II. Atmospheric Neutrino Experiments

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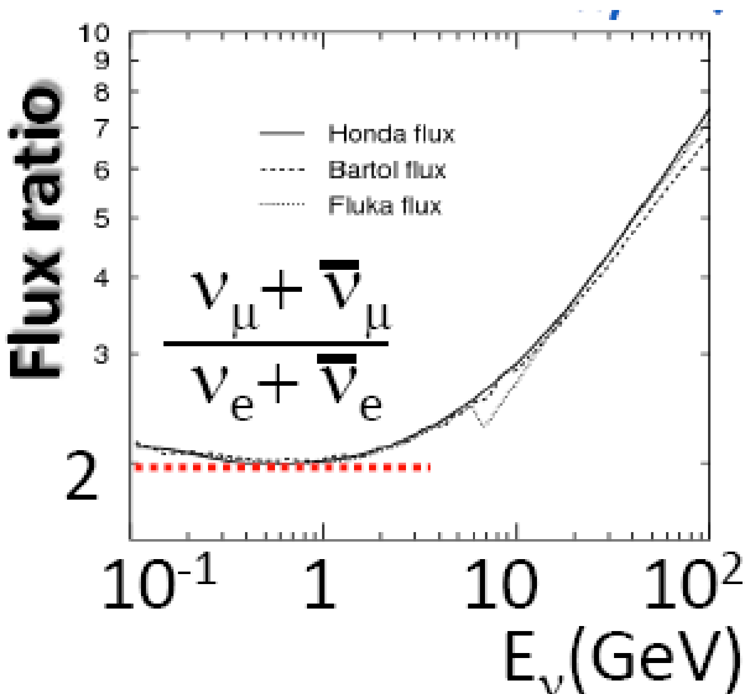
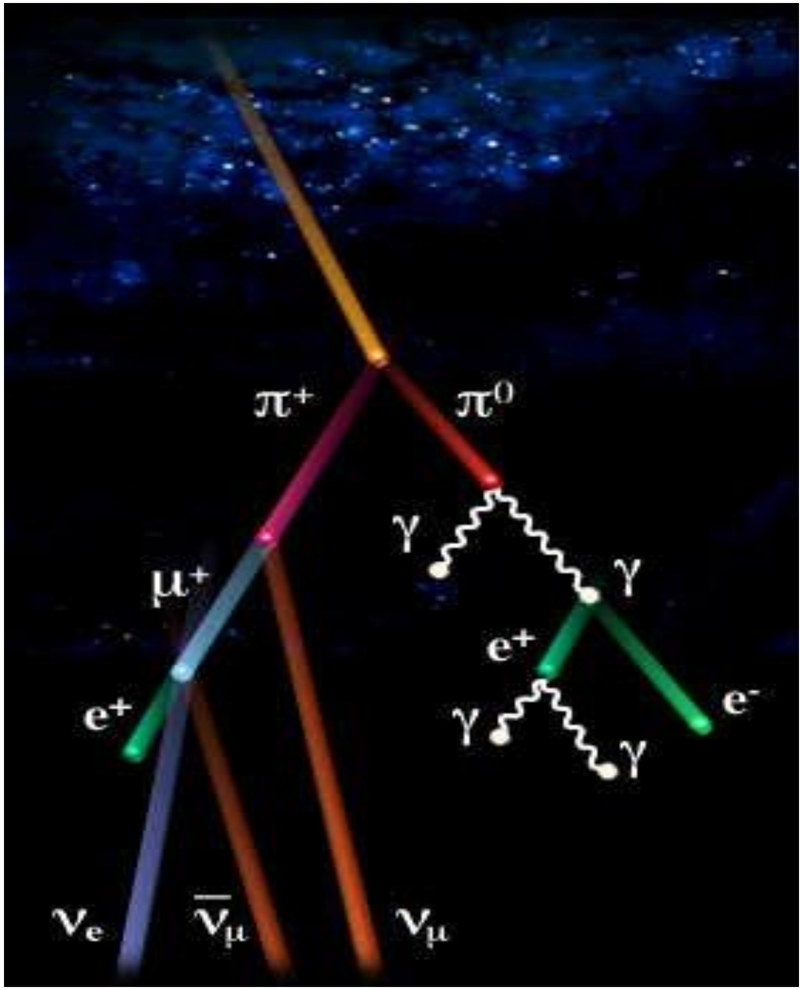
INSS 2014, St. Andrews

Atmospheric neutrinos

$\nu_\mu/\nu_e \approx 2$ at low energies

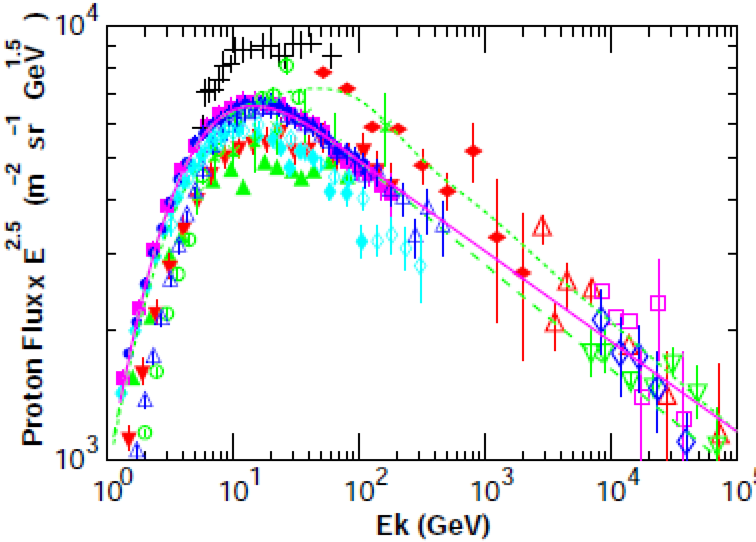
$\nu_\mu/\nu_e > 2$ at high energies since fewer μ decays

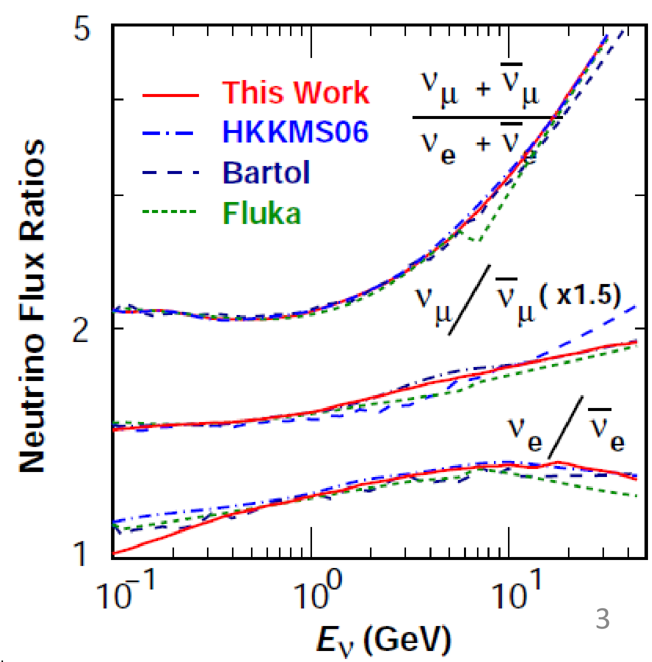




Atmospheric Neutrino Flux

- Need to know:
  - Primary cosmic ray flux(p, He, …)
    - Solar modulation effects
    - Geomagnetic cut-off
  - Hadron interaction model (K/π production)
  - Secondary particle decays
- Many models(teams)
- 3D calculations
- Comparison with experiments
  - HARP
  - SuperK



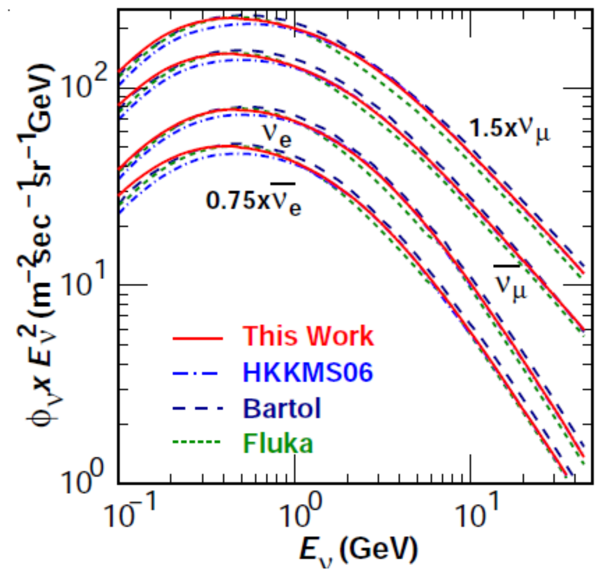


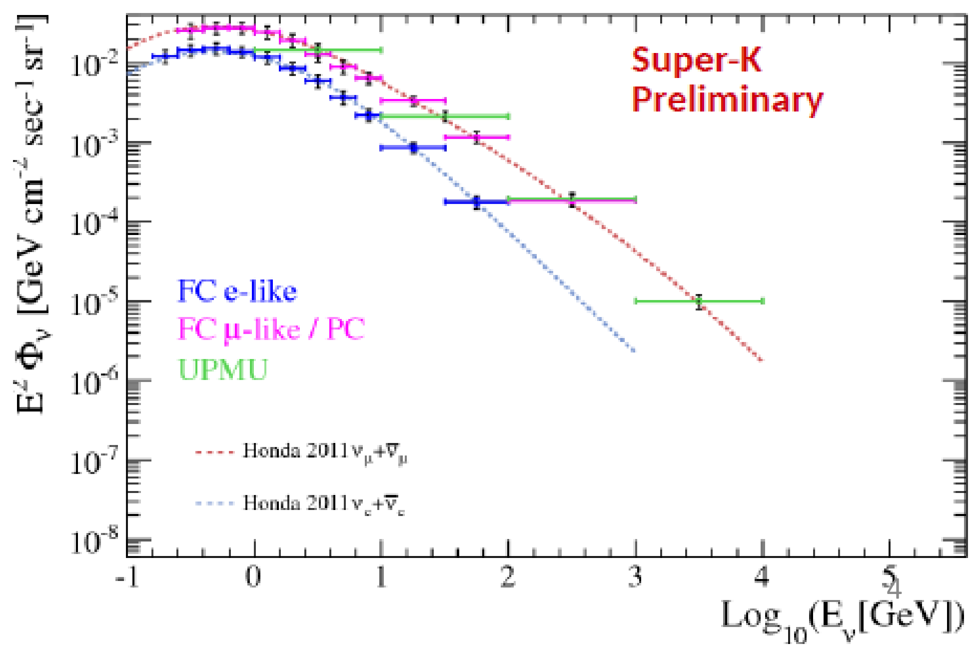
AMS01 gave the most precise results but that of AMS02 has not been used

Example: Honda Model

- Honda Model:
  - Interaction: modified DPMJET-III (>32 GeV)+ modified JAM (< 32 GeV); compared with Fluka and others
  - Geomagnetic model: IGRF
- Absolute flux
  - (15-20)% for P < 1 GeV
  - ~ 7% for P ~ 1- 10 GeV
  - ~ 14% at P ~ 100 GeV
  - ~ 25% at P ~ 1 TeV
- Double ratio of the flux
  - ~ 2% for P ~ 0.5-100 GeV

$$R = \left(\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right)_{data} \Bigg/ \left(\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right)_{MC}$$





arXiv: 1102.2688, 0611418, 0404457

History of Atmospheric Neutrinos

- First detection in 60's
- Indications of anomaly (80's)
- Discovery of the neutrino oscillation by SuperK(1998)
  - Determination of θ_{23} & ΔM^2_{23}
  - ν_μ oscillation: appearance of ν_τ
  - Rejection of other explanations
- Current experiment:
  - SuperK, Icecube
- Main issues now:
  - θ_{23} octant
  - mass hierarchy
  - CP phase
- Future experiments
  - INO, PINGU, HyperK, …

Experimental proposals

- M.A. Markov, Proc. 1960 Annual int. Conf. on HEP at Rochester, Detect high energy atmospheric ν: upward and horizontal muons
- K. Greisen, Ann. Rev. Nucl. Sci. 10(1960)63, water detector for atmospheric ν detection

First detection: Kolar mine in India

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Following the early work [1] carried out at great depths underground in the Kolar Gold Mines in South India, we have specifically designed an experiment for the detection of muons produced

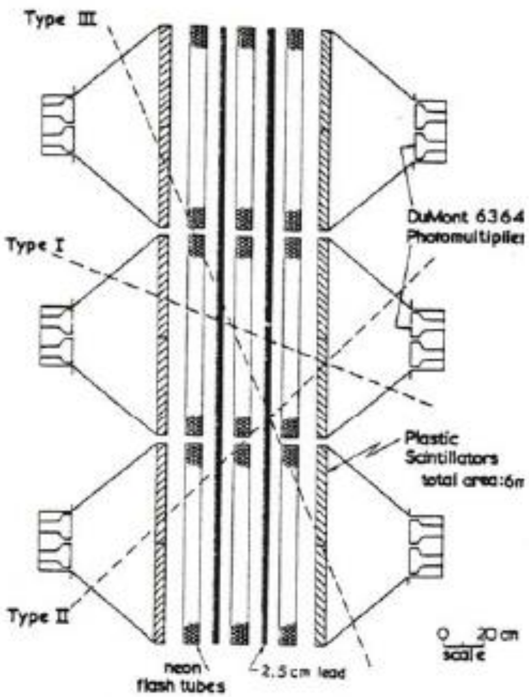
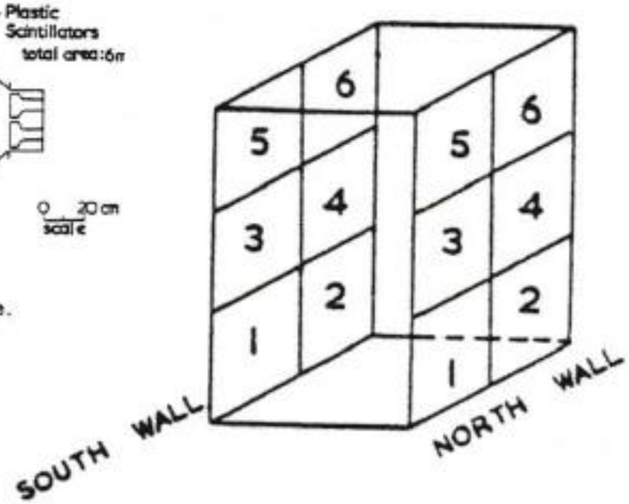


Fig. 1. Neutrino telescope.



S. Miyake *et al.*
July 12, 1965 (Received)
Phys. Lett. 18(1965) 196

Second detection: two weeks later in a gold mine at South Africa

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

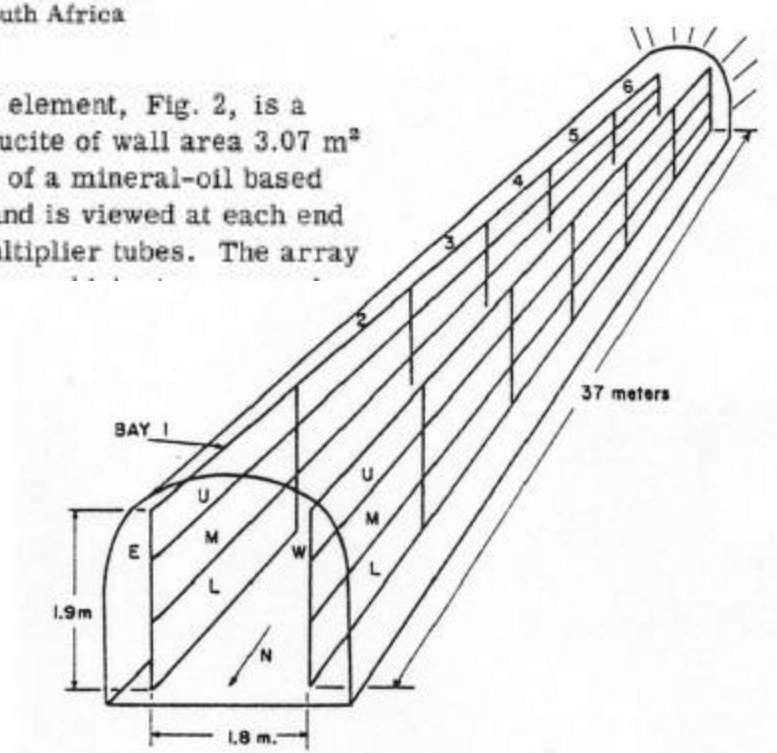
J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa

(Received 26 July 1965)

The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some con-

each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m^2 containing 380 liters of a mineral-oil based liquid scintillator,[4] and is viewed at each end by two 5-in. photomultiplier tubes. The array

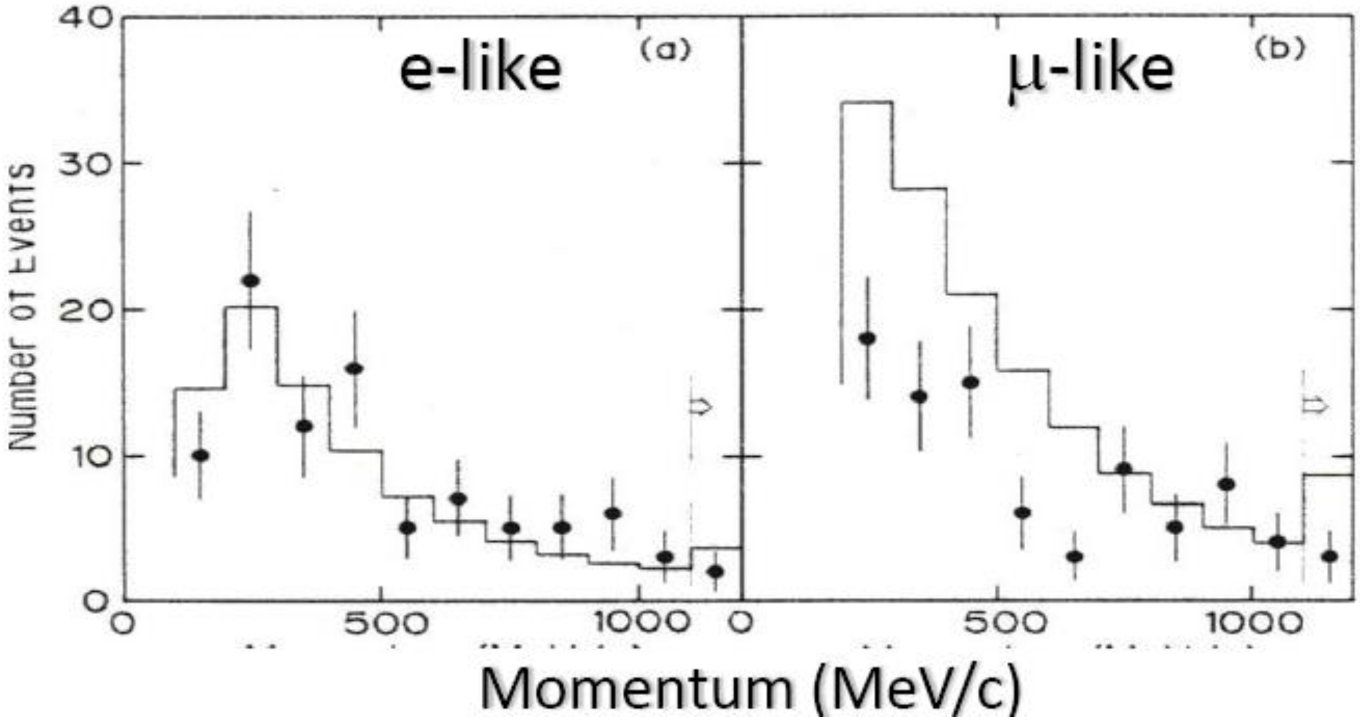


F. Reines *et al.*
July 26, 1965 (Received)
Phys. Rev. Lett. 15, 429 (1965)

First problem

In 1988, Kamiokande saw few μ

R= (Obs./MC)μ-like = 0.59±7% (stat.)



