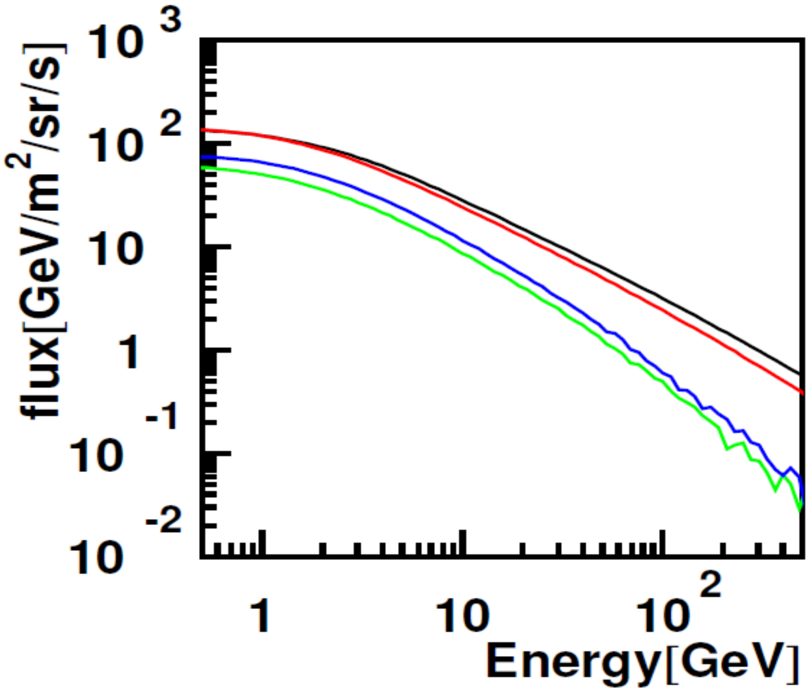
Summary

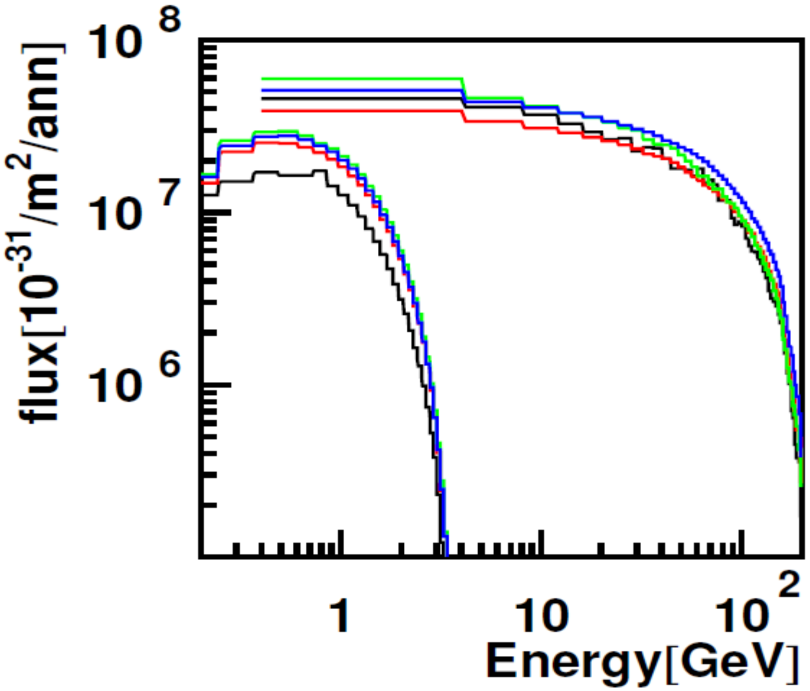
- Super-Kamiokande has access to a wide variety of physics using its high-energy samples

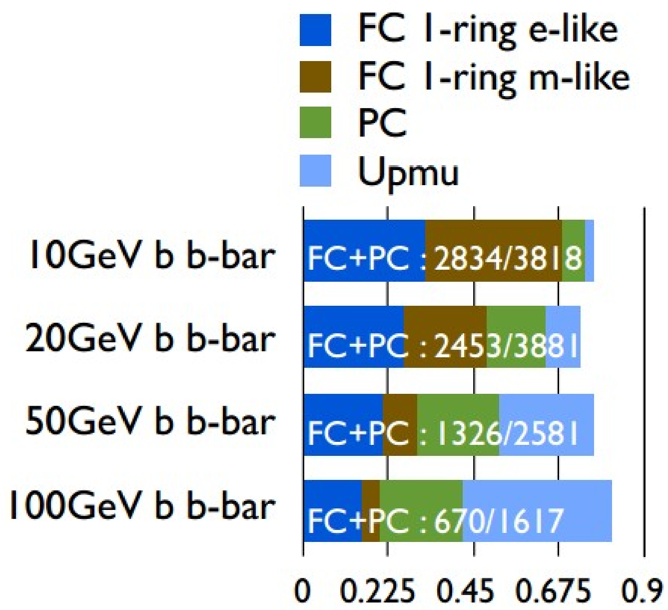
- Currently all oscillation measurements are statistically limited
  - Though this means the future is potentially bright it will take time to get there
  - No indication for a deviation from maximal atmospheric mixing nor for a preferred mass hierarchy so far

- Searches for a both a diffuse excess of neutrinos from the galactic center and a more direct source from dark matter annihilation in the sun have yielded only limits
  - Efforts continue to push thresholds as low as possible to test the lightest WIMP mass scenarios

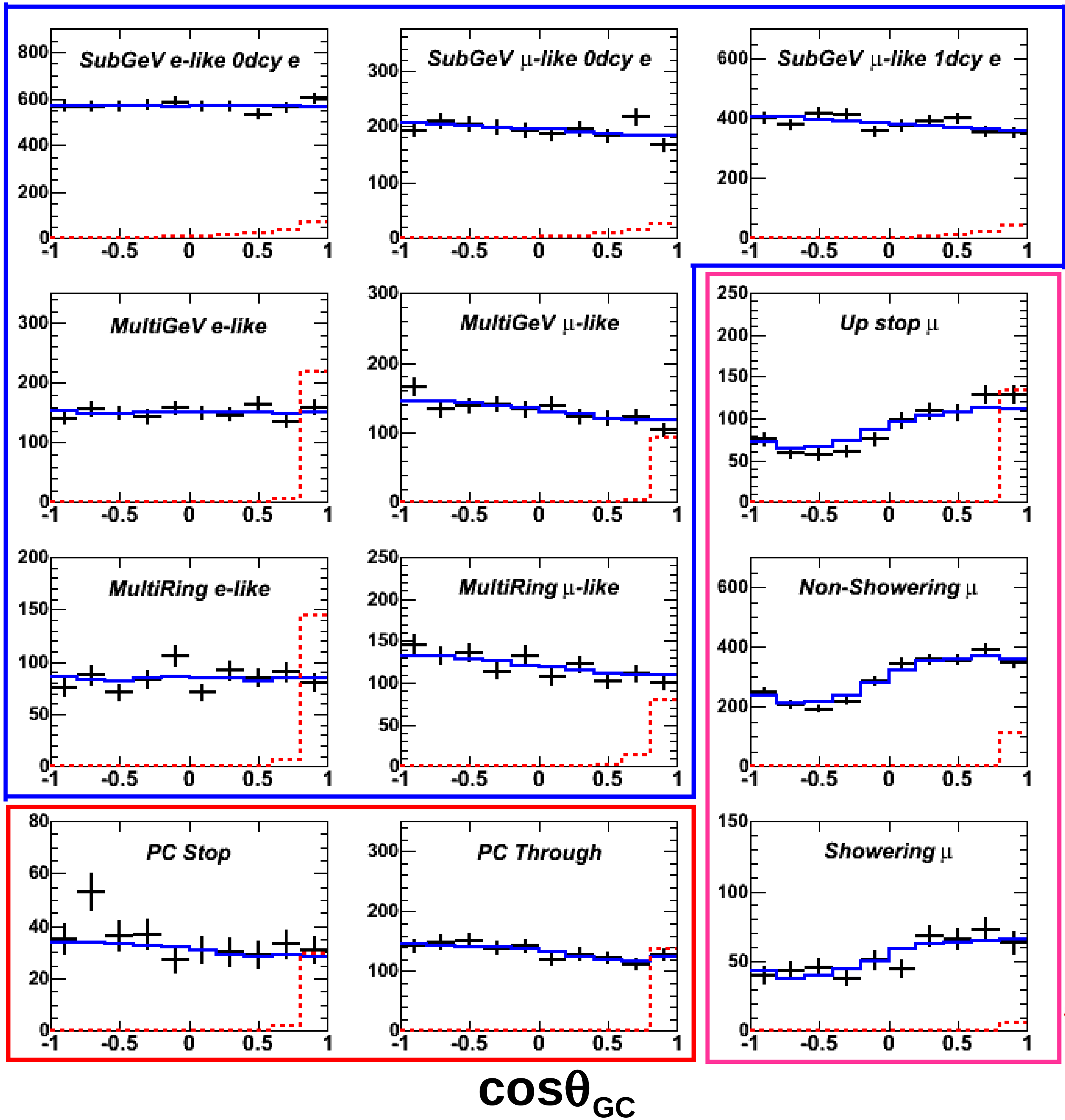
Back Pocket


flux[GeV/m^2/sr/s]
10^3
10^2
10
1
10^{-1}
10^{-2}
1
10
10^2
Energy[GeV]

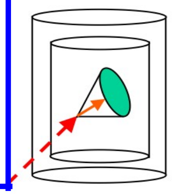

flux[10^{-31}/m^2/ann]
10^8
10^7
10^6
1
10
10^2
Energy[GeV]


FC 1-ring e-like
FC 1-ring m-like
PC
Upmu
10GeV b b-bar
FC+PC : 2834/3818
20GeV b b-bar
FC+PC : 2453/3881
50GeV b b-bar
FC+PC : 1326/2581
100GeV b b-bar
FC+PC : 670/1617
0
0.225
0.45
0.675
0.9

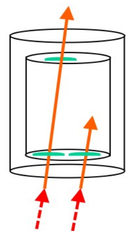
DM signal illustration



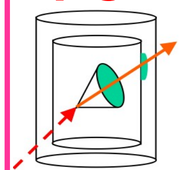
FC



UPMU



PC



M_χ = 100 GeV

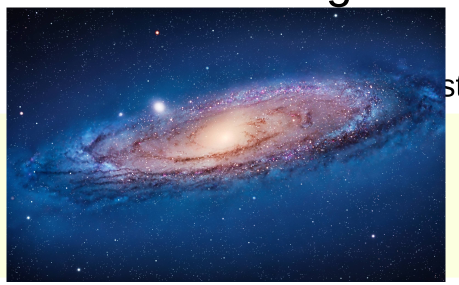
- Assume annihilation into **b-bbar**
- Bin in angle to the galactic center

