

Recent Status & Prospects of Atmospheric Neutrino Oscillation Measurements

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IoP Half-Day Meeting

18 April 2011

Outline

- Atmospheric neutrino & oscillation basics
- Super-Kamiokande Status & Atm. ν Results
 - 2 & 3 Flavour analyses
 - ν_τ appearance
- MINOS
 - 2 Flavour analysis & charge ratio
- Potential measurements
 - ICECUBE

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:

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

L [km]
E [GeV]
 Δm^2 [eV²]

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

Neutrino Oscillations

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atmospheric ν

solar ν
See previous talk

2 flavour approximation:

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

Is θ_{23} maximal?

2 flavour approximation:

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

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

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 Δm^2 [eV²]

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L [km]
 E [GeV]
 Δm^2 [eV²]

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Is θ_{23} maximal?

What is the value of θ_{13} ?

What is the value of δ_{CP} ?

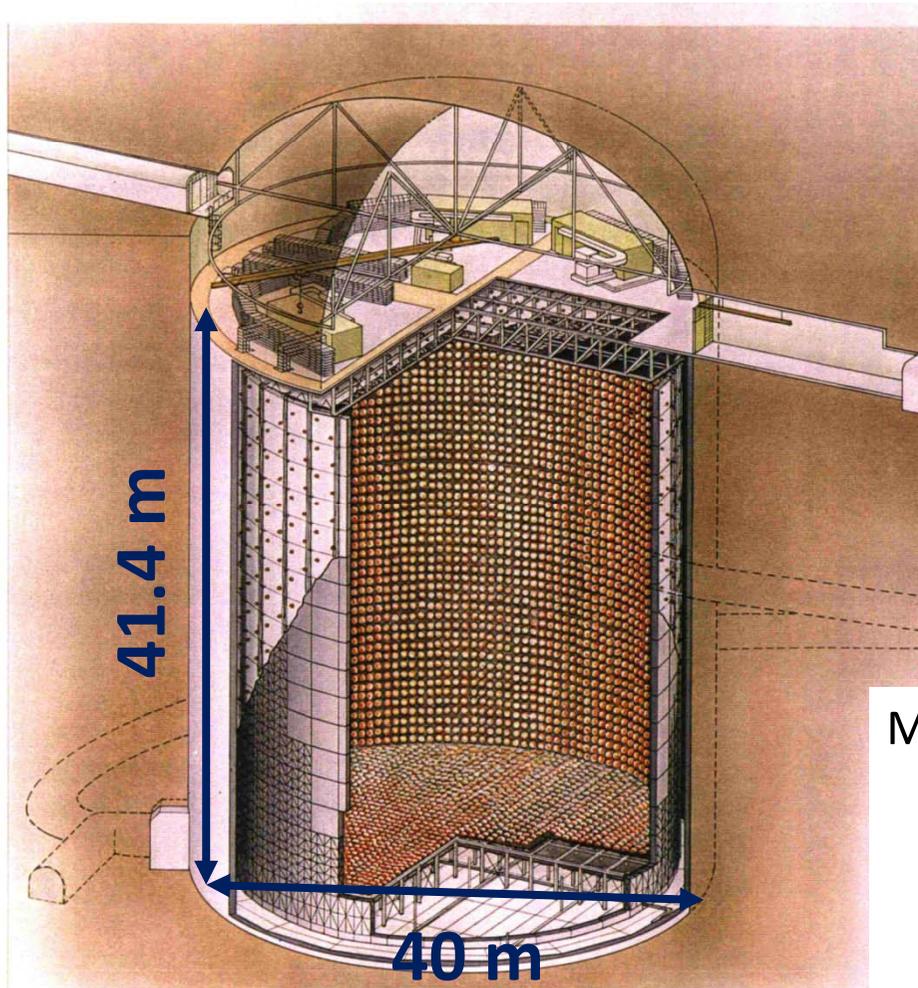
Which mass hierarchy exists?

Do ν_{μ} and anti- ν_{μ} experience the same oscillation parameters?



Super-Kamiokande

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)

Solar neutrinos

Supernova neutrinos (Relic SN's)

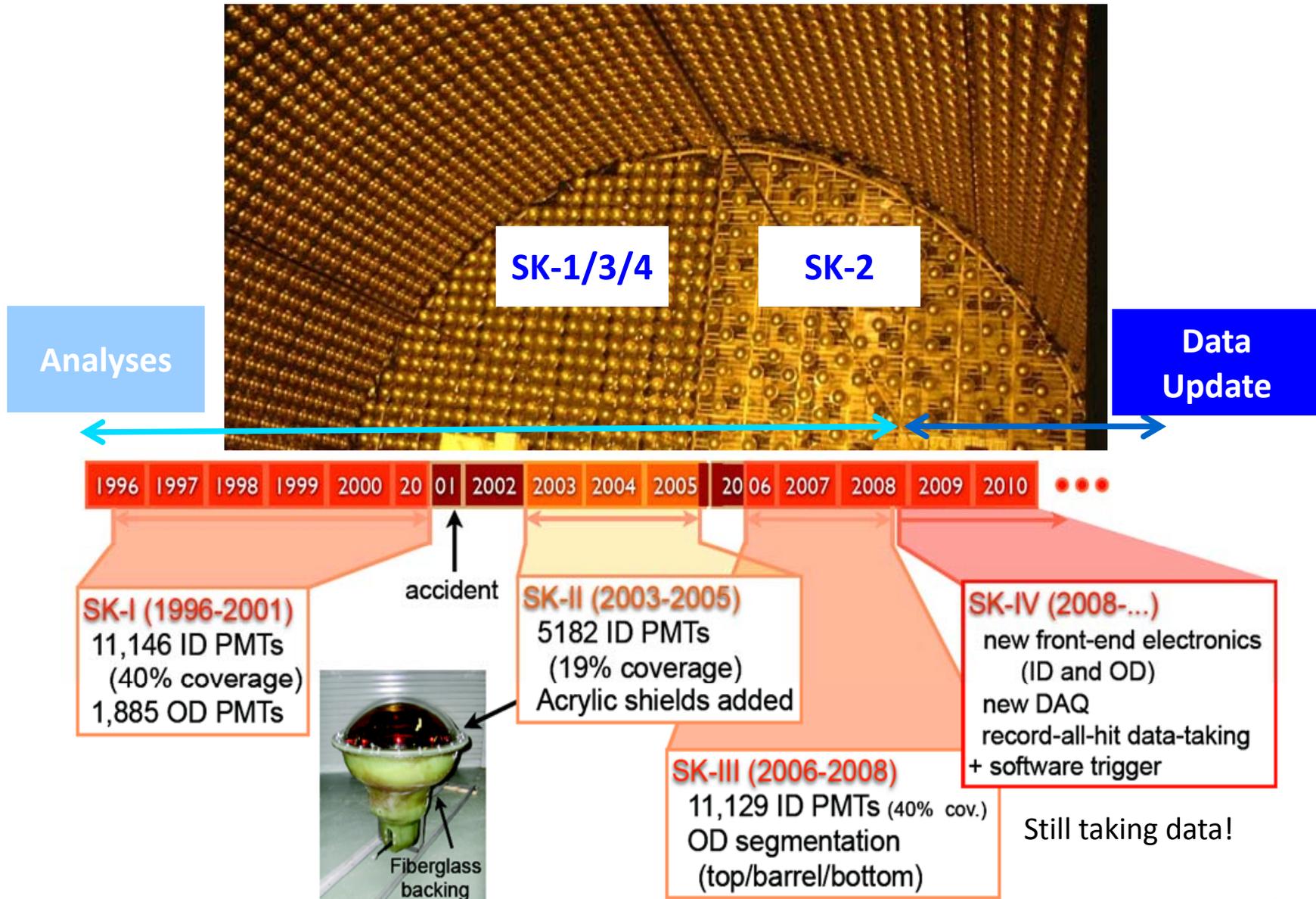
Atmospheric neutrinos

Nucleon decay

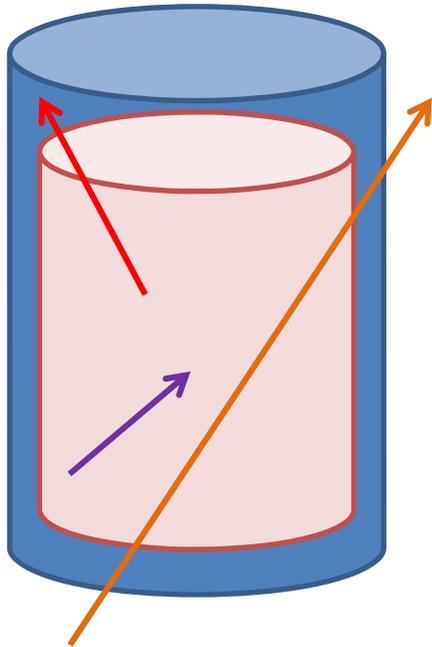
Beam neutrinos: K2K, T2K

Exotic particles

Super-Kamiokande: Generations



SK Event Types



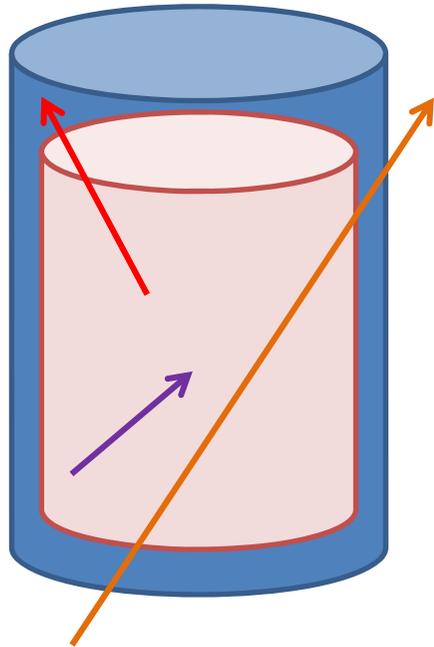
Events divided into different categories for analysis:

Fully Contained (FC) – little to no OD activity

Partially Contained (PC) – activity in OD, interaction vertex in ID

Up μ – Muons coming from below the detector

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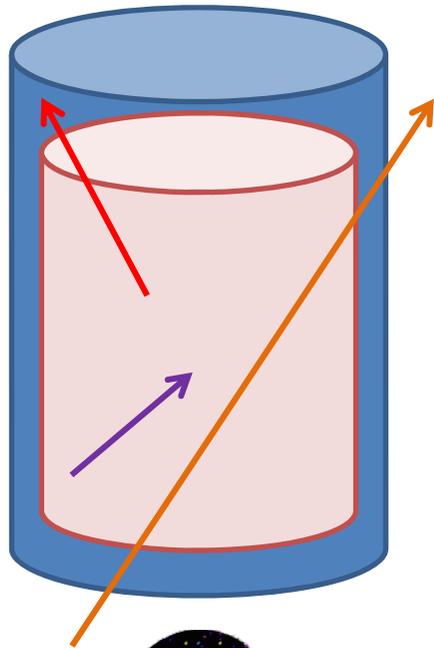
Sub-GeV ($E_{\text{visible}} < 1.33$ GeV):

One ring (R)

Multi-GeV ($E_{\text{visible}} > 1.33$ GeV):

1R or multi-R

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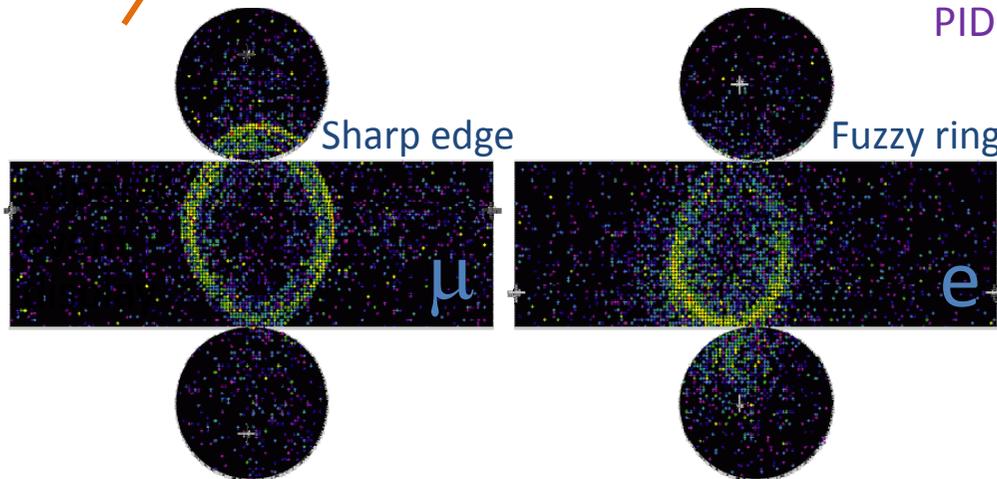
One ring (R) e-like

1R μ -like

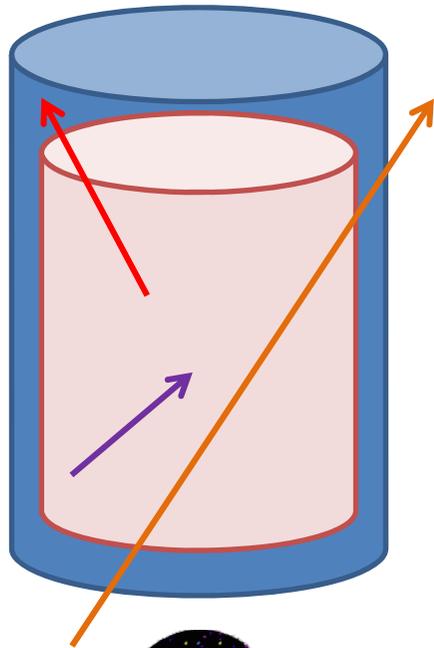
Multi-GeV ($E_{\text{visible}} > 1.33$ GeV):

1R or multi-R, e- or μ -like

PID applied to most energetic ring



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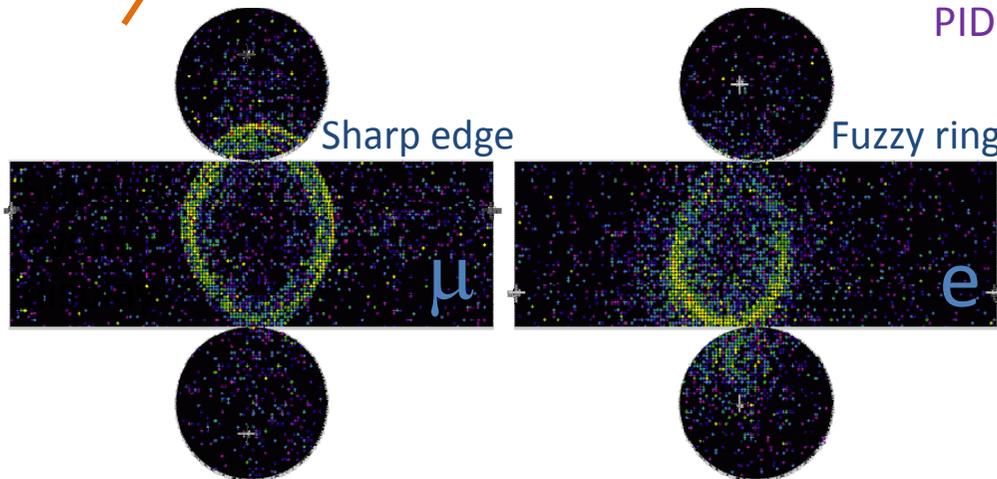
1R μ -like: 0, 1, or 2, decay electron

2R π^0 -like

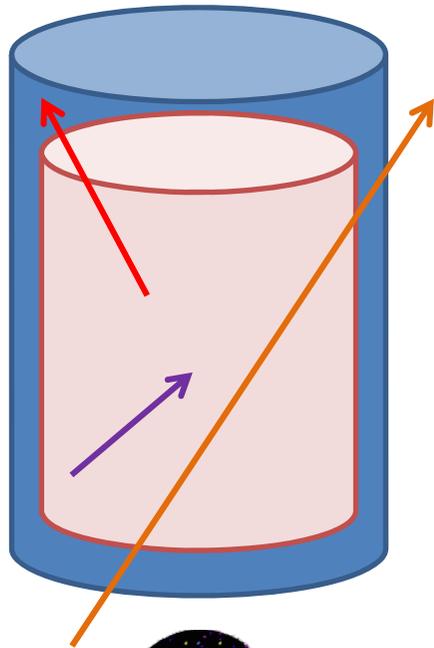
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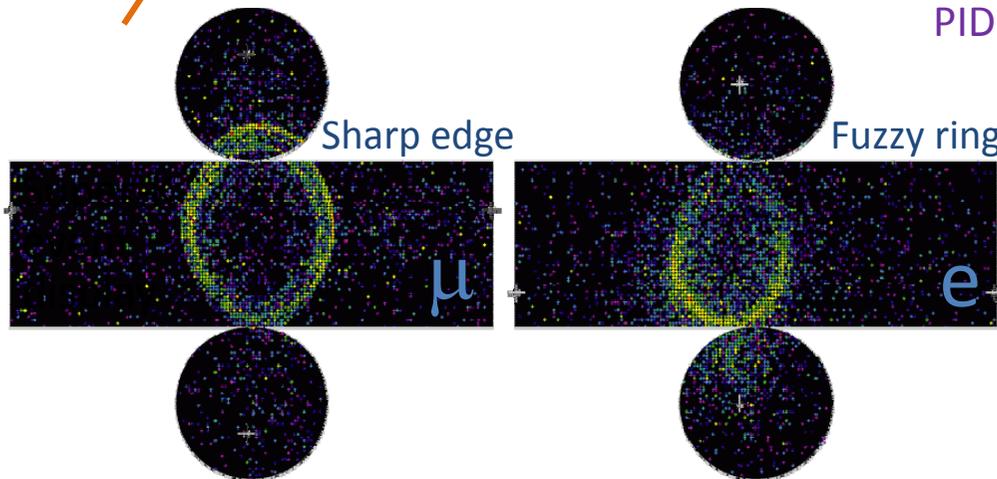
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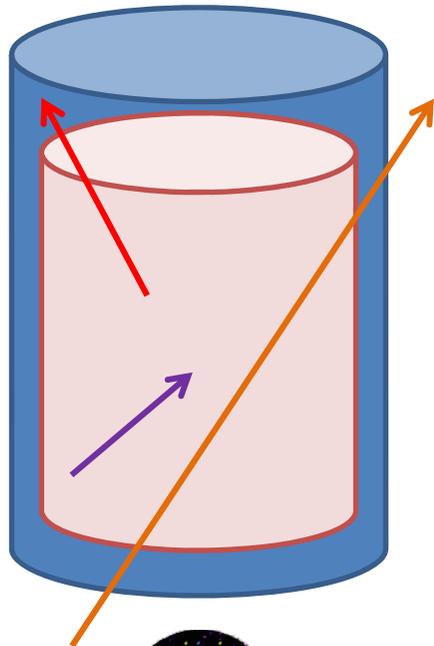
PID applied to most energetic ring