PLB, 205, 416 (1988)

By Kamiokande

Kamiokande & IMB:
Designed for proton decay searches
➔ 1987 observation of supernova ν ➔ 2002 Noble prize

Kamiokande

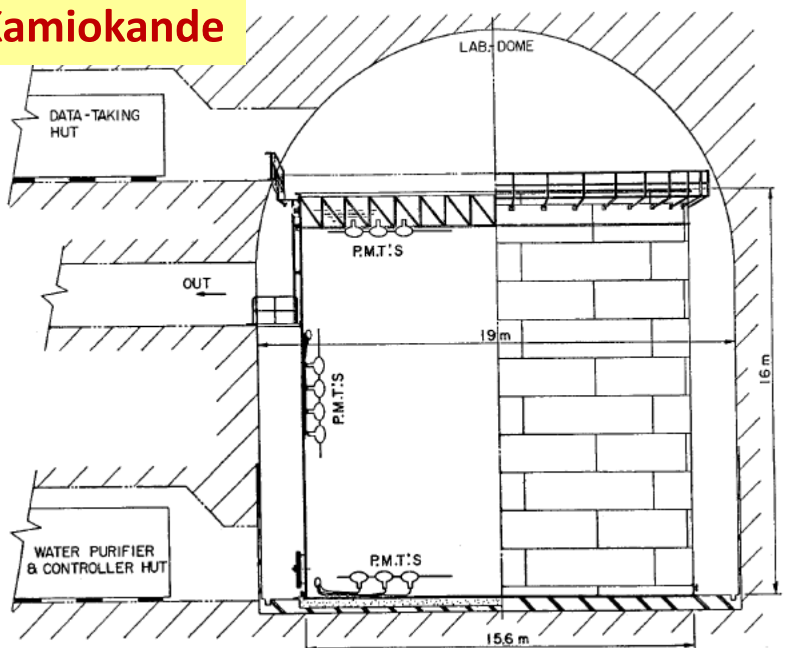
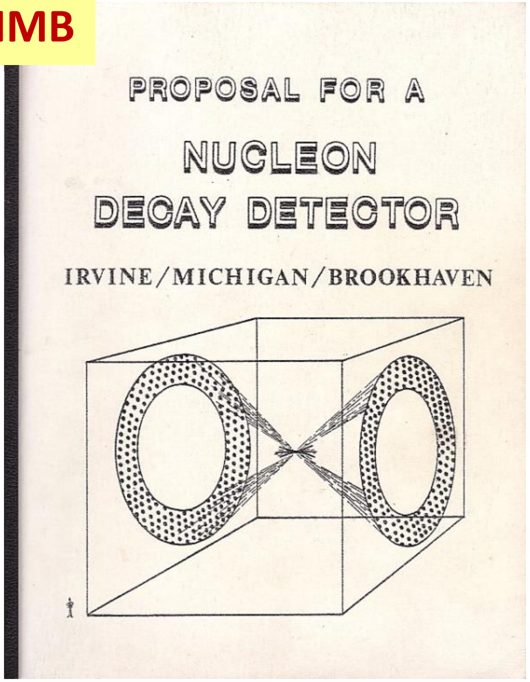


FIG. 3-1

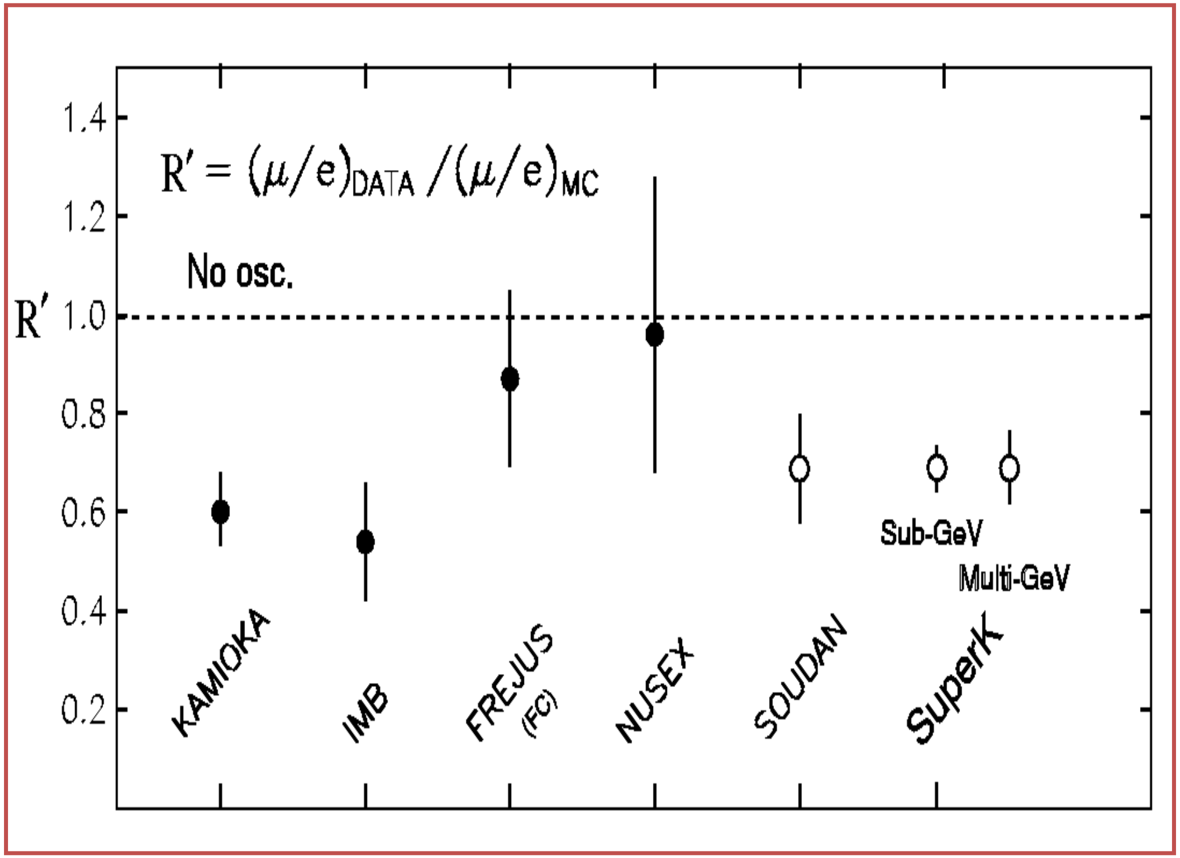
IMB



- 3kt water
- 1000 20” PMT
- 2700 MWE underground
- Operational:1983-1995

- 8 kt (Fid. 3.2 kt)water
- 2048 5” PMT
- 1570 MWE underground
- Operational: 1982-1991

Confused Situation: Few Believed Neutrino Oscillation



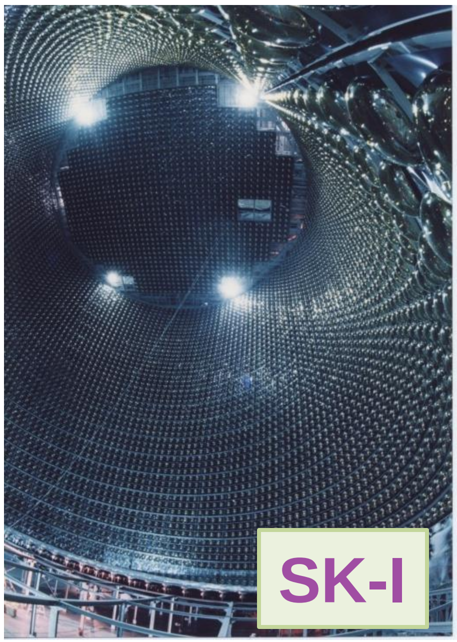
- Neutrino flux is not well known
- Theorists do not believe LMA solution

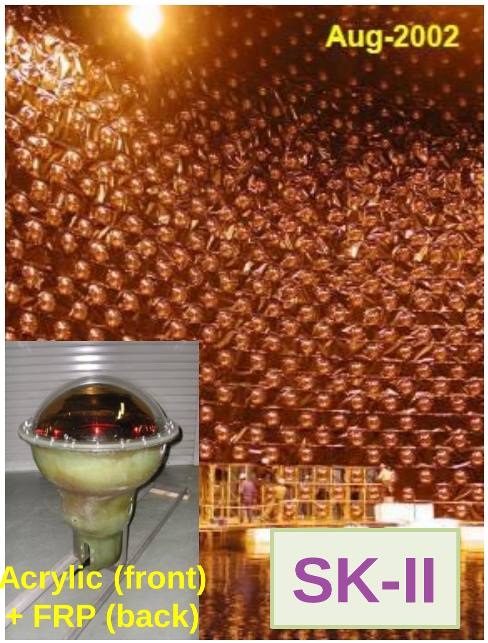
Discovery of Neutrino Oscillation

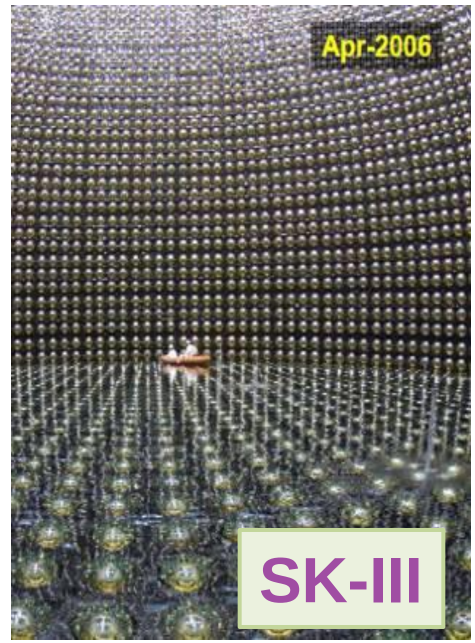
Super-Kamiokande

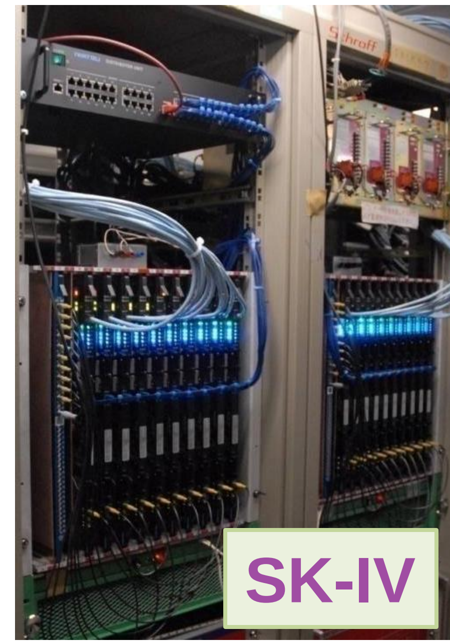
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I SK-II SK-III SK-IV





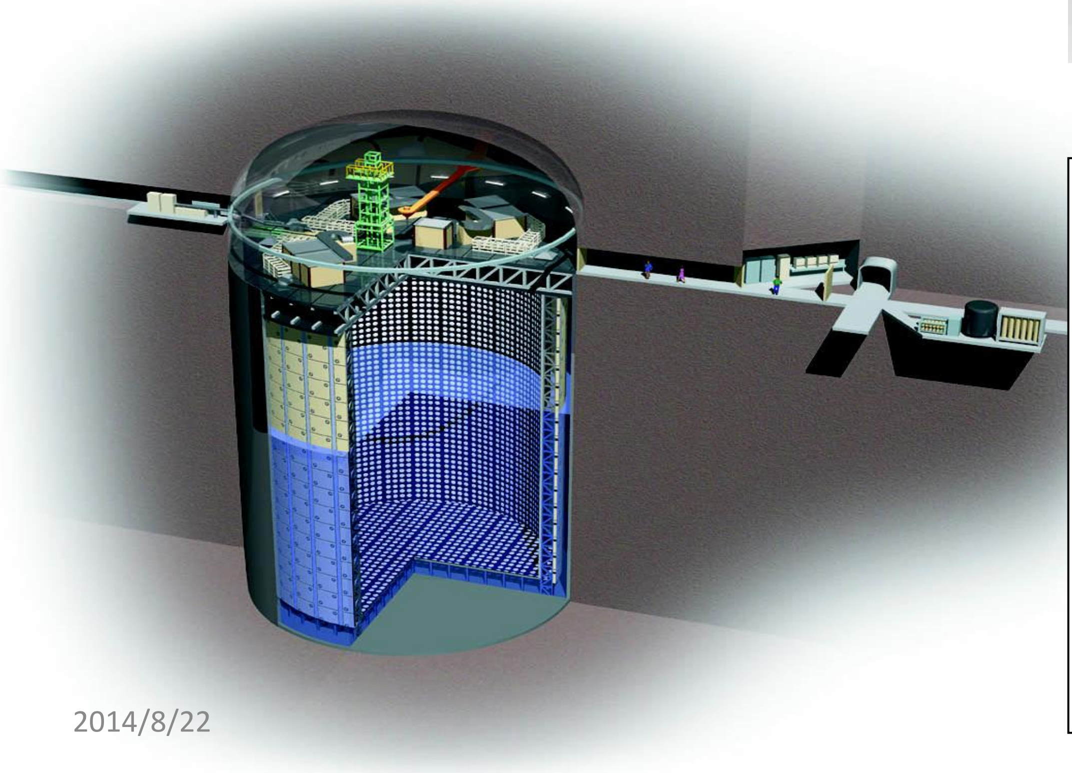




	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Energy Threshold (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Current	Target

Large Area PMT: Key for the Success

- 50 kt water Cherenkov
- 22.5 kt fiducial volume
- Inner detector: 11146 20" PMT
- Outer detector: 1885 8" PMT
- 1000 m underground



- 6 p.e./MeV → resolution:
  - 14.2%@10 MeV (solar & Supernova ν)
  - 1.7+0.7/sqrt(E(GeV)) % (Atmospheric ν, single ring μ)

Neutrino Detection

Signals(CC):

$\nu_\mu + N \rightarrow \mu + N' + x$

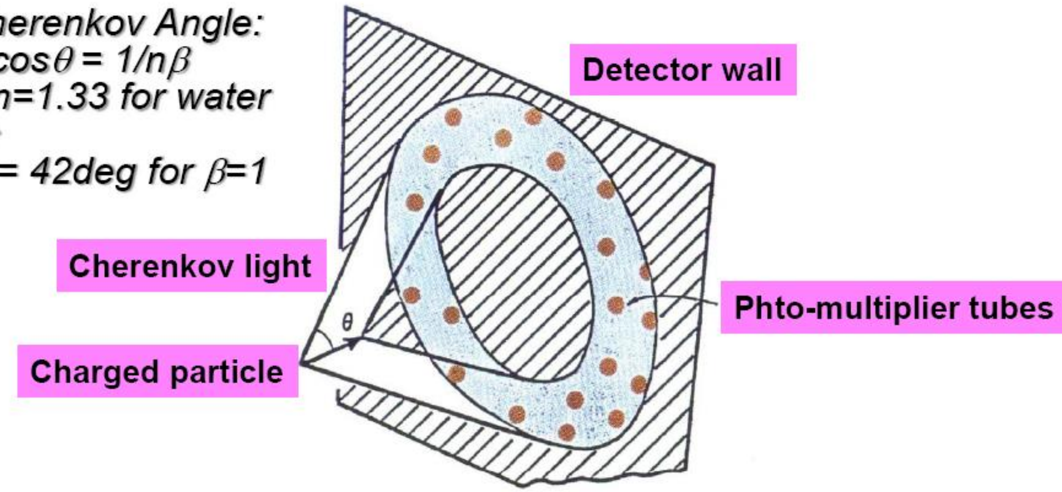
$\nu_e + N \rightarrow e + N' + x$

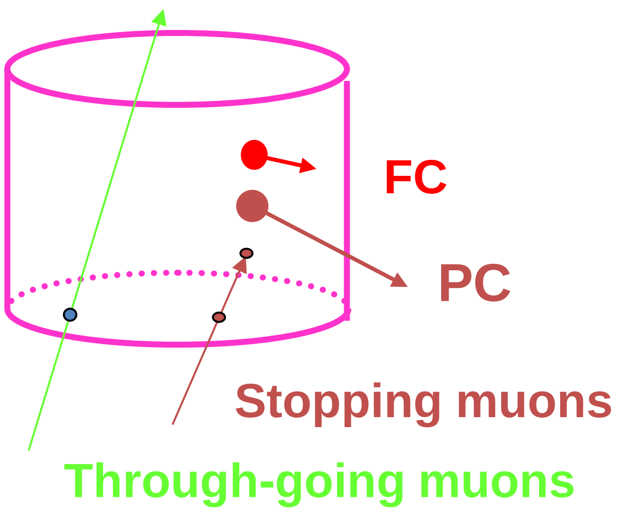
Backgrounds(NC):