DATA
SK1,2,3

OSC ATM MC

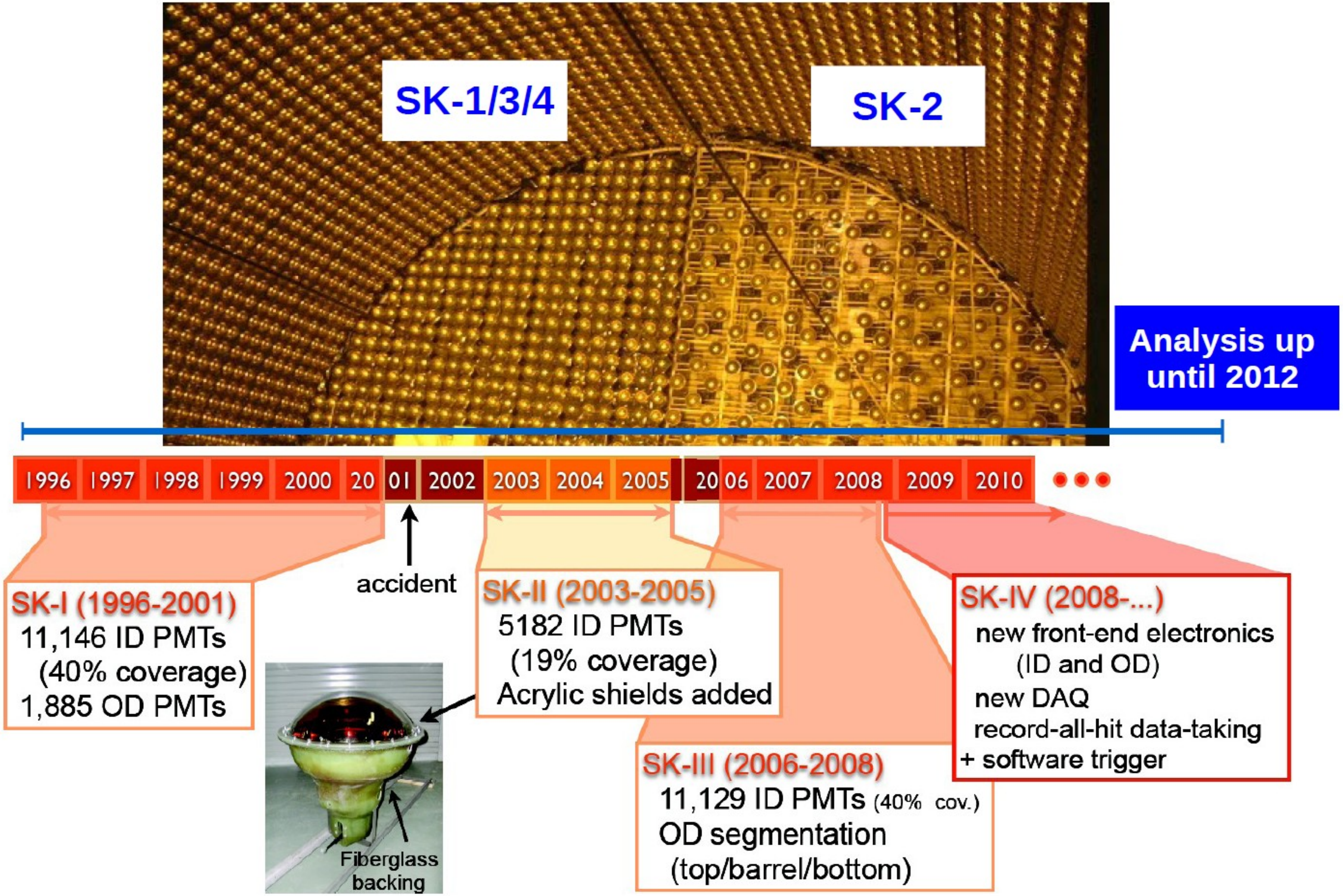
NON-OSC ATM MC

DM signal



stration

Super-Kamiokande : Generations



- Hyper-K design is 20% photocoverage with SK-IV style electronics

Search for Diffuse Dark Matter Annihilation

assume 100%

$\chi + \chi \rightarrow \nu + \nu$

» Distinctive signatures:

Monoenergetic $\mathbf{E_\nu = M_\chi}$

Isotropic

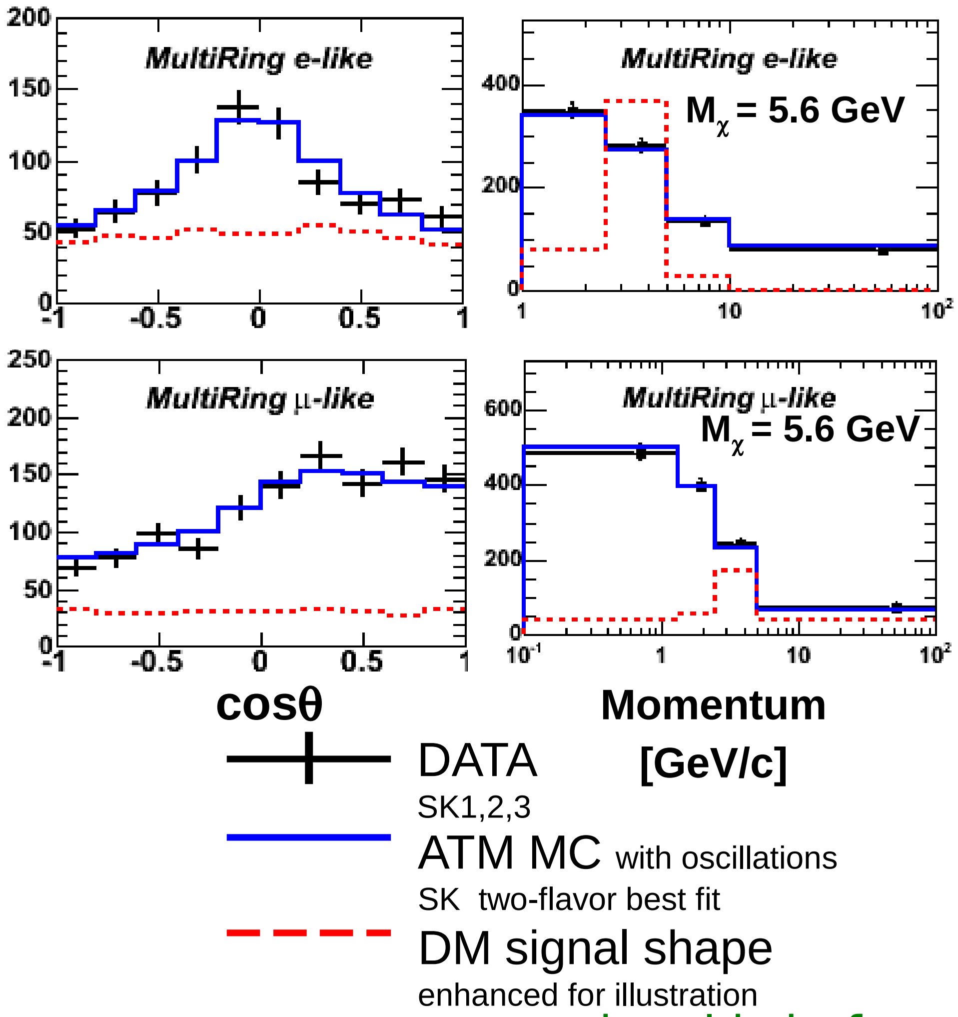
» Search in atmospheric neutrino data from SK-I, -II & –III
livetime: FC/PC 2806 days, UPMU 3109 days

» Simulate signal in NUMU, NUE and NUTAU

» **FIT:** for each tested WIMP mass, find the best configuration of ATM MC + DM signal that would match DATA the best

» using all SK samples:
e-like + mu-like FC+PC+UPMU
(wide energy range)

EXAMPLE: illustration of **5.6 GeV** WIMP annihila1tion signal



signal is before FIT

Fit Results

- FIT based on E_{vis} & cosθ distr., systematics included (120 sys. terms fitted)
- No allowed excess of DM-induced ν's for M_χ in range 3GeV – 3 TeV

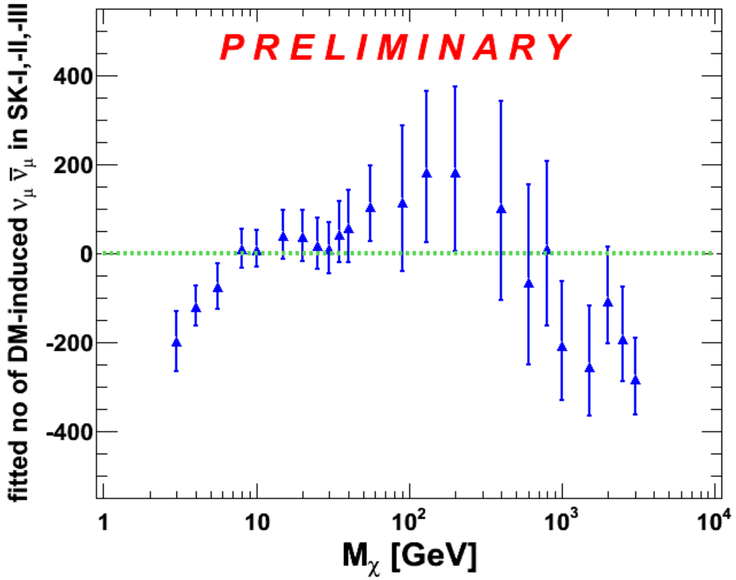
Limit on <σV>

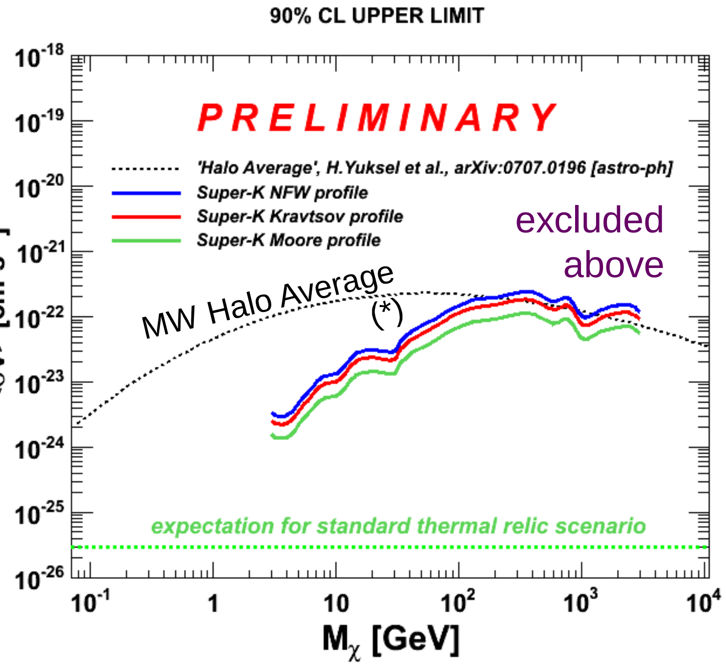
- Focus on signal arising from Milky Way halo (diffuse flux)
- Conservative upper limit on WIMP total self-annihilation cross section

$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot m_\chi^2} \frac{dN}{dE}$$

$J_{\Delta\Omega}$ *integrated intensity over all sky related to DM halo density profile; includes information about DM density cusp in GC*

*(*) **H.Yuksel et al., Phys. Rev. D76, 123506 (2007), arxiv: 0707.0196 [astro-ph]***





How many ν_τ are expected at Super-K ?

