Atmospheric Neutrino Oscillations & Super-Kamiokande

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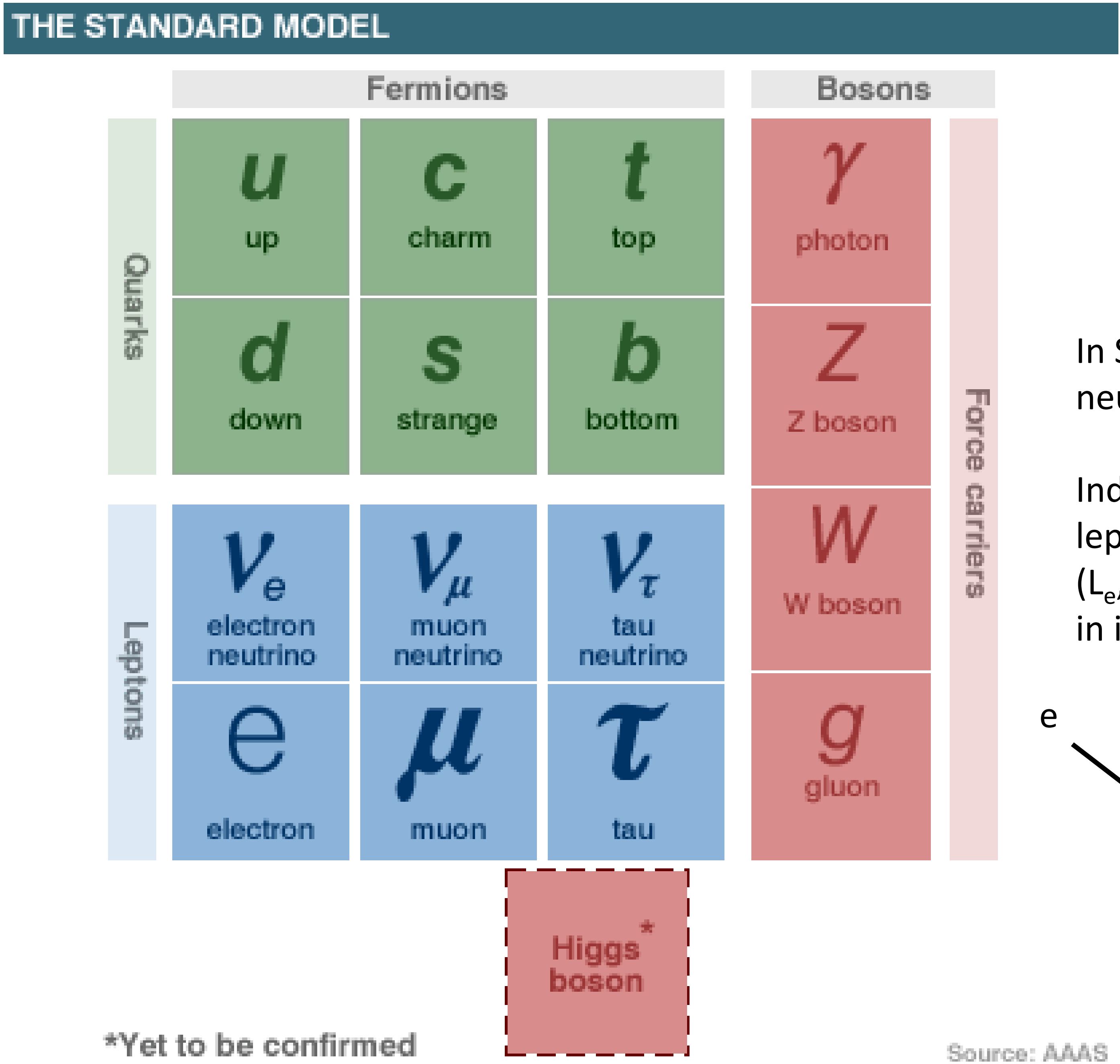
Queen Mary, University of London Seminar

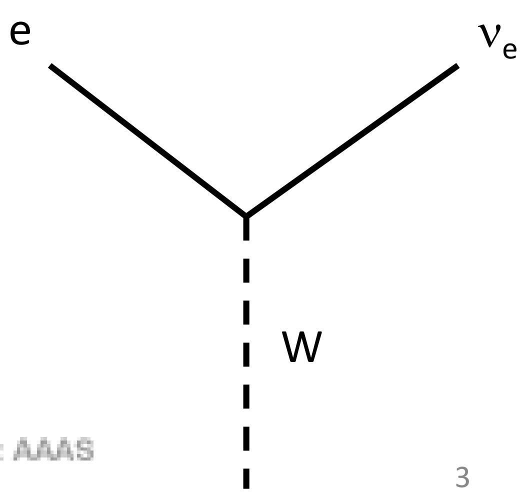
Outline

- Neutrino oscillations
- Super-Kamiokande
  - Detector, simulation, & reconstruction
- The atmospheric neutrino anomaly
- Various Super-Kamiokande results
  - 2 flavour zenith angle analysis
  - 3 flavour analysis
  - Tau neutrino appearance
  - (anti-)neutrino oscillations (CPT invariance)
- Other experiments



In Standard Model, neutrinos are massless

Individual and global lepton flavour # (L_e,L_μ,L_τ) is conserved in interactions, e.g.:



Neutrino Oscillations

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

Flavour eigenstate

Mixing matrix

Mass eigenstate

$$P\left(\nu_\alpha \overset{\alpha\neq\beta}{\rightarrow} \nu_\beta\right) \approx \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) \approx 1 - \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)$$

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

L [km]
E [GeV]
Δm^2 [eV^2]

Individual lepton flavour # conservation is violated

Total lepton # is still conserved

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

Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2 flavour approximation:

$$P\left(\nu_\alpha \xrightarrow{\alpha\neq\beta} \nu_\beta\right) \approx \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\right)$$

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atmospheric ν

solar ν

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atmospheric ν

solar ν

$\sin^2 2\theta_{23} \approx 1.0$
$|\Delta m^2_{23}| \approx .0023$ eV^2
From atm. ν & long-baseline experiments

Is θ_{23} maximal?

2 flavour approximation:

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Is θ_{23} maximal?
What is the value of θ_{13}?
What is the value of δ_{CP}?

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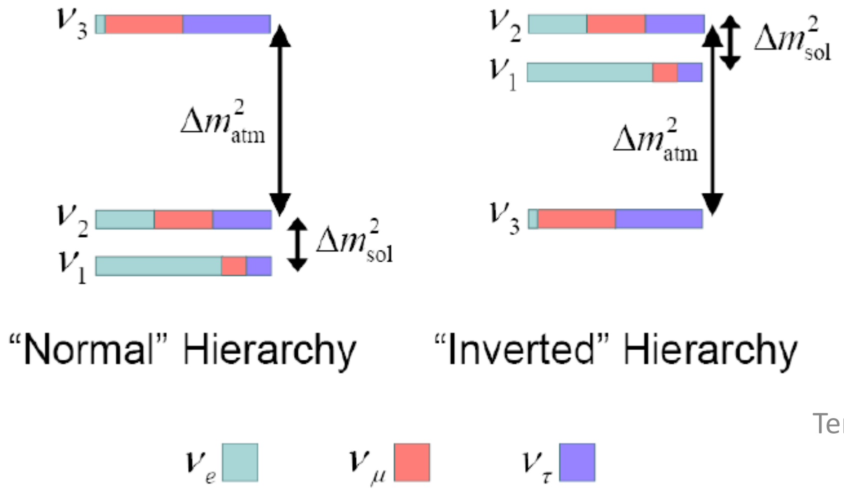


Is θ_{23} maximal?
What is the value of θ_{13}?
What is the value of δ_{CP}?
Which mass hierarchy exists?
Do neutrinos & anti-neutrinos have the same oscillation parameters (i.e. is CPT violated)?

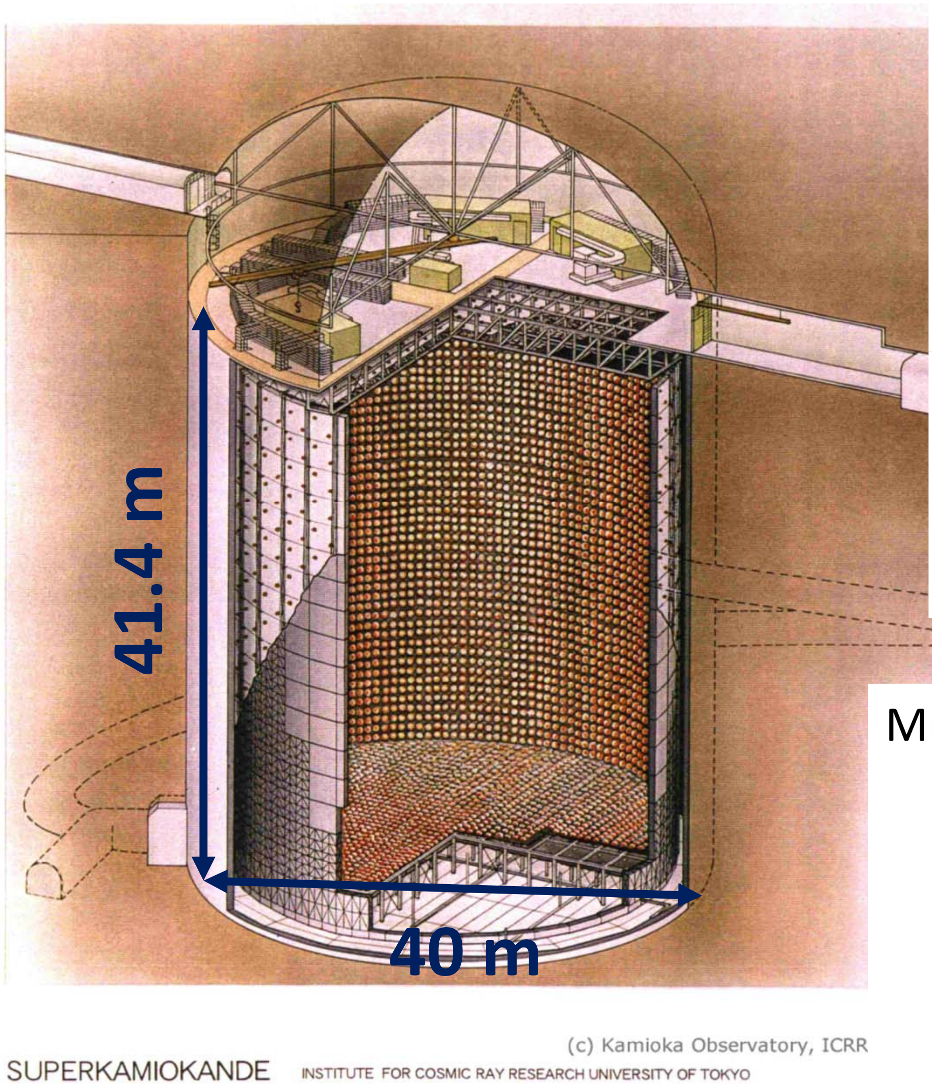
Super-Kamiokande

50 kton water Cherenkov detector
22.5 kton fiducial volume

Depth of 2700 m.w.e
cosmic ray background ~3 Hz

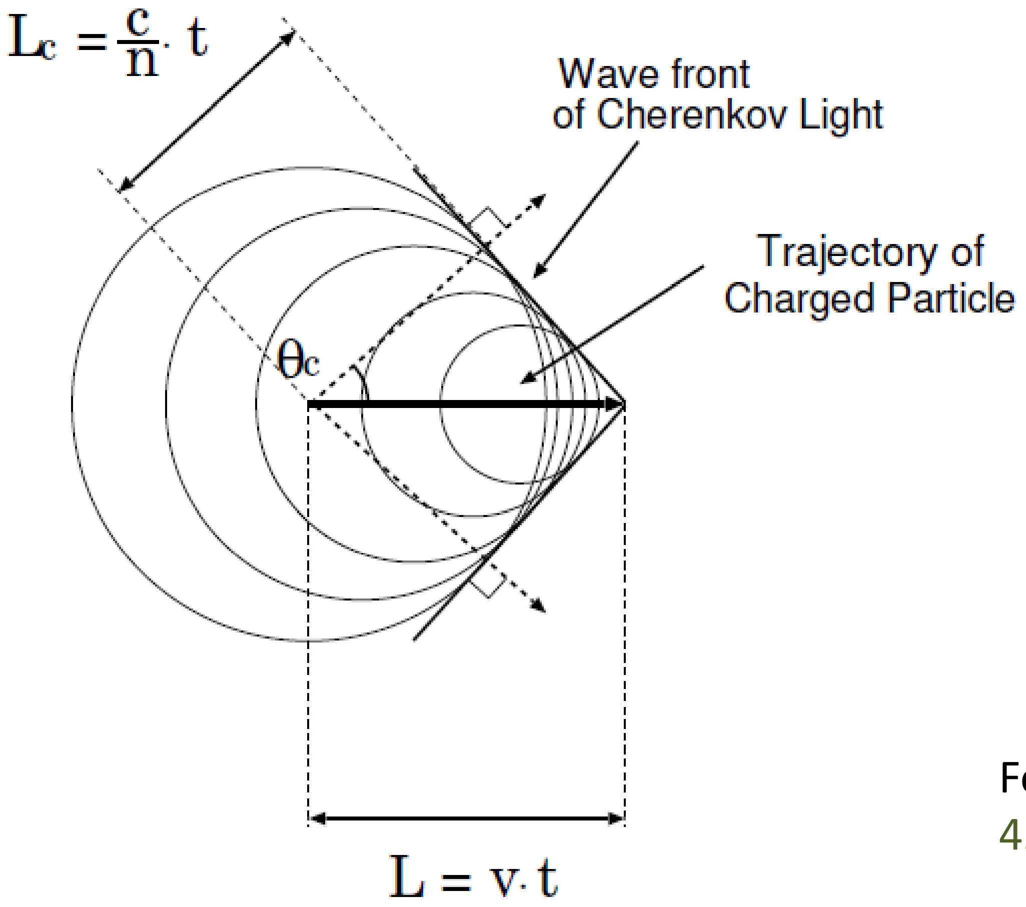
Roughly ~10 Atmospheric ν per day

Inner detector (ID) 11,146 50 cm PMTs
~ 2 ns timing resolution
39% photo-coverage
Outer detector (OD) 1,885 20 cm PMTs



Multi-purpose detector: (this talk)
- Nucleon decay
- Solar neutrinos
- Supernova neutrinos (Relic SN's)
- Atmospheric neutrinos
- Beam neutrinos: K2K, T2K
- Exotic particles