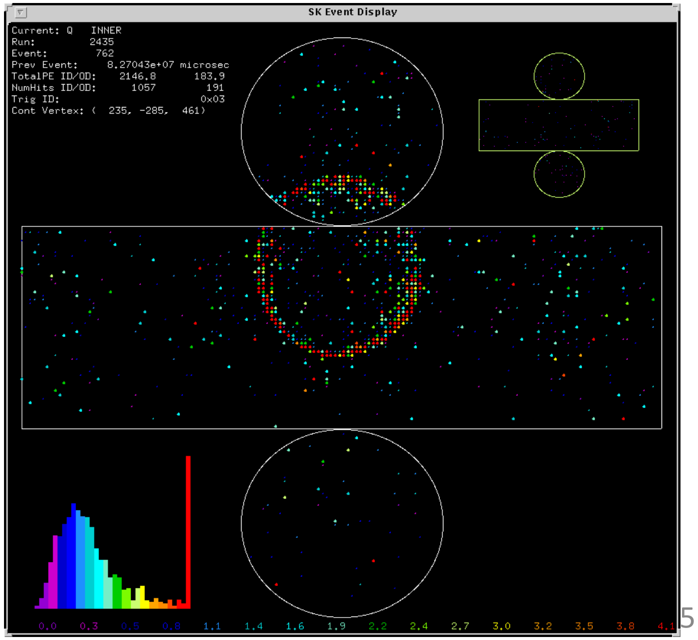
$\nu_\mu + N \rightarrow \nu_\mu + N' + x$

$\nu_e + N \rightarrow \nu_e + N' + x$

Cherenkov Angle:
$\cos\theta = 1/n\beta$
$n=1.33$ for water
$\rightarrow$ $\Theta = 42$deg for $\beta=1$

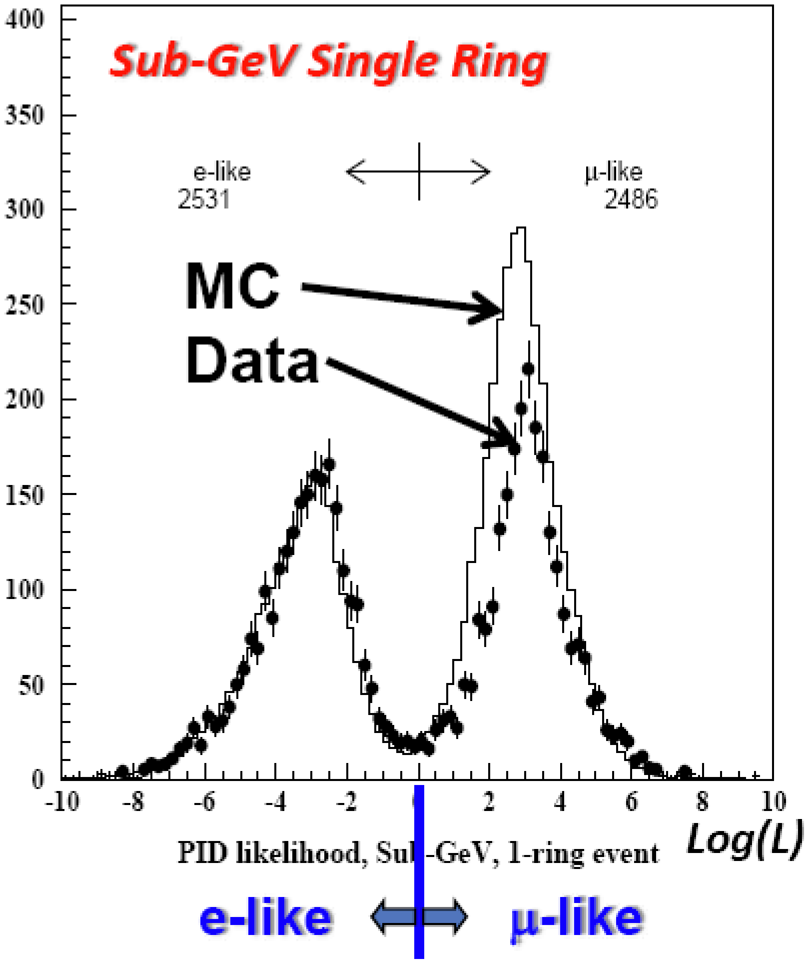


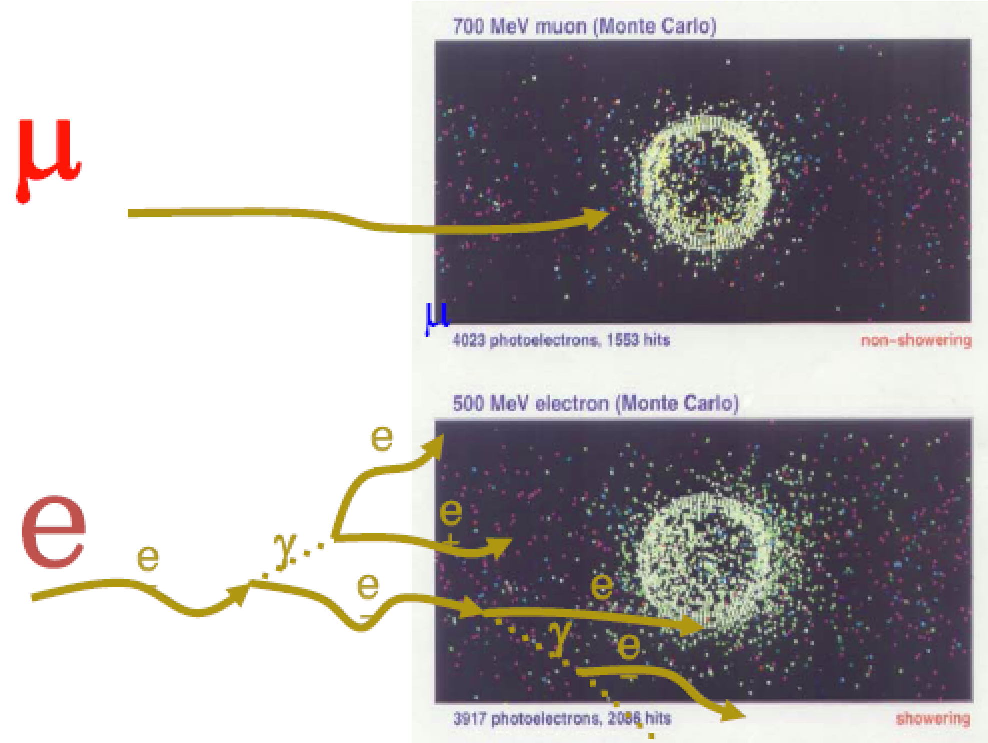




μ / e separation

Likelihood for particle identification



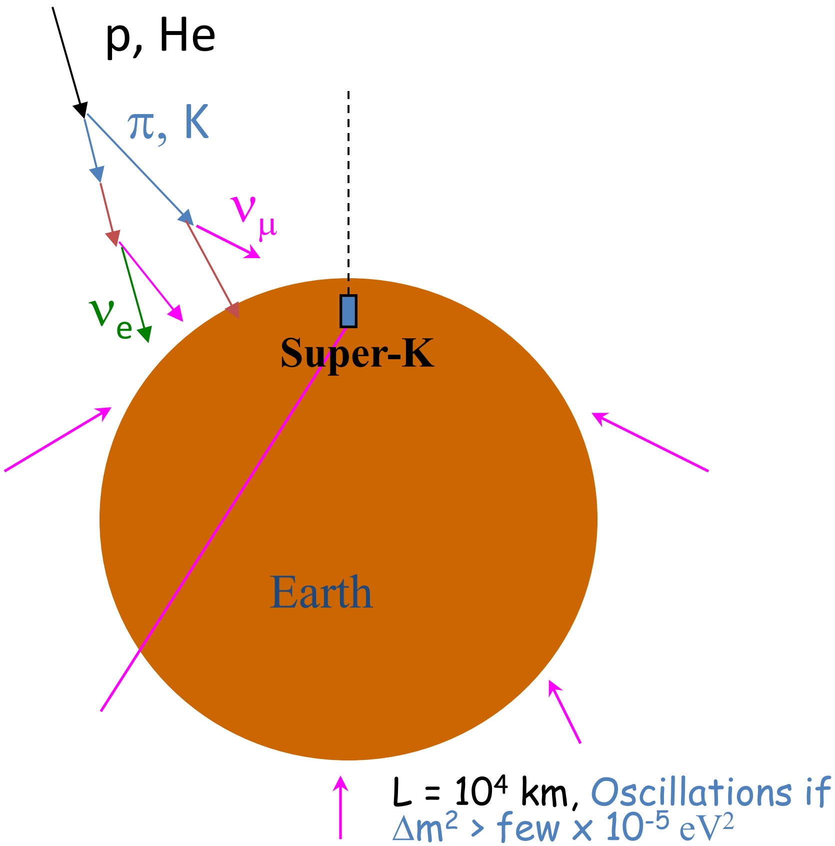


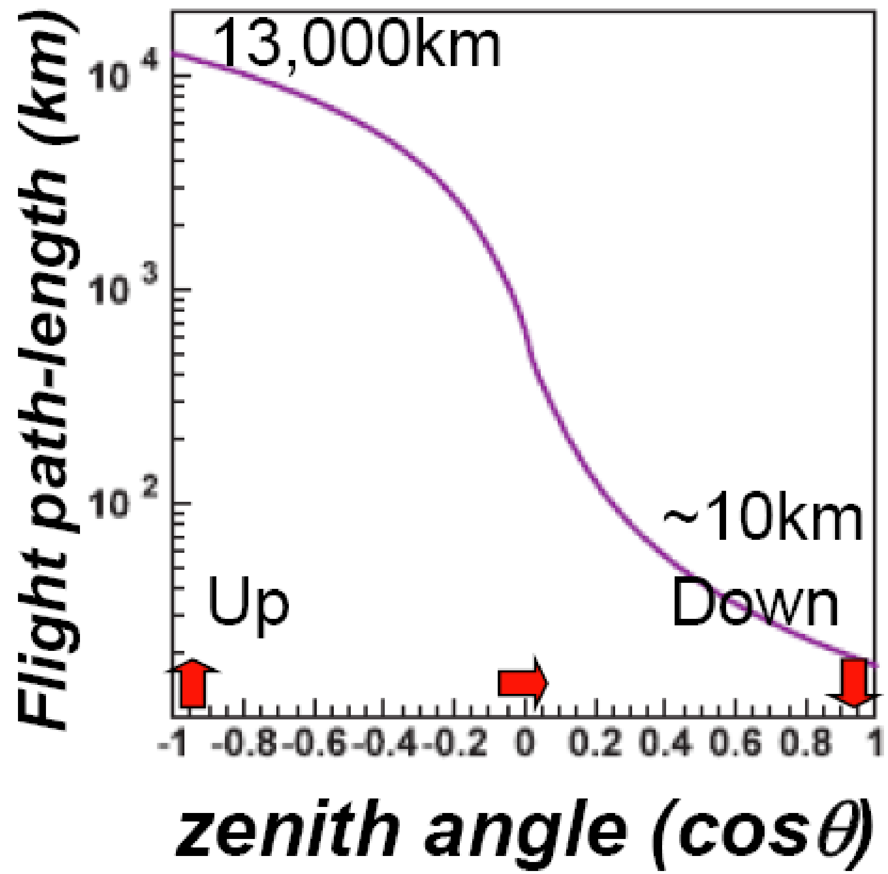
Mis-identification:

0.6 ± 0.1 %	for sub-GeV
~ 2 %	for multi-GeV

Checked by cosmic ray μ (decay electrons), e/μ beam at KEK (E261A)

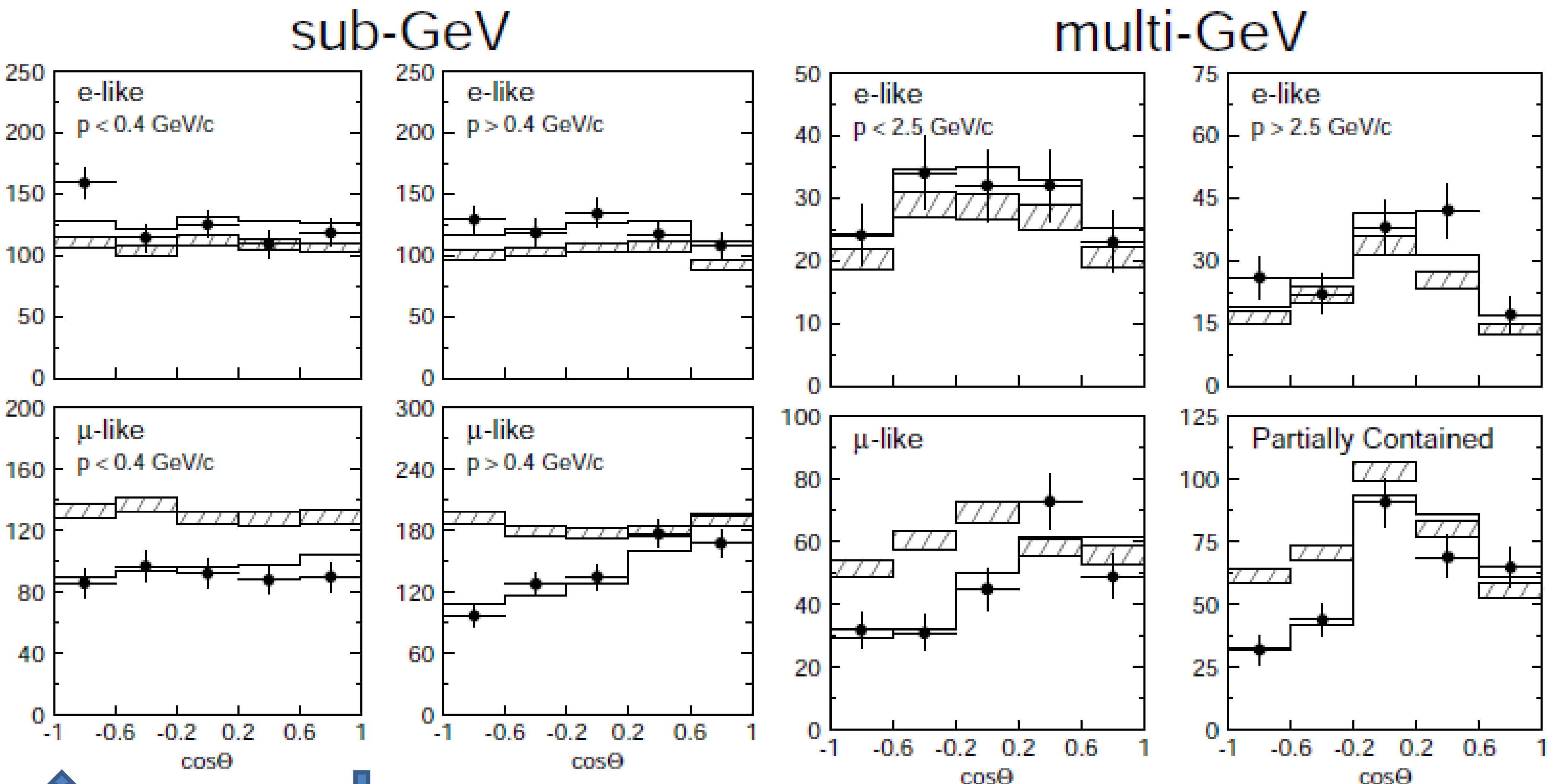
Atmospheric Neutrinos at SuperK





$E_\nu \sim$ 300 MeV - 2 GeV

Discovery of Atmospheric Neutrino Oscillation



Up **Down**

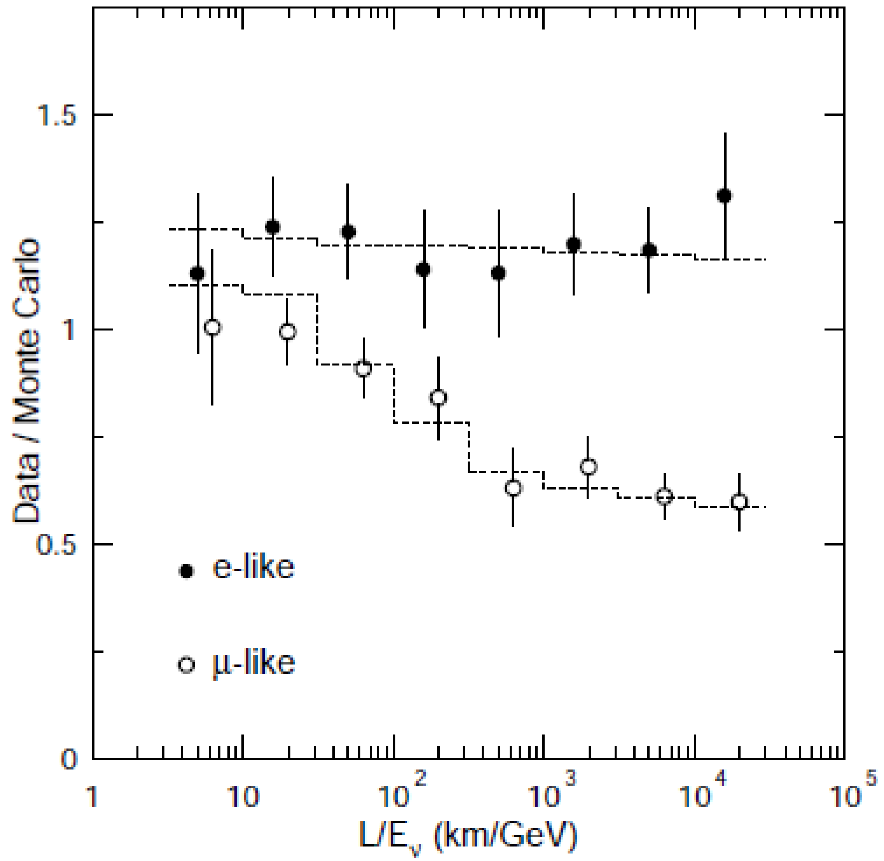
Phys. Rev. Lett. 81(1998) 1562-1567; citation > 4100