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Solar**

- If $\theta_{13} > 0$, Multi-GeV resonant enhancement of $\nu_\mu \leftrightarrow \nu_e$ is expected for upward-going neutrinos
  - Look like τ events, but SK data are consistent with $\theta_{13} = 0$ so this effect is considered as a systematic
- Solar oscillations exist ($\theta_{12} > 0$) so $\nu_e \leftrightarrow \nu_\tau$ is expected at low energies (< 500 MeV), well below τ production threshold

For 4.1 years / 22.5 kton
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.4\ 10^{-3}\ eV^2$, expect ~78 ν_τ

ν Oscillations:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

ν mass eigenstates ≠ flavor eigenstates

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Solar**

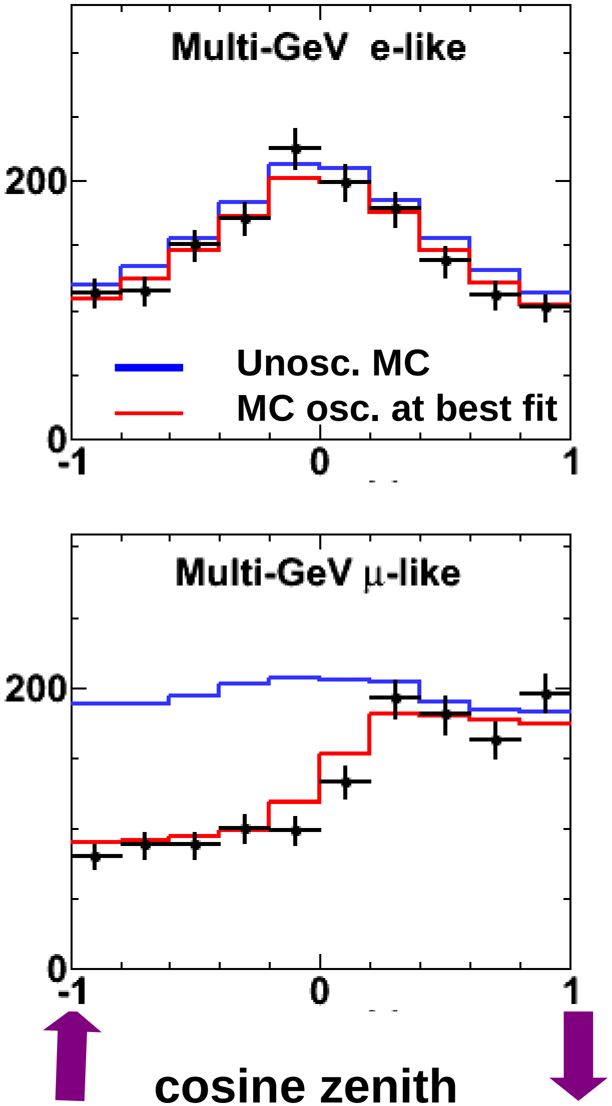
Additionally two mass splittings: Δm^2_{12}, Δm^2_{13}, δ_{cp}

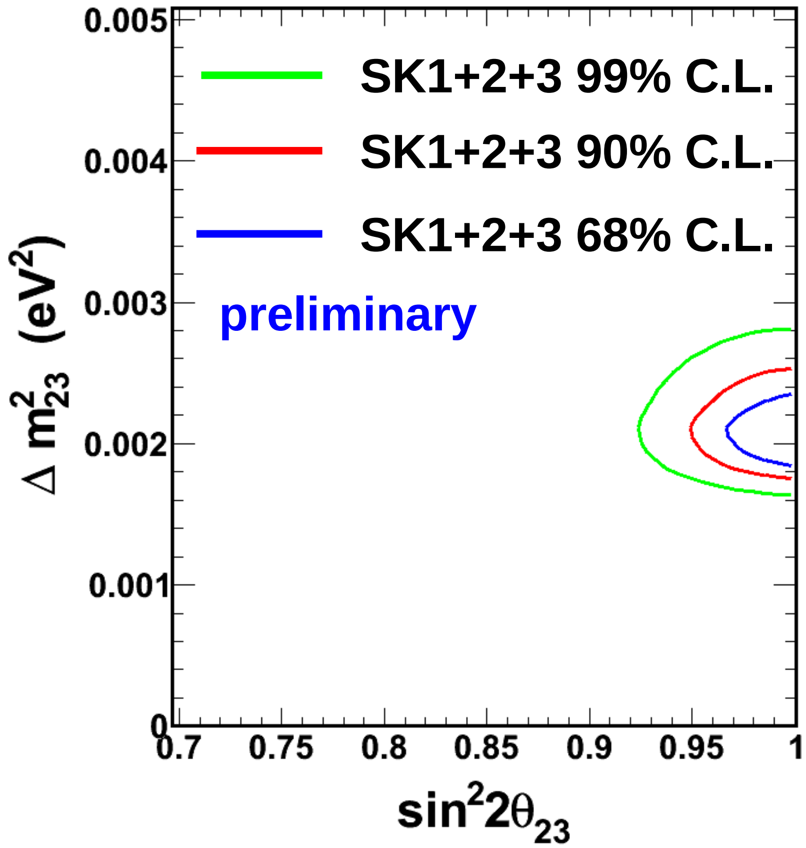
To first order experiments are sensitive to oscillations between two active ν's:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right) \quad \left[\frac{eV^2 \, km}{GeV} \right] \qquad \Delta m^2 \equiv m_2^2 - m_1^2$$

Two-Flavor Analysis

- High statistics
  - > 28,000 ν events





Best Fit: (physical):

$\Delta m^2 = 2.1 \times 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.0$

$\chi^2 = 468 / 418$d.o.f

Systematic Errors

Systematic uncertainties for expected ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis (23 error terms)	21.6	20.2
Tau related:		
Tau neutrino cross section	25.0	25.0
Tau lepton polarization	7.2	11.8
Tau neutrino selection efficiency	0.4	0.5
LH selection efficiency	4.8	–
NN selection efficiency	–	3.0
Total:	32.6	34.4

Systematic errors on the *expected* number of ν_τ

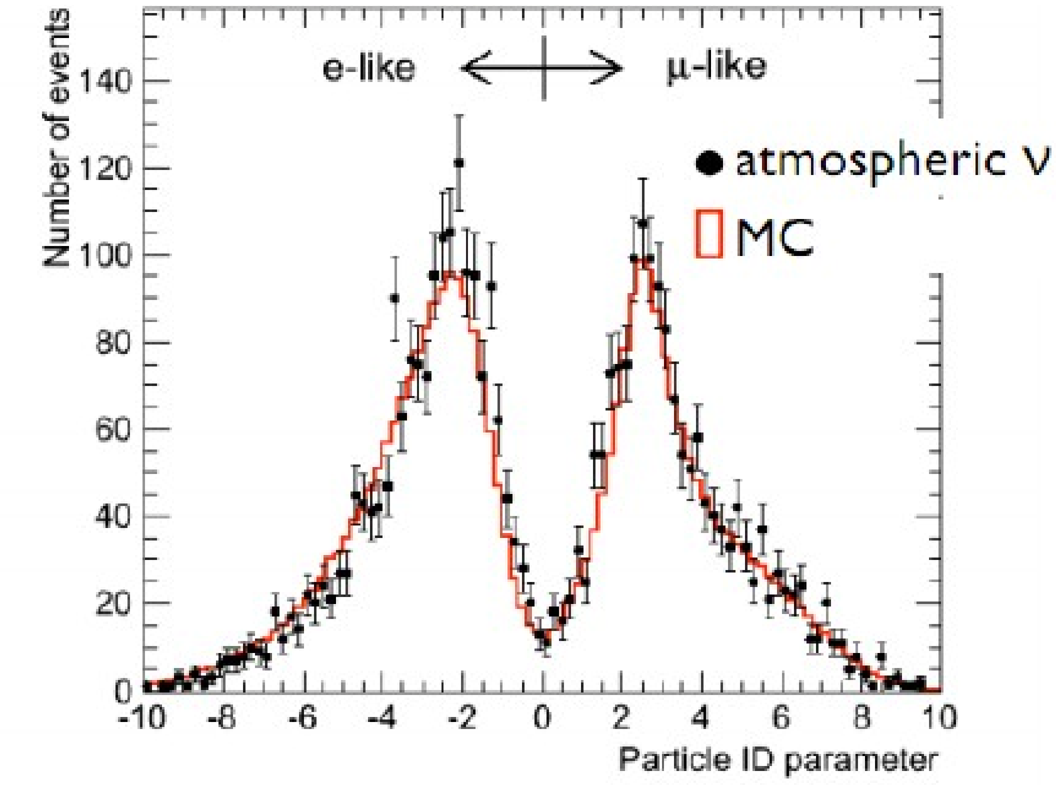
→ 78.4 ± 27 (syst.)

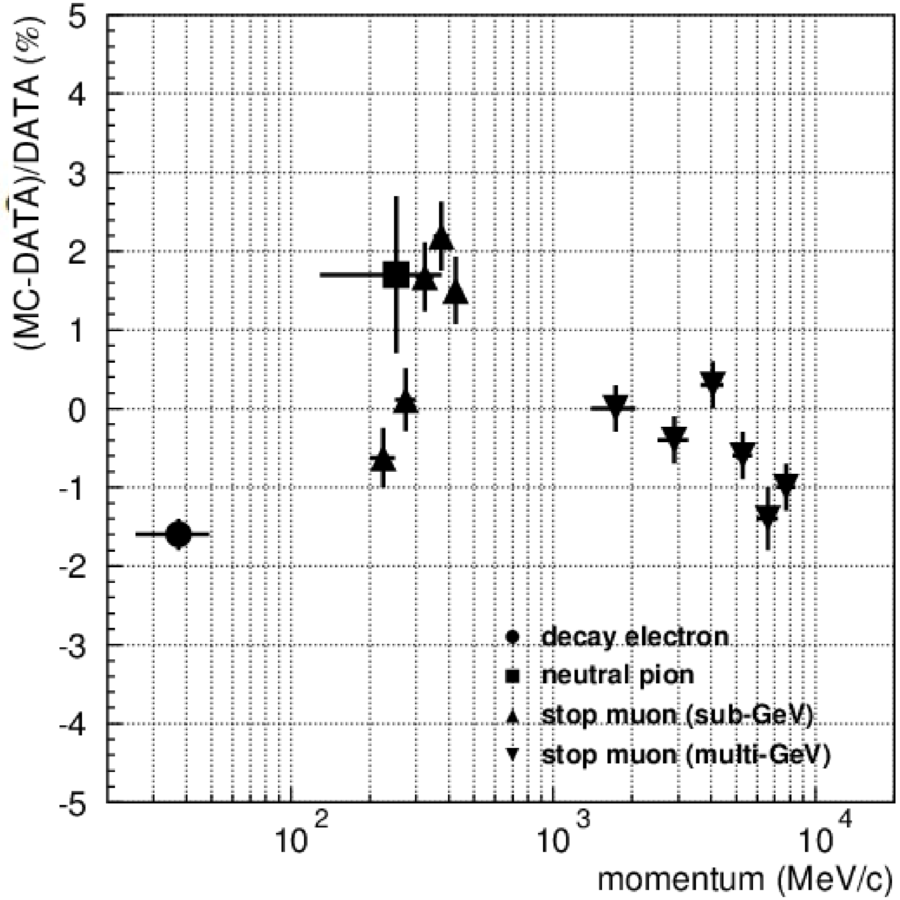
Systematic uncertainties for observed ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis:		
Flux up/down ratio	6.5	5.7
Flux horizontal/vertical ratio	3.6	3.2
Flux K/π ratio	2.4	2.8
NC/CC ratio	4.3	3.8
Up/down asym. from energy calib.	1.4	< 0.1
Oscillation parameters:		
$0.0020 < \Delta m^2_{23} < 0.0027\,\mathrm{eV}^2$	+5.8 −2.6	+8.8 −3.3
$0.93 < \sin^2 2\theta_{23} < 1.00$	−3.3	−3.9
$0.0 < \sin^2 2\theta_{13} < 0.15$	−20.6	−17.9
Total:	+10.7 −22.9	+12.0 −20.3

Systematic errors on the *observed* number of ν_τ

→ $134^{+16.0}_{-27.2}$ (syst.)