Cherenkov Radiation



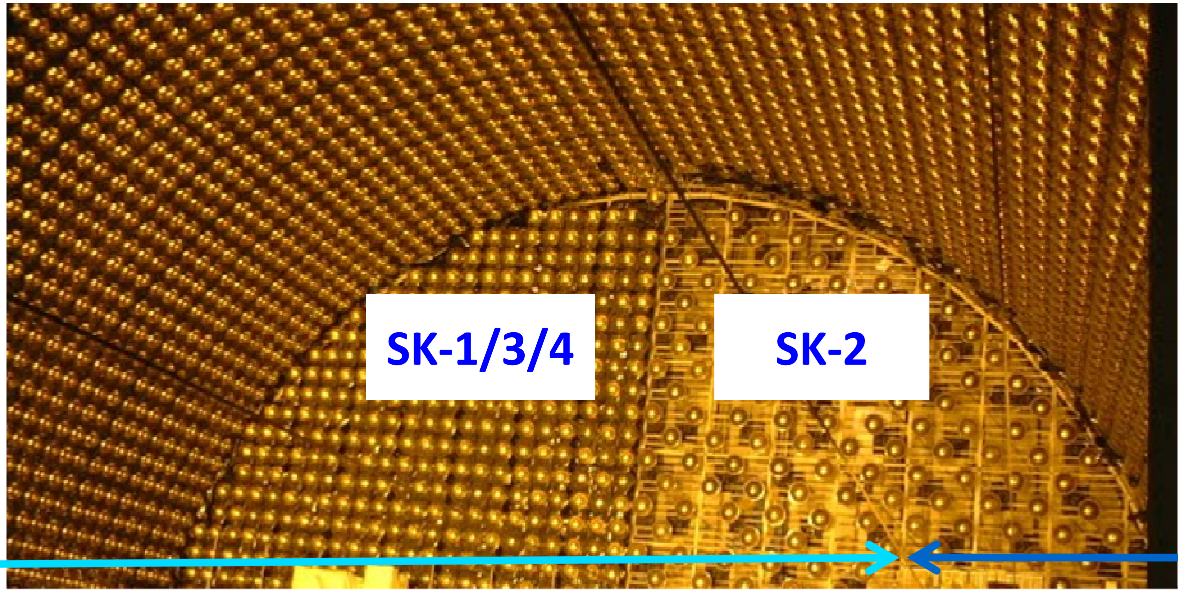
Wave front created by charged particle going faster than the speed of light in a medium

Angle related to index of refraction of medium

$$\cos\theta_C = \frac{1}{n(\lambda)\beta}$$

For SK, the maximum θ_C is roughly 42 degrees

Super-Kamiokande: Generations



Analyses

Data Update

1996 | 1997 | 1998 | 1999 | 2000 | 20 | 01 | 2002 | 2003 | 2004 | 2005 | 20 | 06 | 2007 | 2008 | 2009 | 2010 ...

accident

SK-I (1996-2001)
11,146 ID PMTs
(40% coverage)
1,885 OD PMTs

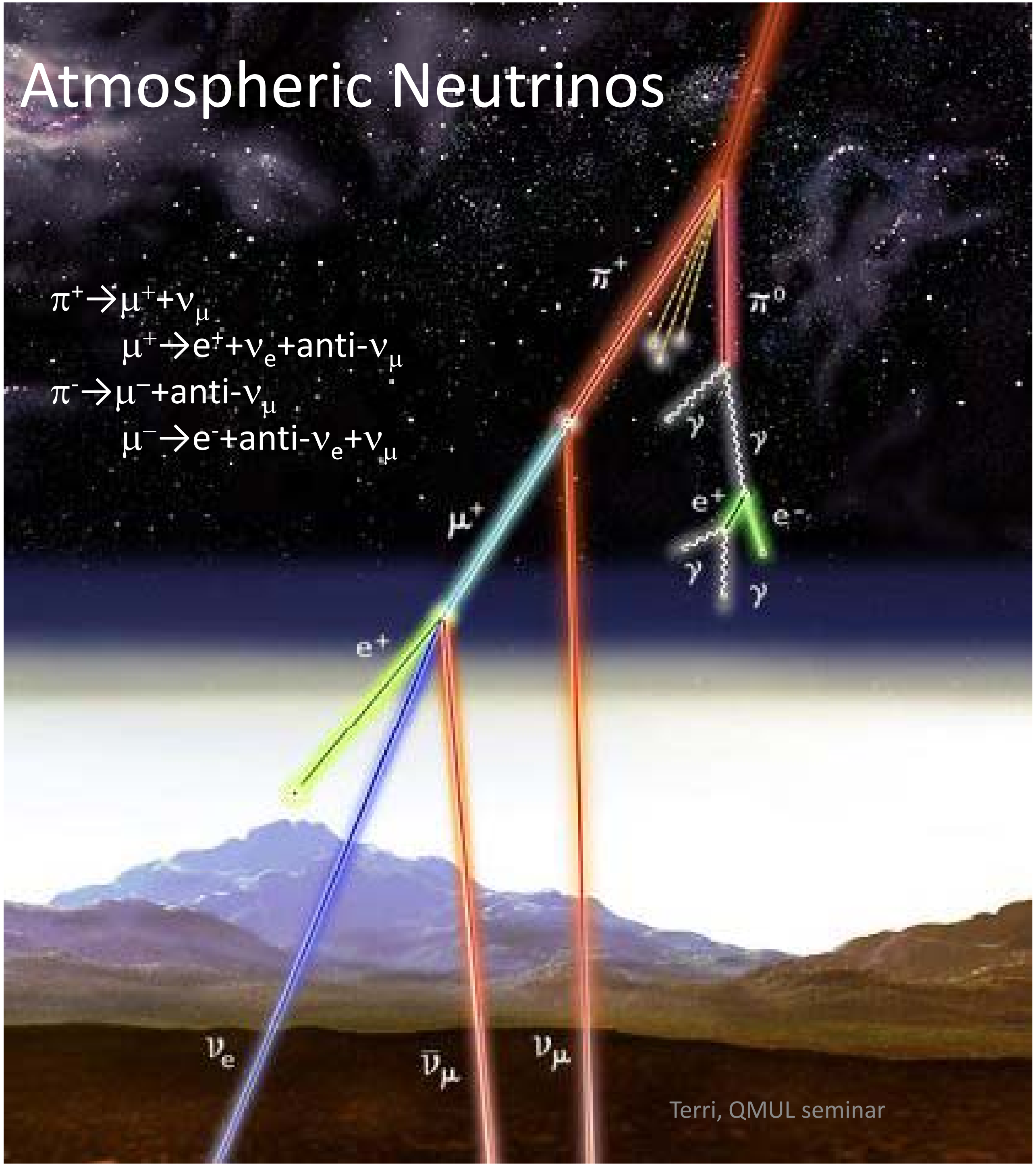
SK-II (2003-2005)
5182 ID PMTs
(19% coverage)
Acrylic shields added

SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)

SK-IV (2008-...)
new front-end electronics
(ID and OD)
new DAQ
record-all-hit data-taking
+ software trigger

Still taking data!

Atmospheric Neutrinos



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \text{anti-}\nu_\mu$

$\pi^- \rightarrow \mu^- + \text{anti-}\nu_\mu$

$\mu^- \rightarrow e^- + \text{anti-}\nu_e + \nu_\mu$

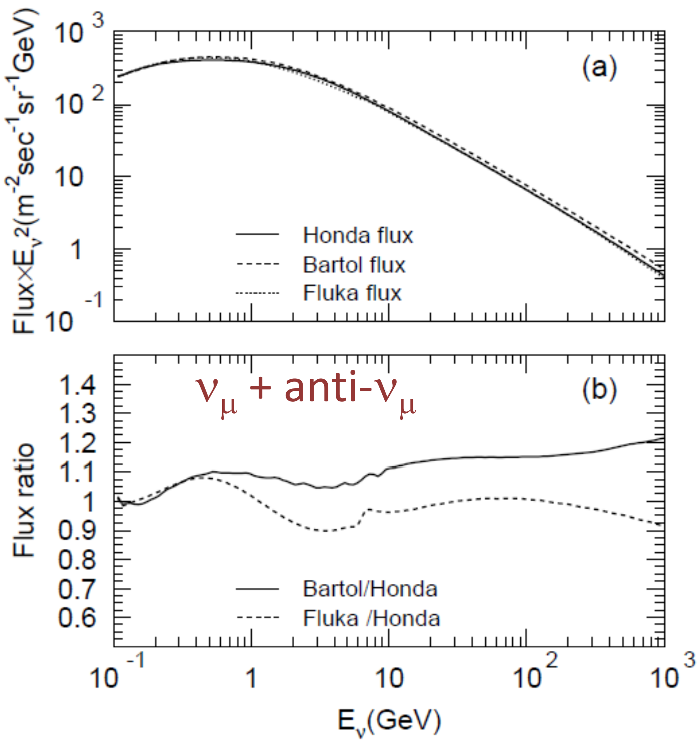
Created by cosmic ray interactions with the atmosphere

Mainly pions produced

$\nu_\mu:\nu_e$ ratio is ~2:1

Anti-$\nu_\mu:\nu_\mu:\nu_e$ ~ 1:1:1

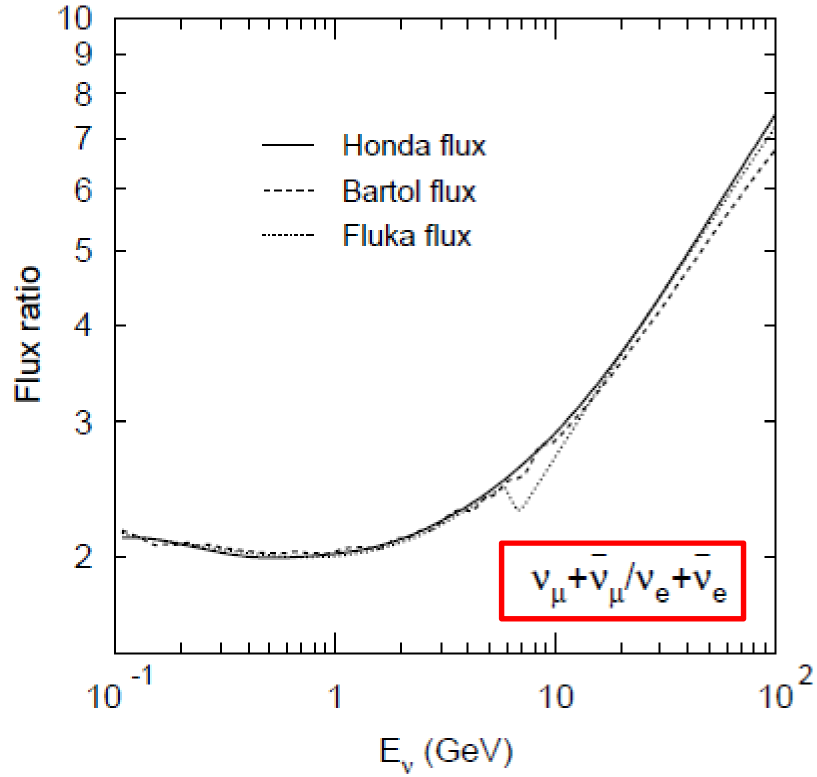
Atmospheric Neutrino Simulation:



Atmospheric neutrino flux model is from Honda *et al.* specifically at Super-Kamiokande

Uses changes in solar activity (minimum to maximum)

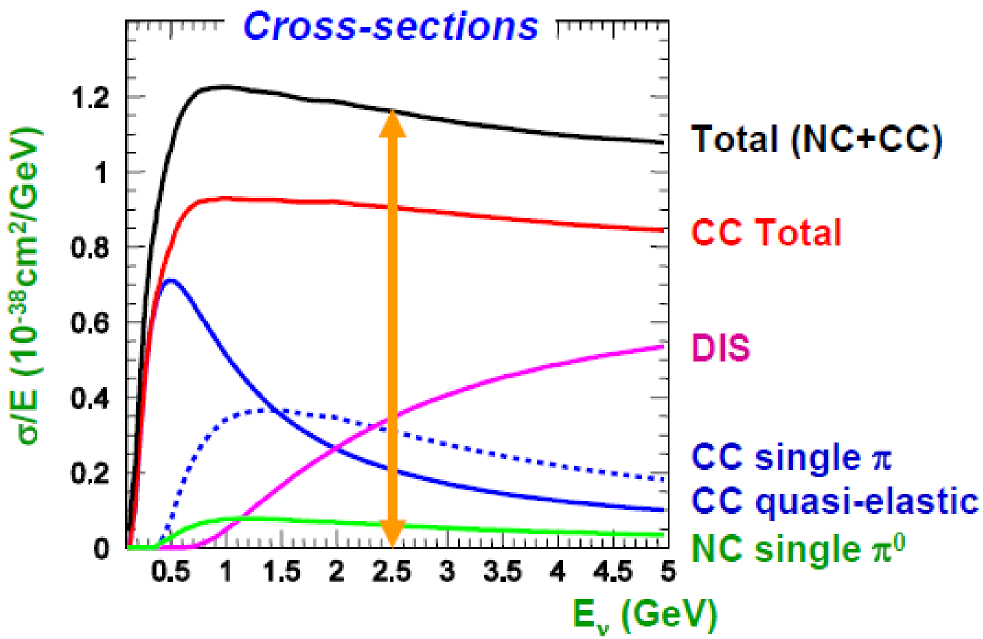
Cross checks from two other fluxes

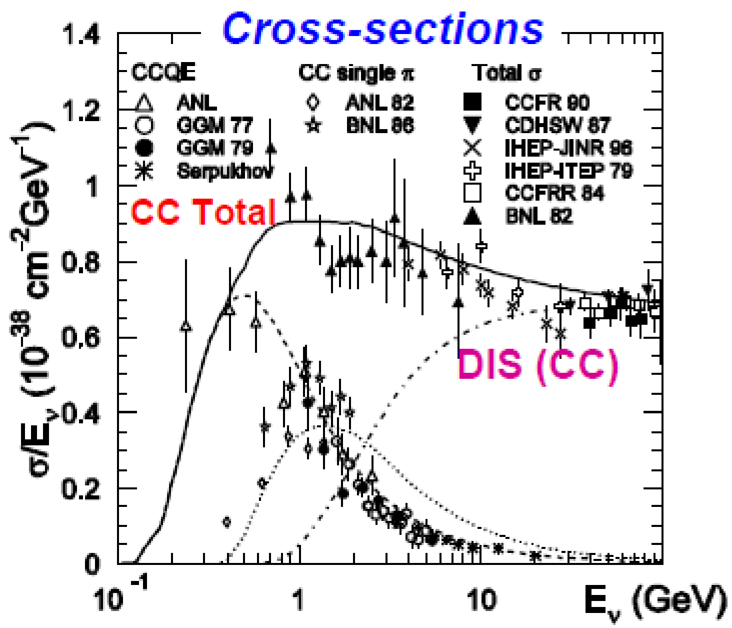


Cosmic μ bkg uses mountain profile to determine background contributions

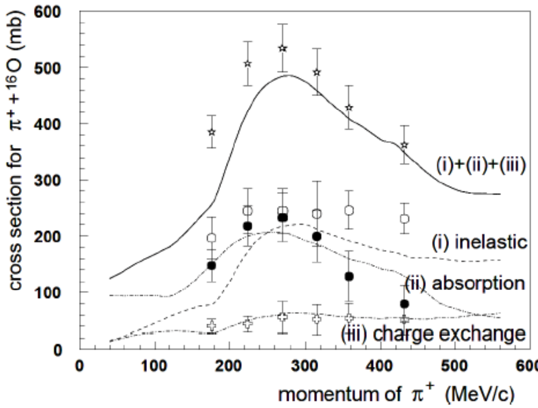
NEUT

In-house ν interaction MC
Valid from range 100 MeV-~TeV
Also used in K2K, SciBooNE, & T2K