More deficit on:

- **muon-like flux**
- **upward direction**
- **High energy**

Further Evidence

- No oscillation evidence for e-like event: no $\nu_\mu \leftrightarrow \nu_e$ oscillation
- Consistent with reactor experiments such as Chooz and Palo Verde

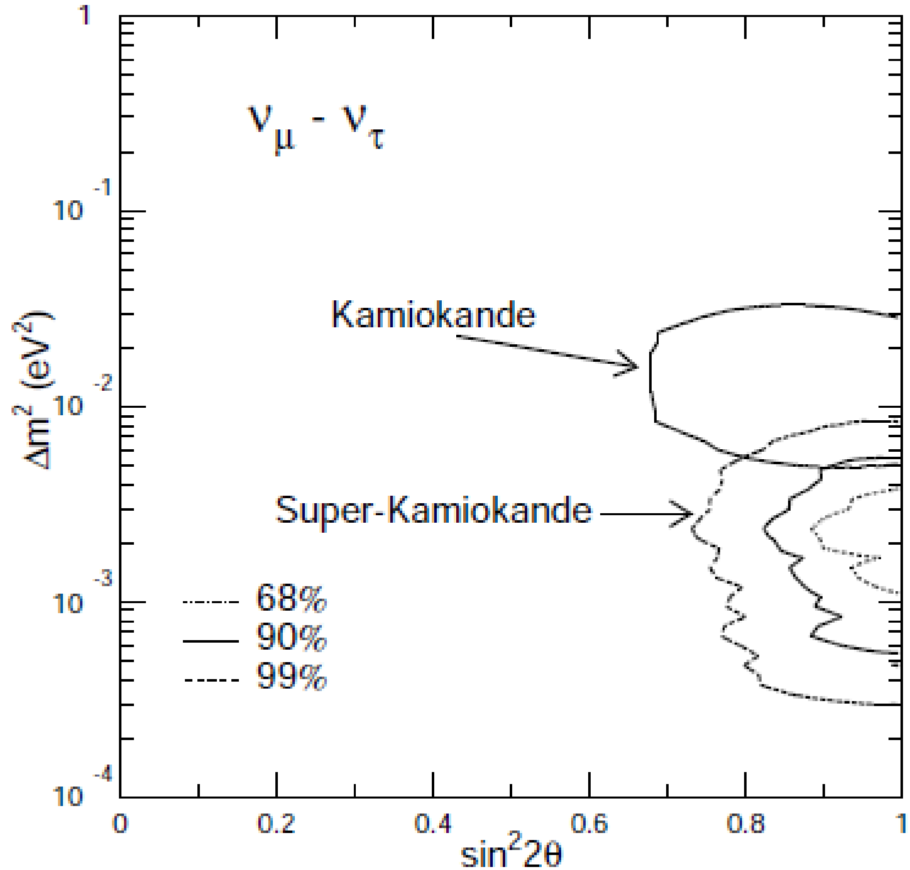


Oscillation Analysis

$$\chi^2 = \sum_{cos\Theta,p} (N_{DATA} - N_{MC})^2/\sigma^2 + \sum_j \epsilon_j^2/\sigma_j^2$$

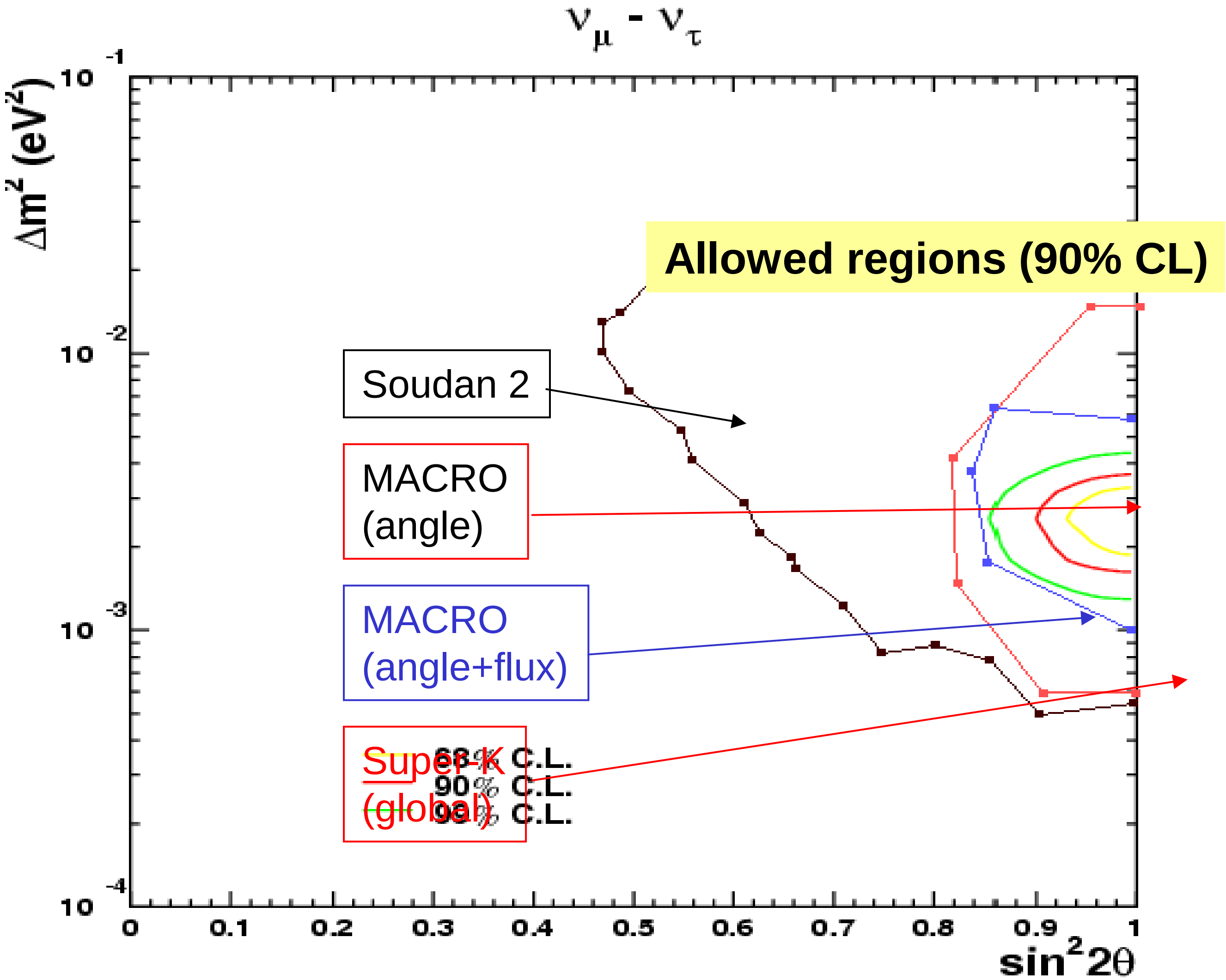
Data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillation with

$\sin^2 2\theta > 0.82$
$5\times10^{-4} < \Delta m^2 < 6\times10^{-3}$ } **90%CL**



Phys. Rev. Lett. 81(1998) 1562-1567

Confirmed by Other Experiments



Later on by MINOS and T2K

Where ν_μ goes ?

- **Possibilities:**
  - $\nu_\mu \rightarrow \nu_\tau$: No matter effect
  - $\nu_\mu \rightarrow \nu_s$: matter effect

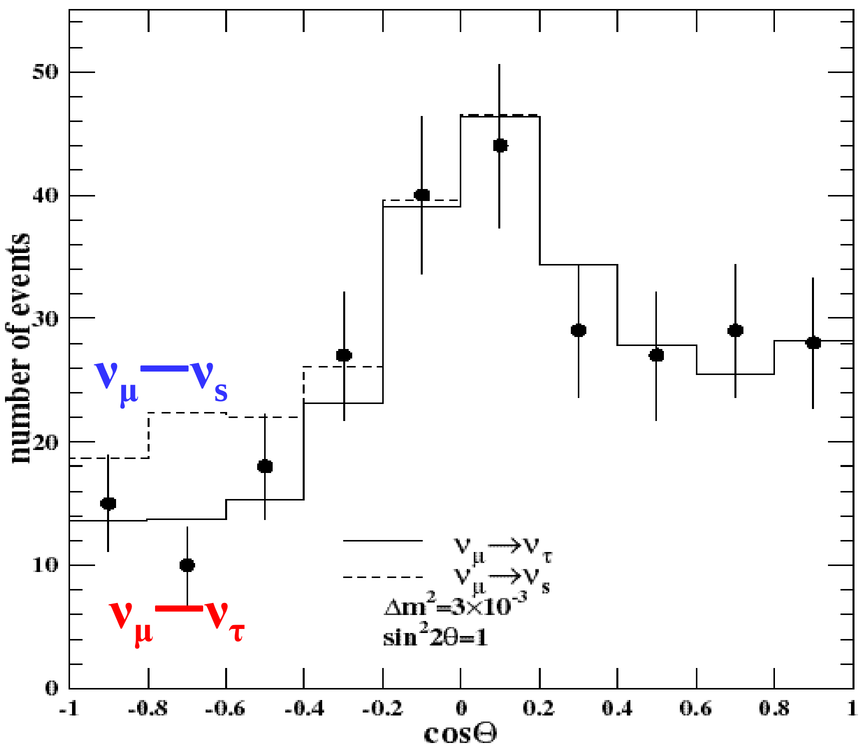
- **Results:**
  - $\nu_\mu \Rightarrow \nu_s$ unlikely
  - $\nu_\mu \Rightarrow \nu_\tau$ seen at 2.5 σ
    - Latest result: 3.8 σ

Matter Effect in the Earth

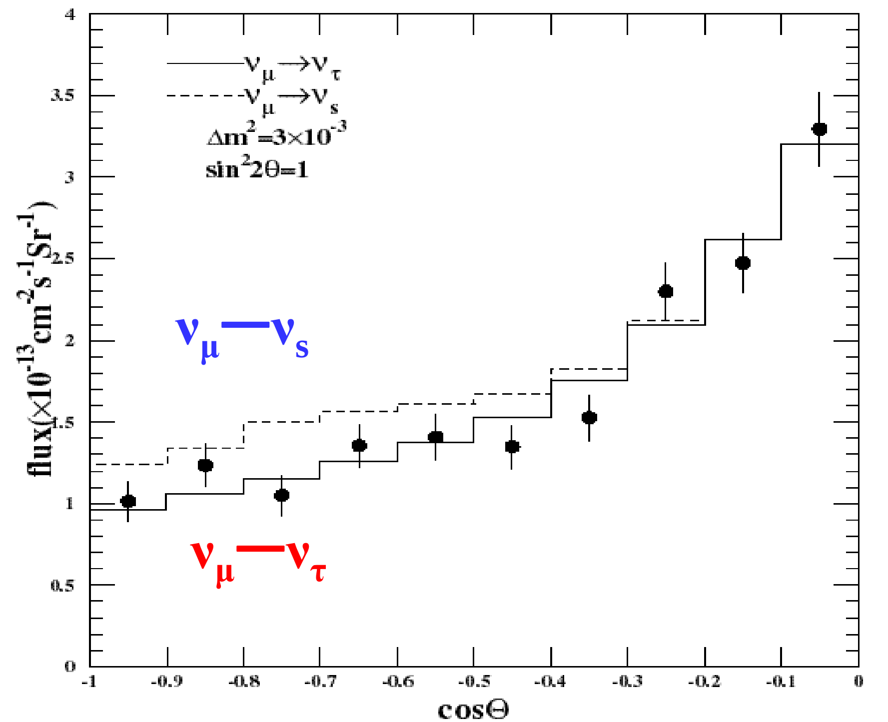
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2VE_\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

$\sin^2 2\theta \sim 1$, $E_\nu > 20\text{GeV}$
$\Rightarrow \sin^2 2\theta_m \ll 1$

zenith angle distribution of high E (E_{vis}>5GeV) PC events (1144days)



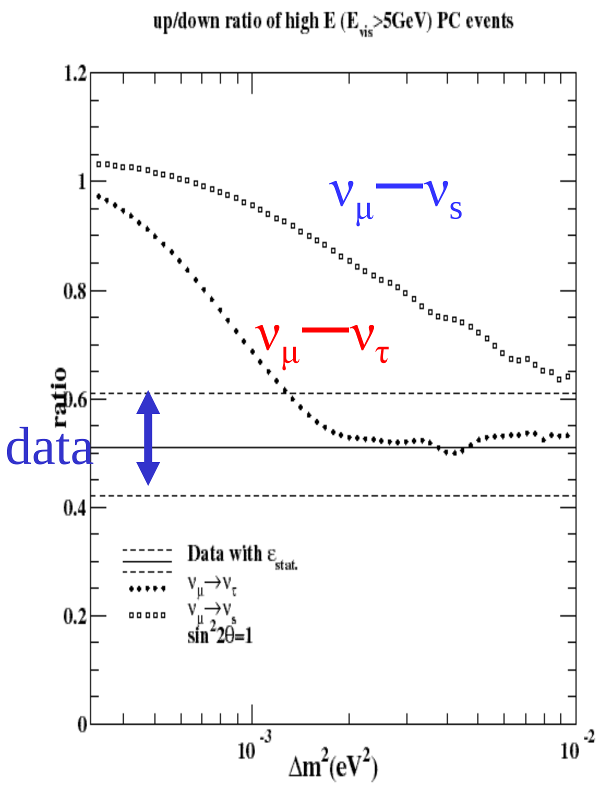
zenith angle distribution of upward through going μ events (1138days)