SK-IV Detector Performance





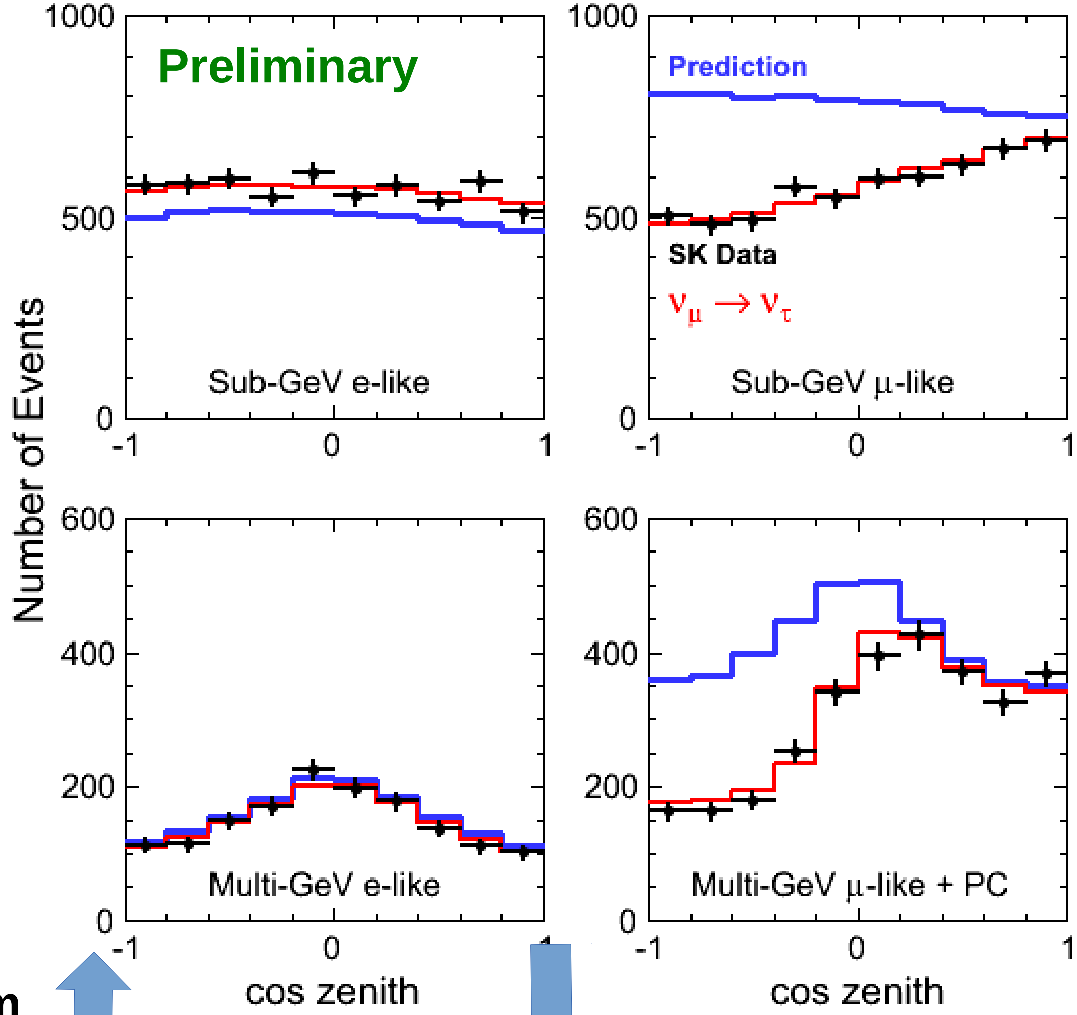
- Good Particle ID permance
  - 1% MIS PID Probability
- Absolute energy scale uncertainty has been narrowed to less than about 2%
  - ~ 1% above 1 GeV

Single-Ring Atmospheric ν Data

Lepton momentum

< 1330 MeV

> 1330 MeV



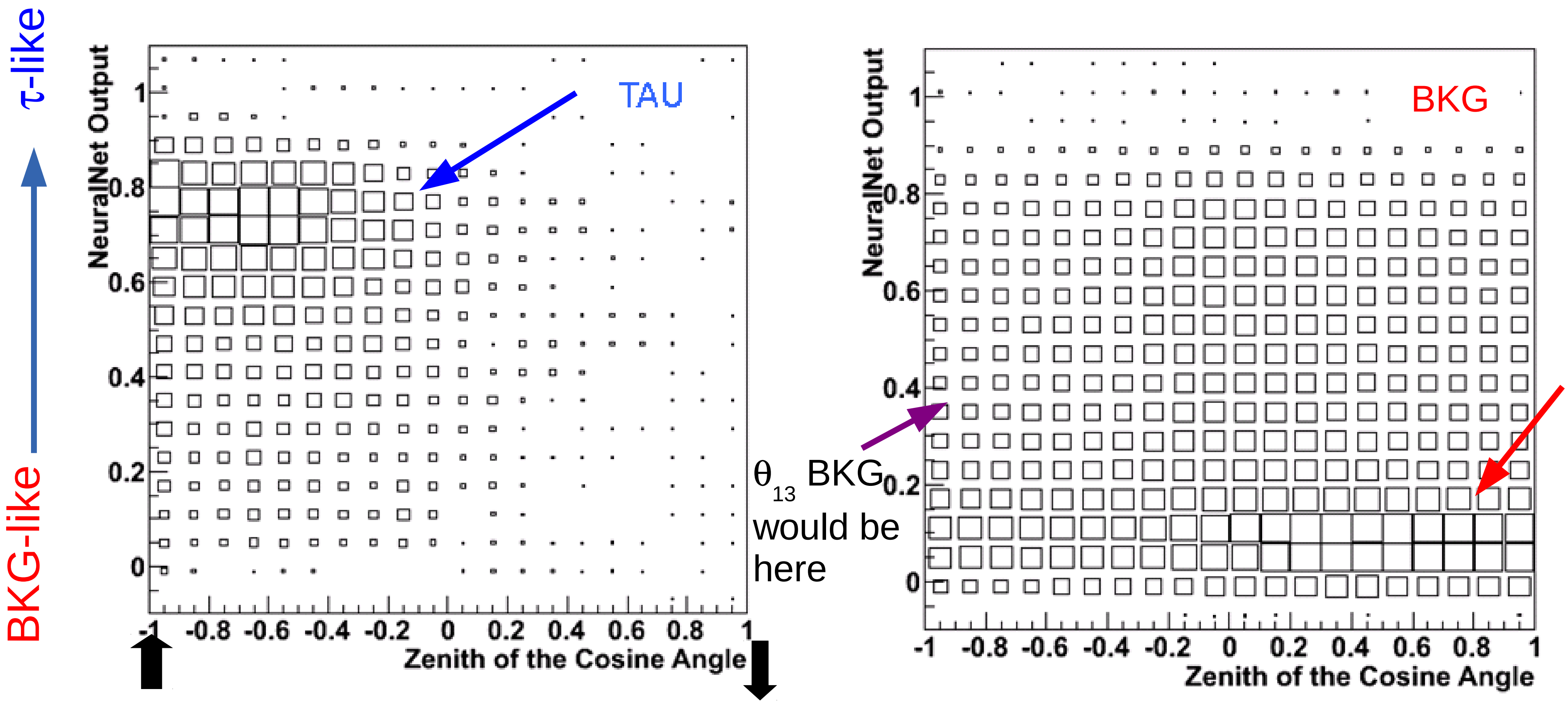
"Longer" Baseline: **~10,000 km**

30 km

» Upward going μ-like events are disappearing !
  - Not being compensated by an increase in the e-like event rate

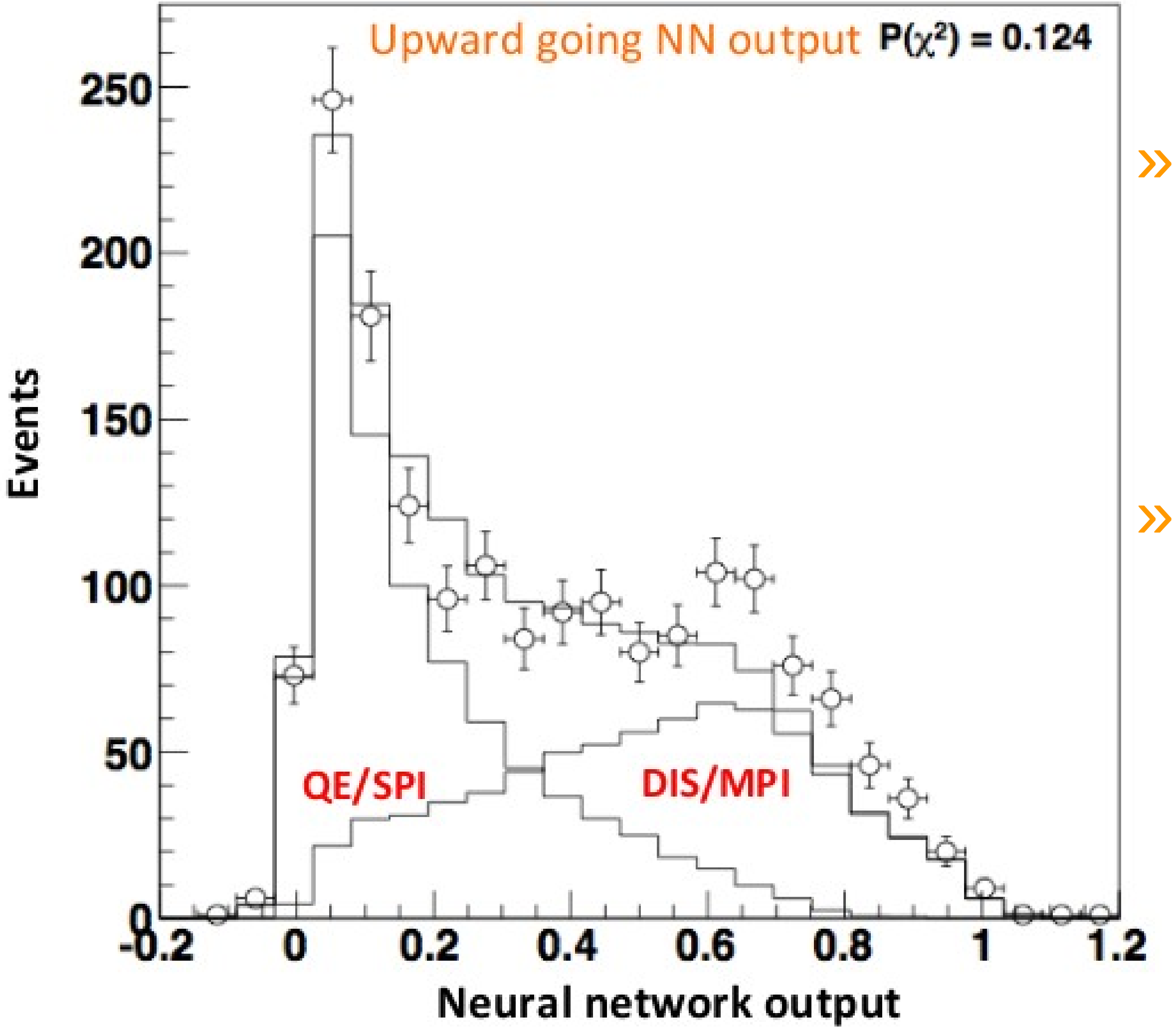
Fitting Technique

- Use an un-binned two-dimensional likelihood fit to extract the most from the data
- Previous analysis (PRD 2006) fit only in one dimension
  - Events with NN output > 0.5   in this plot