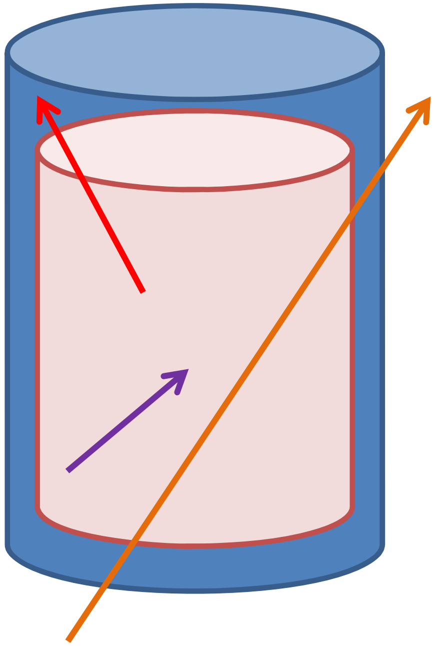


Includes base cross sections & nuclear effects, validated on external data sets



CCQE & NCEL: Smith-Moniz w/ RFG
Resonant/coherent interactions: Rein-Sehgal
DIS: GRV98 w/ Bodek-Yang correction

SK Event Reduction:

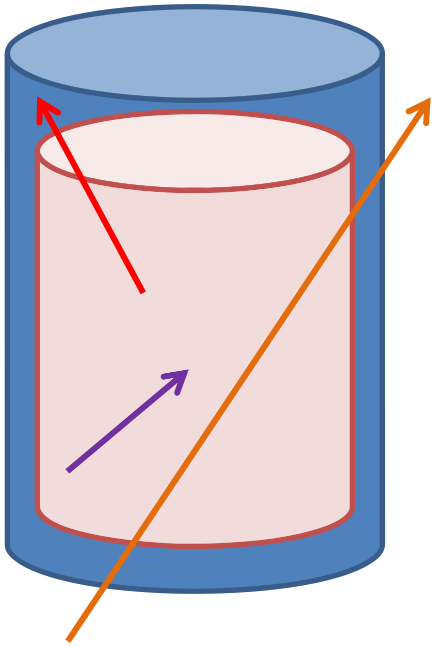


Events divided into different categories for analysis:
Fully Contained (FC) – little to no OD activity
Partially Contained (PC) – activity in OD & ID
Upμ – Muons coming from below the detector

Extract 10 events from a background of more than a million

FC:
Total charge in 300 ns timing window >200 photoelectrons (p.e.)
Less than half of the light is in any ID PMT
Little OD activity
>100 μs window between events
Remove flashers
Inside FV with at least 30 MeV visible energy

SK Event Reduction:



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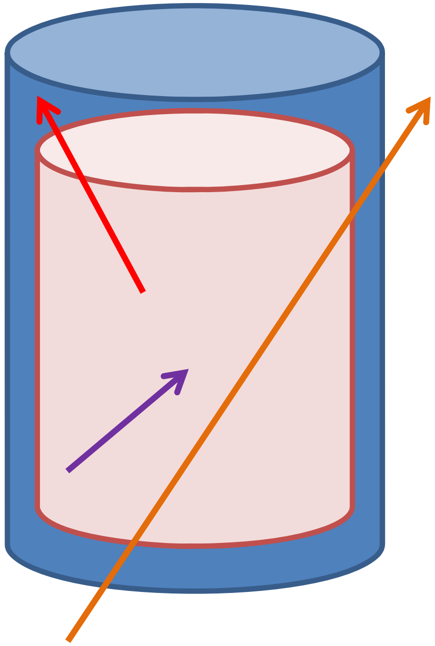
PC:
>3000 p.e. & travels at least 2.5 m in ID
>100 μs window between events
Must have clusters in the OD
Remove flashers
At least 150 cm from corner
Fail through-going muon cuts
Must pass various goodness-of-fit cuts on reconstructed vertex & direction

SK Event Reduction:



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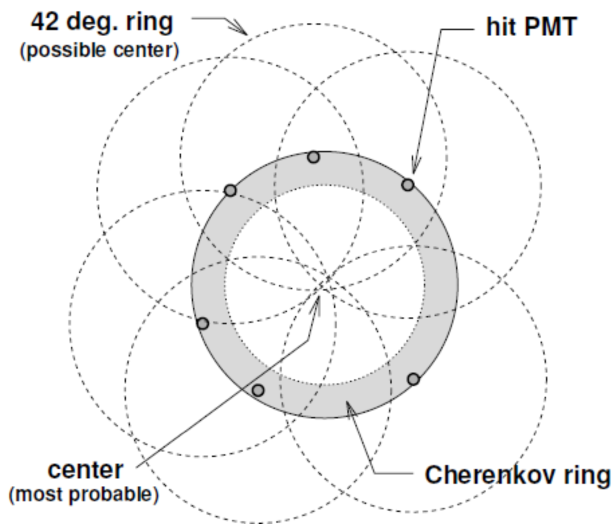
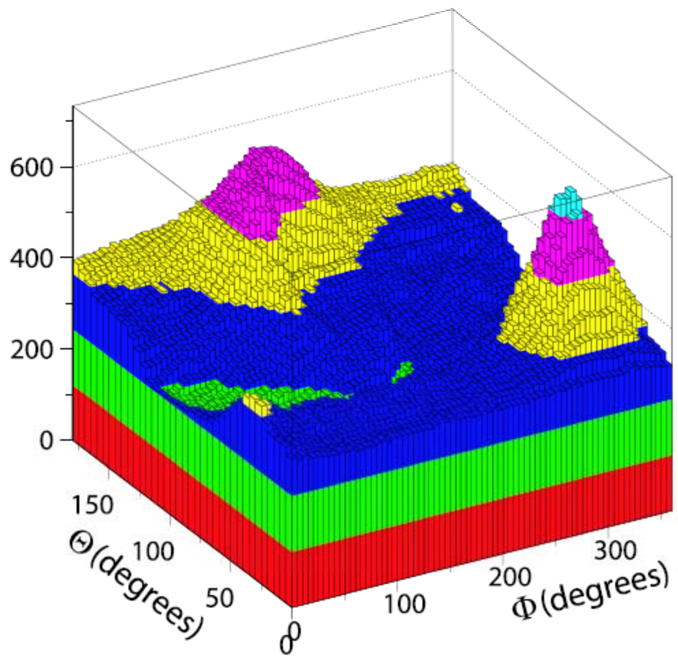
Upμ:
10 OD PMT hits w/in 8 m of track entrance or exit point
8000<p.e.<1.75e6 in ID
Must be more than 7m in track length
Various fitters applied (remove muons from top of tank)
Eye scan applied by at least 2 physicists
>= 10 hits at exit point means through-going μ
Otherwise, stopping μ

Event Reconstruction

Initial vertex fit based on PMT timing
Direction based on summed vector of weighted charge in each PMT
Cherenkov angle fitted



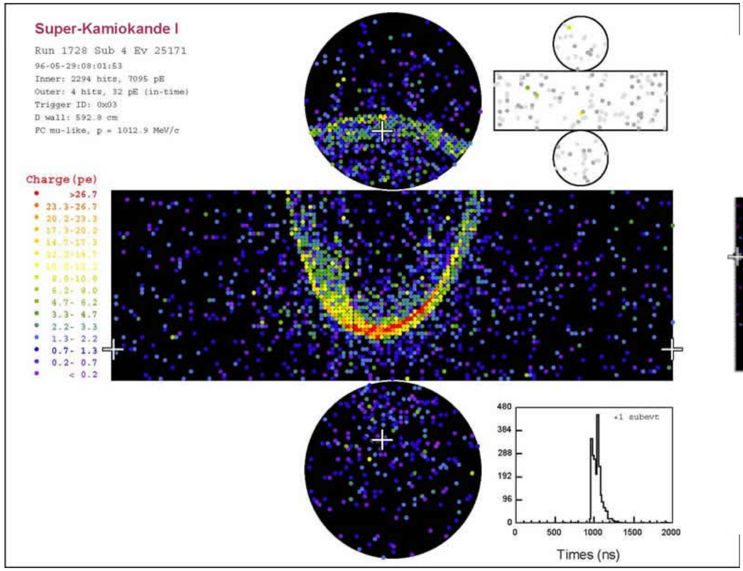


Ring counting (Hough transform + likelihood) up to 5 rings
PID applied (see next slide)
Momentum determined (corrected charge fraction in 70 degree half-angle cone)
Precise vertex for single ring events based on PID & Cherenkov angle

Ring Types & Particle ID

muons leave rings with sharp edges
electrons undergo pair production , producing a fuzzy ring

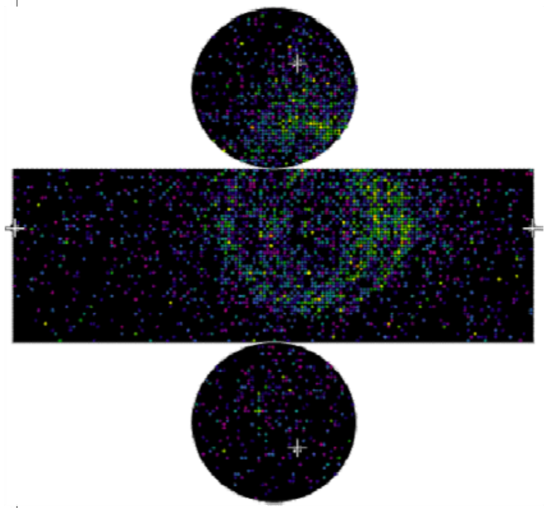
non-showering



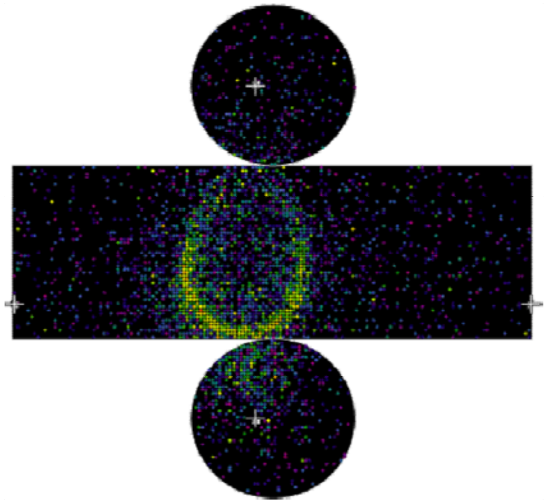
muon, charged pion, proton

μ-like

multi-ring



showering

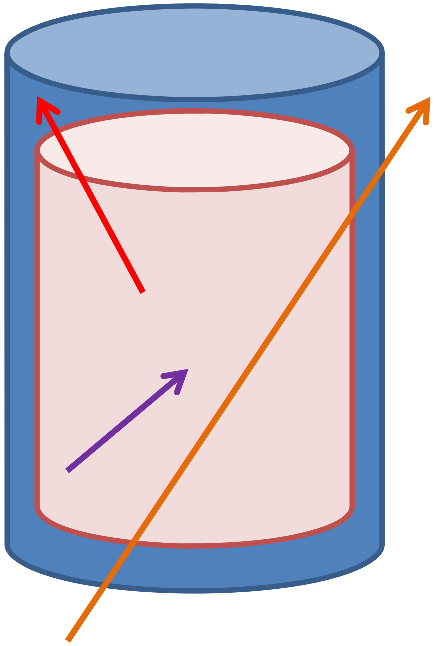


electron, photon

e-like

PID verified @ KEK test
beam w/ 1kton detector

SK Event Types



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Upμ – Muons coming from below the detector

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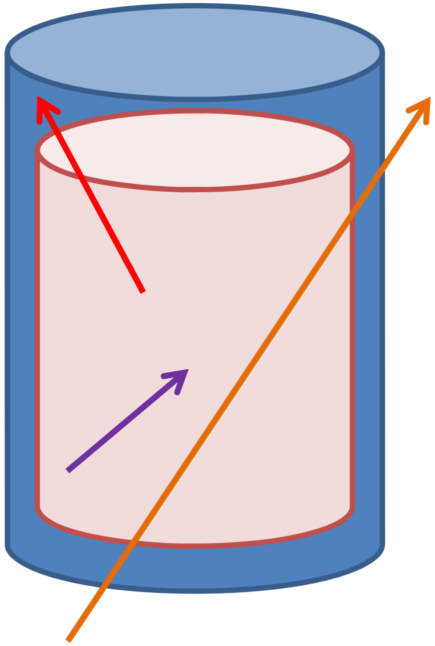

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Sub-GeV ($E_{visible}$<1.33 GeV):
One ring (R)

Multi-GeV ($E_{visible}$>1.33 GeV):
1R or multi-R

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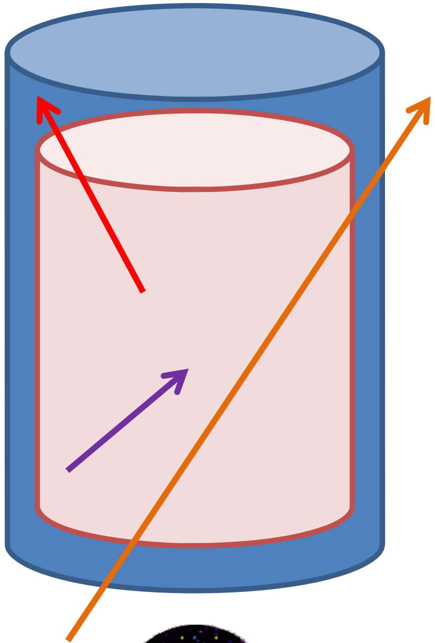