Stopping – stops in OD

Though-going – exits OD

SK Event Types



Events divided into different categories for analysis:

Fully Contained (FC) – little to no OD activity

Partially Contained (PC) – activity in OD, interaction vertex in ID

Up μ – Muons coming from below the detector

Sub-GeV ($E_{\text{visible}} < 1.33$ GeV):

One ring (R) e-like: 0 or 1 decay electron or π^0 -like

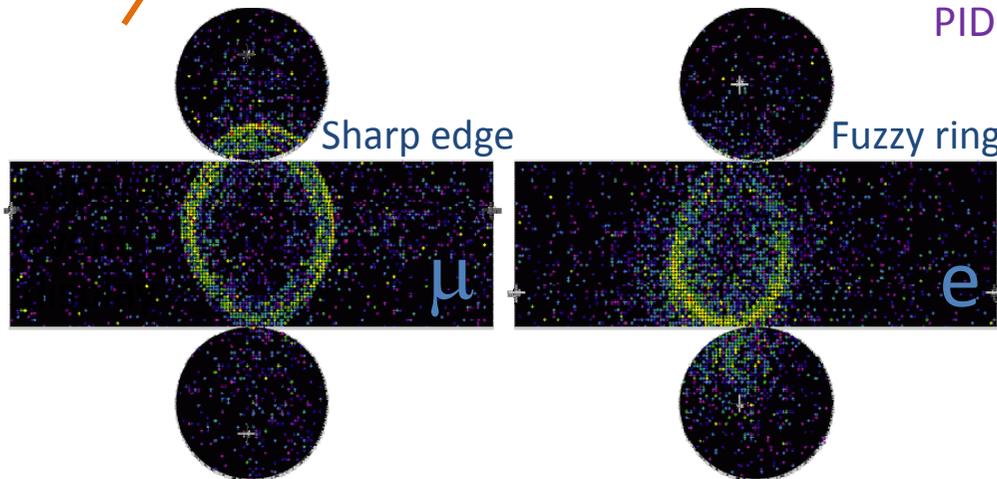
1R μ -like: 0, 1, or 2, decay electron

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Stopping – stops in OD

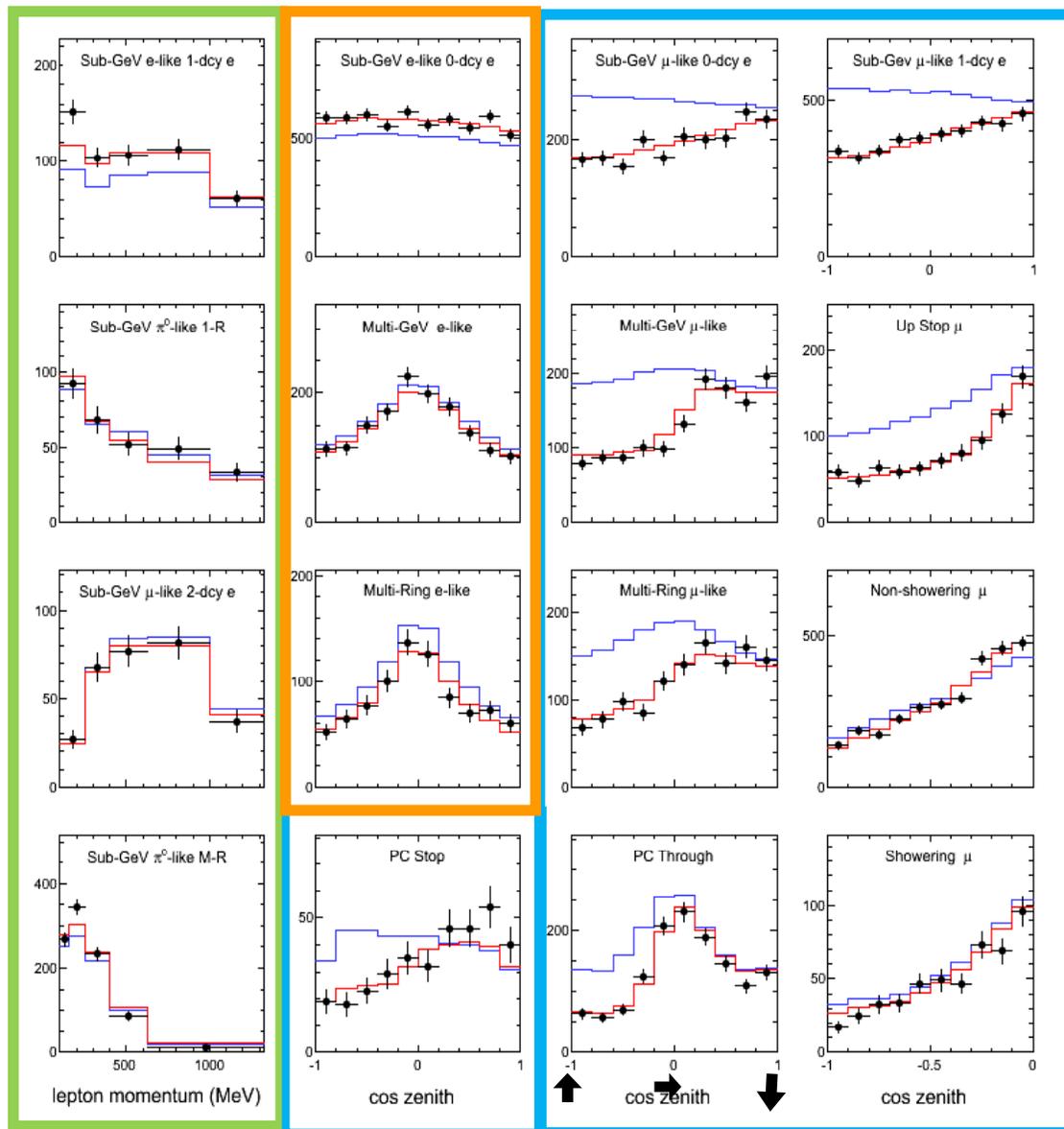
Though-going – exits OD

Stopping – stops in ID

non-showering

showering

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



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

μ -like **e-like**

momentum

Live time:

SK-I

1489d (FCPC)

1646d (Upmu)

SK-II

799d (FCPC)

828d (Upmu)

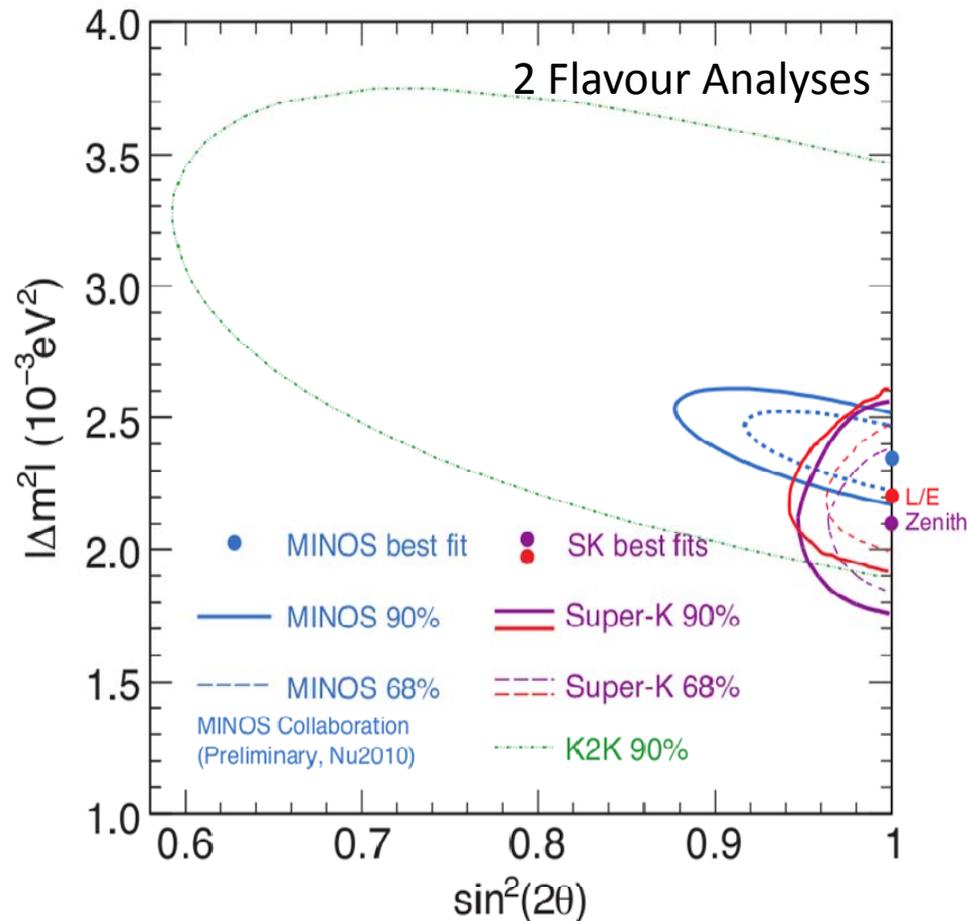
SK-III

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)