- Tau and Background events appear in dramatically different regions of the plot
  - The signal appears exclusively in the upward-going direction

Deep Inelastic Scattering



- » Neural network is very good at selecting DIS events
  - Fit is sensitive to uncertainties in the scattering cross section
- » To balance the fit and enable it to find the correct number of tau events we also include the DIS/non-DIS ratio as an additional fitting parameter

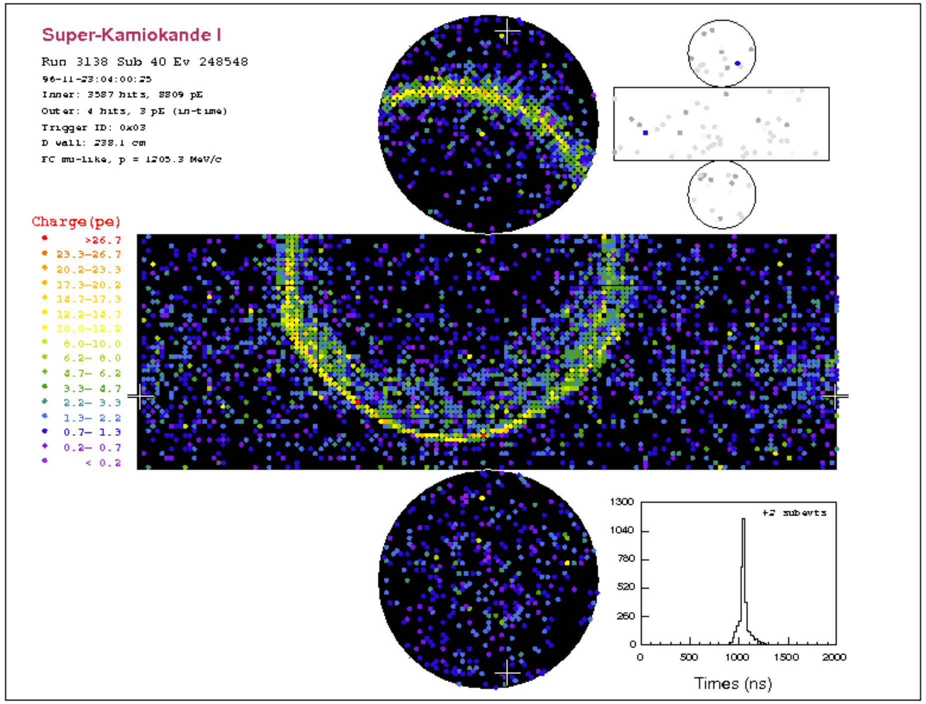
Something Exotic Going On?

$$CPT \;:\; P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

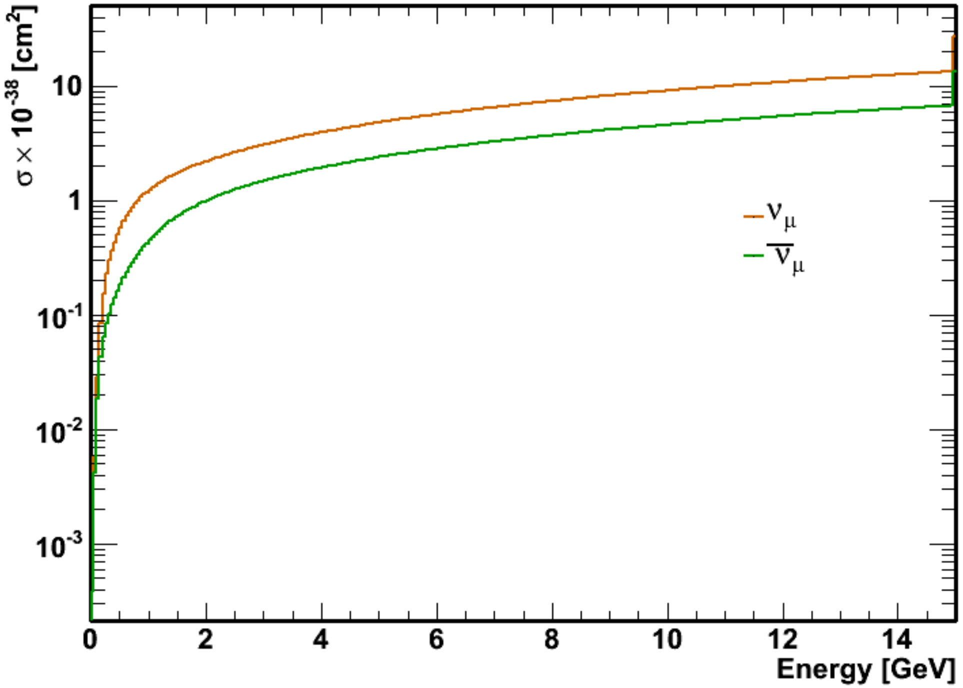
- We expect the disappearance probabilities of neutrinos and antineutrinos to be the same by CPT

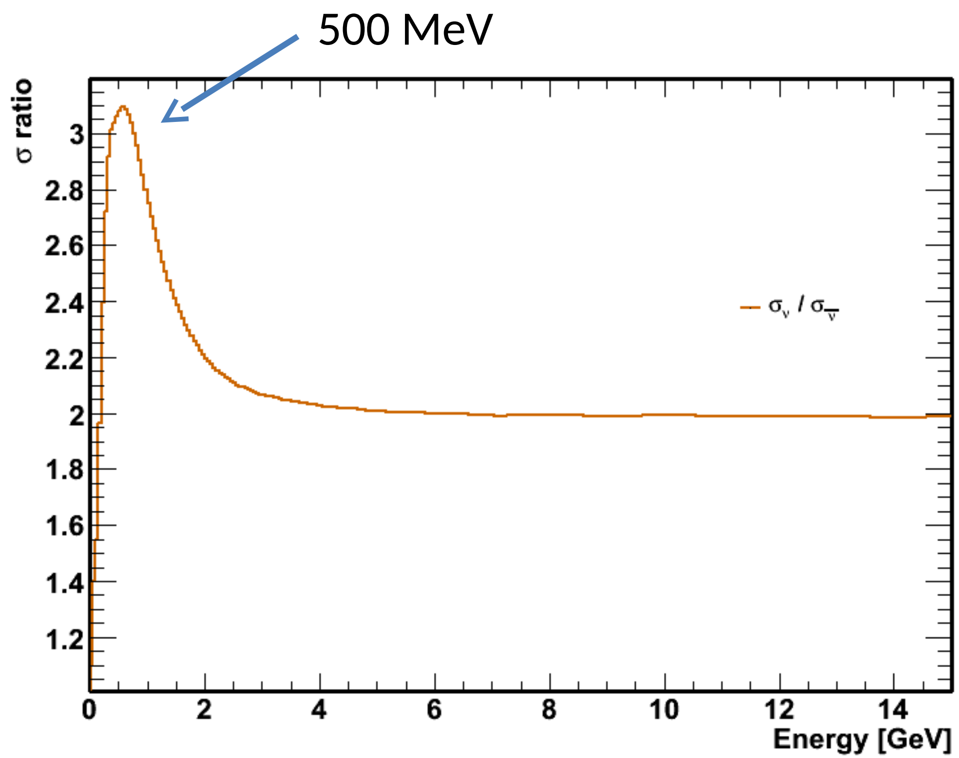
- Can we test for differences in the disappearance probabilities with Super-K ?
  - **YES**
  - Neutrinos and Antineutrinos are present in the flux

- However
  - No net magnetic or electric fields at SK
  - Cherenkov production is the same for l±
  - **No event-by-event** sign discrimination



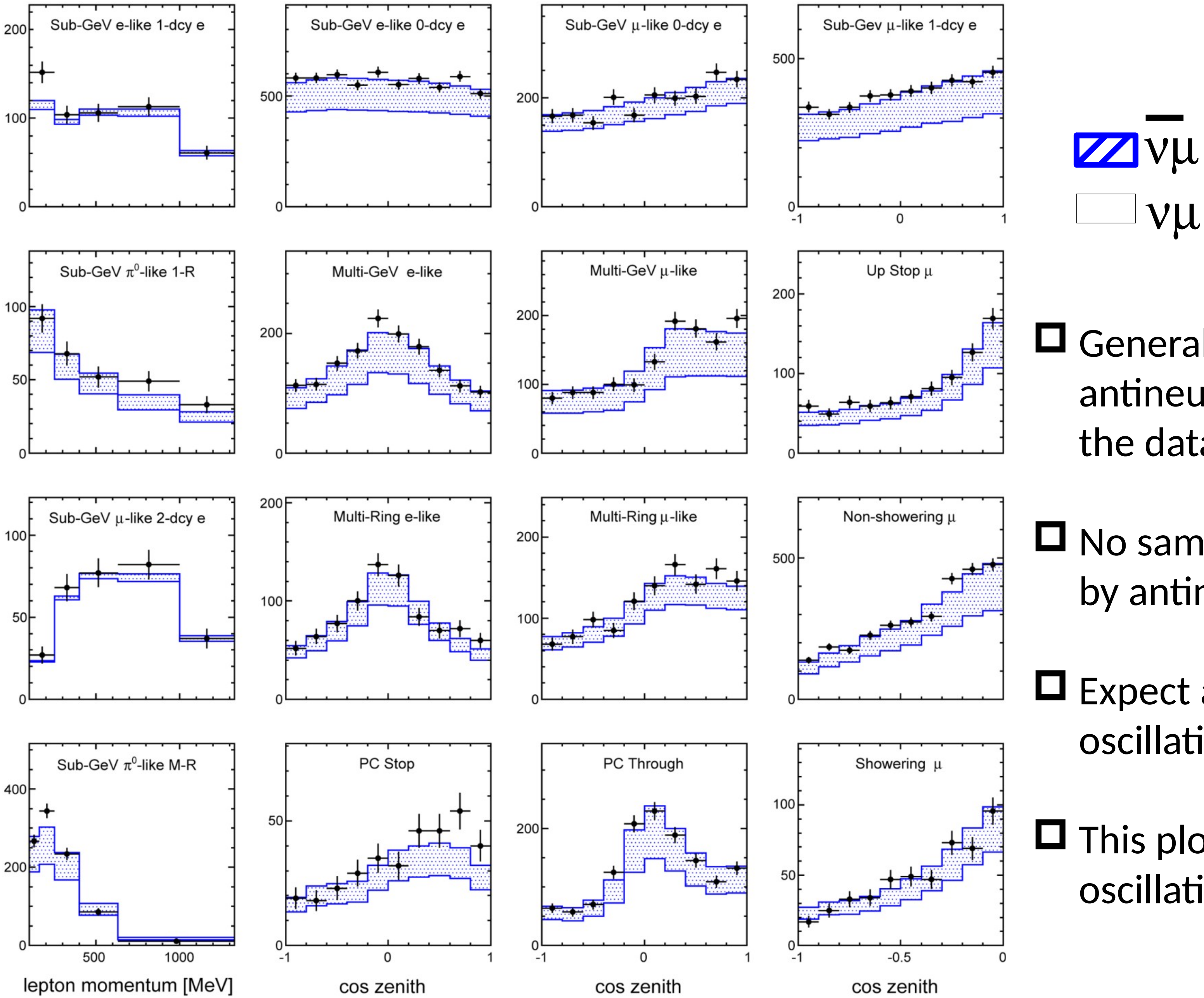
Neutrino and Anti-neutrino Cross Sections