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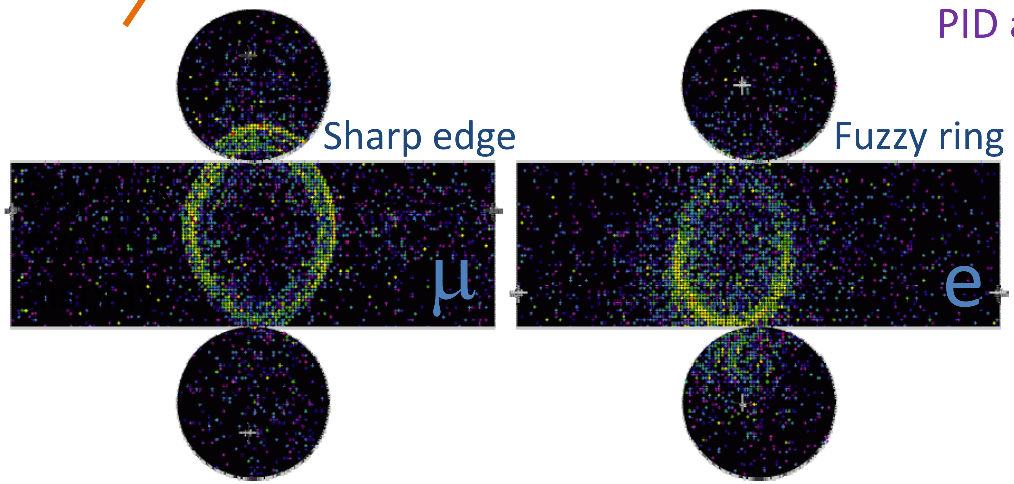
1R or multi-R, e- or μ-like

PID applied to most energetic ring



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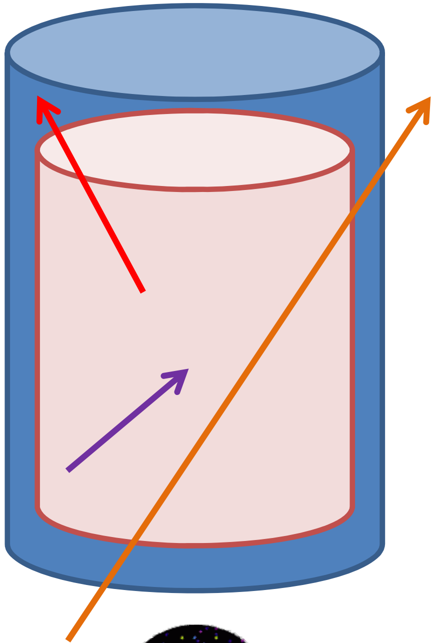

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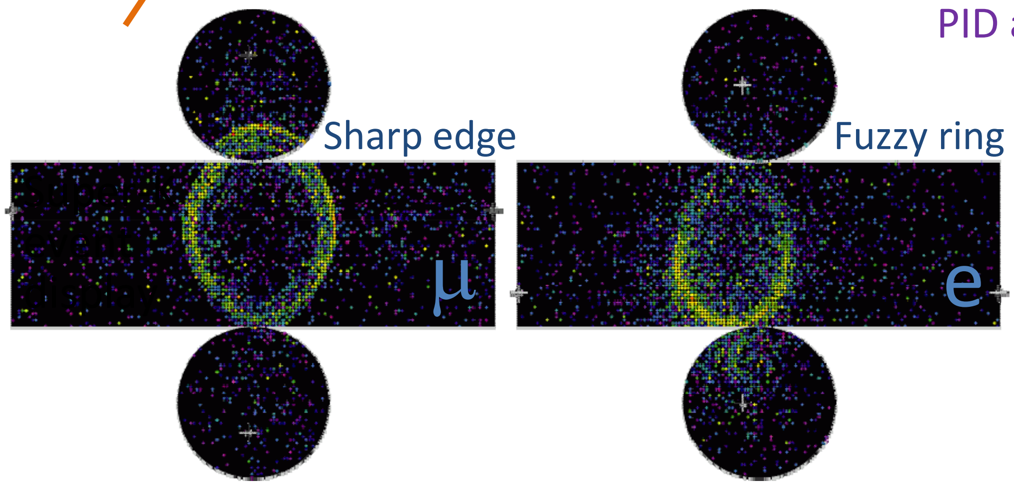

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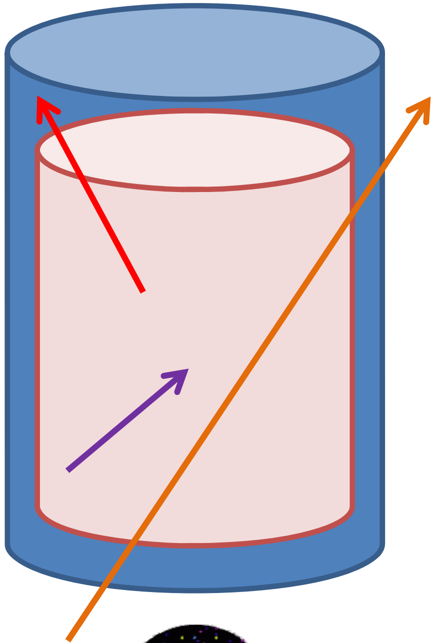

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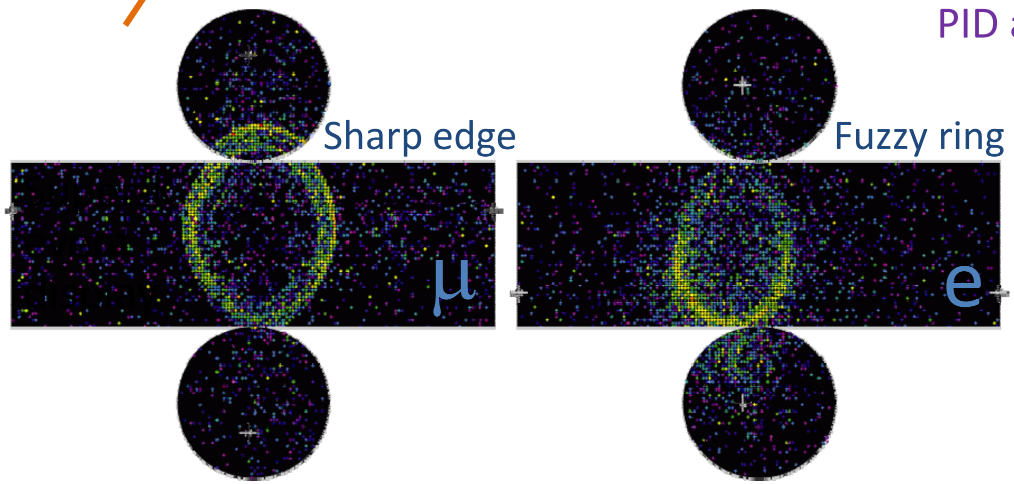
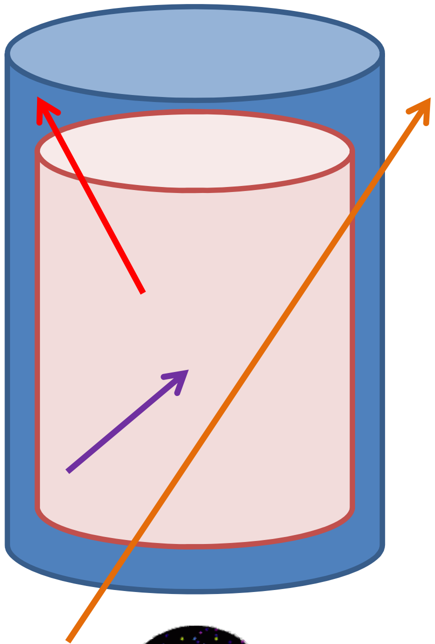


Stopping – stops in OD

Though-going – exits OD

SK Event Types



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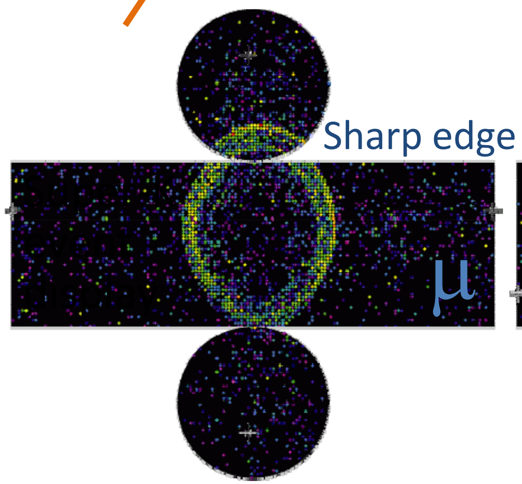
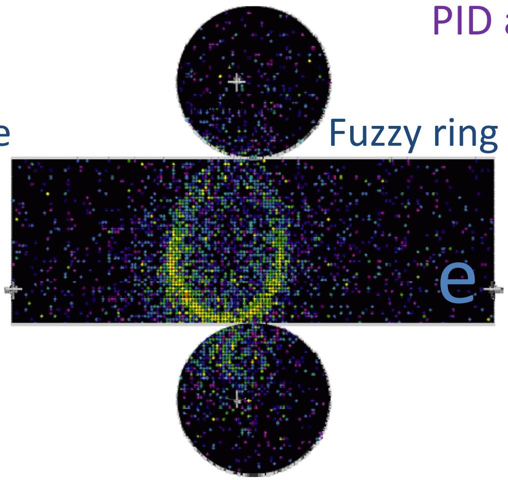




Stopping – stops in OD

Though-going – exits OD

Stopping – stops in ID

non-showering

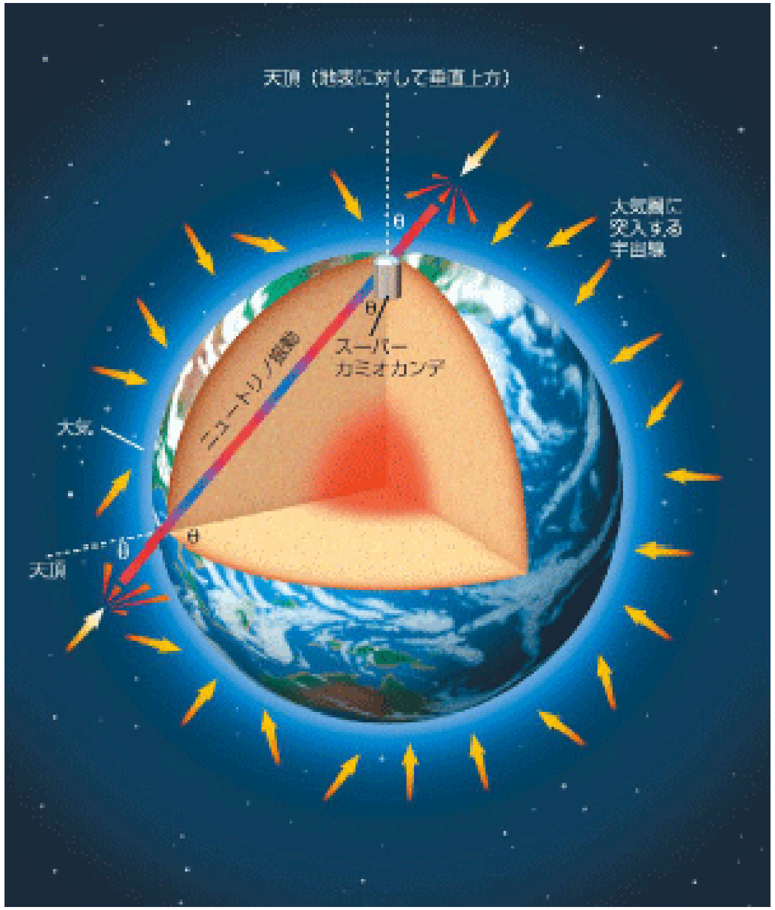
showering

Atmospheric Neutrino Anomaly

- Double ratio of flavours
  - $R = N_{Data}(\mu/e)/N_{MC}(\mu/e)$
- Early experiments show considerable difference in R
  - Thought to be problem of water Cherenkov detectors since they were a new technology

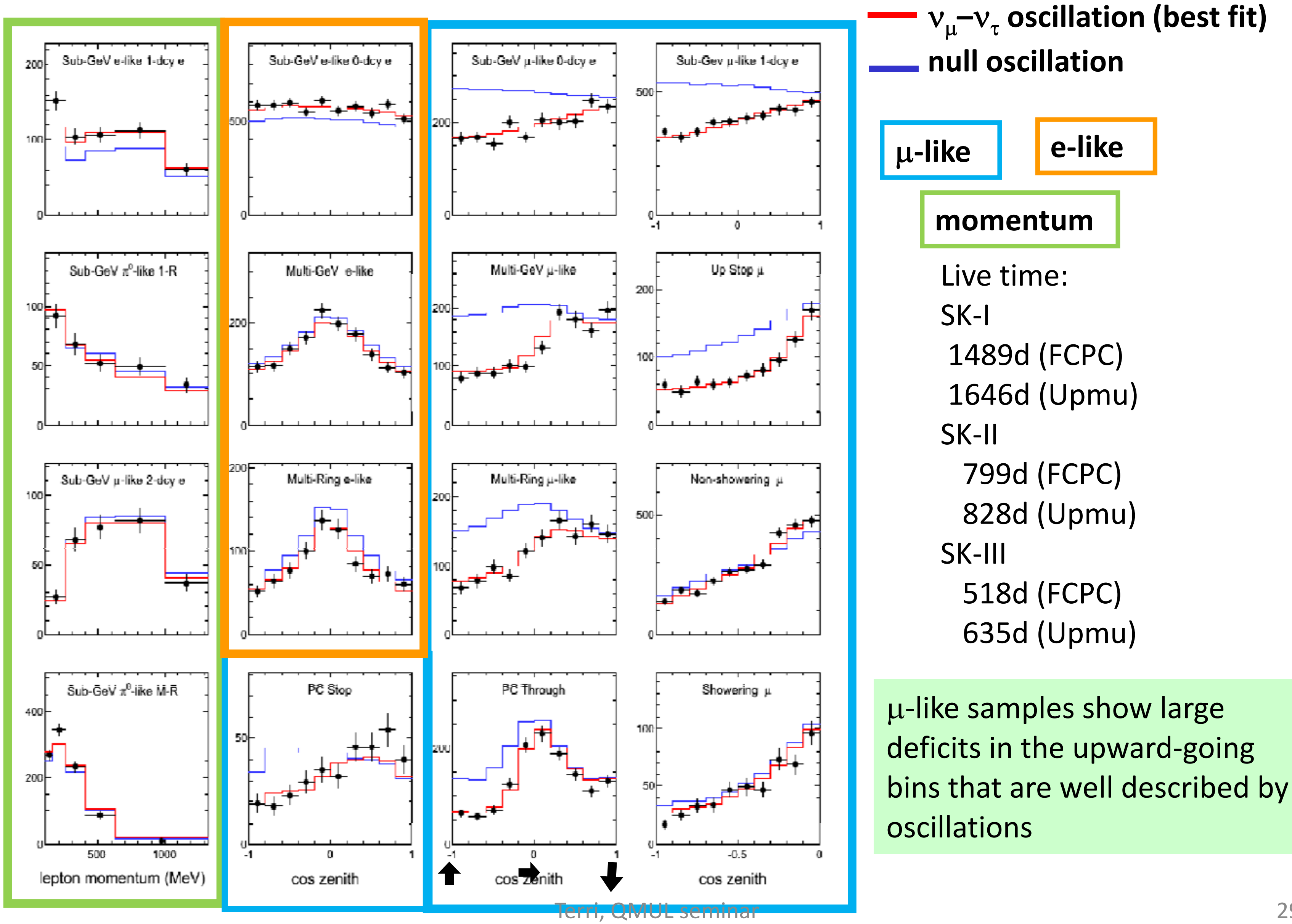
Experiment	Method	Exposure (kt·year)	Flavor Ratio $R(\mu/e)$
IMB	Water Cherenkov	7.7	$0.54 \pm 0.05 \pm 0.012$ (Sub-GeV)
		2.1	$1.40\ ^{+0.41}_{-0.30} \pm 0.3$ (Multi-GeV)
Kamiokande	Water Cherenkov	7.7	$0.60\ ^{+0.06}_{-0.05} \pm 0.05$ (Sub-GeV)
		8.2	$0.57\ ^{+0.08}_{-0.07} \pm 0.07$ (Multi-GeV)
NUSEX	Iron Calorimeter	0.74	$0.96\ ^{+0.32}_{-0.28}$
Fréjus	Iron Calorimeter	1.56	$1.00 \pm 0.15 \pm 0.08$
Soudan-2	Iron Calorimeter	5.1	$0.68 \pm 0.11 \pm 0.06$
Super-K	Water Cherenkov	92	$0.658 \pm 0.016 \pm 0.05$ (Sub-GeV)
		92	$0.702\ ^{+0.032}_{-0.030} \pm 0.101$ (Multi-GeV)