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

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

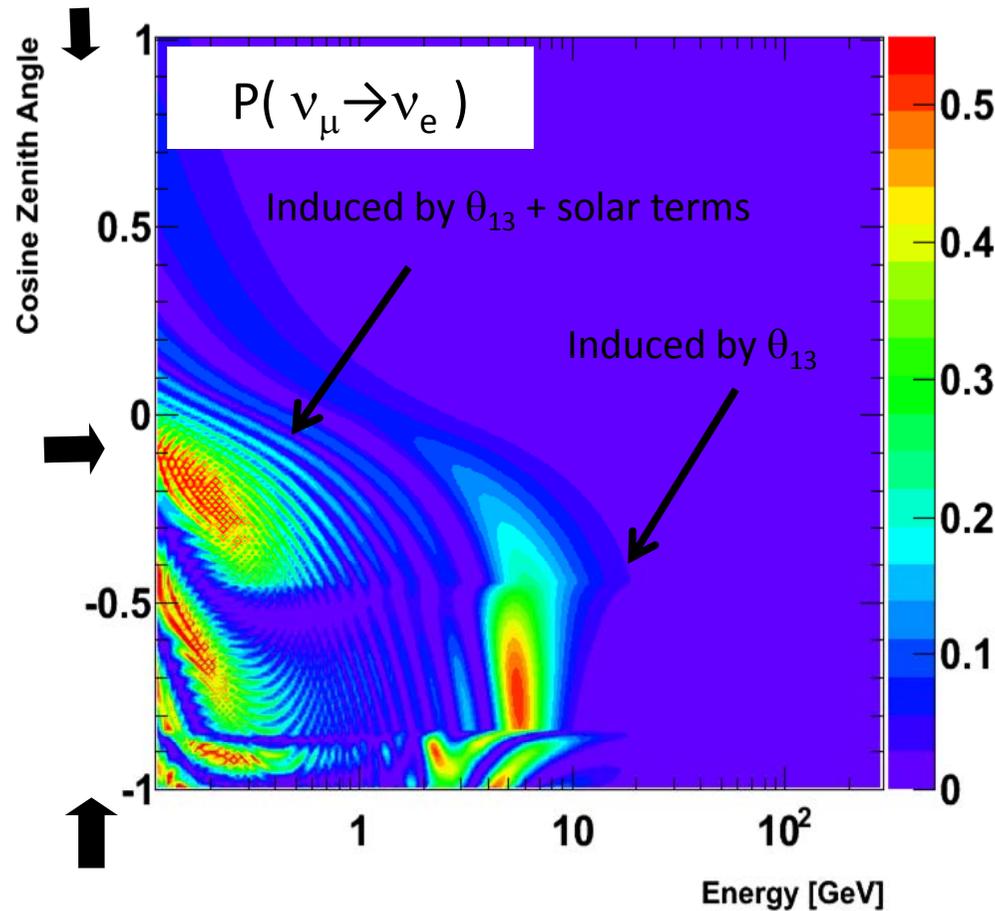
SK L/E Analysis (1σ) (2 flavour)

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

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

Experiments are in **good agreement** about these oscillation parameters
 SK Data disfavour other types of disappearance strongly, sterile $\nu \sim 7\sigma$

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, $< 1\text{GeV}$, are moderated by octant of θ_{23}

$$\Delta_\theta \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \text{Matter Driven}$$

$$+ \Delta_2(\Delta m_{12}^2) \quad \text{Solar Terms}$$

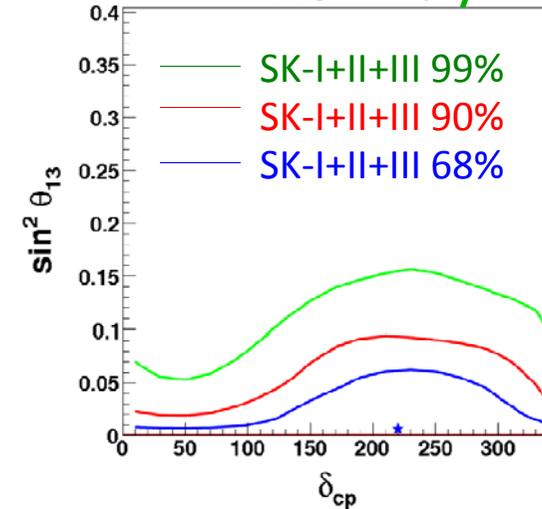
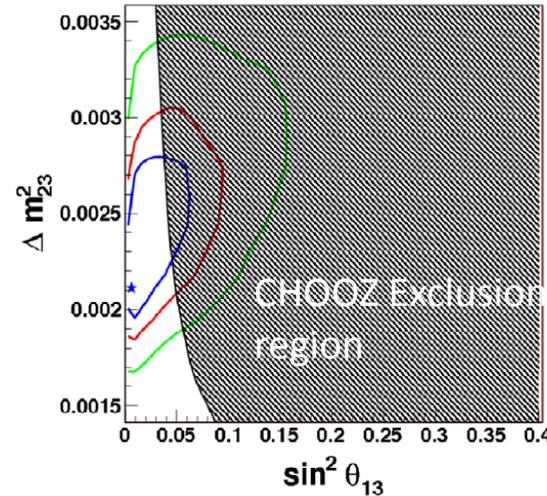
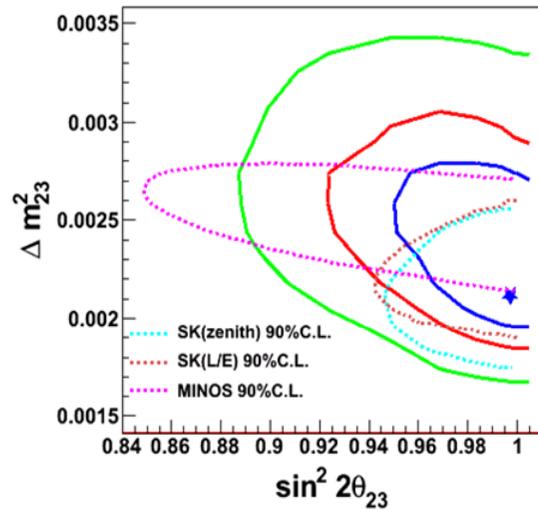
$$+ \Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

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

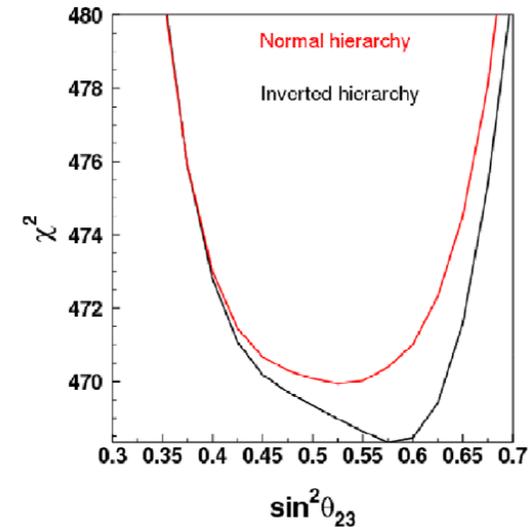


$\chi^2_{\min} = 469.94 / 416 \text{dof}$

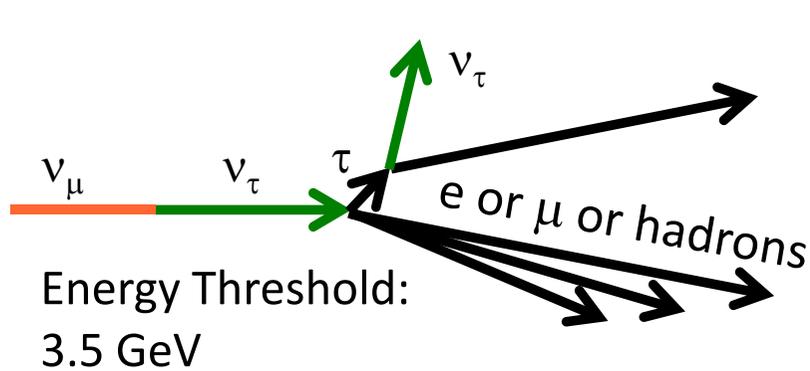
Parameter	Best point
$\Delta m^2_{23} (\times 10^3)$	2.11 eV ²
$\sin^2 \theta_{23}$	0.525
$\sin^2 \theta_{13}$	0.006
CP- δ	220°

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

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



ν_τ Appearance at Super-K



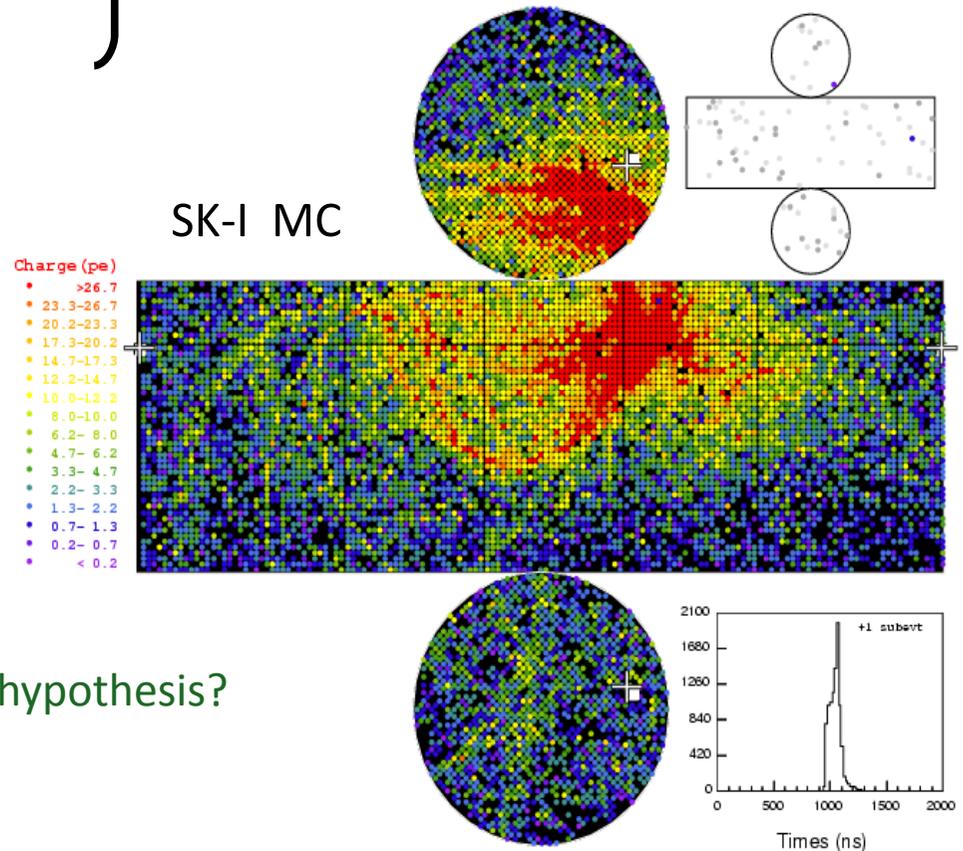
Many Cherenkov light producing particles
Most events are DIS interactions