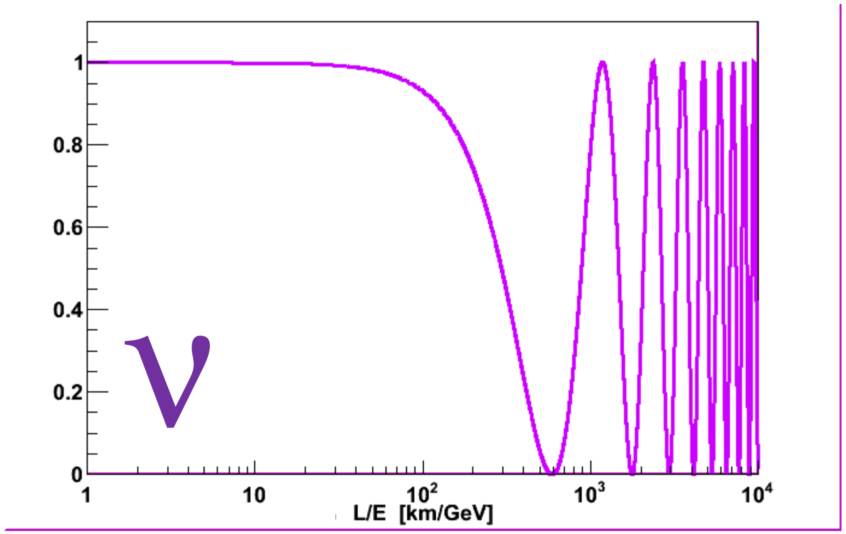
- Cross sections differ as a function of energy
  - Varying by a factor of x2-3

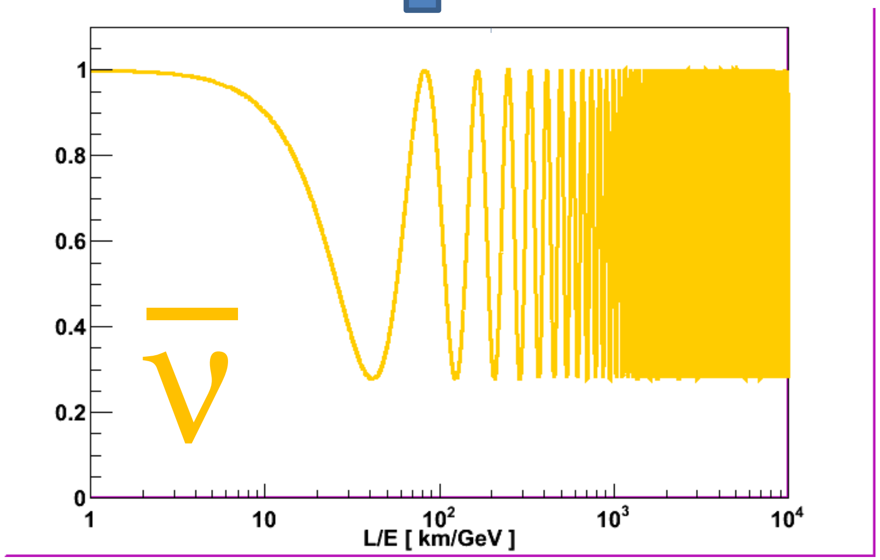
- Expect more neutrinos than antineutrinos
  - Relative compositions will vary as a function of energy
  - Different sensitivities to L/E

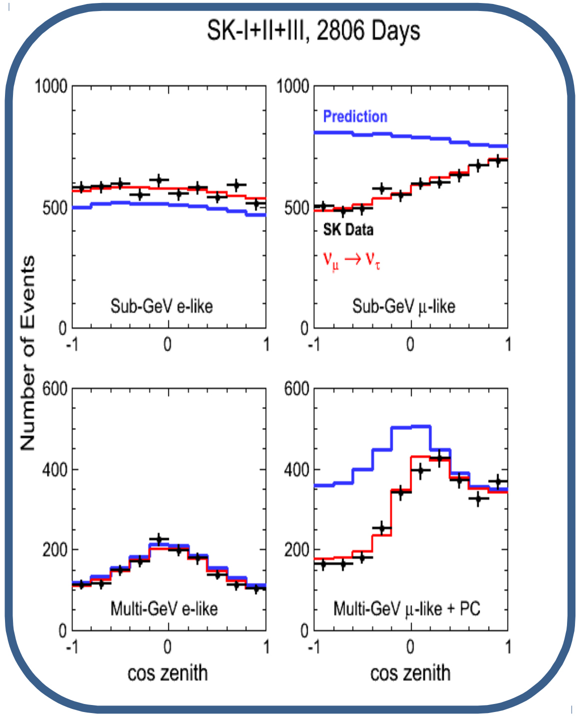


- Generally there are fewer antineutrinos expected in the data
- No sample is dominated by antineutrinos
- Expect a weaker oscillation constraint
- This plot includes equal oscillation parameters

In the End, the technique is simple



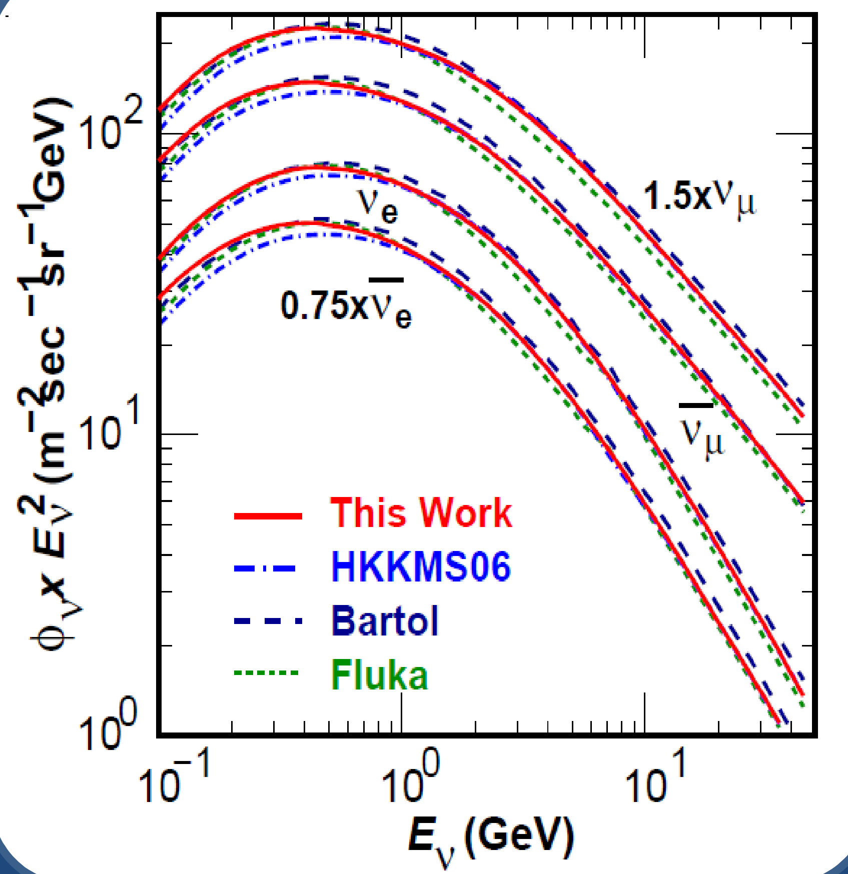




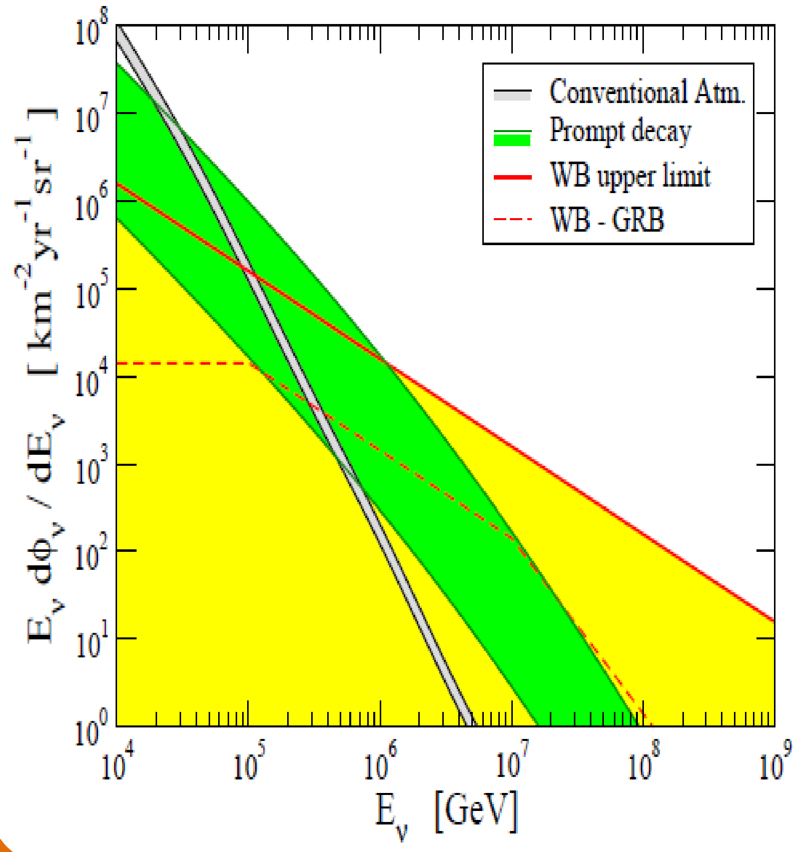
- Without event-by-event discrimination we ask whether or not the observed zenith angle distribution of the data is consistent with the **sum** of separately oscillating **neutrino** and **antineutrino** spectra