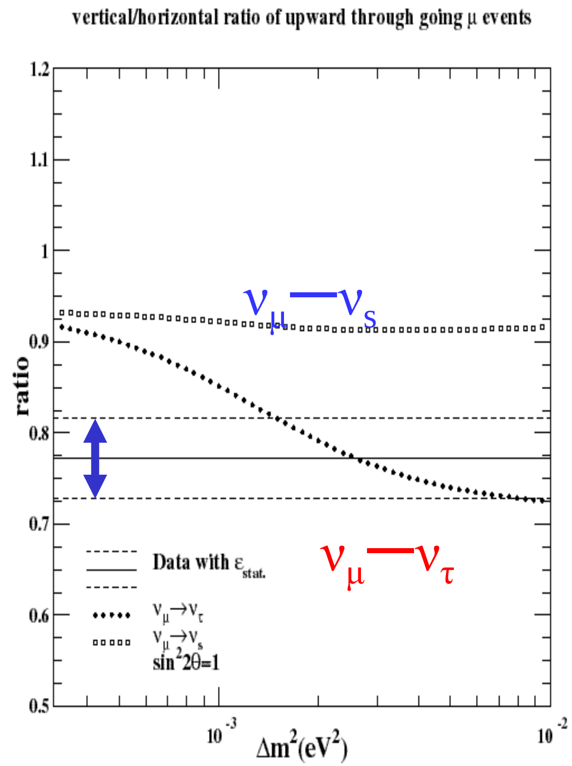


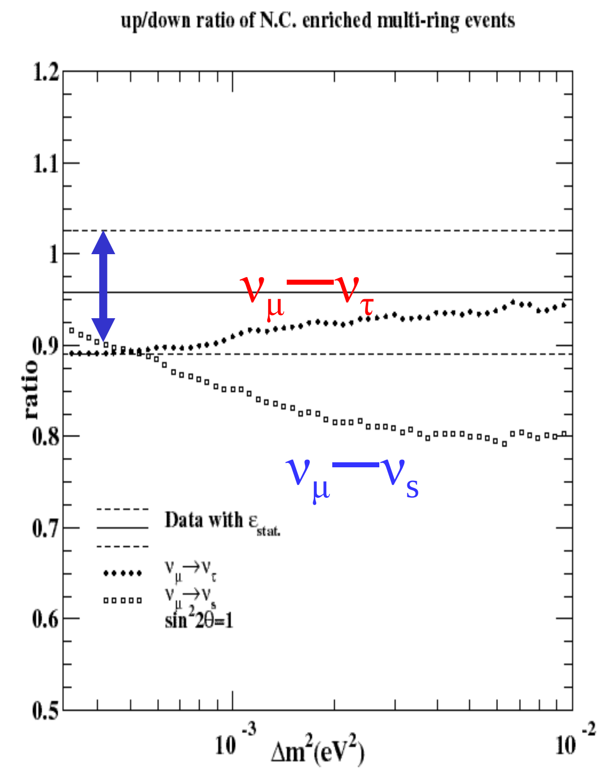
PC, Evis>5GeV
<Eν>∼25GeV
up/down ratio

up through going μ
<Eν>∼100GeV
vertical/horizontal ratio

$\nu_\mu \leftrightarrow \nu_\tau$ VS $\nu_\mu \leftrightarrow \nu_s$







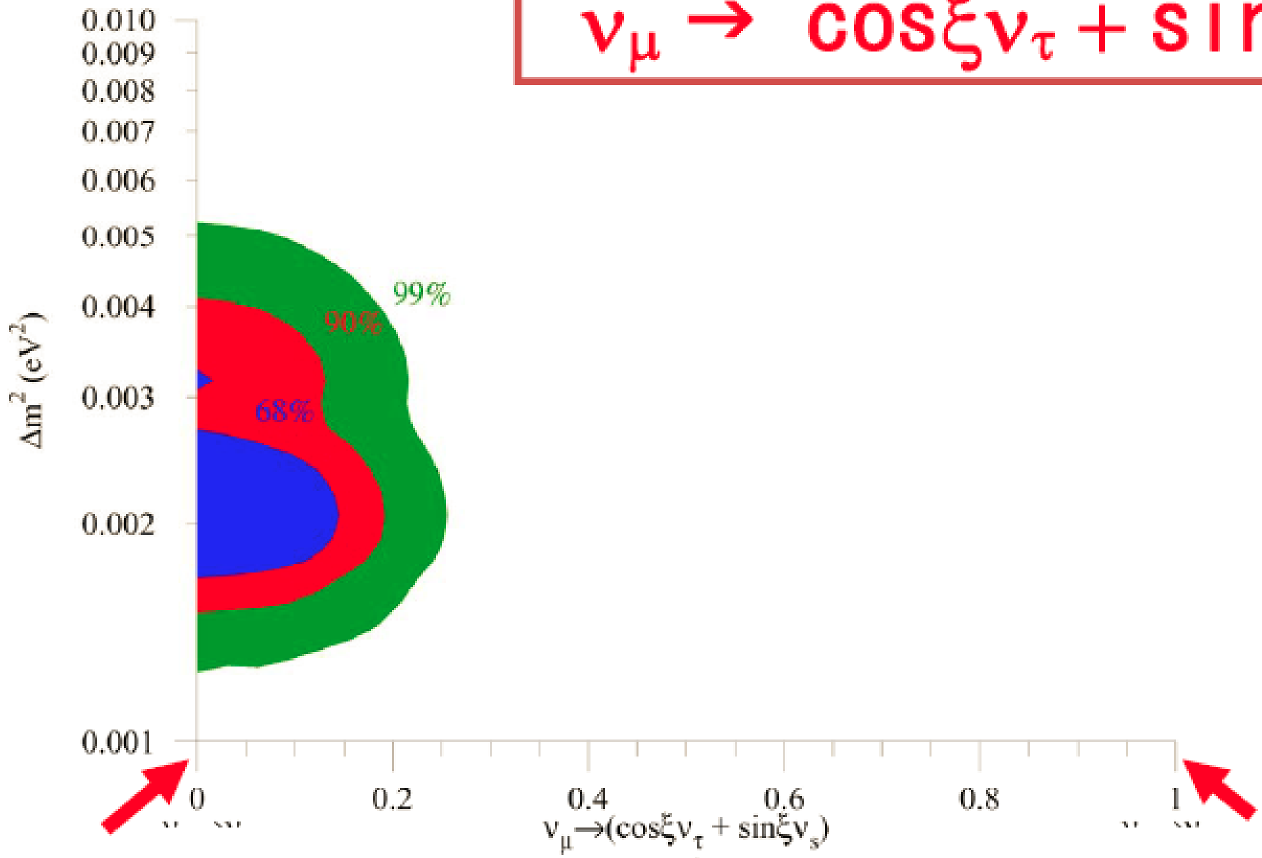
high energy PC
up/down ratio

up through μ
vertical/horizontal ratio

NC enrigh
multi ring event
up/down ratio

Limits on ν_s

$\nu_\mu \rightarrow \cos\xi\,\nu_\tau + \sin\xi\,\nu_s$



pure $\nu_\mu \rightarrow \nu_\tau$

$\sin^2\xi$

pure $\nu_\mu \rightarrow \nu_s$

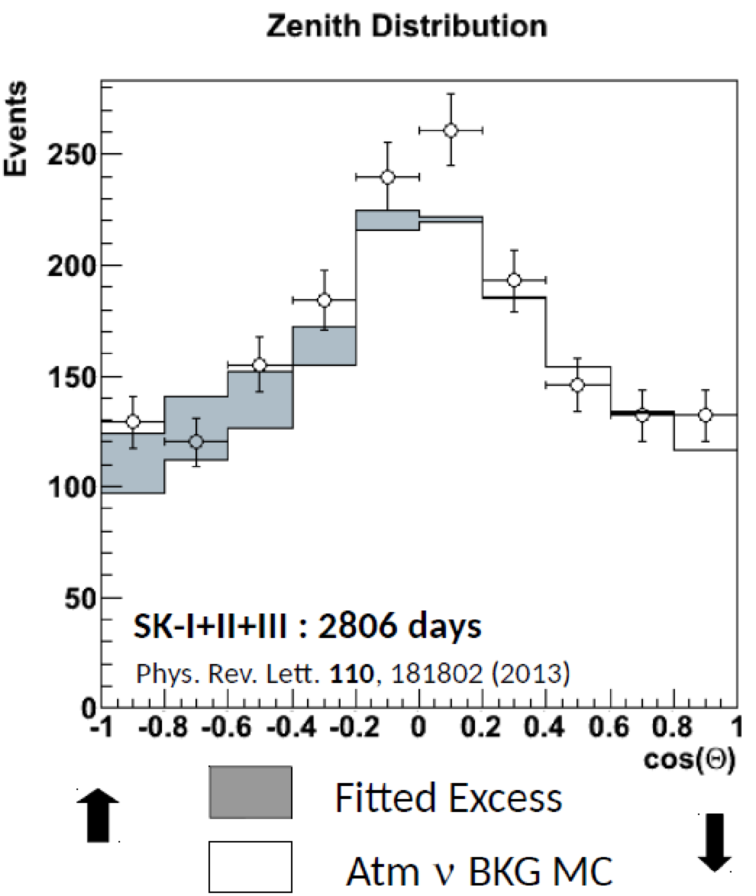
ν_τ appearance at SuperK

- Looking for events consistent with
  - hadronic tau decays
  - Oscillation induced upward-going
  - Based on neural-network, 60% eff.

$\beta = 0$: no ν_τ

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

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	1.42 ± 0.35

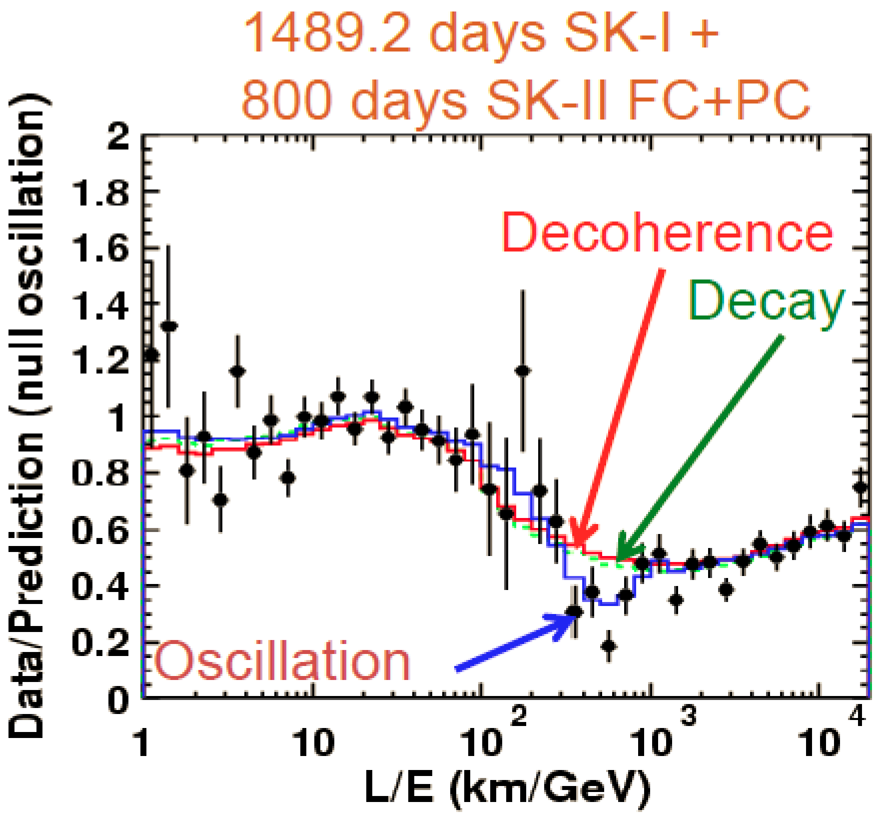


This corresponds to
180.1 ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

PhysRevLett.110.181802

Other Exotic Hypotheses

- Exotic hypothesis to explain the SuperK 1998 atmospheric data: decoherence and neutrino decay
- SNO results removed the neutrino decay hypothesis
- KamLAND results removed the decoherence explanation
- SuperK data later disfavored all of them

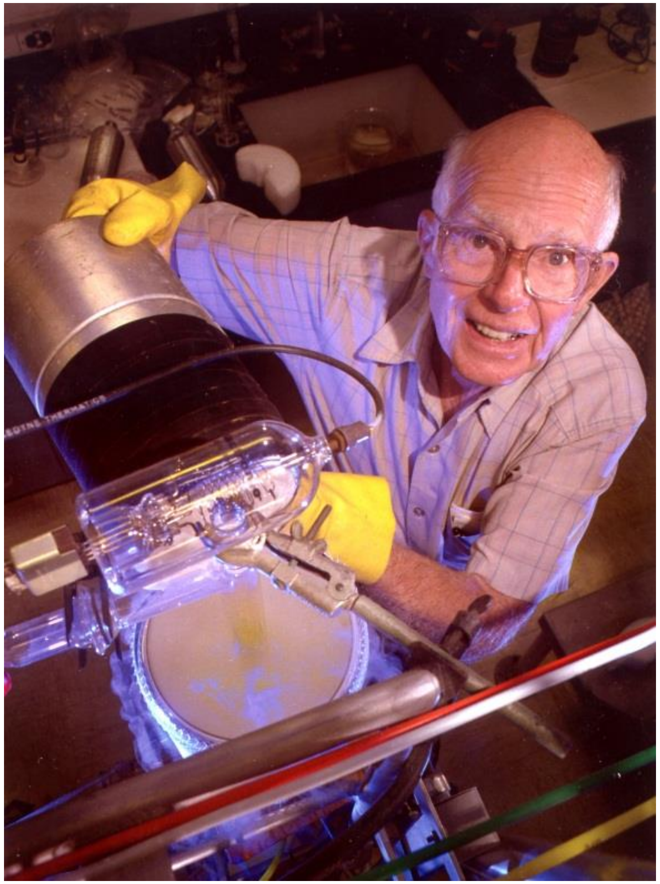


4.8 σ to decay
5.3 σ to decoherence

A Great Milestone

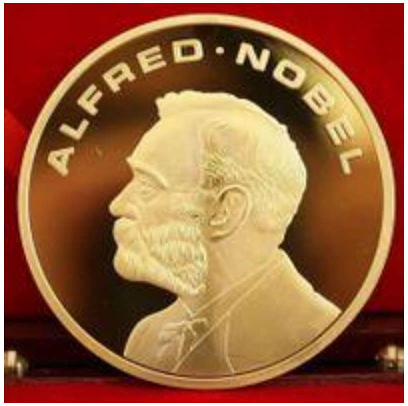
M. Koshiba

Supernova Neutrinos



R. Davis

Solar Neutrinos



2002 Nobel Prize

For the detection of cosmic neutrinos

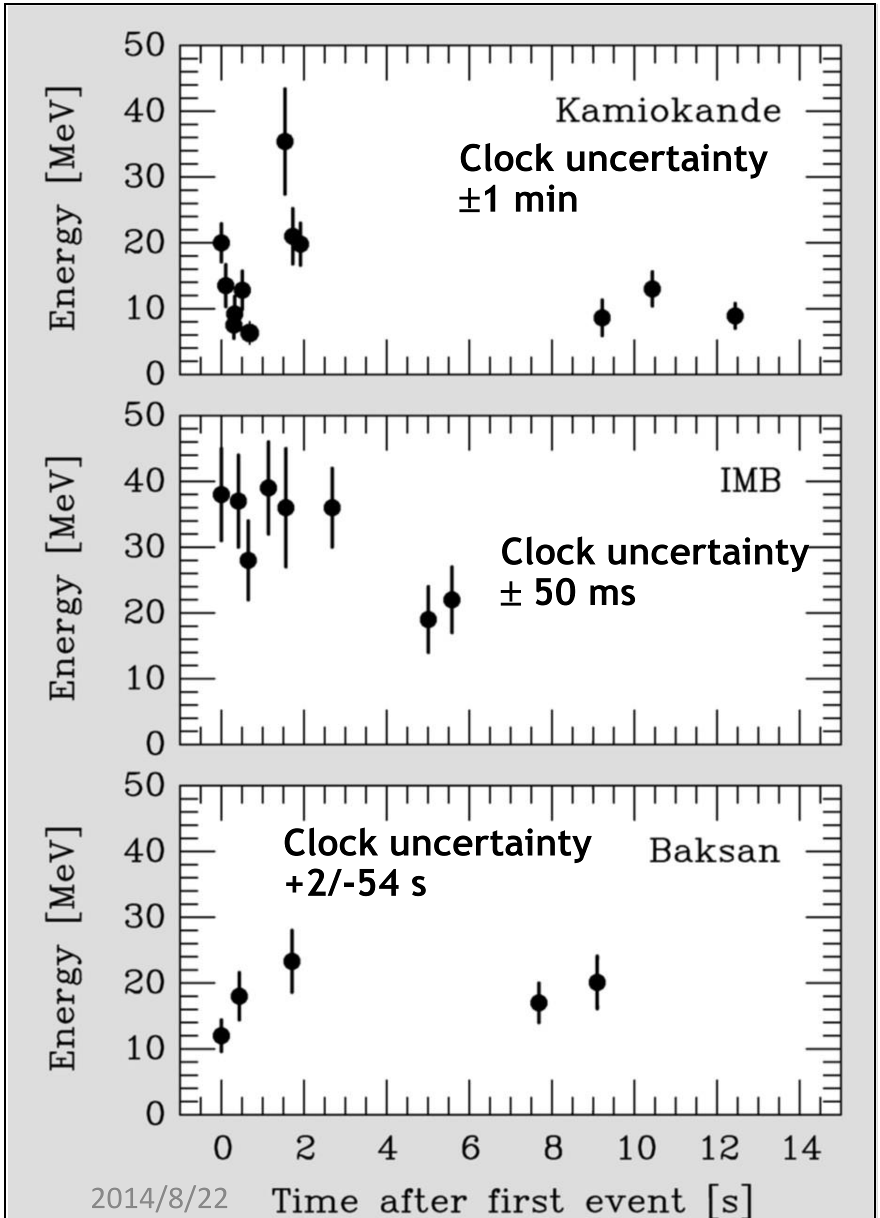
Supernova Neutrinos

- **Basic facts:**
  - **Energy:**
    - **Gravitational binding energy:**

      $E_b \approx 3 \times 10^{53}$ erg
    - **99%   Neutrinos**
    - **1%   Kinetic energy of explosion (1% of this into cosmic rays)**
    - **0.01% Photons, outshine host galaxy**
  - **Neutrino Energy: 1 - 50 MeV**
- **Very good for Supernova study, neutrino mass measurement, and many others**
- **Frequency: ~ 1/galaxy/100 years**

Within our galaxy(~10 kpc), a supernova explosion can happen at any time from now

1987A Supernova Neutrinos

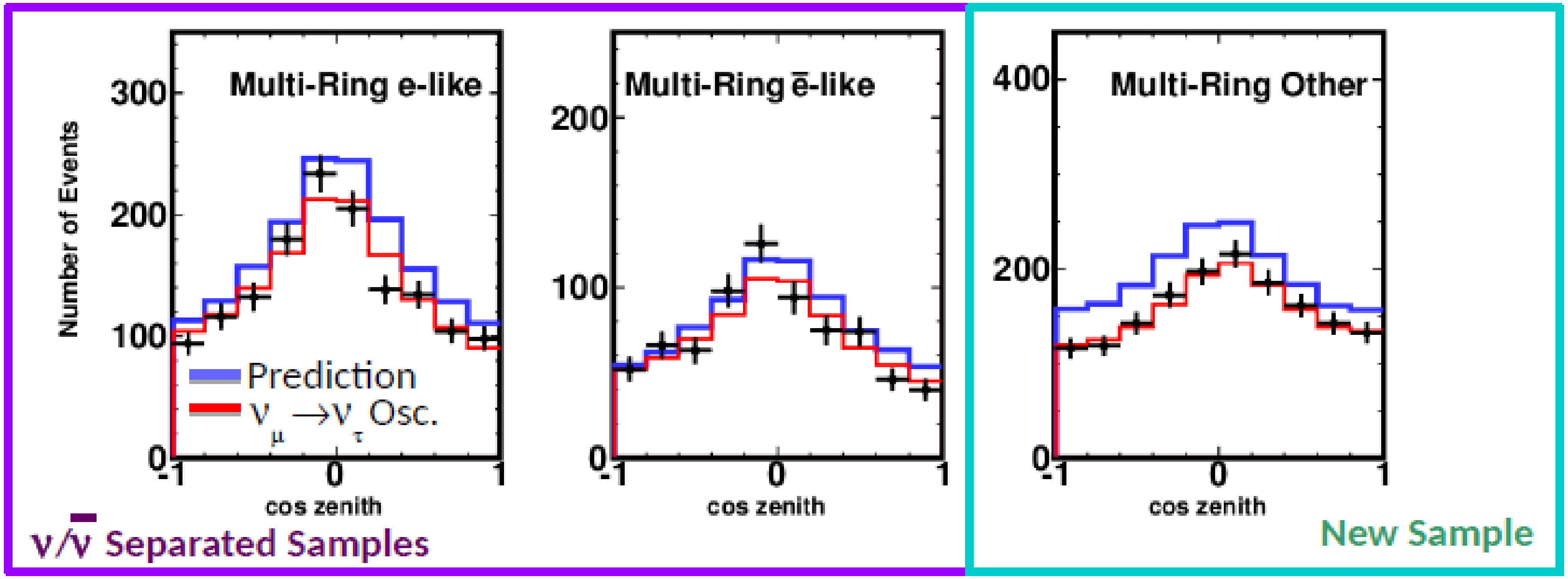


- On Feb. 23, 1987A Supernova exploded, two weeks after the completion of the Kamiokande upgrade.
- Distance: 50 kpc
- No. of neutrino events seen:
  - Kamiokande: 12/3000t
  - IMB: 8/8000t
  - Baksan: 5/ 200t
- Within clock uncertainties, signals are contemporaneous