Negligible primary flux

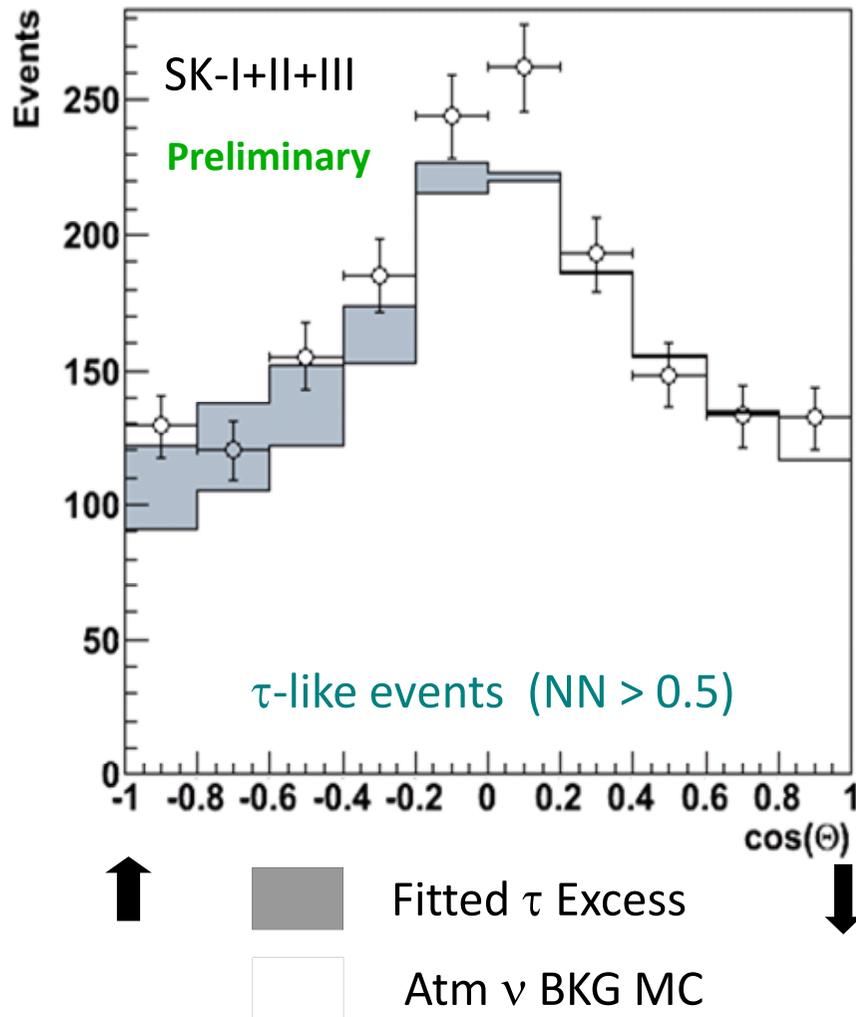
→ Observed tau events would be oscillation induced

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

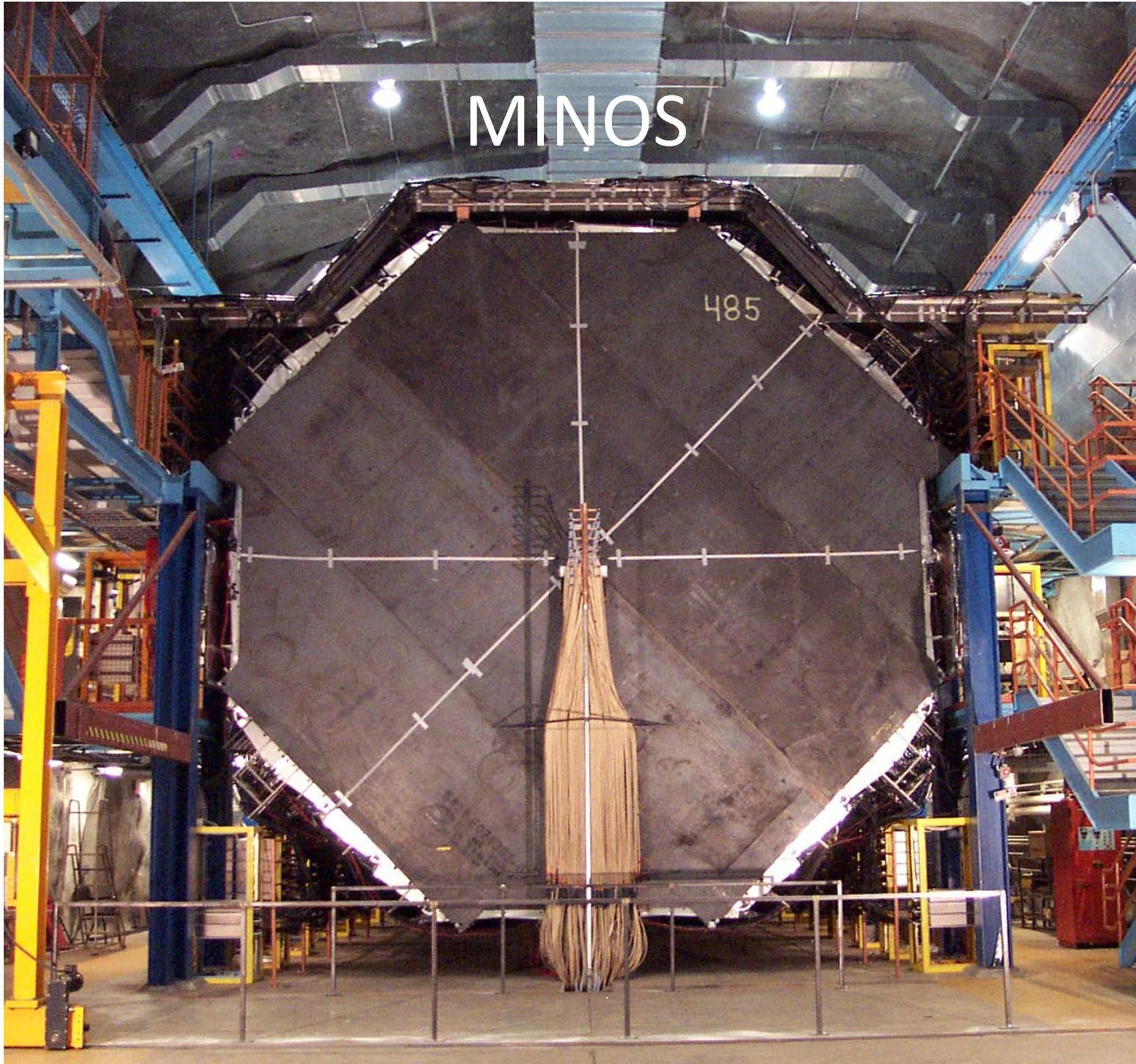
Fit corresponds to 213.6 τ events

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)



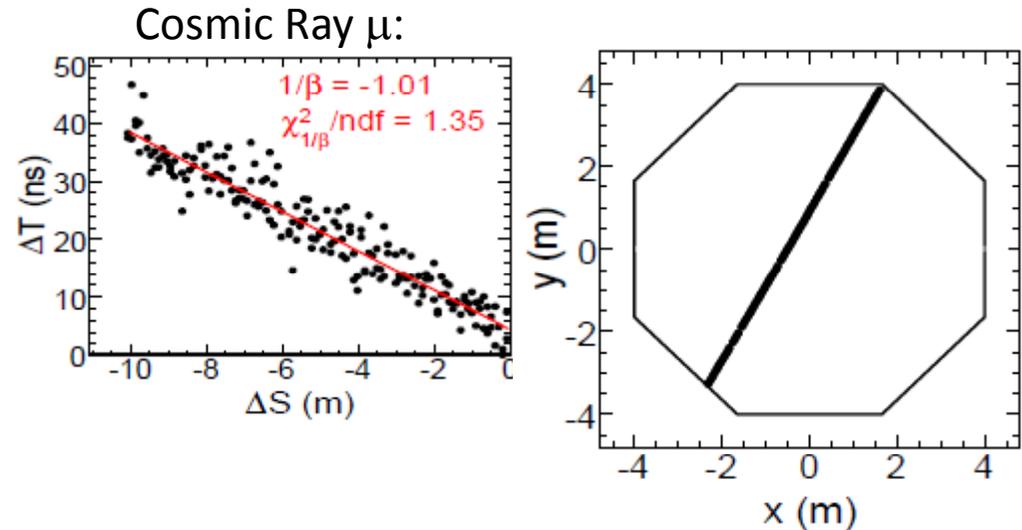
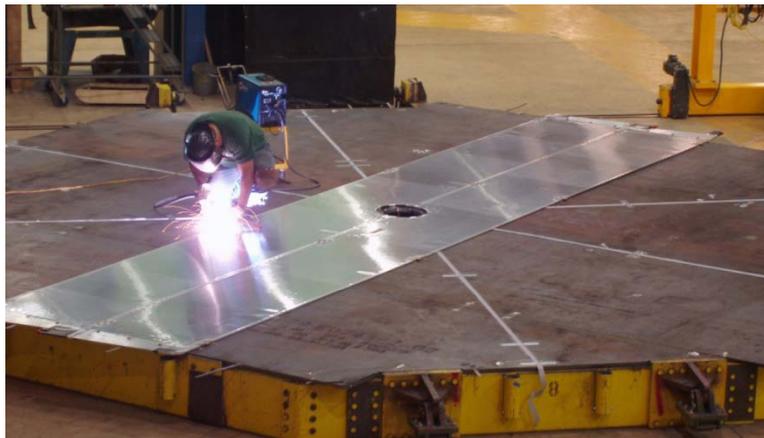
MINOS