- This is an *ad hoc* test …

Atmospheric Neutrino Fluxes

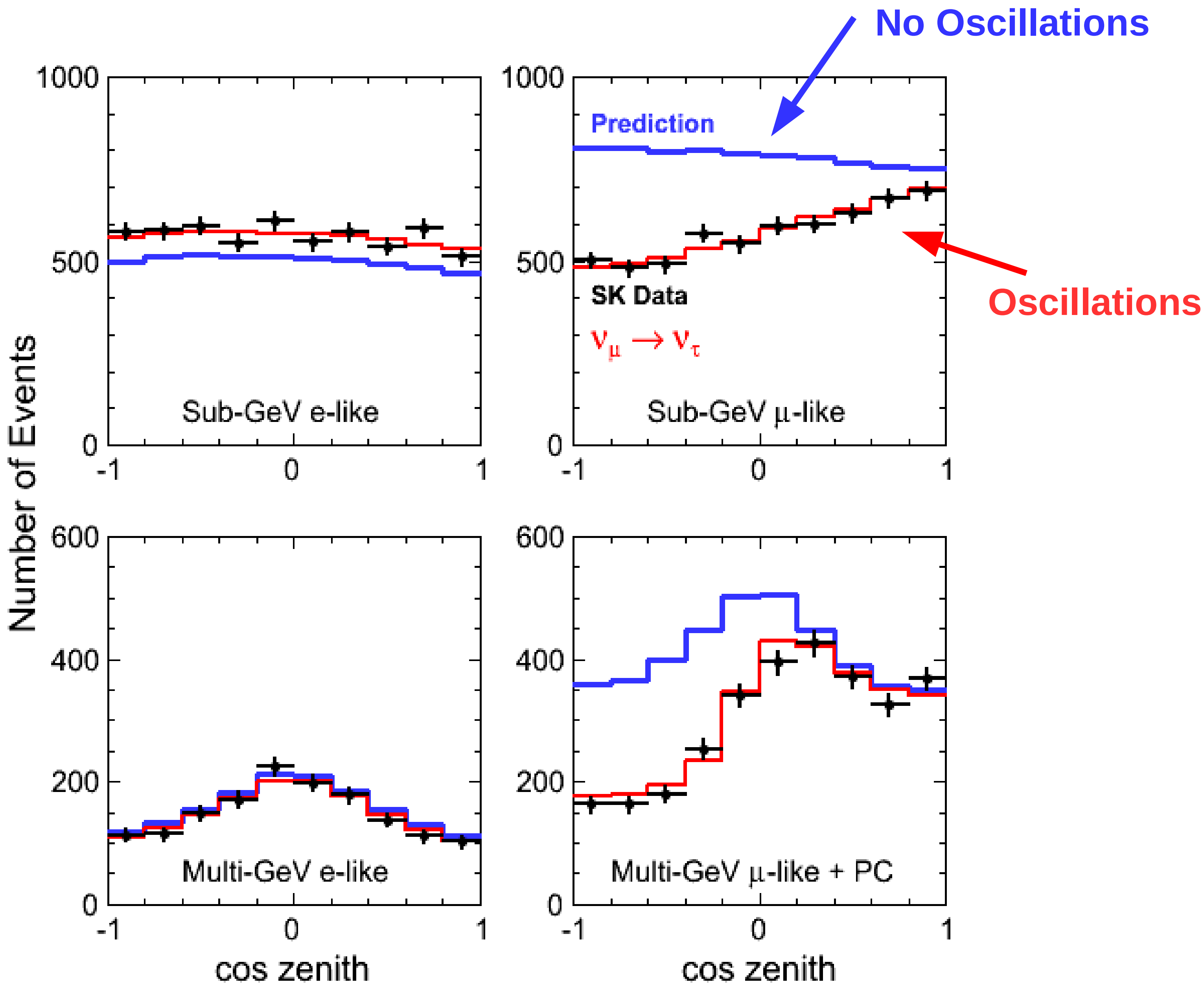


- "Conventional" flux used to discover neutrino oscillations
  - Wide variation in L/E
- Absolute flux known to ~20%
- Shape known to ~5-10%



- "Prompt" Flux from the production and decay of charmed mesons:
- Currently unmeasured

Super-K Data: Electron-like and Muon-like Events

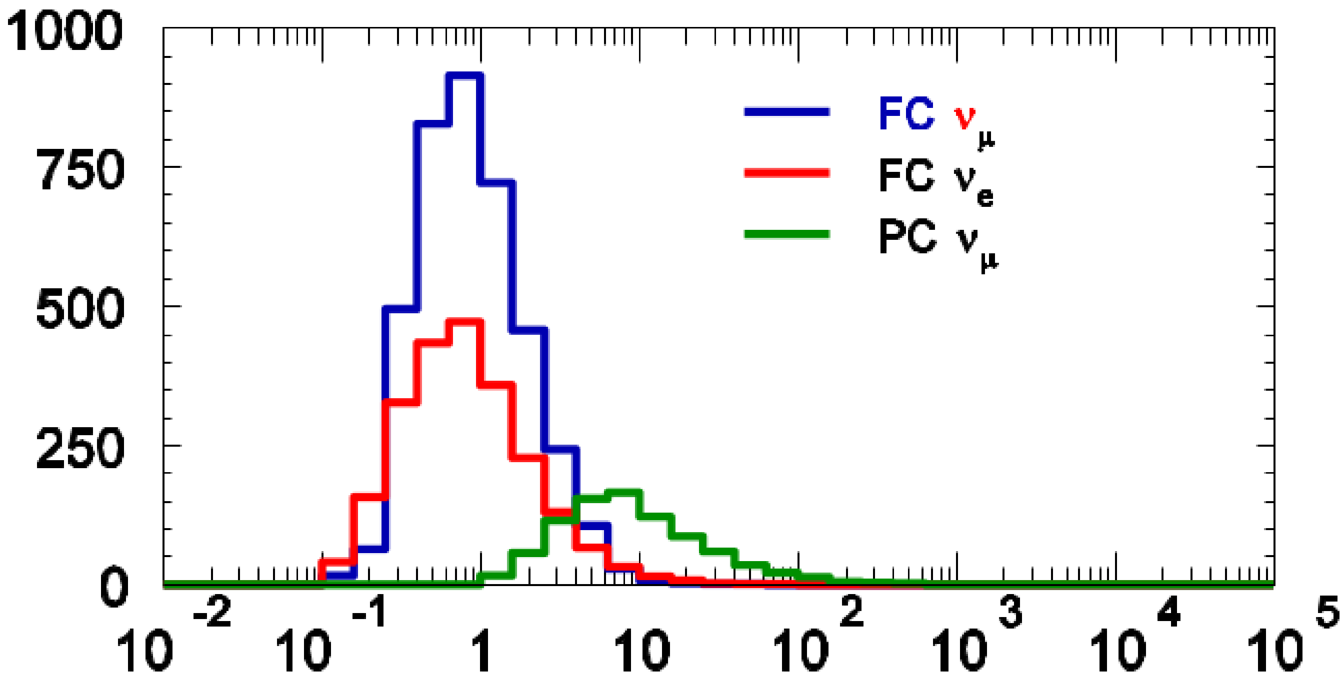


A Word about systematic errors

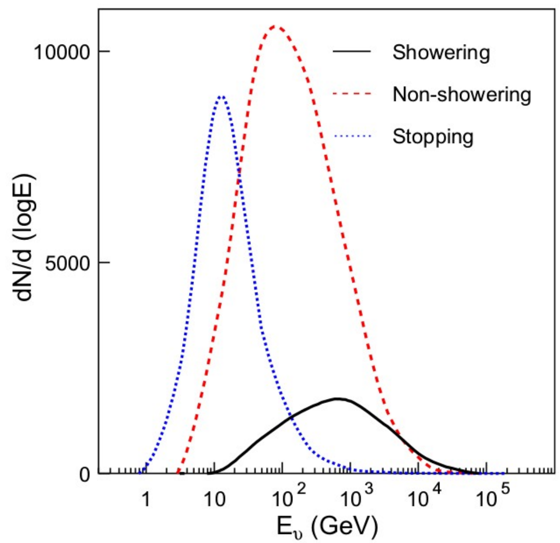
- The standard Super-K disappearance analysis is currently statistics limited
  - Will continue for another 30 or 40 years
  - This limitation naturally extends to the ν, $\bar{\nu}$ separated analysis

- Nonetheless 122 Sources of systematic error are considered

Error	Range	Error %	Comment
$\nu\mu$ / $\bar{\nu}\mu$ Flux Ratio	0.1 < E < 1 GeV	2	Taken as the difference between flux models
	1 <E < 10 GeV	6	
	10 GeV < E	6	
$\nu\mu$ / $\bar{\nu}\mu$ Cross Section Ratio	CCQE	~10	Difference of cross section models as a function of energy
	Single Meson Production	~10	
Flux Normalization	E < 1 GeV	25	Energy dependent in these ranges
	1 GeV < E	7	
Decay Electron Tagging	-	1.5	Single efficiciency



1000
750
500
250
0
FC ν_μ
FC ν_e
PC ν_μ
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5



Showering
Non-showering
Stopping
dN/d (logE)
10000
5000
0
1
10
10^2
10^3
10^4
10^5
E_ν (GeV)

$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

$\boldsymbol{J}_{\Delta\Omega}$ *is integrated intensity over all sky* $\Delta\Omega=4\pi$*,*
depends on DM halo density profile

Comparison with IceCube

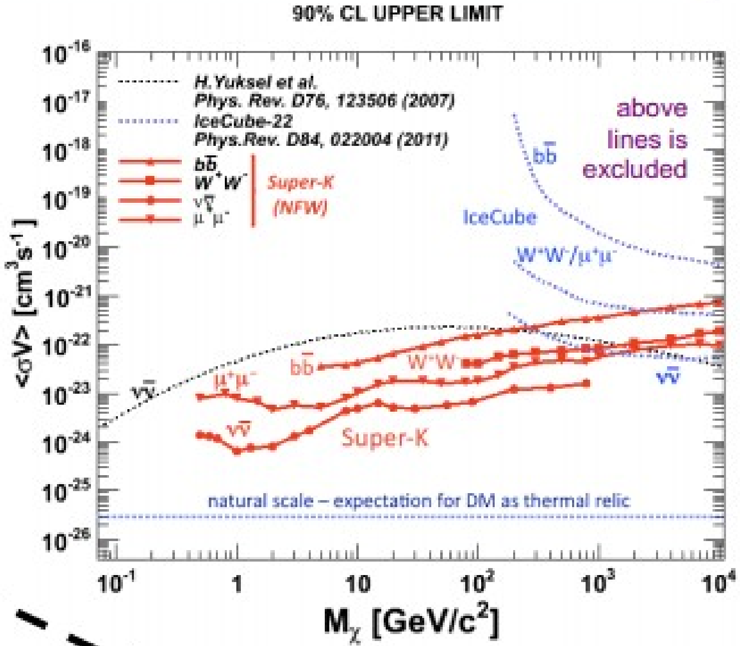
livetime x detector effective area x received DM signal intensity (proportional to DM density squared) x fraction of dN/dE

Super-K: SK1+2+3 (1996-2008)

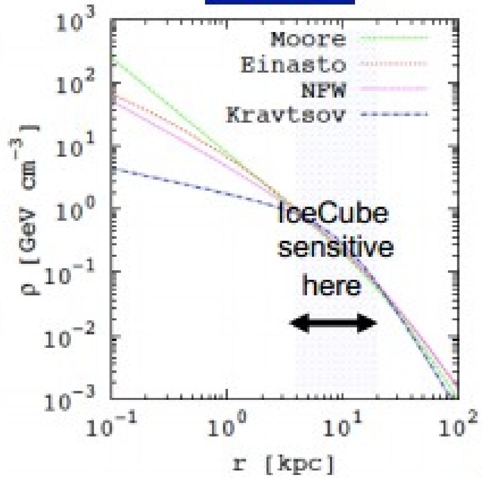
SK = 3109.6 live days x ~10^3 m^2 effective area