Zenith Angle Distributions



- Way to check to see if the atmospheric neutrino ratios are similar based on where in the atmosphere neutrino was created
- Neutrino production should be the same regardless of direction
  - See if systematically different or directionally dependent

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



Live time:

SK-I

1489d (FCPC)

1646d (Upmu)

SK-II

799d (FCPC)

828d (Upmu)

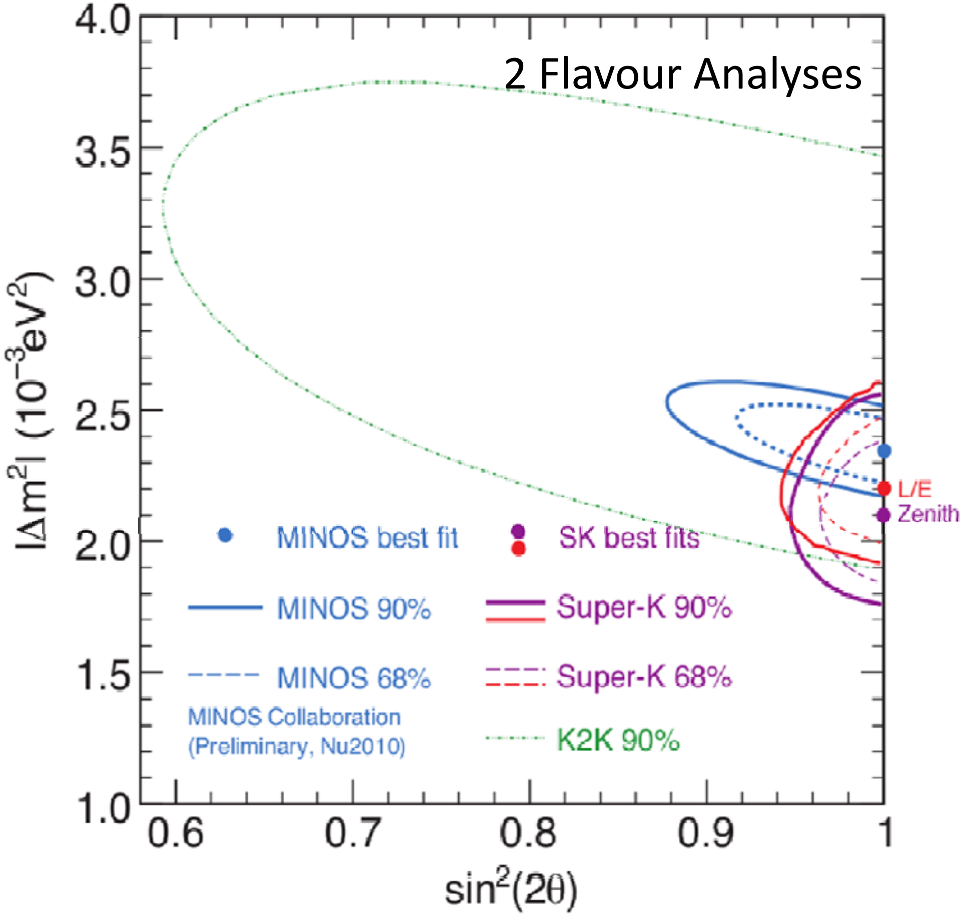
SK-III

518d (FCPC)

635d (Upmu)

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

Global Picture of Atm. ν Osc. Parameters



SK Zenith Analysis (1σ) (2 flavour)

$\Delta m_{23}^2 = 2.11^{+0.11}_{-0.19} \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} > 0.96$ (90% C.L.)

SK L/E Analysis (1σ) (2 flavour)

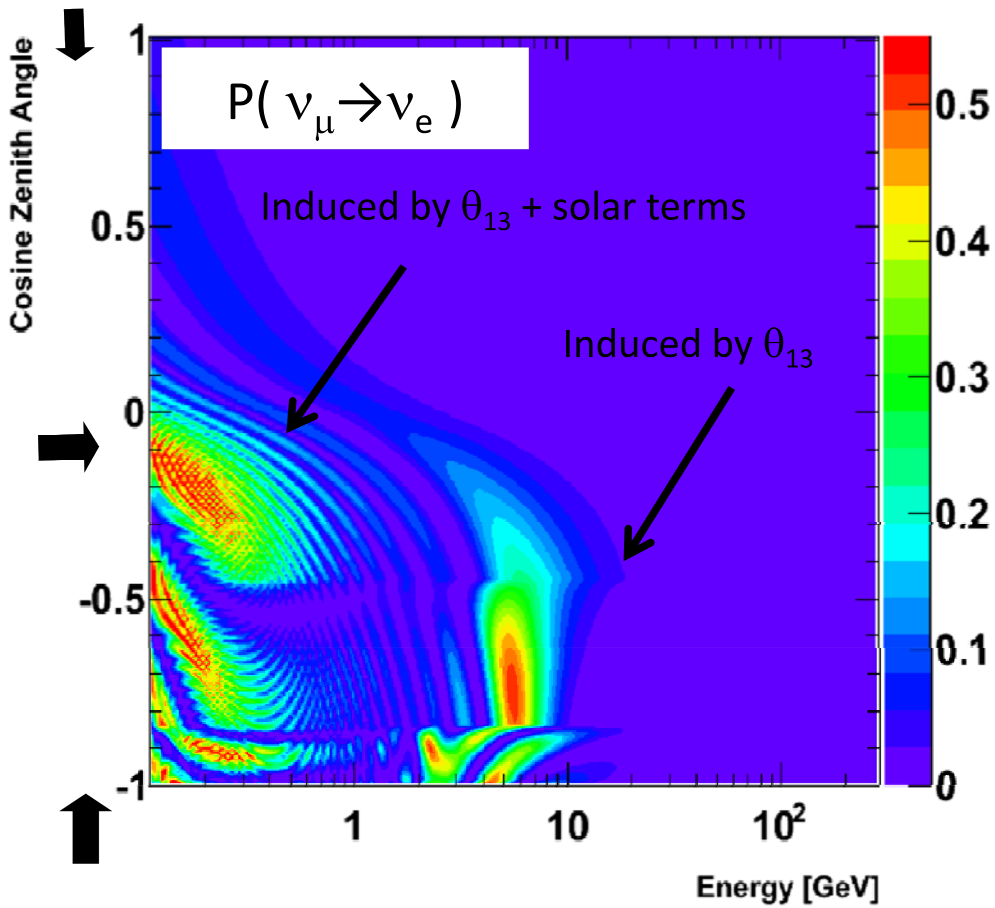
$\Delta m_{23}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} > 0.96$ (90% C.L.)

Experiments are in good agreement about these oscillation parameters

SK Data disfavour other types of disappearance strongly, sterile ν ~7σ

Three-Flavour Oscillations in Matter



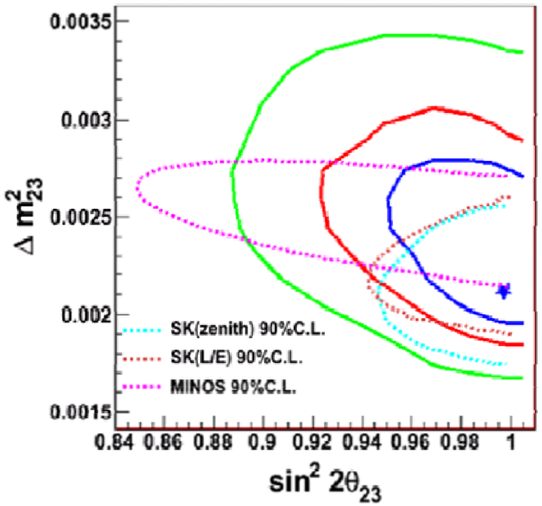
- Presence of electrons in the Earth alter the neutrino interaction potential and induce additional $\nu_\mu \rightarrow \nu_e$ oscillations
- Higher energy, 2-10 GeV, (anti-)neutrinos experience resonant enhanced transitions, for normal (inverted) hierarchy
- Lower energy oscillations, < 1GeV , are moderated by octant of θ_{23}

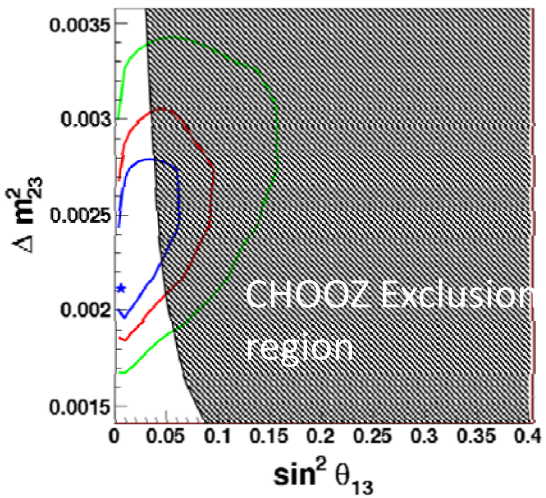
$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \textbf{Matter Driven}$$
$$+\Delta_2(\Delta m_{12}^2) \quad \textbf{Solar Terms}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

Interference term sensitive to δ_{cp}

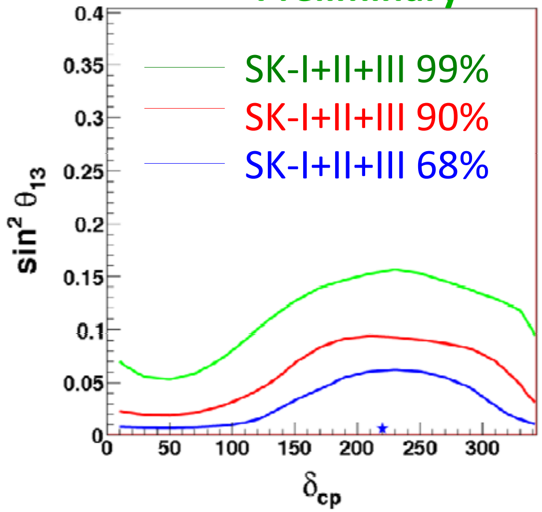
Simultaneously considering all of these effects gives sensitivity to many of the remaining questions on oscillation physics...

Full Three-Flavour Oscillation Analysis (Normal Hierarchy)





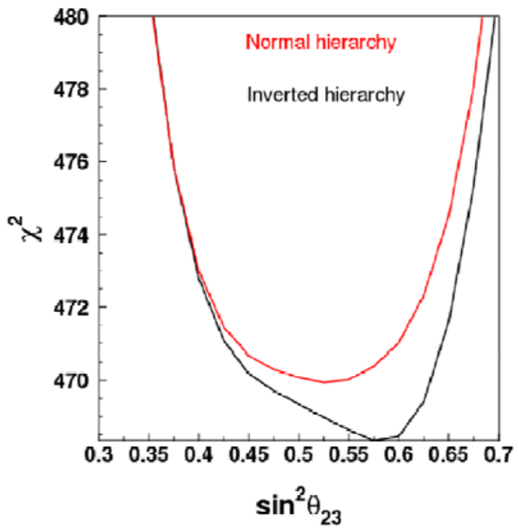
Preliminary



χ^2_{min} = 469.94 /416dof

Parameter	Best point
Δm^2_{23} (x10³)	2.11 eV²
$\sin^2\theta_{23}$	0.525
$\sin^2\theta_{13}$	0.006
CP-δ	220°

T2K: $0.03<\sin^2\theta_{13}<0.28$

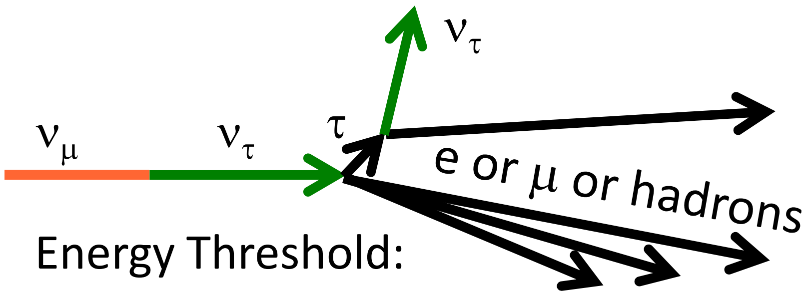


No strong preference for either hierarchy ($\Delta\chi^2$ = 1.6)