485

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

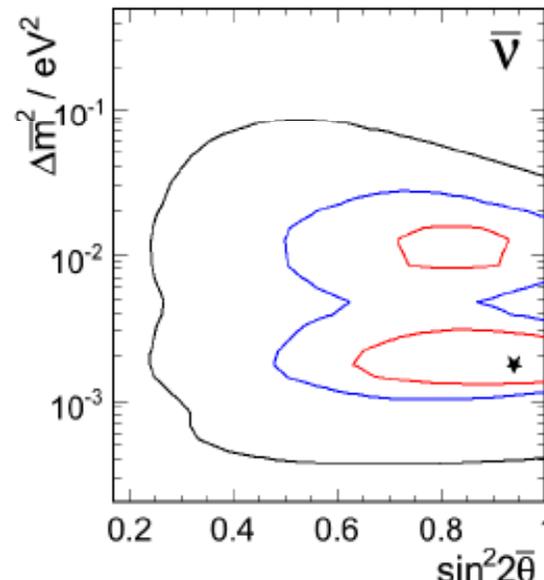
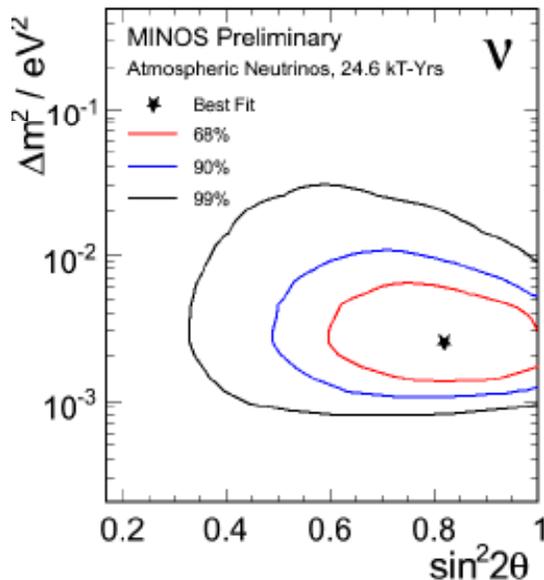
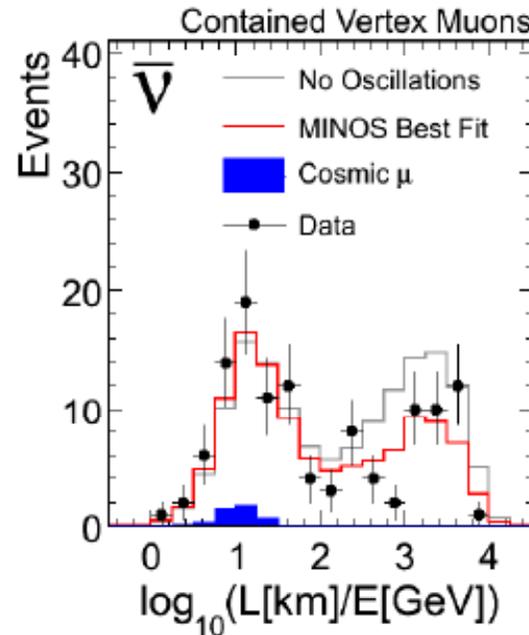
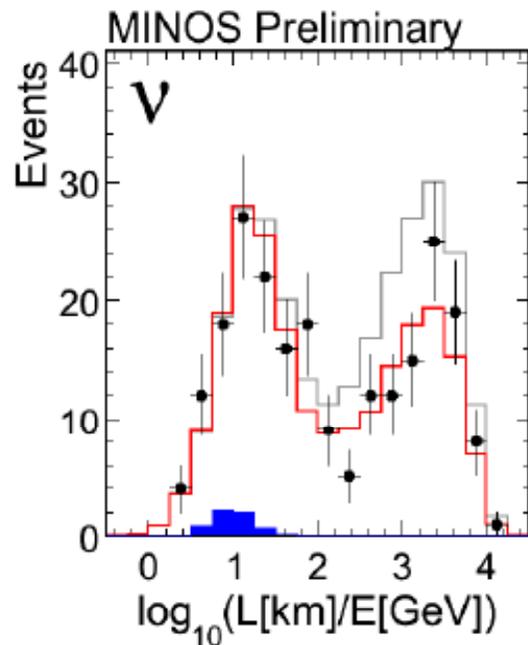


Select muon tracks:

- Single track only
- Vertex starts inside fiducial volume
- Good timing & track quality cuts
- Separate by charge (+/-)
- Separate by momentum:
 $p < 10$ GeV, $10 \text{ GeV} < p < 100$ 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:

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

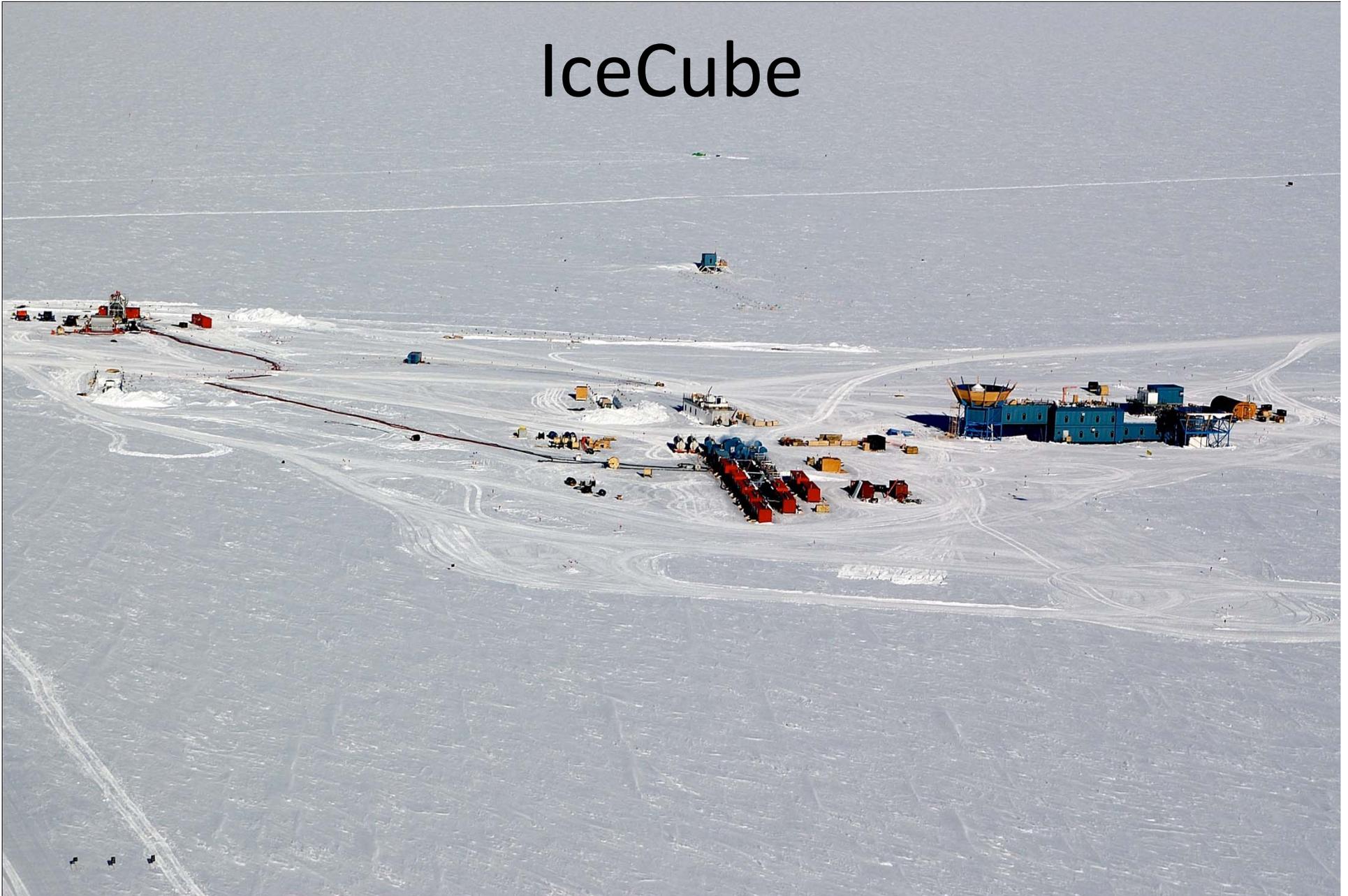
- Fit oscillations separately for neutrinos and anti-neutrinos. Testing CPT symmetry:

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

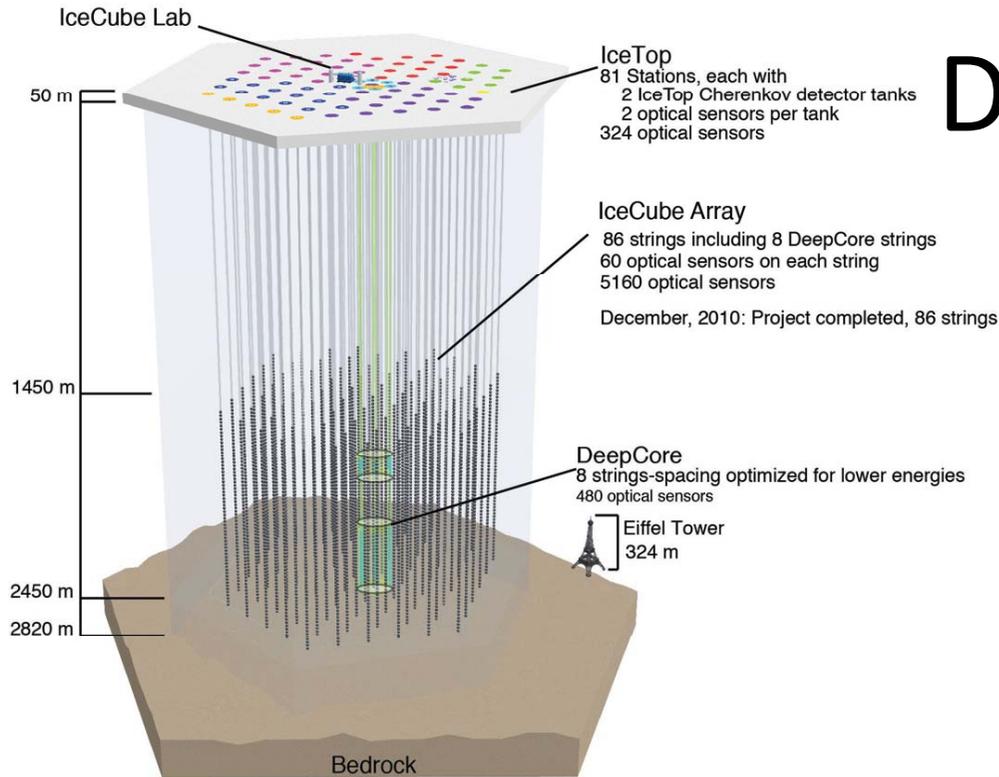
90% C.L, at maximal mixing.

From MINOS Collaboration

IceCube



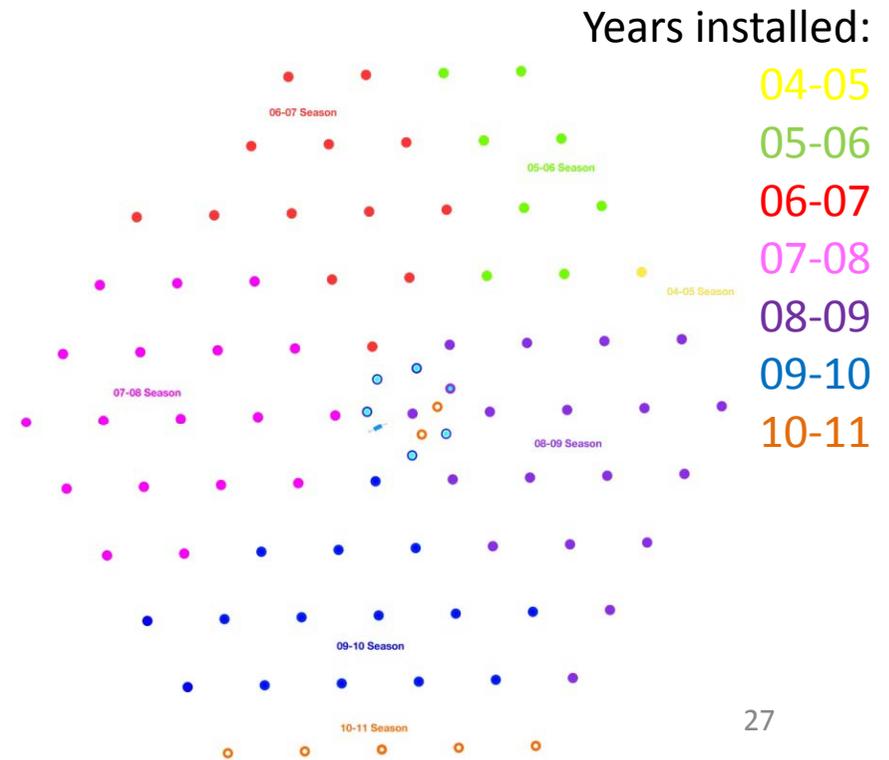
Detector Setup



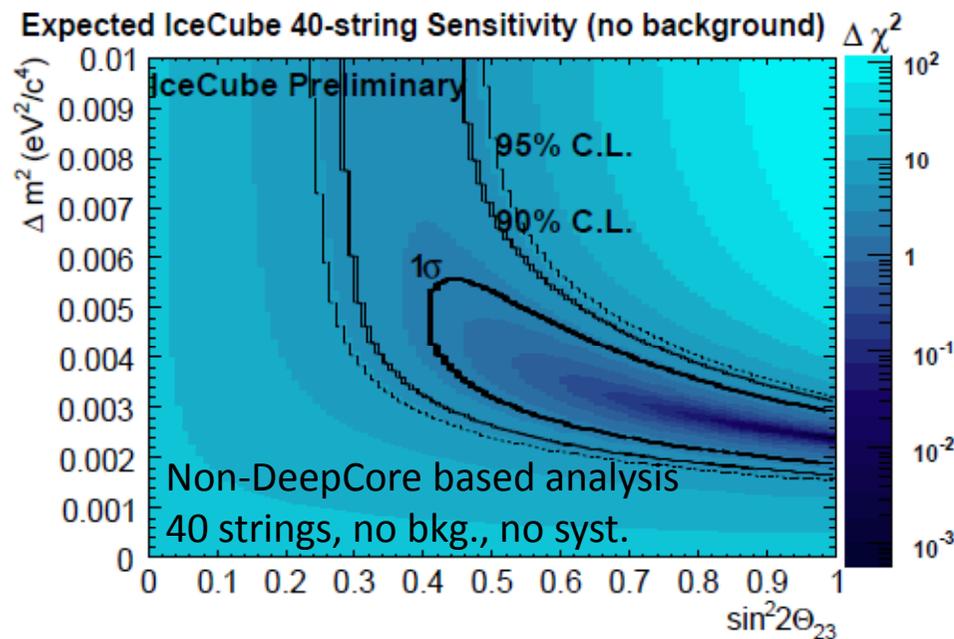
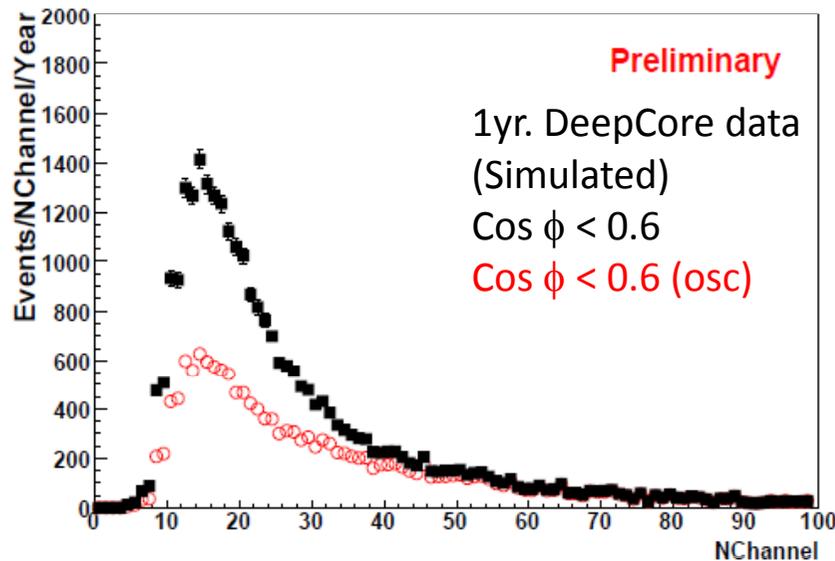
Neutrino astronomy experiment
located at South Pole

~1 km³ volume

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



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
 - ν_τ appearance searches
 - Mass hierarchy

Summary

- Have multiple experiments able to observe atmospheric neutrino oscillations
- 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
 - 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