IceCube = 276 live days x ~10^5 m^2 effective area
x ~0.006 of SK's received intensity
x 0.2 fraction of dN/dE

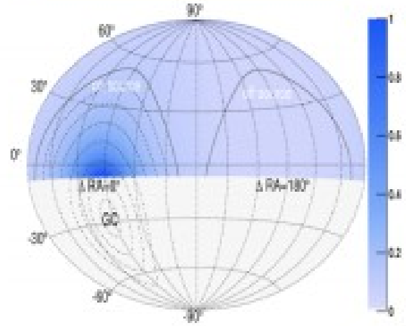
SK / IceCube = ~ 93
for mu+mu- 200 GeV WIMP



DM halo

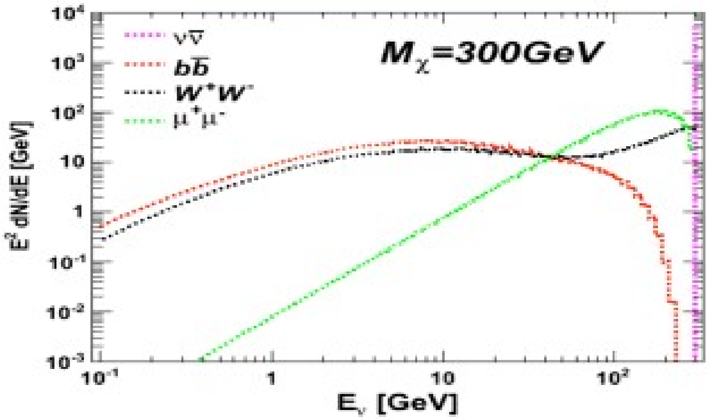


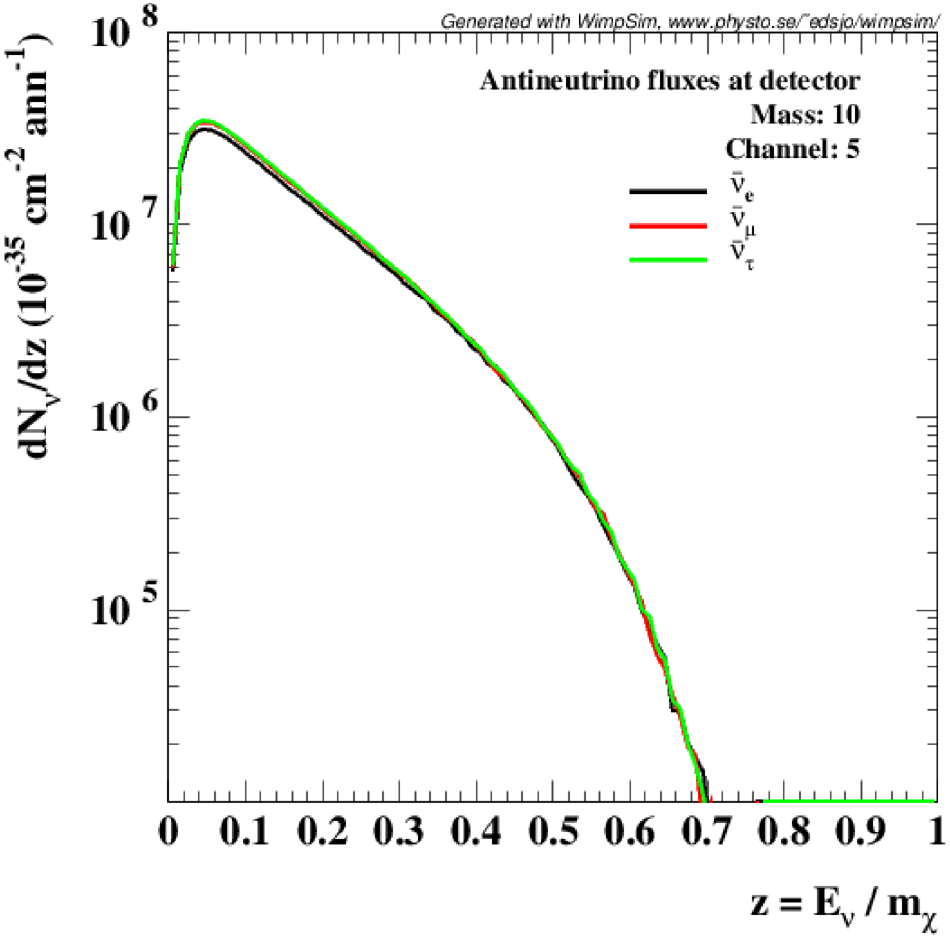
IceCube sky coverage



IceCube does not see GC

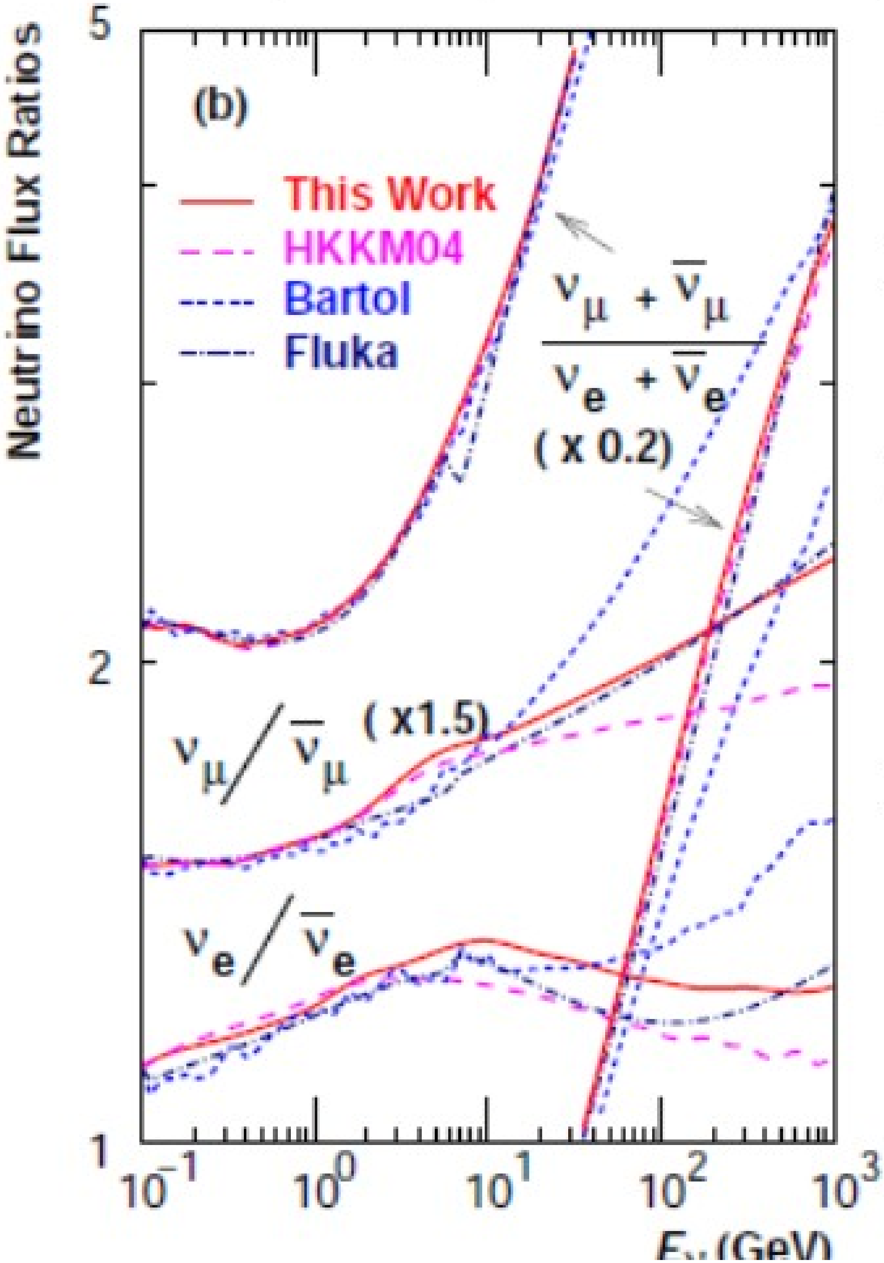
DM-ind neutrino multiplicity





Generated with WimpSim, www.physto.se/~edsjo/wimpsim/
Antineutrino fluxes at detector
Mass: 10
Channel: 5
$\bar{\nu}_e$
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
dN_ν/dz (10^{-35} cm^{-2} ann^{-1})
10^8
10^7
10^6
10^5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$z = E_\nu / m_\chi$

M. Honda, et. Al Phys.Rev.D75:043006,2007



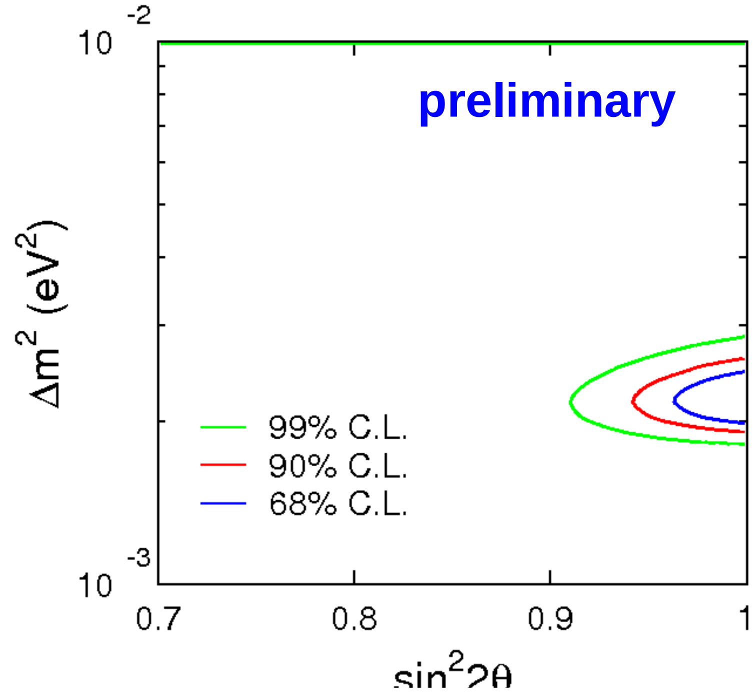
- Single π^+ production is slightly favored at lower primary cosmic ray energies (+20%)
- Multiple π production at higher energies. Slightly more π^+ than π^- production, and are more energetic on average
- Results in more neutrinos since
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$

- At higher energies the muons increasingly reach the ground before decaying
  - Lose energy in the Earth before decay
  - or are captured
  - Decreased high energy ν_e flux

L/E Analysis: SK-I + II + III

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

- **Construct a sample with good resolution (> 70%) in L/E**
- **Use FC and PC Samples**
- **High purity in CC ν_μ interactions**
  - **> 93% for all samples and SK geometries**



Best Fit: Oscillations (physical):

$\Delta m^2 = 2.2 \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1.0$

χ^2 = 119 / 126 d.o.f

ν Decoherence ruled out at 4.4 σ

ν Decay ruled out at 5.4 σ