No preference for θ_{23} octant or δ_{CP}

From R. Wendell NNN2010

ν_τ Appearance at Super-K

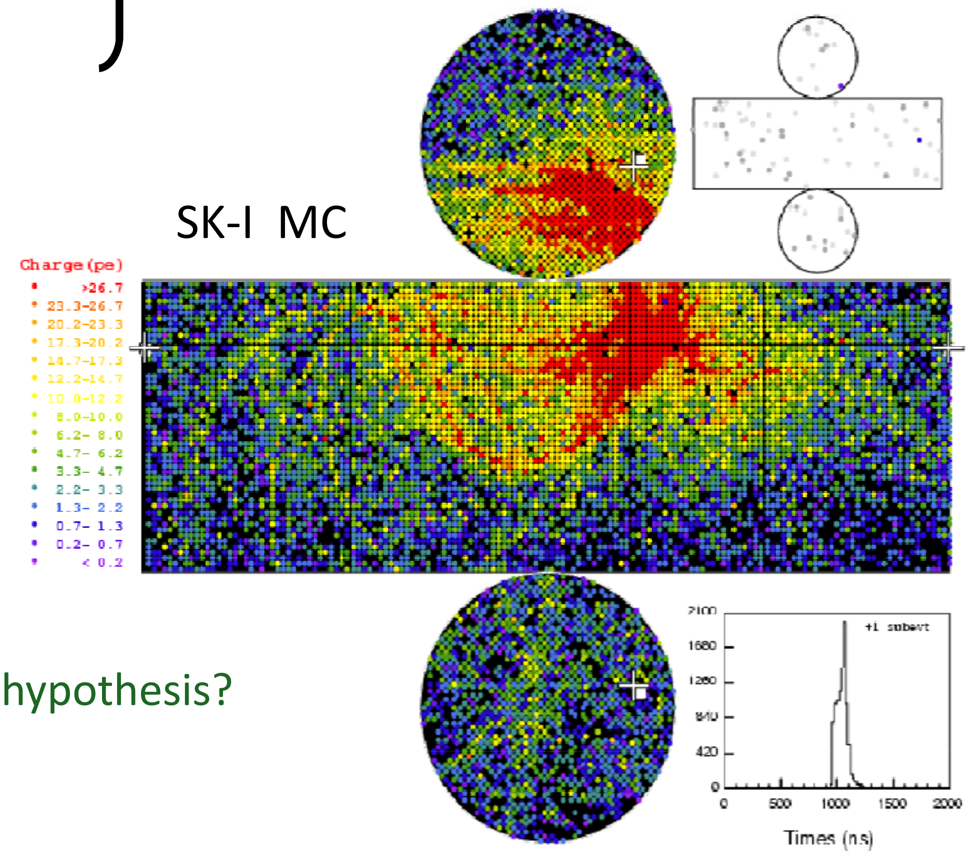


Energy Threshold:
3.5 GeV

- Many Cherenkov light producing particles
- Most events are DIS interactions

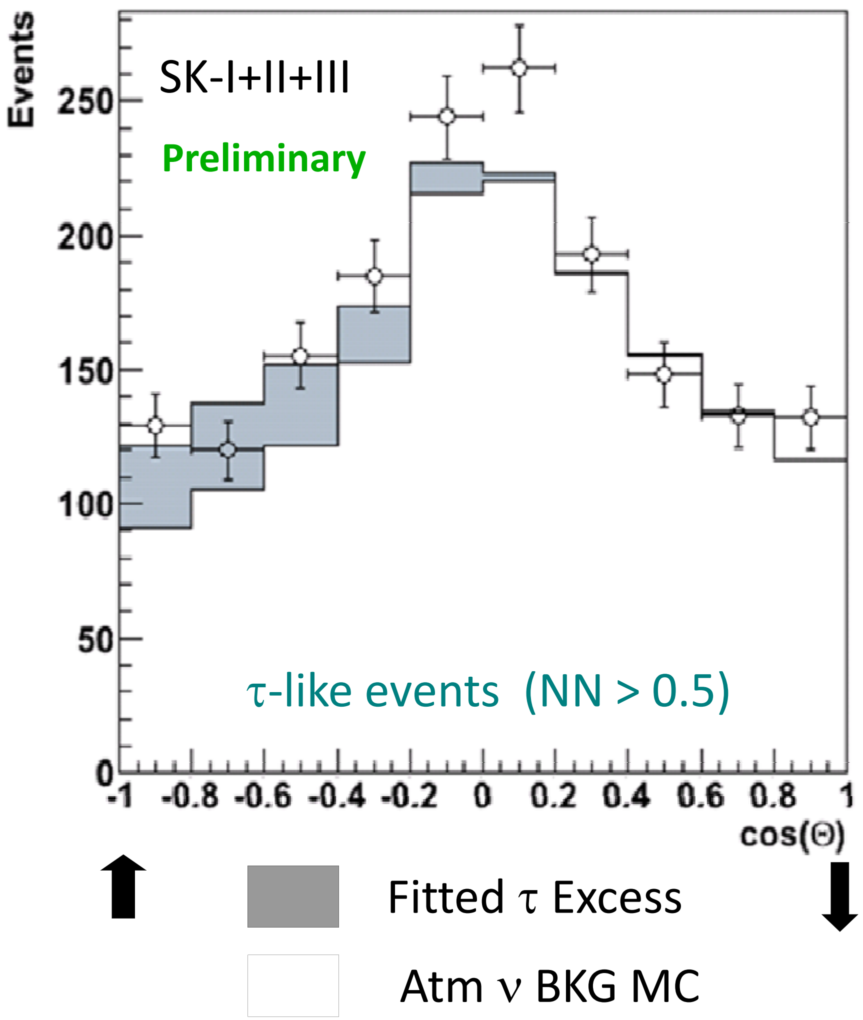
Negligible primary flux
→Observed tau events would be oscillation induced

Complicated event topology complicate identification of the leading lepton



How inconsistent is the “no appearance” hypothesis?

SK τ Appearance Fit Results (Updated)



Update of Phys. Rev. Lett. **97**, 171801 (2006) (SK-I only) NN analysis

Fit corresponds to 213.6 τ events

SK data is inconsistent with no τ appearance at 3.8σ

Expected significance: 2.6σ
Previous result: inconsistent at 2.4σ

One of two experiments so far to observe some signal of ν_τ appearance (OPERA being the other)

ν/Anti-ν oscillations

Motivated from recent MINOS indications of different osc. parameters of ν & anti-ν

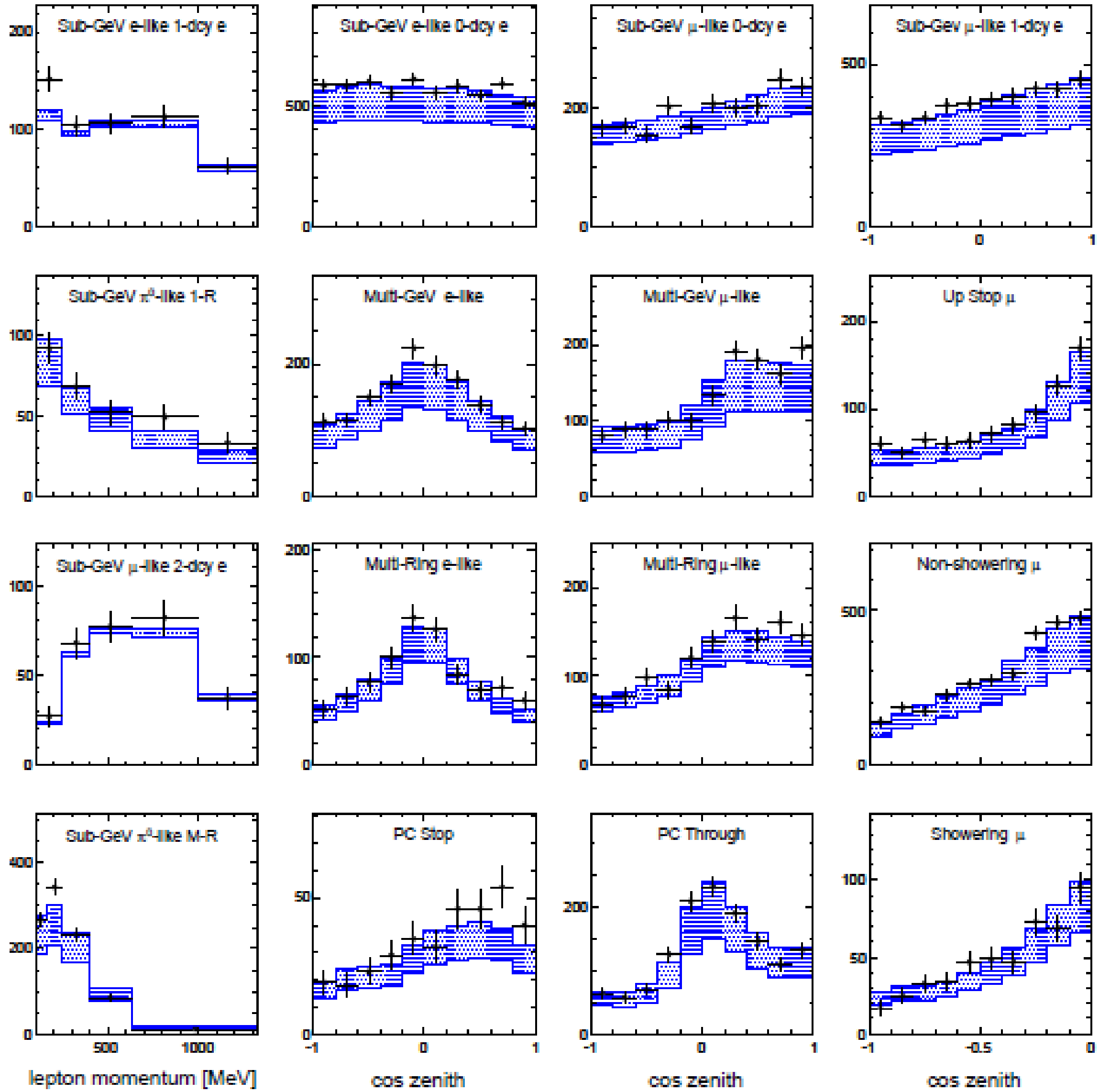
SK applies an ad hoc 2 flavour model, fit osc. parameters individually for ν & anti-ν

$$P(\nu_\mu \to \nu_\mu) \;=\; 1 - \sin^2 2\theta \sin\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \;=\; 1 - \sin^2 2\bar{\theta} \sin\left(\frac{\Delta \bar{m}^2 L}{4E}\right)$$

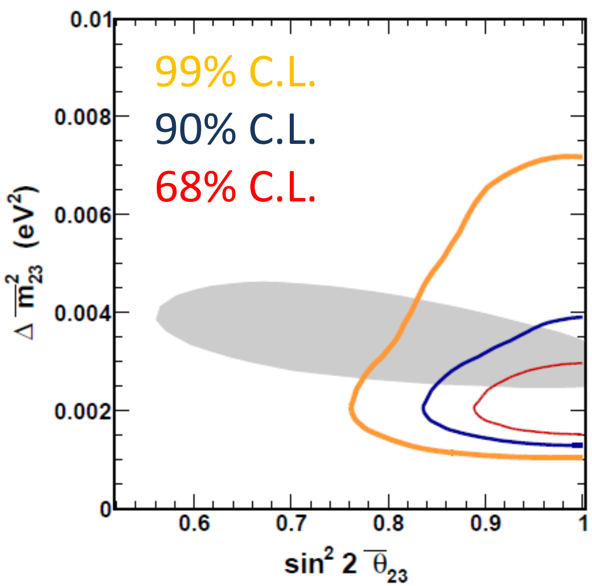
Divide into samples same as with normal 2 flavour oscillation fit

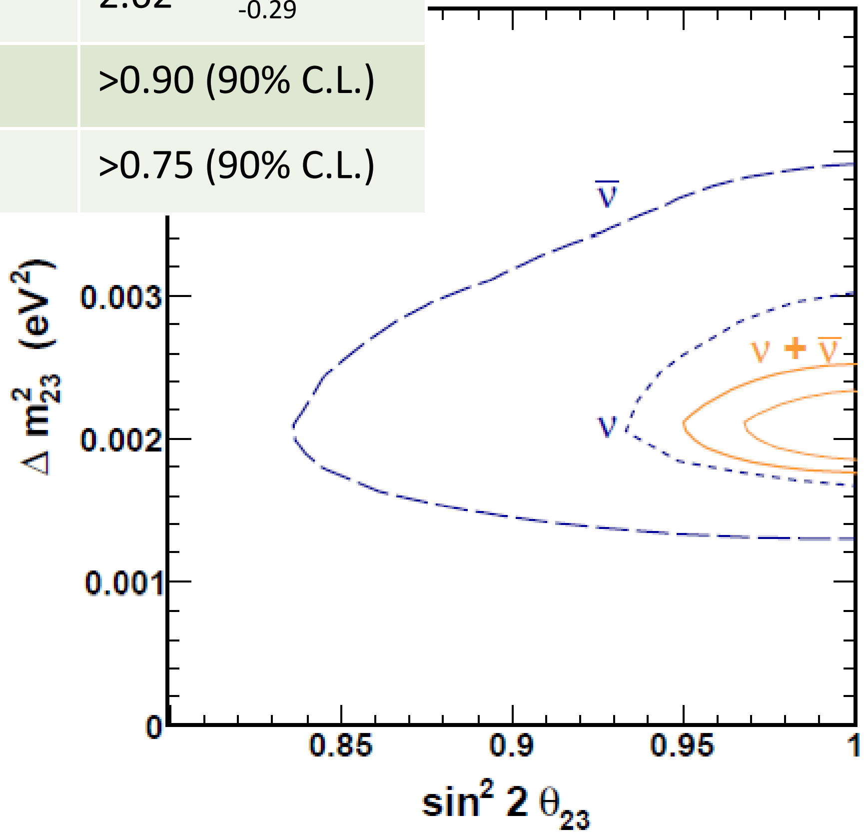
MC histogram is best fit, w/ blue region anti-ν contribution