Lesson learned:
Large mass
Low energy threshold
Always on

Recent Three-flavor Analysis

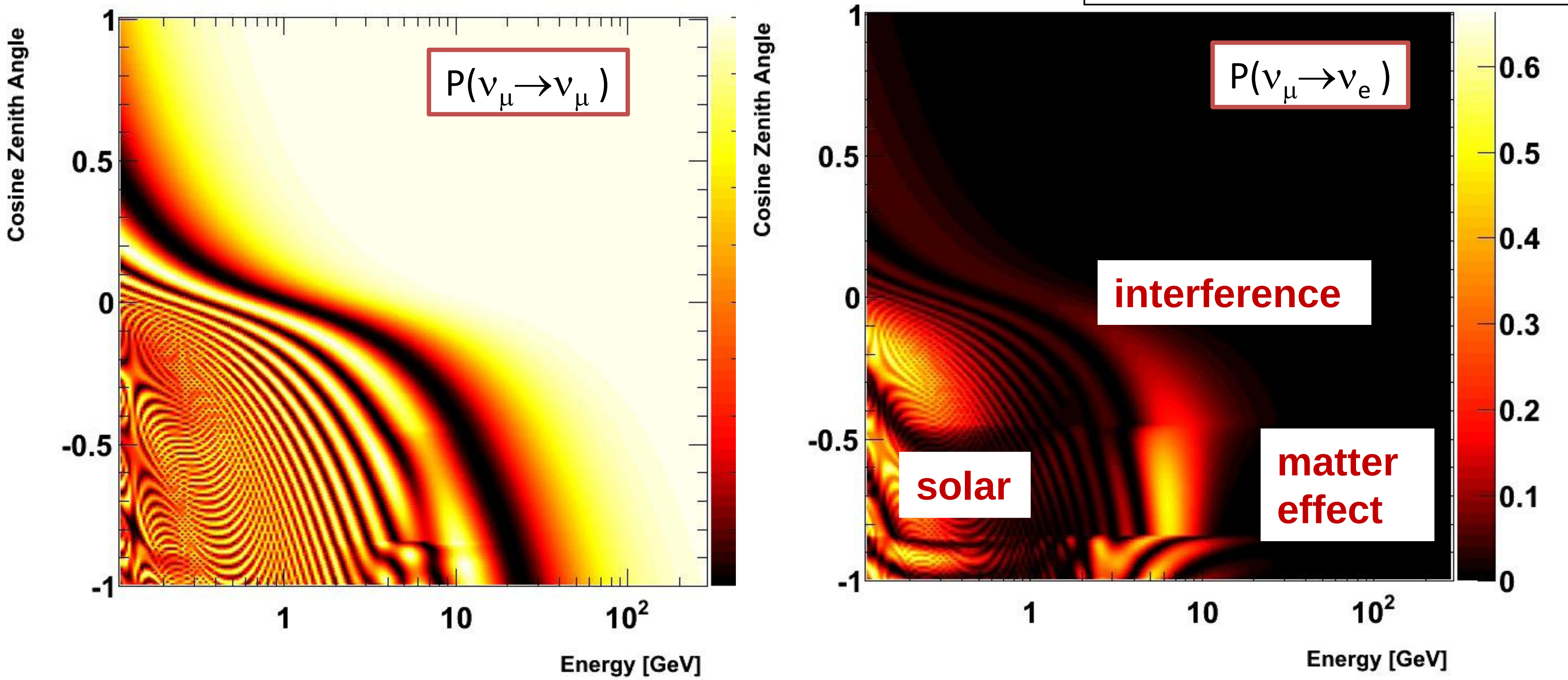
- In additional to $\nu_\mu \leftrightarrow \nu_\tau$ oscillation described by $\sin^2 2\theta_{23}$ and $\Delta m^2{}_{32}$, three-flavor oscillation analysis takes into account sub-leading effects such θ_{13}, CP phase δ, matter effect, etc.



- Improved systematic error treatment
- 1775 days of SK-IV data, 4581.4 days total: 282.2 kton yrs

Sub-leading Effects

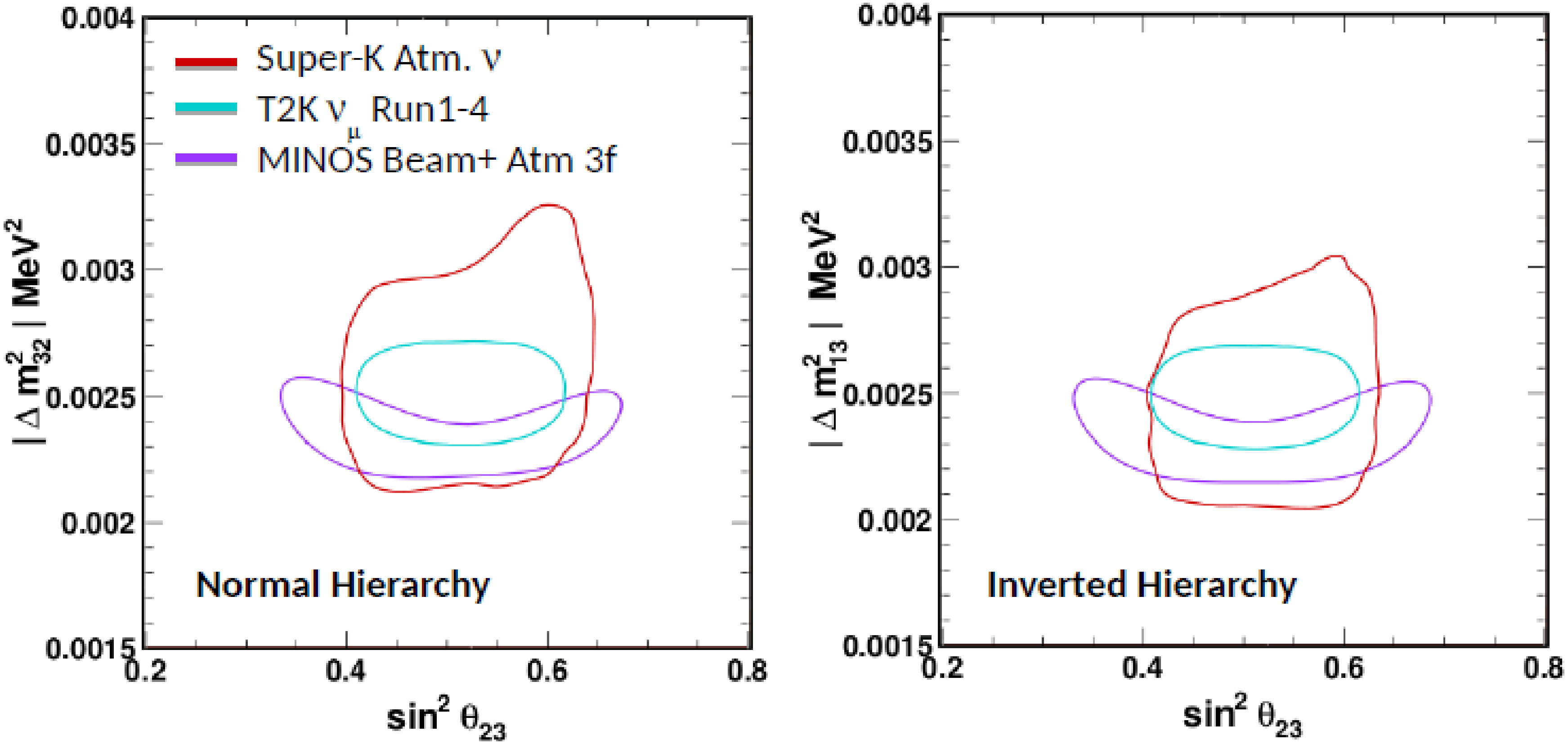
Roger Wendell@Neutrino 2014



- Thanks to the huge statistics and large θ_{13}, we can look for:
  - Mass hierarchy: enhanced high E upward going ν_e due to the matter effect
  - Octant of oscillation: enhanced low energy ν_e due to the solar term
  - CP phase δ: interference between these two

Oscillation Parameters

Preliminary

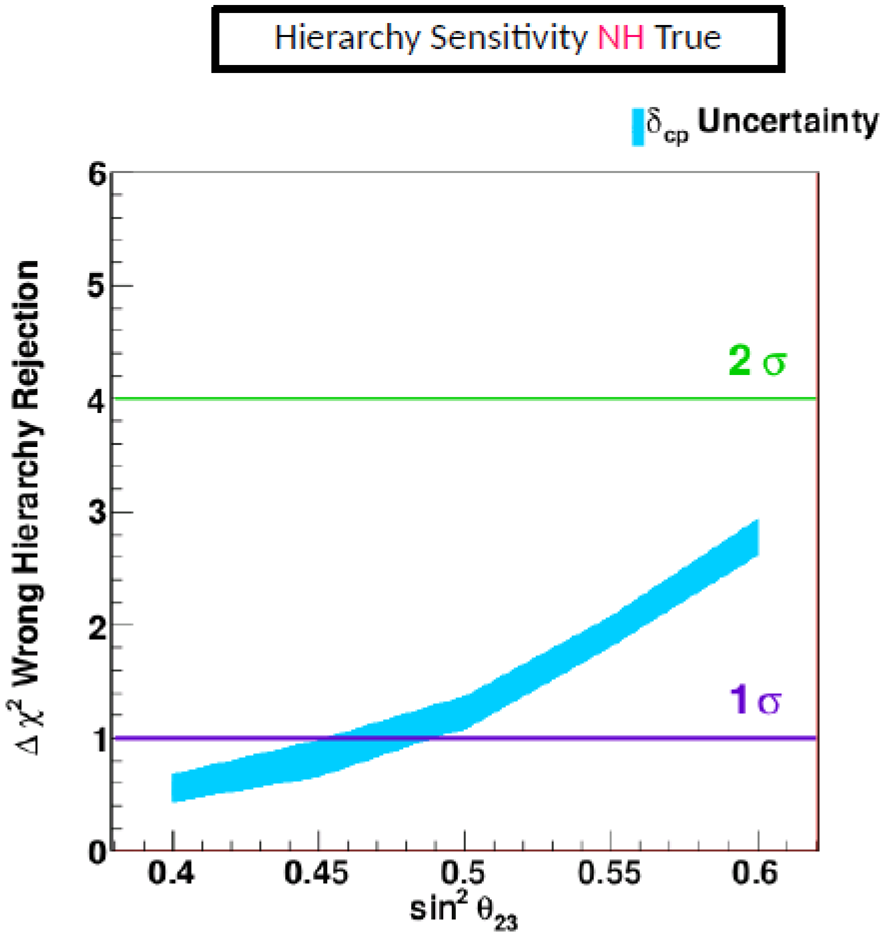


- **Global fit:**

$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NH)	$2.48^{+0.05}_{-0.07}$	$\sin^2\theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32}_{-1.15}$
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IH)	$2.38^{+0.05}_{-0.06}$	$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.38}$

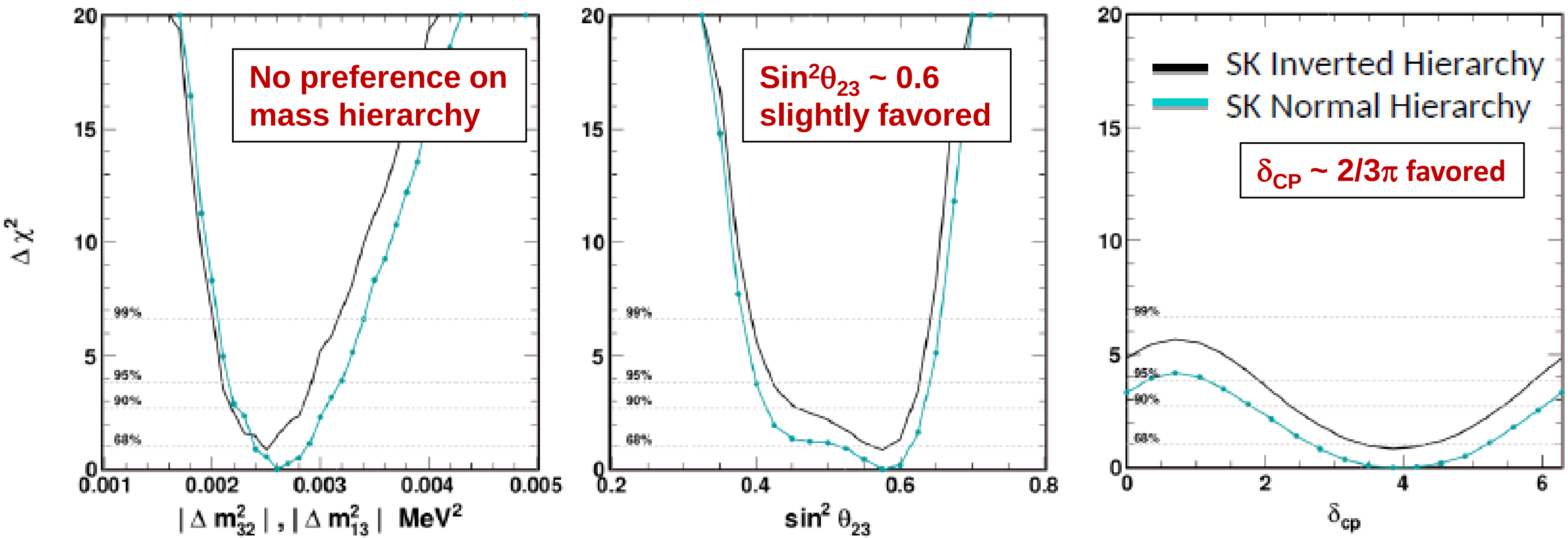
Mass Hierarchy Determination

- Through matter effect: long-baseline accelerator neutrinos, atmospheric neutrinos
  - dependent to matter density, $\sin^2\theta_{23}$ and δ_{CP}
- Through interference of ΔM^2_{32} and ΔM^2_{31} : reactor neutrinos
  - Independent of matter density, $\sin^2\theta_{23}$ and δ_{CP}



SuperK

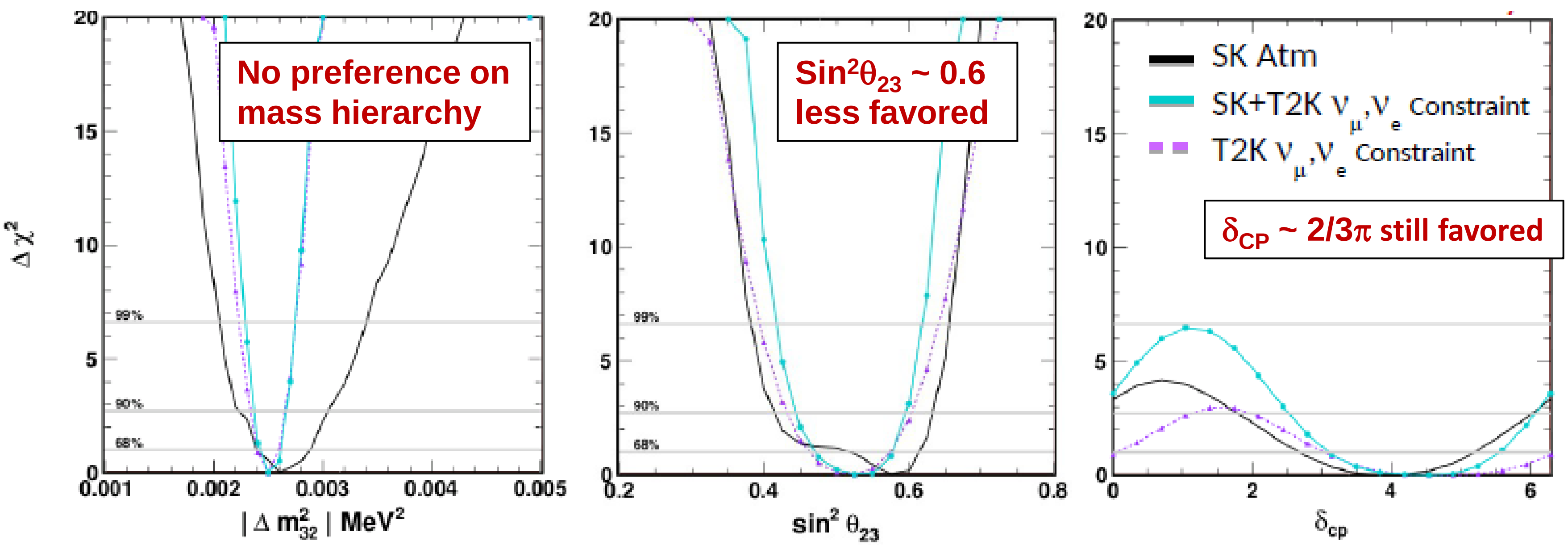
Fitting Results: SuperK only



Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23}(x10^{-3})$
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

- θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error

Fitting Results: SuperK + T2K

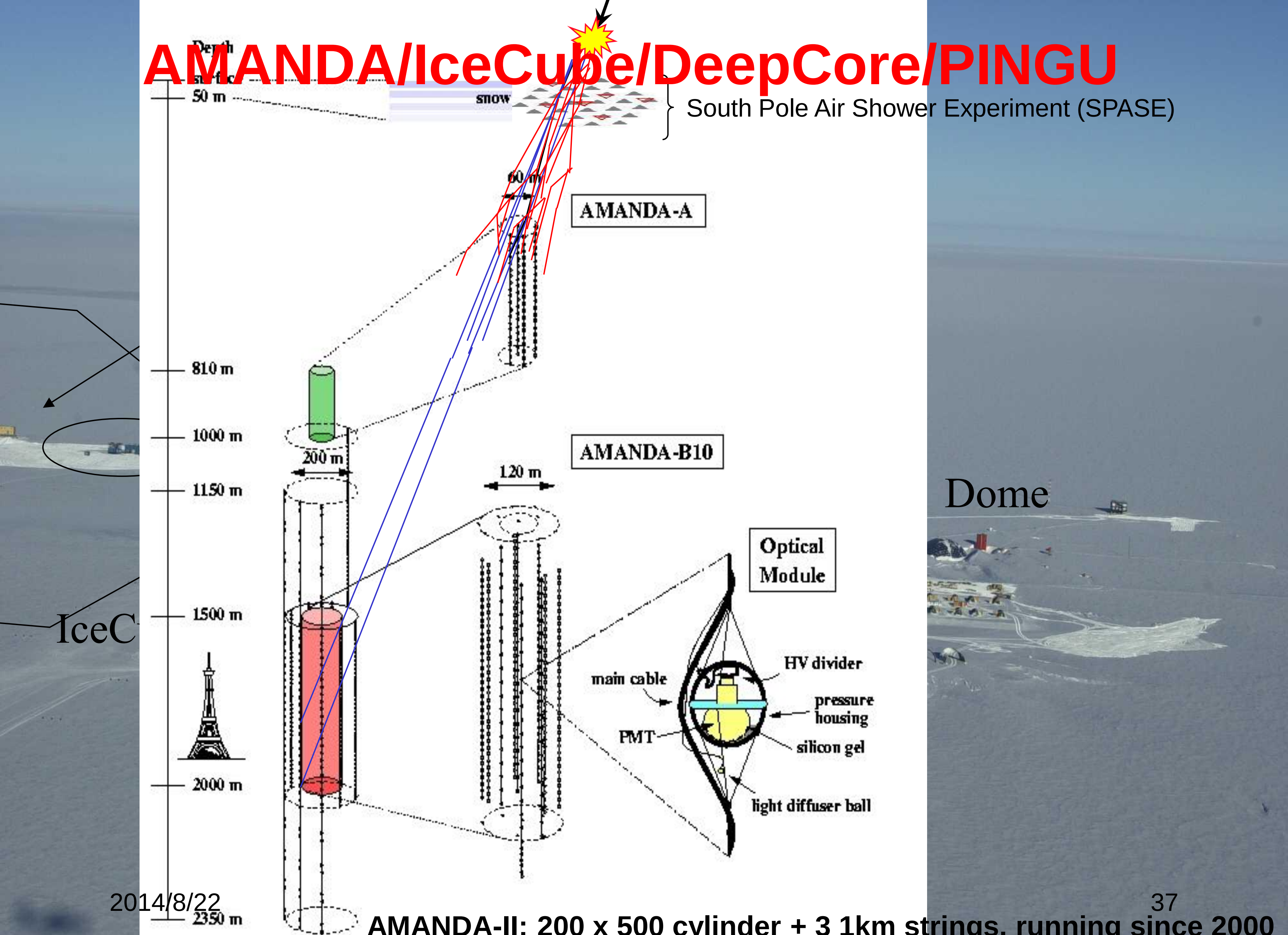


Fit (543 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23}(\mathrm{x}10^{-3})$
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

- $\chi^2_{IH} - \chi^2_{NH}$ = **-1.2** (-0.9 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

Same detector, generator and reconstruction: easy for systematic error correlation
MINOS is not included yet

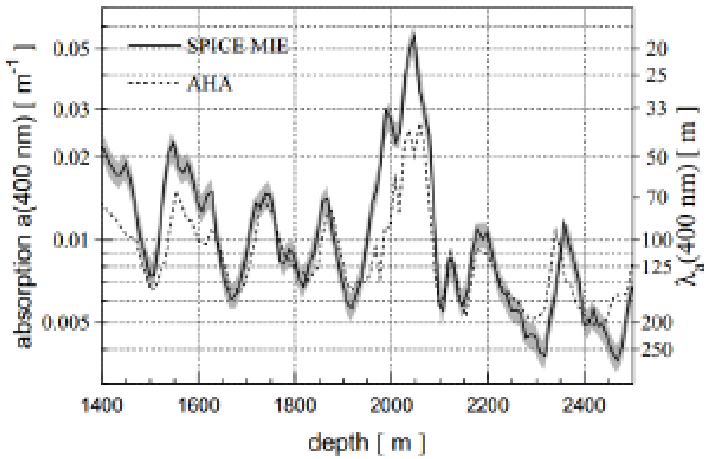
AMANDA/IceCube/DeepCore/PINGU



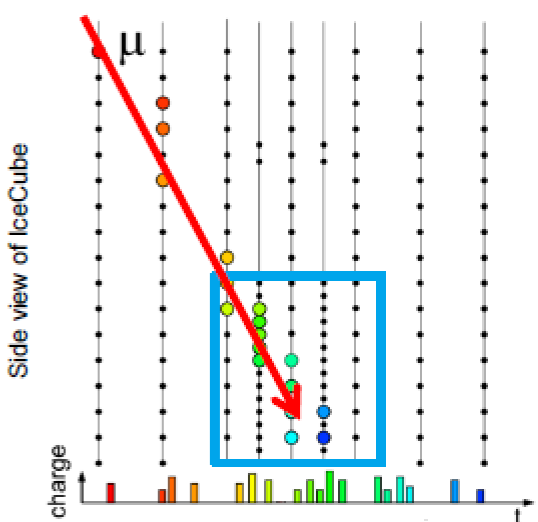
AMANDA-II: 200 x 500 cylinder + 3 1km strings, running since 2000

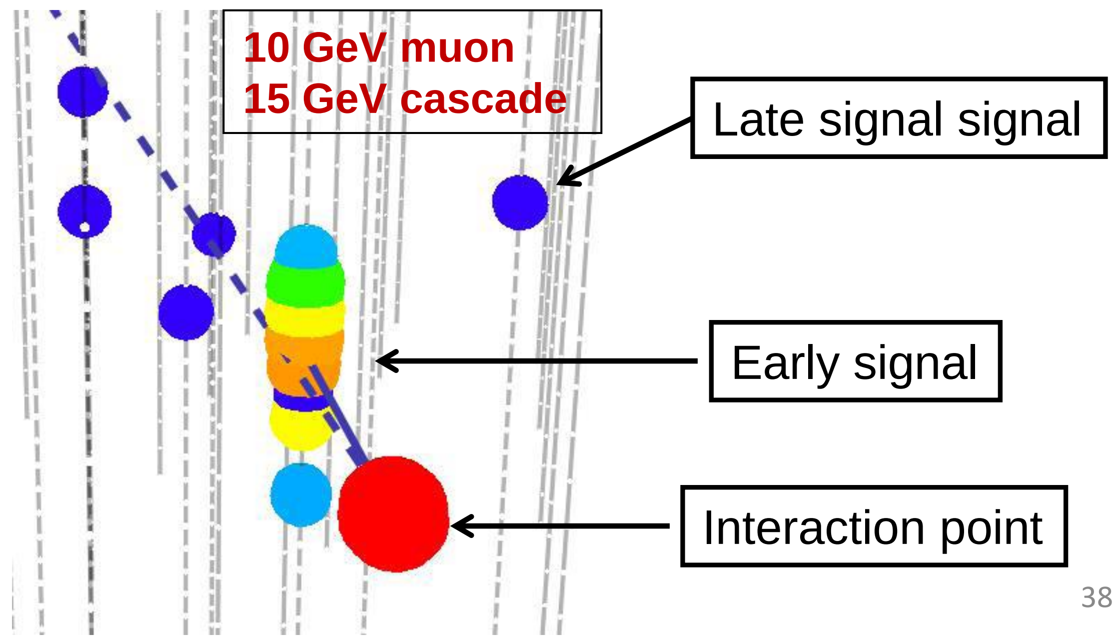
IceCube/DeepCore

- IceCube: 5160 PMTs over 1 km^3
- DeepCore: 600 PMTs over 0.02 km^3
- Sensors separation: 7-70 m
- Light yield： a few p.e. @ 10 GeV
- Cosmic-μ rate is 10^6 higher than ν
- No calibration in-situ

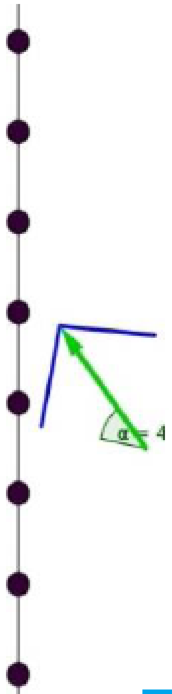


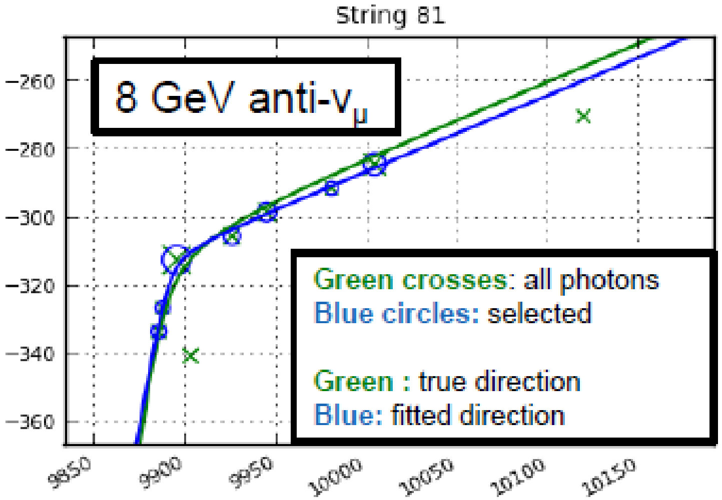
Optical properties of the medium





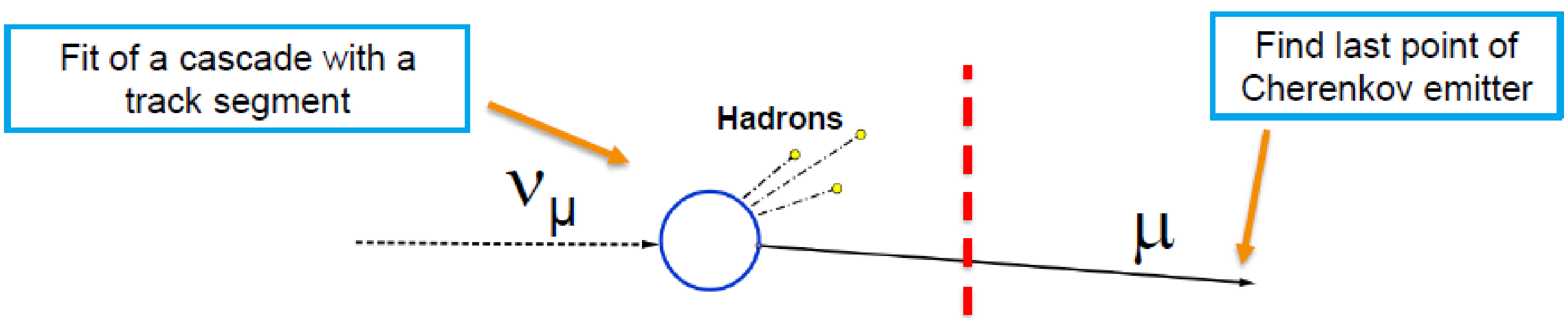
Event Reconstruction





- No. of direct photons → quality
- Hyperbola orientation → zenith angle

$$E_{reco} = E_\mu(R_\mu) + E_{vertex}(E_{had}, \vec{x}_{vertex})$$

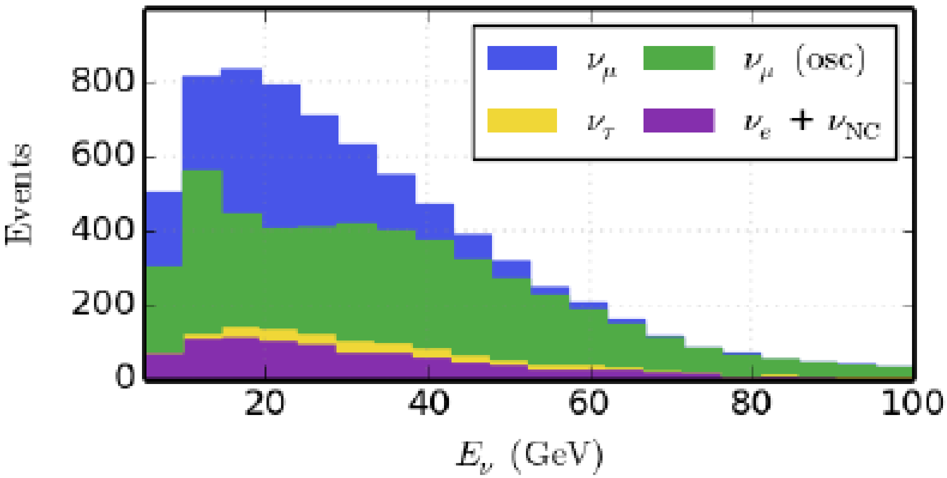


Uses the parameterized light emission of particles

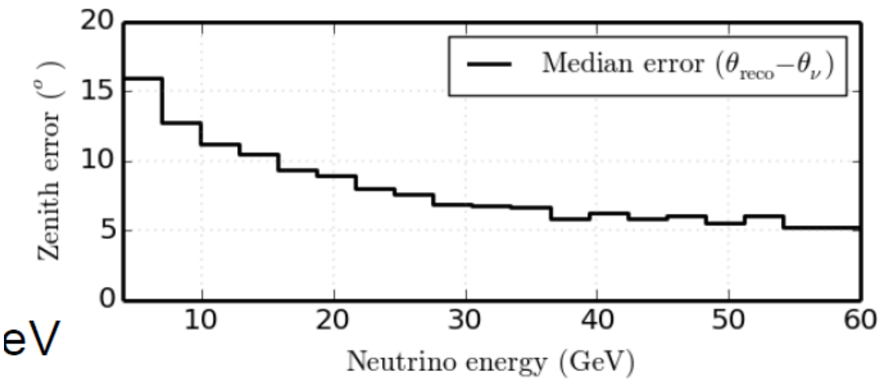
Optical properties of the ice included

Data Sample and Resolution

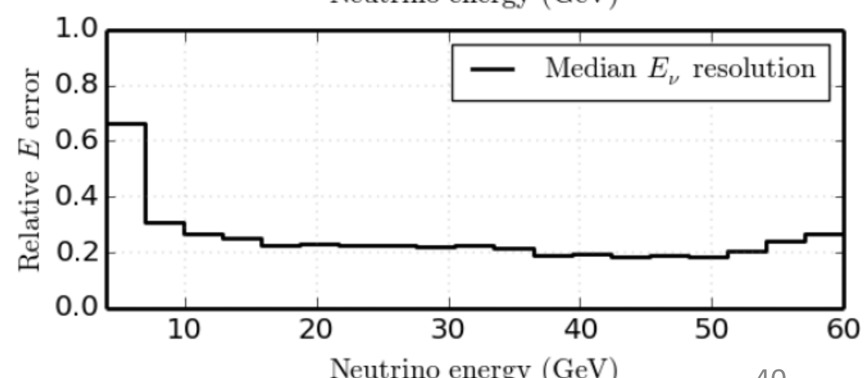
True energy distribution of final sample



- Over 100,000 ν triggers/year ➔ huge statistical power
- MC expectation: ~7000 events, ~1900 disappeared
- 5293 events selected