References

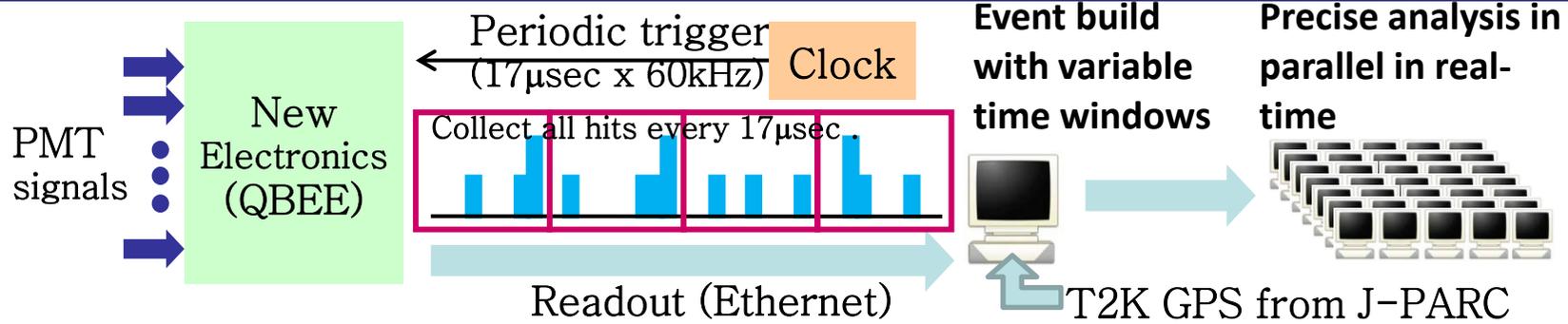
- SK
 - R. Wendell, NNN2010 Presentation
 - Phys. Rev. Lett. **97**, 171801 (2006)
 - arXiv:1002.3471v2
- MINOS
 - arXiv:hep-ex/0701045v2
 - http://www-numi.fnal.gov/pr_plots/pr_atm.pdf
- IceCube
 - C. Rott, ICRC 2009, session HE.2.2, contribution 785.
 - M. D'Agostino, arXiv:0910.0215 [astro-ph.HE]
 - D. Grant et al., ICRC 2009, session HE.2.2, contribution 1336.

BACKUP SLIDES

SK-IV Upgraded DAQ system

IEEE Trans. Nucl. Sci. 57 (2010) 428

SK-I,II,III: partial data above threshold were read (1.3 μ sec window x3kHz)
SK-IV: All hits are read, then apply complex triggers by software.



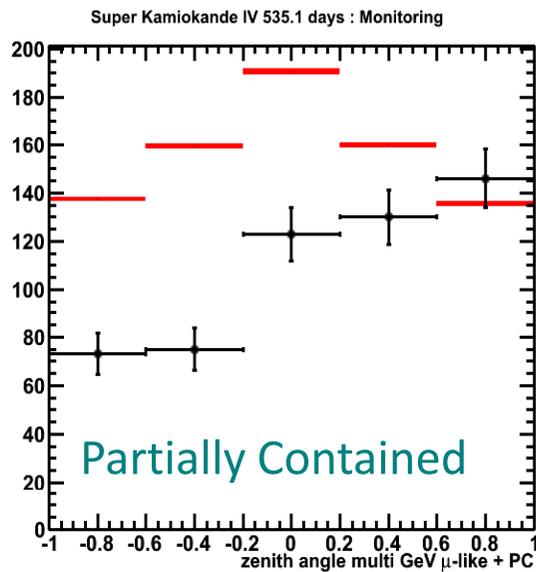
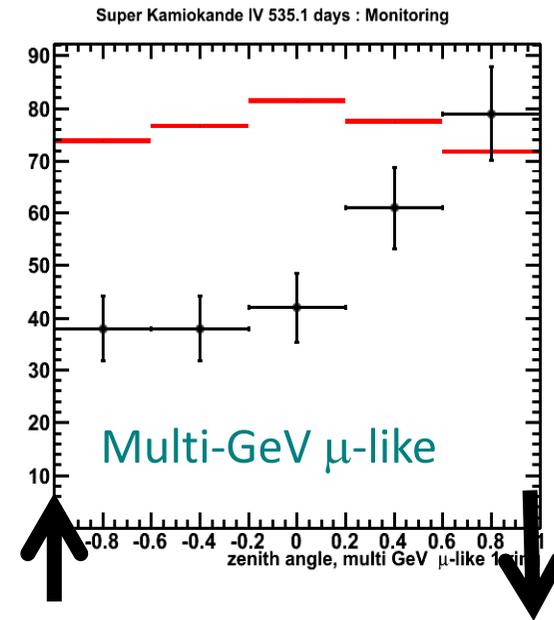
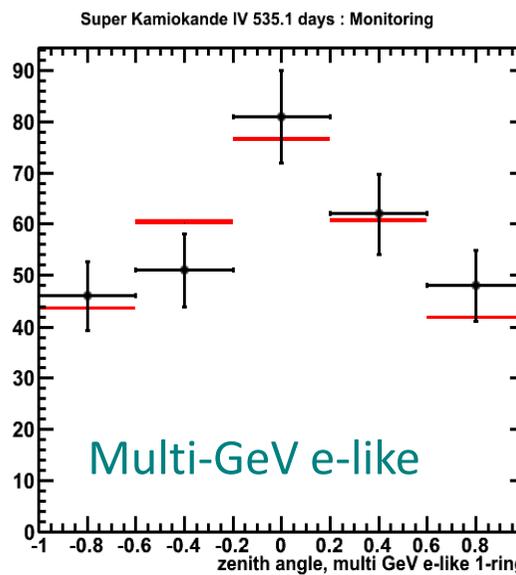
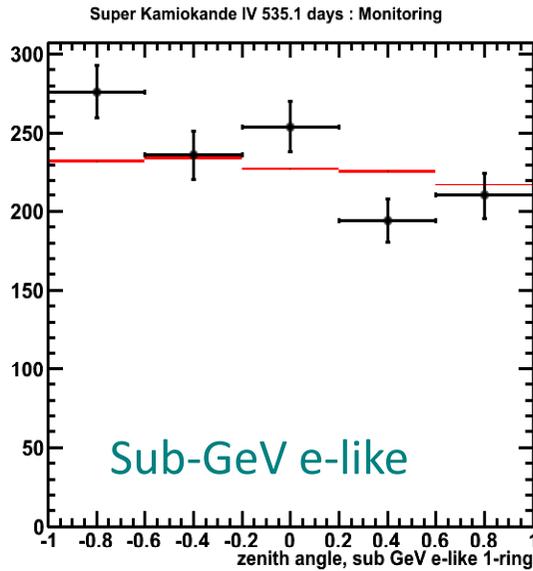
Typical event time windows:

Super-Low-Energy (SLE) events (<~6.5MeV):	-0.5/+1.0 μ sec	high rate (~3kHz)
Normal events(>~6.5MeV):	-5/+35 μ sec	decay electrons
Supernova Relic ν (SRN) candidates(>~10MeV, No OD):	-5/+535 μ sec	neutrons
T2K events:	-512/+512 μ sec	at T2K beam spill timing

Wider dynamic range for charge measurement of each channel (>2000 pC) **x5**
 No dead time up to ~6MHz/10sec for Supernova burst neutrinos **x100**
 Apply precise event reconstruction to remove more low-e BG events in real-time

SK-IV Atmospheric Neutrino Data

Preliminary



 Unoscillated SK-IV MC

SK-IV data is looking good

No official analyses yet with this data set

Though, you can see oscillations already

Oscillation Parameters from 3 Flavor Fit

Parameter	Normal Hierarchy (90% C.L.)	Inverted Hierarchy (90% C.L.)
Δm^2_{23}	.0021 eV ²	.0021 eV ²
$\sin^2\theta_{13}$	0.0 (0.04)	0.006 (0.09)
$\sin^2\theta_{23}$	0.5	0.53

@ 90% C.L. $0.407 \leq \sin^2\theta_{23} \leq 0.583$

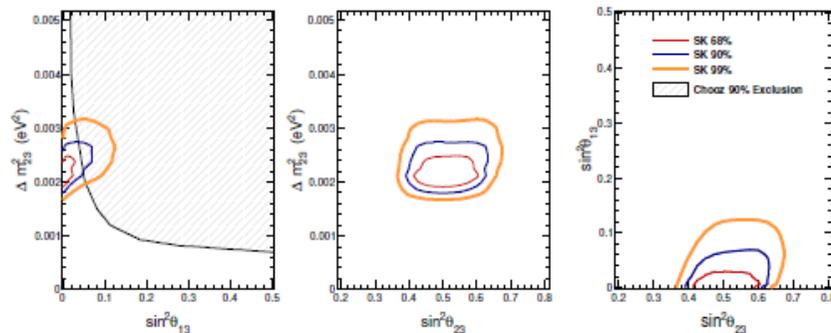


FIG. 7: (color online). Normal hierarchy allowed regions at 68% (thin line), 90% (medium), and 99% (thick) C.L. for the SK-I+II+III data. The shaded region in the first panel shows the Chooz 90% exclusion region.

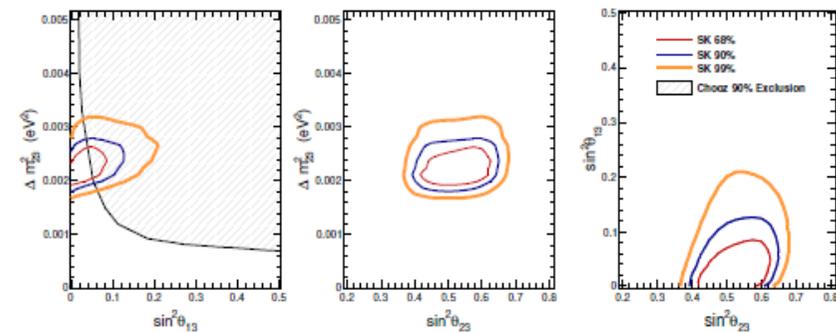


FIG. 8: (color online). Inverted hierarchy allowed regions at 68% (thin line), 90% (medium), and 99% (thick) C.L. for the SK-I+II+III data. The shaded region in the first panel shows the Chooz 90% exclusion region.