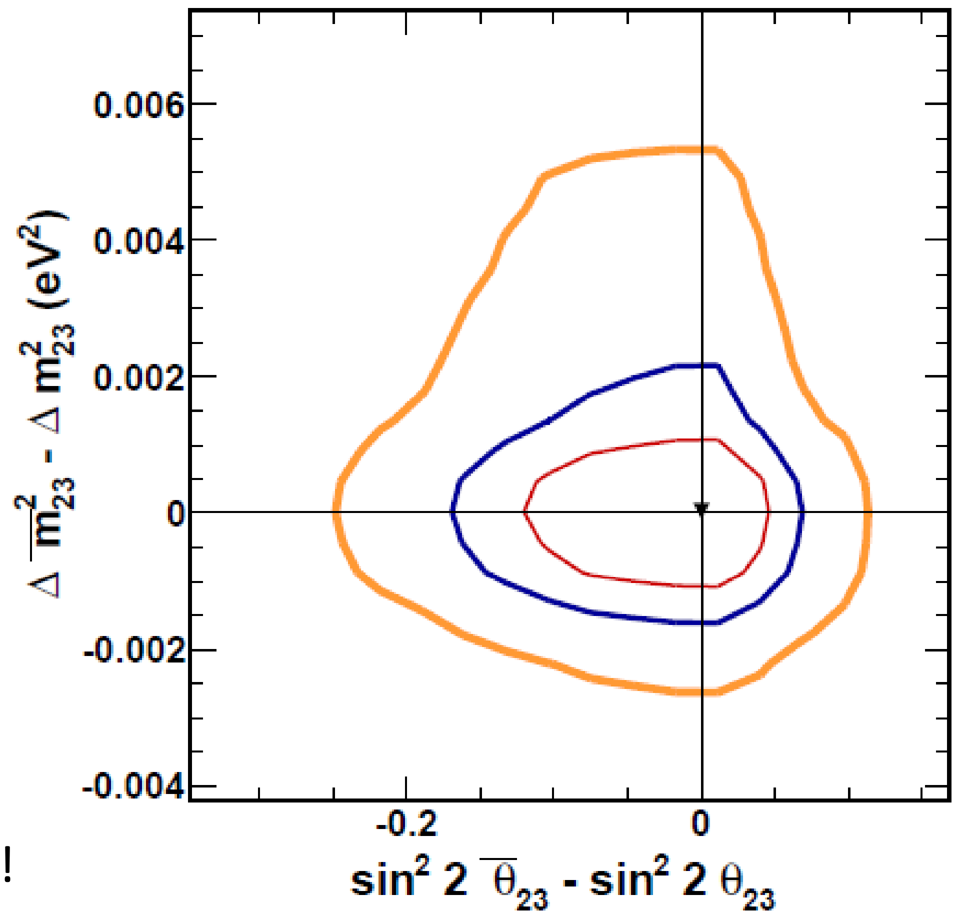
ν/Anti-ν Osc. Results

Parameter	Best Fit	90% C.L.	Three-Flavour	MINOS Best Fit
Δm^2/1e-3 eV^2	2.1	1.7-3.0	1.7-3.3	$2.32^{+0.12}_{-0.08}$
Anti-Δm^2/1e-3 eV^2	2.0	1.3-4.0	1.2-4.0	$2.62^{+0.32}_{-0.29}$
$\sin^2 2\theta$	1.0	.93-1.0	.93-1.0	>0.90 (90% C.L.)
Anti-$\sin^2 2\theta$	1.0	.83-1.0	.78-1.0	>0.75 (90% C.L.)





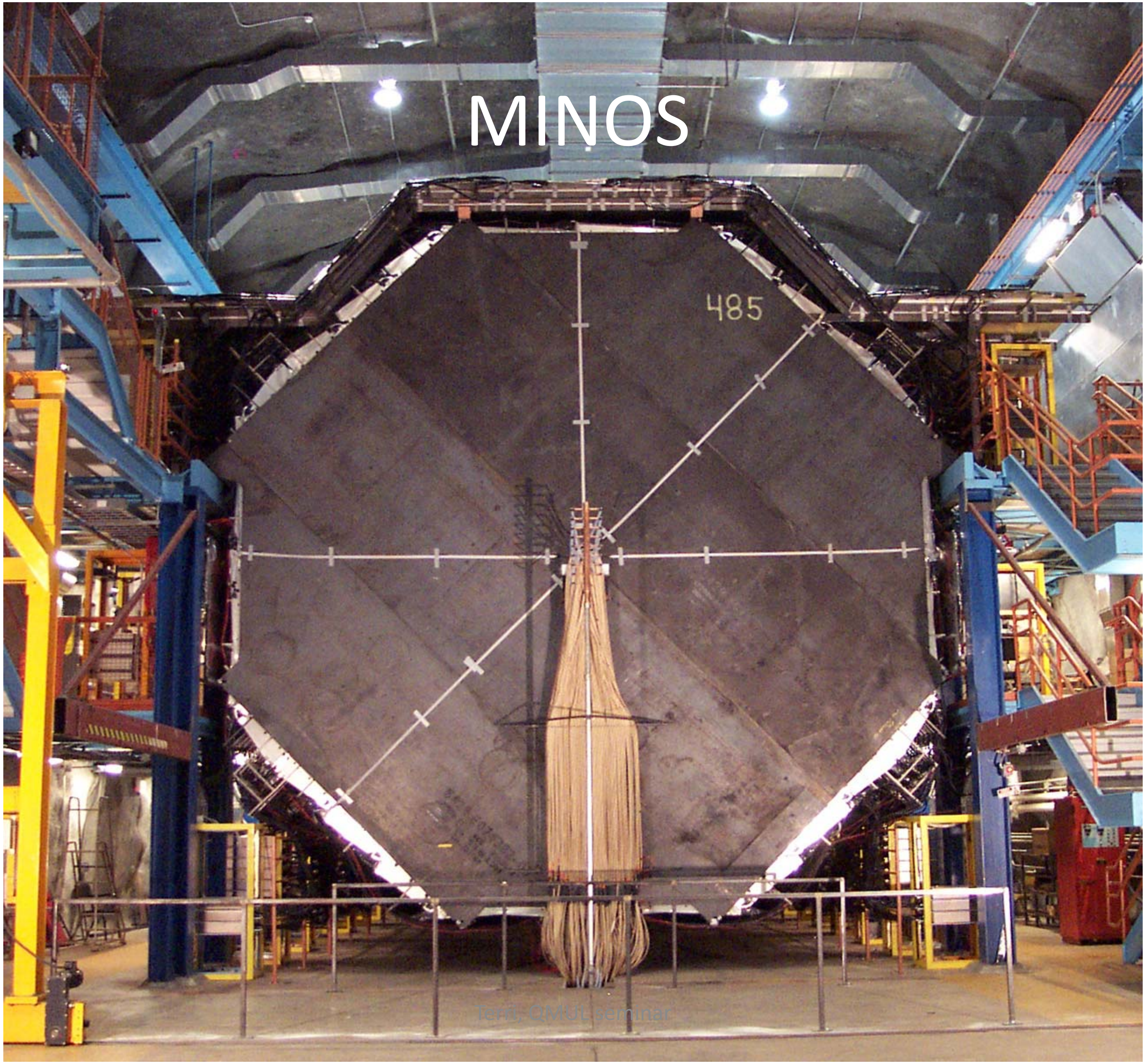
Do ν & Anti-ν Have Same Oscillation Parameters?



Short answer: yes!

Updated MINOS beam results indicate same answer (hep-ex 1202.2772)

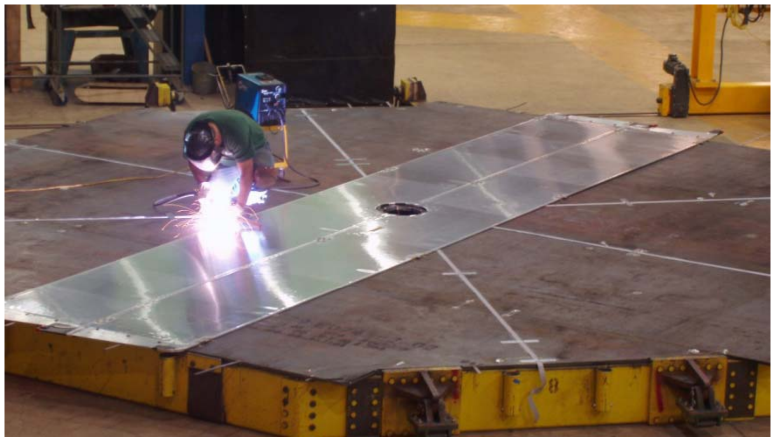
MINOS



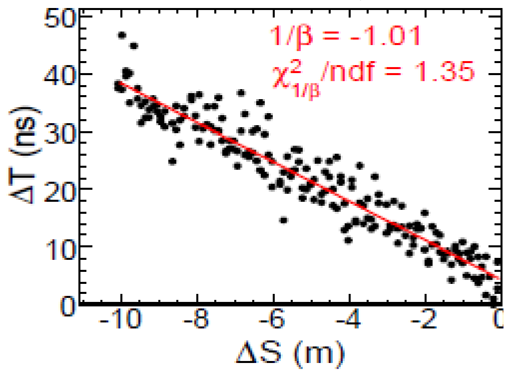
Far Detector Description and Event Types

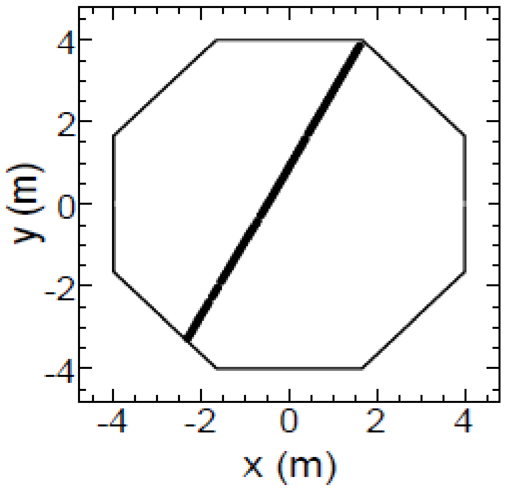
Far detector (5.4 kton):
In Soudan Mine, 2070 m.w.e.
486 2.54 cm thick steel planes
484 scintillator planes, 1 cm thick

Magnetic field average ~1.3 T
Can separate differently charged tracks



Cosmic Ray μ:

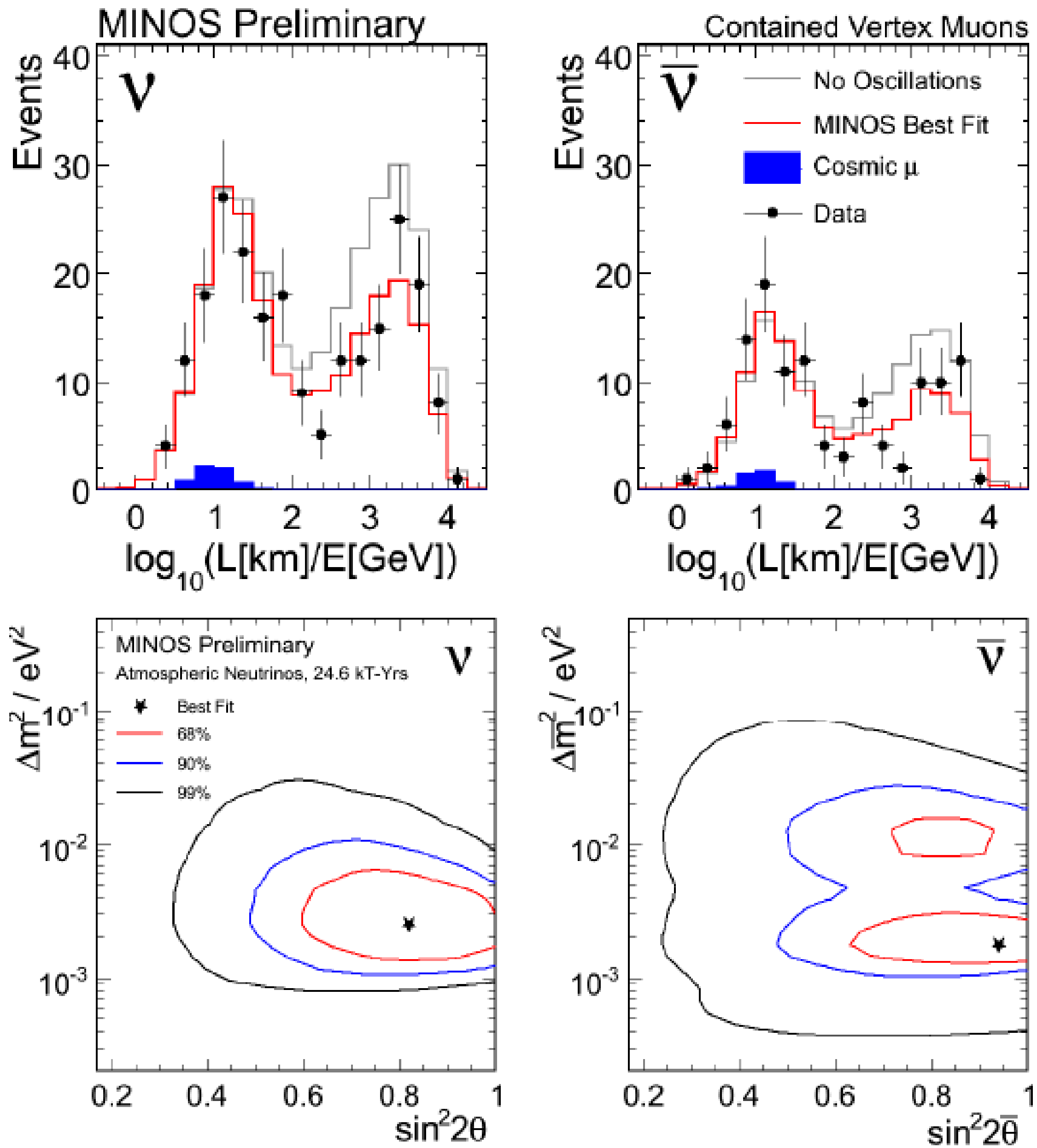




Select muon tracks:
- Single track only
- Vertex starts inside fiducial volume
- Good timing & track quality cuts
- Separate by charge (+/-)
- Separate by momentum:
  - p<10 GeV, 10 GeV<p<100 GeV, Unknown

Event selection taken from hep-ex/0701045v2

Atm. ν results (NEUTRINO 2010)



- ❑ **Atmospheric neutrino results based on 1657 live-days of far detector data (24.6 kt-yrs).**
- ❑ **Observe 1128 candidate events:**
  - ◇ **572 contained vertex muons.**
  - ◇ **292 contained vertex showers.**
  - ◇ **264 ν-induced rock muons.**
- ❑ **MINOS detector is magnetised, enabling direct separation of neutrinos and anti-neutrinos. Measuring charge ratio:**

$$R^{data}_{\bar{\nu}/\nu} / R^{MC}_{\bar{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

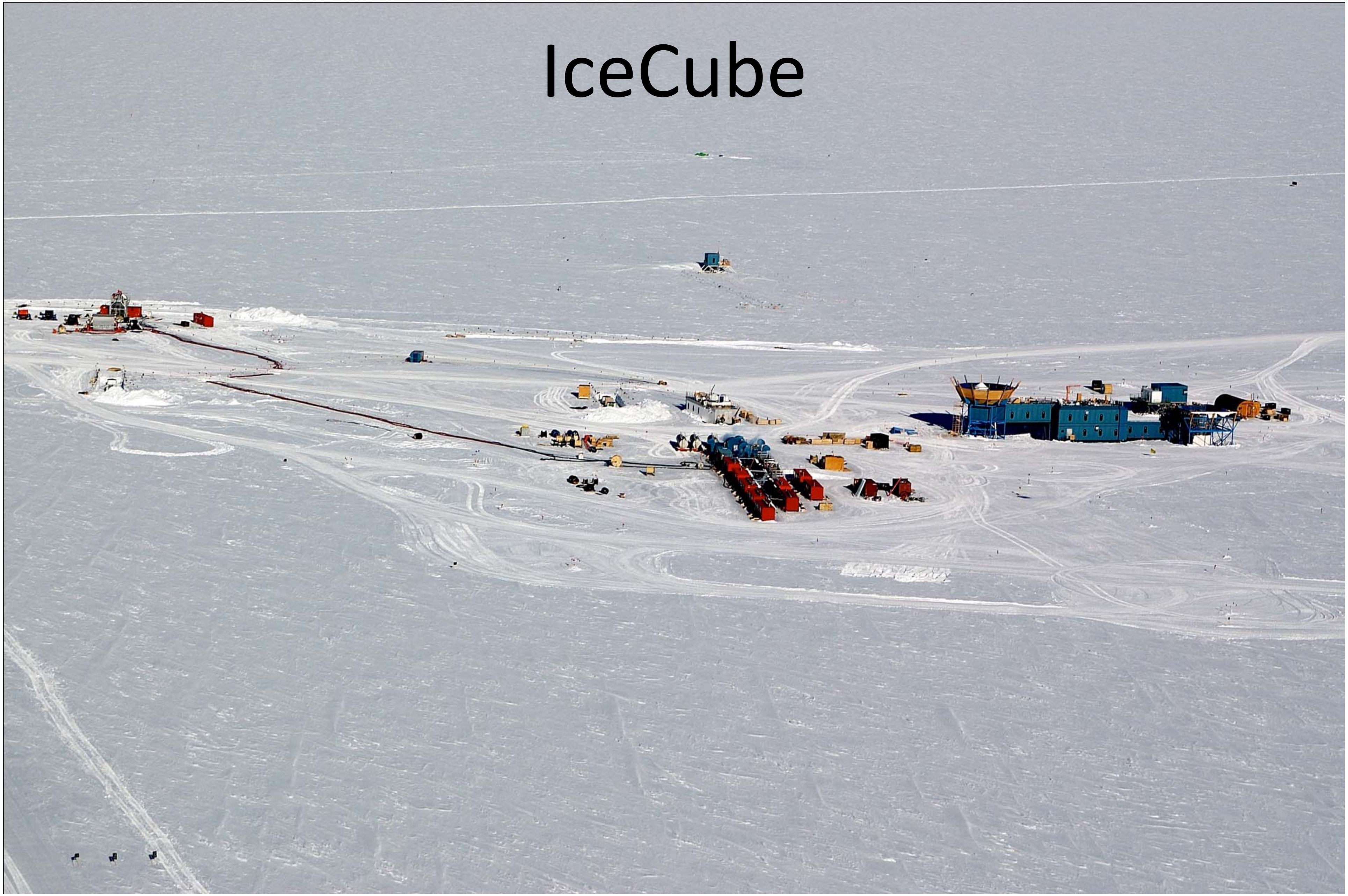
- ❑ **Fit oscillations separately for neutrinos and anti-neutrinos. Testing CPT symmetry:**

$$|\Delta m^2| - |\Delta \overline{m}^2| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\,eV^2$$

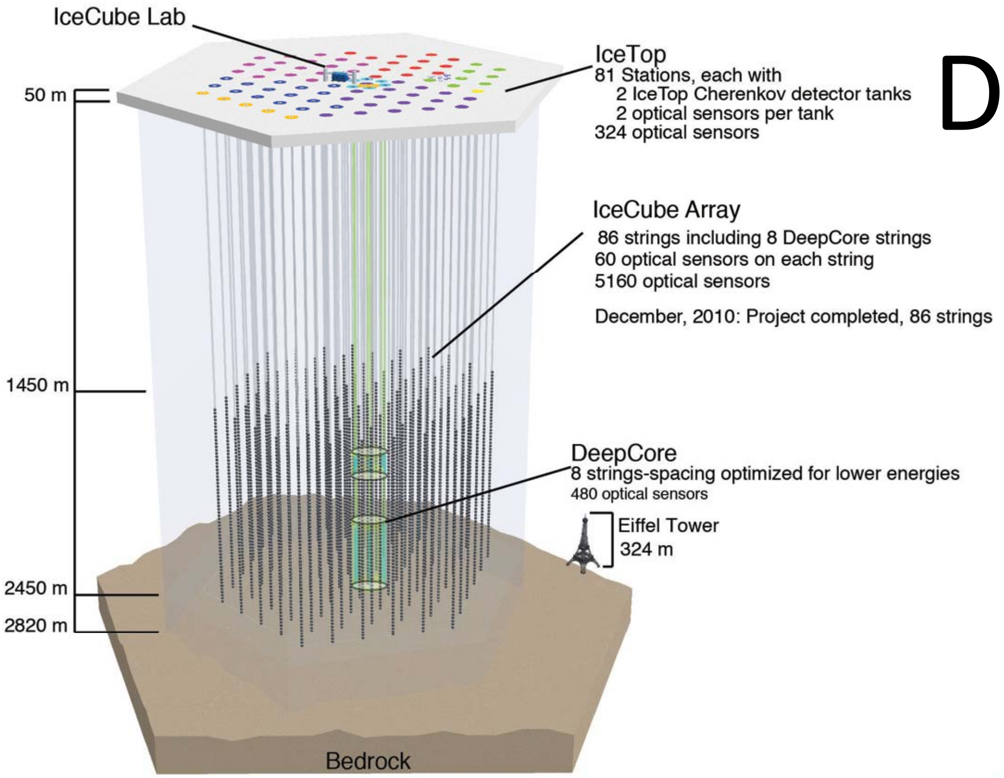
90% C.L, at maximal mixing.

From MINOS Collaboration

IceCube



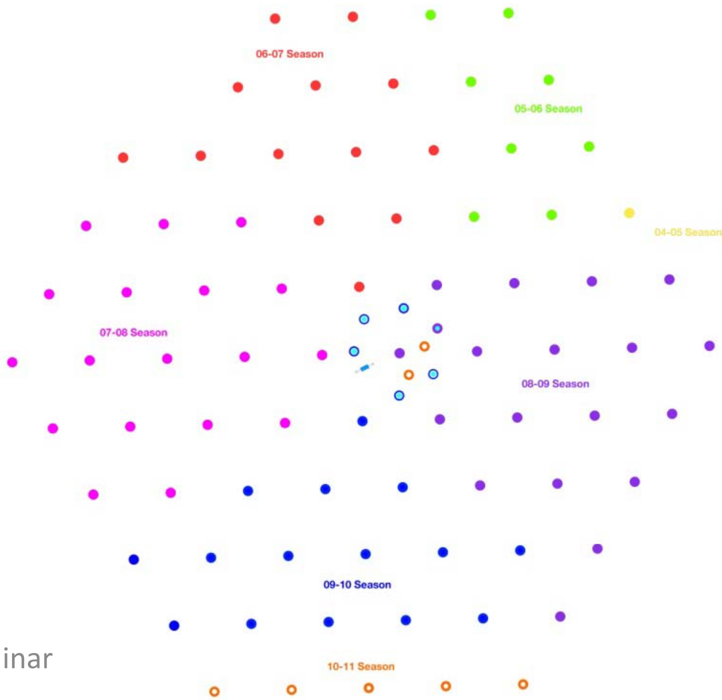
Detector Setup



Neutrino astronomy experiment located at South Pole

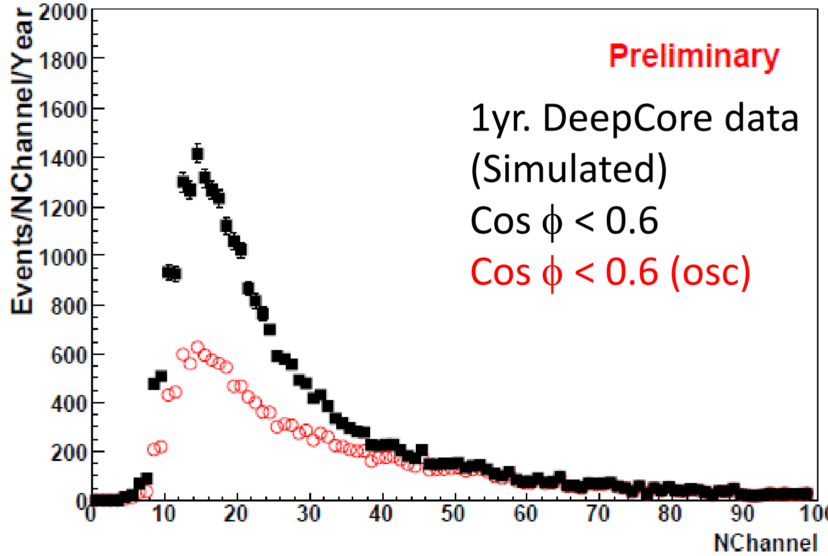
~1 km^3 volume

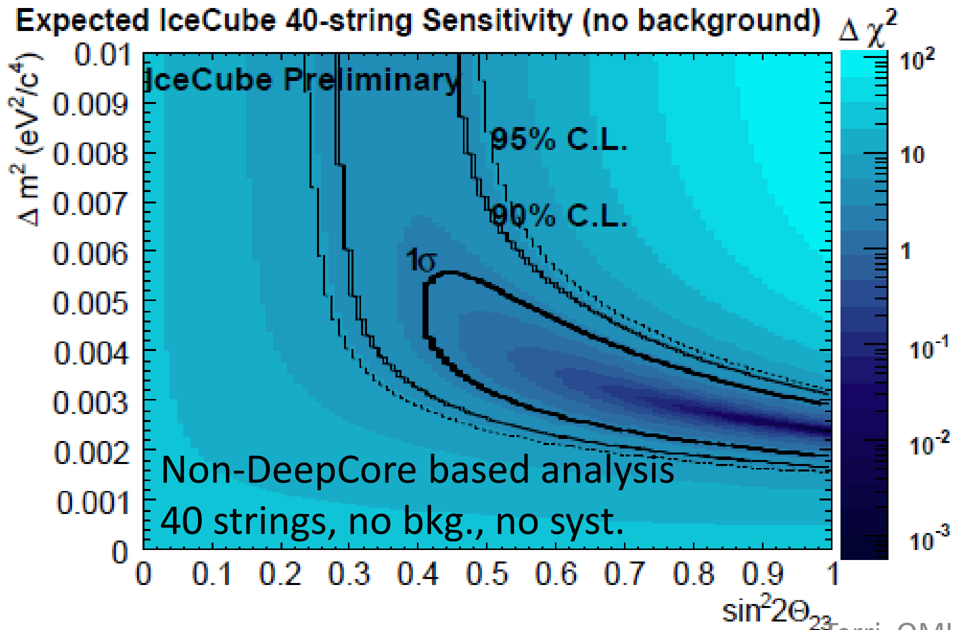
Searching for HE & UHE neutrinos from various astrophysical sources e.g. Supernova, γ-ray bursts, black holes, dark matter



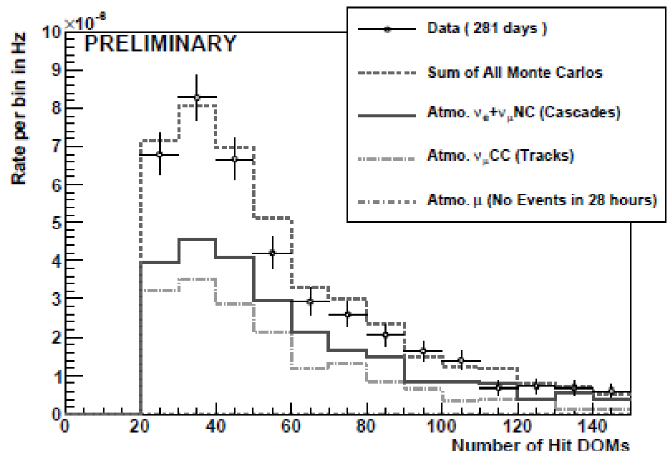
Years installed:
04-05
05-06
06-07
07-08
08-09
09-10
10-11

Possible Atmospheric ν Measurements





- Atm. ν one of two backgrounds to ν astronomy
  - Needs to be well-measured
- Future measurements may include:
  - Atm. ν oscillation parameter measurement
    - 10 GeV threshold
  - ν_τ appearance searches
  - Mass hierarchy



Type	C^{sig} ν_e^{NC}	ν_e^{CC}	ν_μ^{NC}	C^{bg} ν_μ^{CC}	MC Sum	N^{obs}
Bartol	25	312	314	455	1106	-
Honda	18	245	287	415	965	-
Data	-	-	-	-	-	1029

Summary

- Super-Kamiokande holds the world's best oscillation measurements from atmospheric neutrinos
  - Still competitive w/ MINOS's long-baseline measurements in the 23 sector
  - One of two experiments to see τ appearance
  - Confirms ν & anti-ν oscillation atmospheric neutrino oscillation parameters are statistically consistent
  - Now also searching for θ_{13}, δ_{CP}, and mass hierarchy
- MINOS able to measure CPT using atmospheric neutrino sample
  - No violations yet observed
- Possible contributions by other experiments anticipated

Backup

Selected/Biased Neutrino History

- First proposed in 1930 by Pauli to explain beta decay energy spectrum
- First observed by Reines and Cowan in 1956
  - Savannah River experiment records inverse beta decay signal
- Homestake Experiment begins in 1968, Solar Neutrino Problem
  - Followed later by the Atmospheric Neutrino Anomaly
- Early 1980s, IMB becomes the first water Cherenkov experiment
  - Followed soon by the Kamiokande detector
  - Built to look for proton decay
- In 1998 Super-Kamiokande reports that neutrinos have mass
  - First physics beyond the Standard Model

3 event classes

FC Reduction:
Little to no OD activity (less than 25 hit PMTs) w/in +/-400 ns window around trigger
Must have at least 200 photoelectrons in 300 ns window
No PMT may have more than ½ the light
At least 30 MeV in visible energy
Separated by at least 100 us
Remove events w/ at least 10 hit PMTs w/in 8m of where a particle could enter
Remove "flasher" PMTs
Remove stopping muons & invisible muons based on hits in various sliding windows
PC Reduction:
Travel at least 2.5 m into ID
Have at least 3000 p.e. In ID
Separated by at least 100 us
Have large cluster of p.e. in OD 8m around entrance point w/ Cherenkov ring having high angle WRT entrance proposed entrance point
Eye scan by 2 physicists
Upmu:
Between 8000 & 1.75e6 p.e.
At least 7m track length