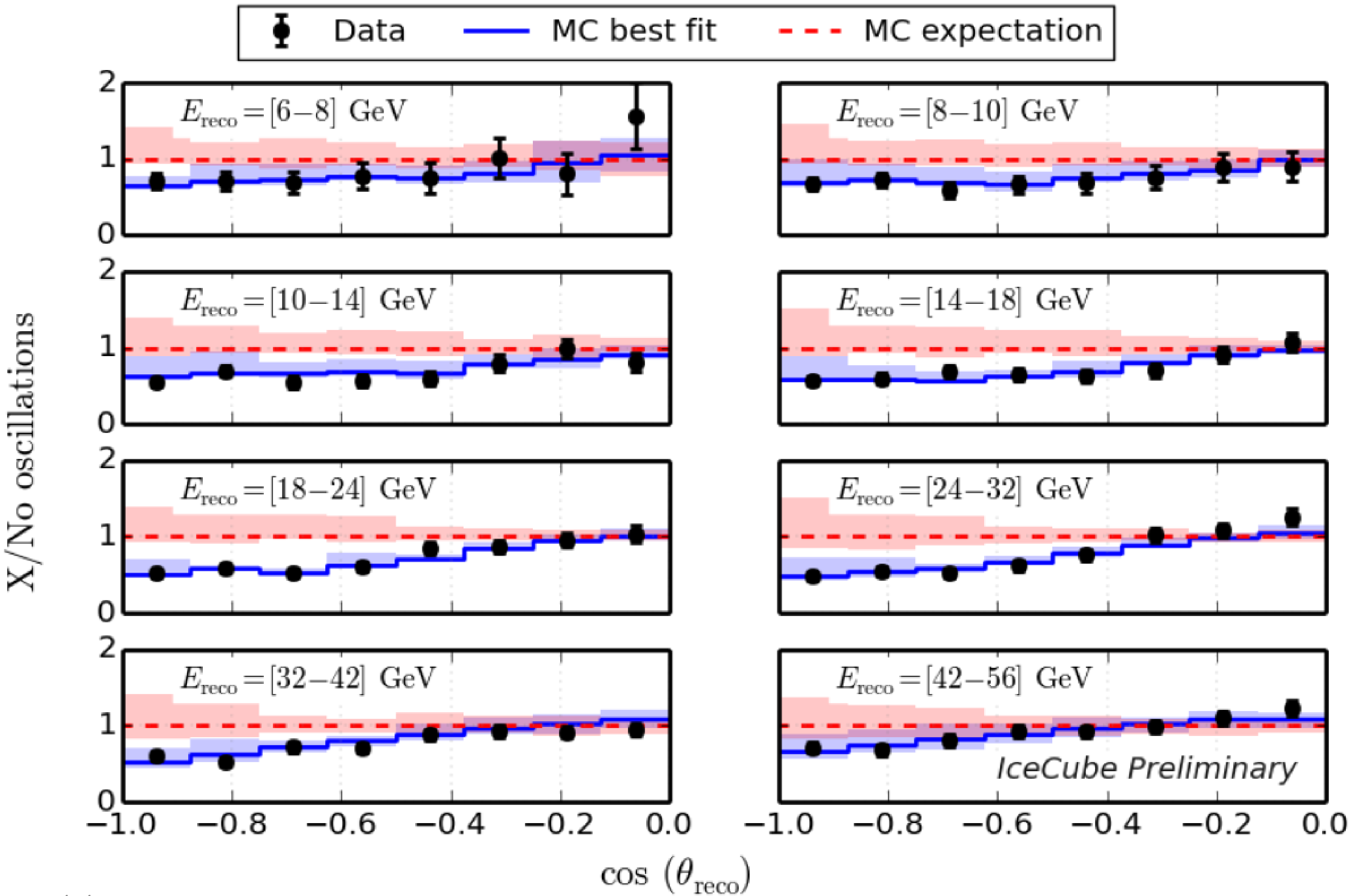
eV



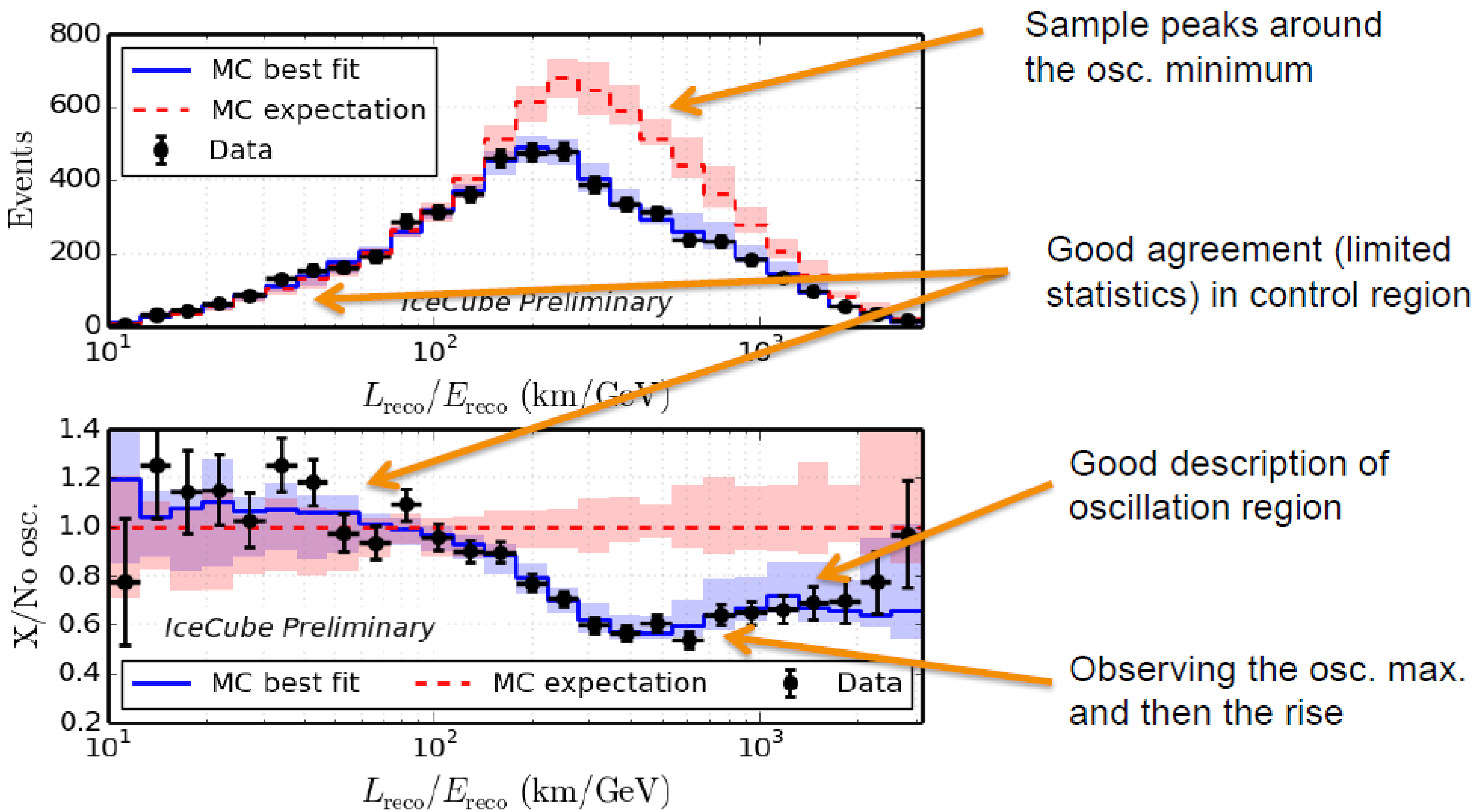
Energy resolution:
- 30% @ 10 GeV
- not reliable @ < 10 GeV
- escape FV @ > 50 GeV

Angular resolution:
- 12° @ 10 GeV
- 15° @ low energy
- 5° @ high energy

Atmospheric Neutrino Oscillation

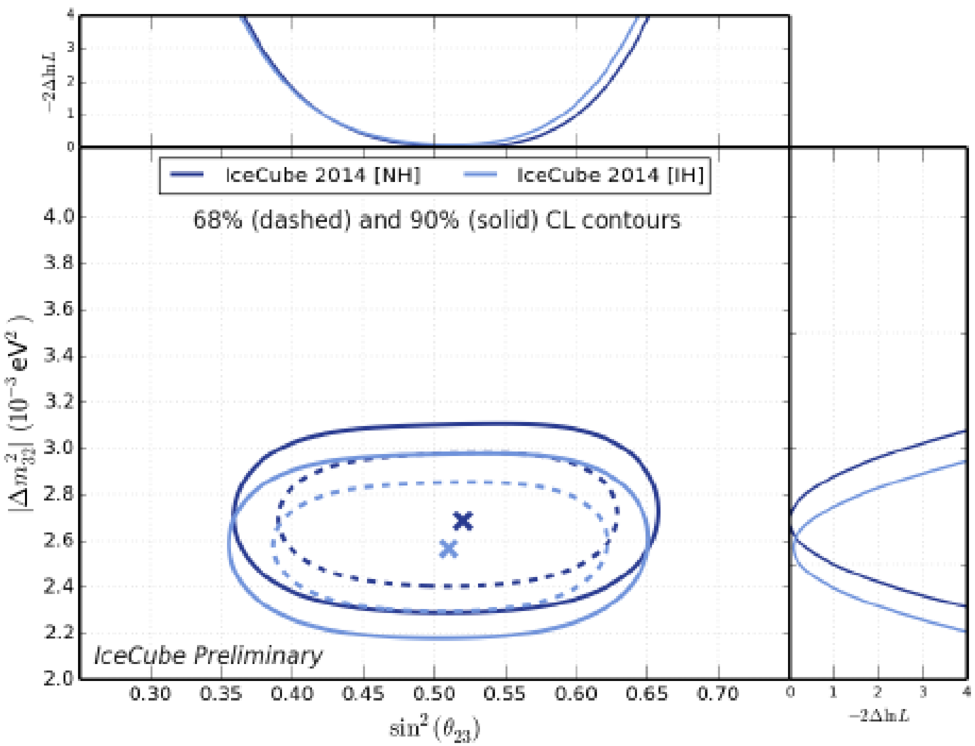


Further Evidence



Results

Parameter	Normal hierarchy		Inverted hierarchy	
	Best fit	68% CI	Best fit	68% CI
$\sin^2(\theta_{23})$	0.512	0.422 – 0.600	0.509	0.417 – 0.594
Δm^2_{32} (10^3 eV^2)	2.684	2.503 - 2.877	2.563	2.385 - 2.754



5293 events selected (2011-2014)

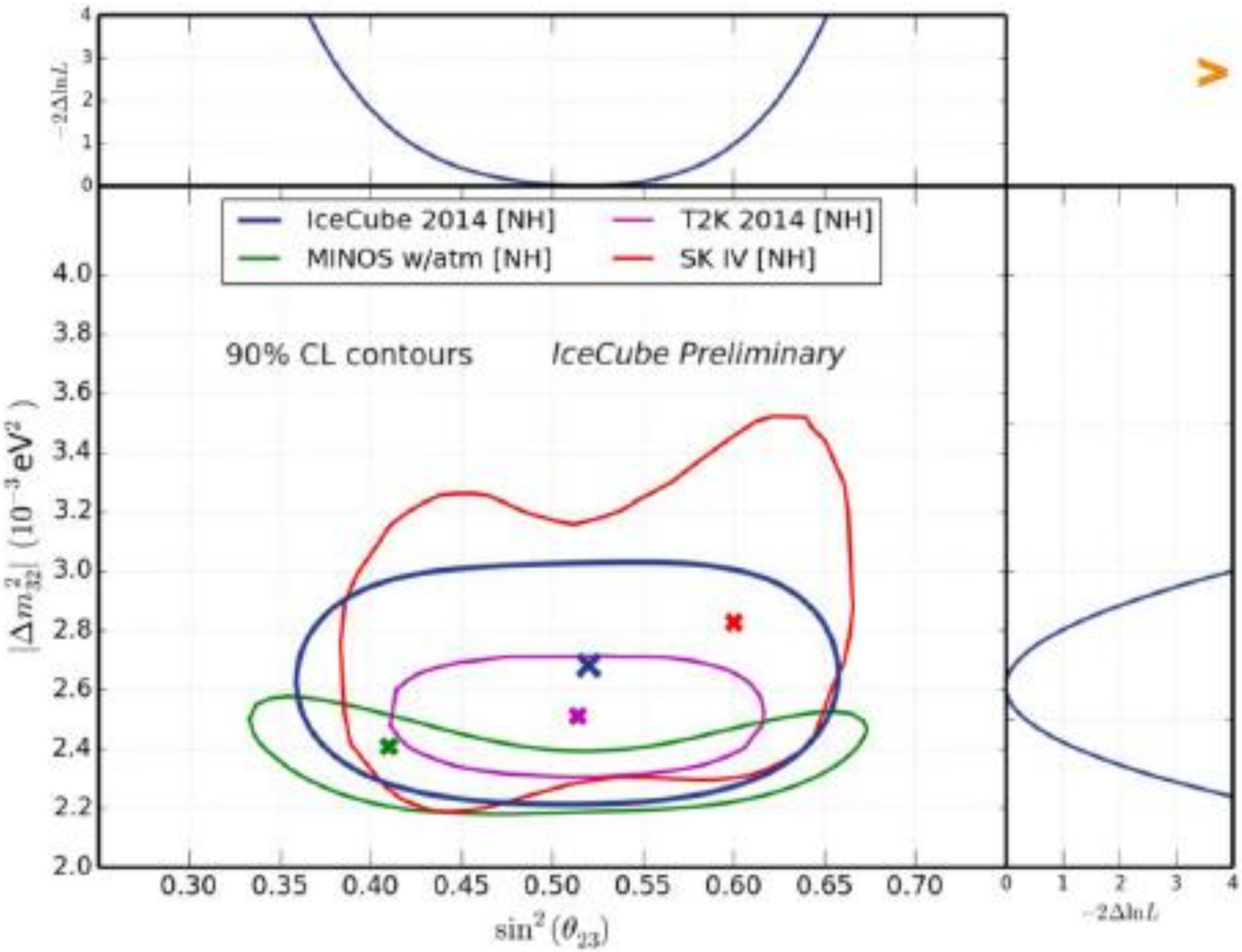
χ^2 = 45.5 / 56 dof

No preference for NH vs IH

1σ preference matter/vacuum

Parameter	Deviation at best fit
Flux at horizon	- 1 σ
Spectral index	+ 0.48 σ
ν_e deviation	- 0.62 σ
DOM eff.	+ 0.02 σ
Scattering in ice columns	+ 0.63 σ

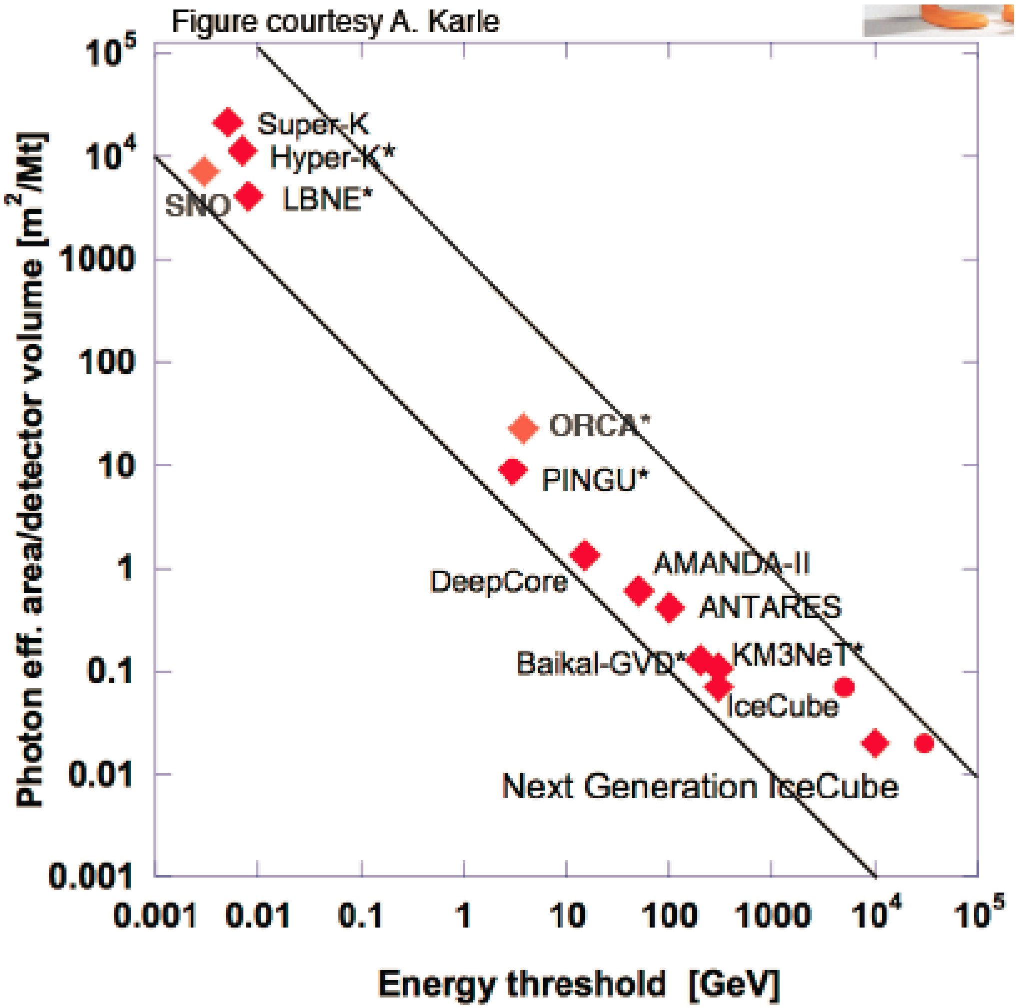
Already Very Competitive



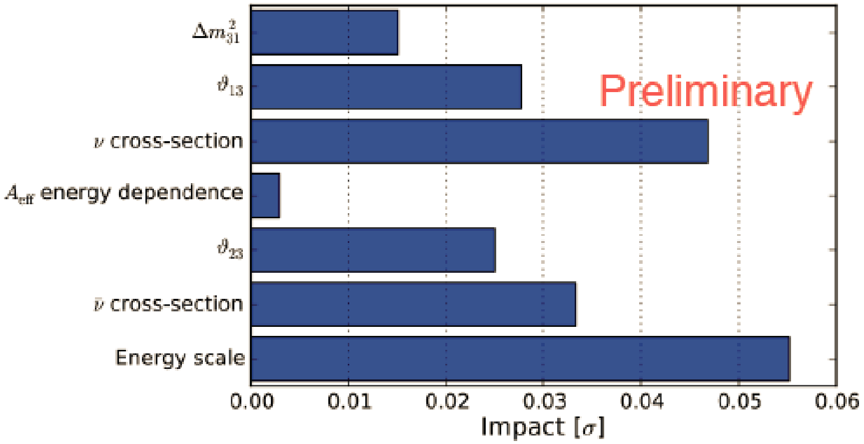
Future Experiments

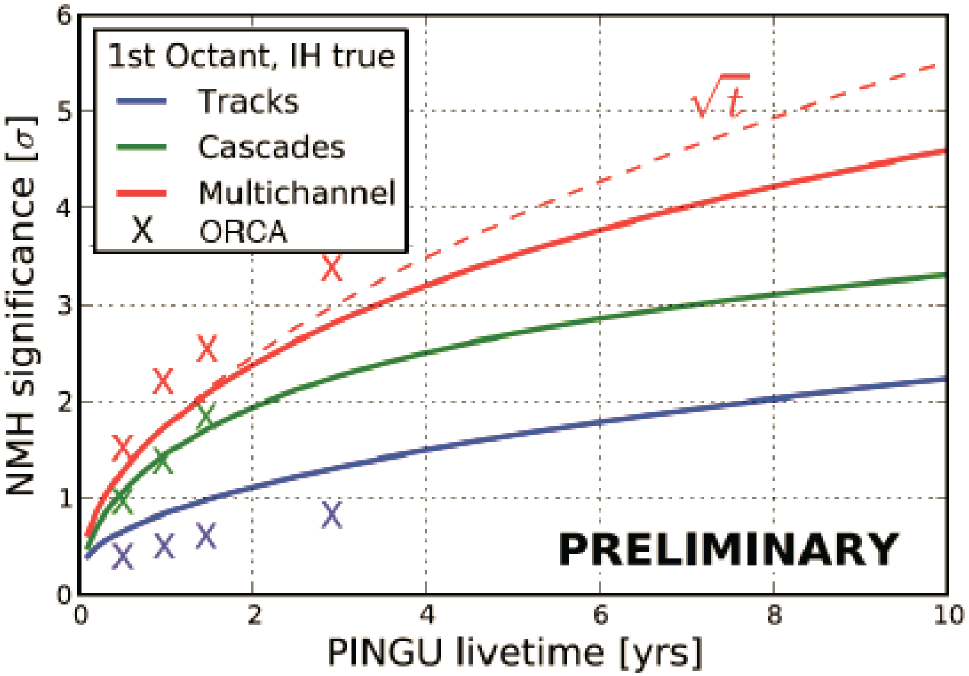
PINGU (& ORCA)

- A large ice(water) Cerenkov detector with E_{thresh}< 10 GeV
  - Adding 40 strings
  - ~ 20m string spacing
  - ~ 3-5 m DOM spacing
  - ~ 20× photocathode density
  - IceCube as the VETO
- Target mass: +10 Mt



PINGU (& ORCA)



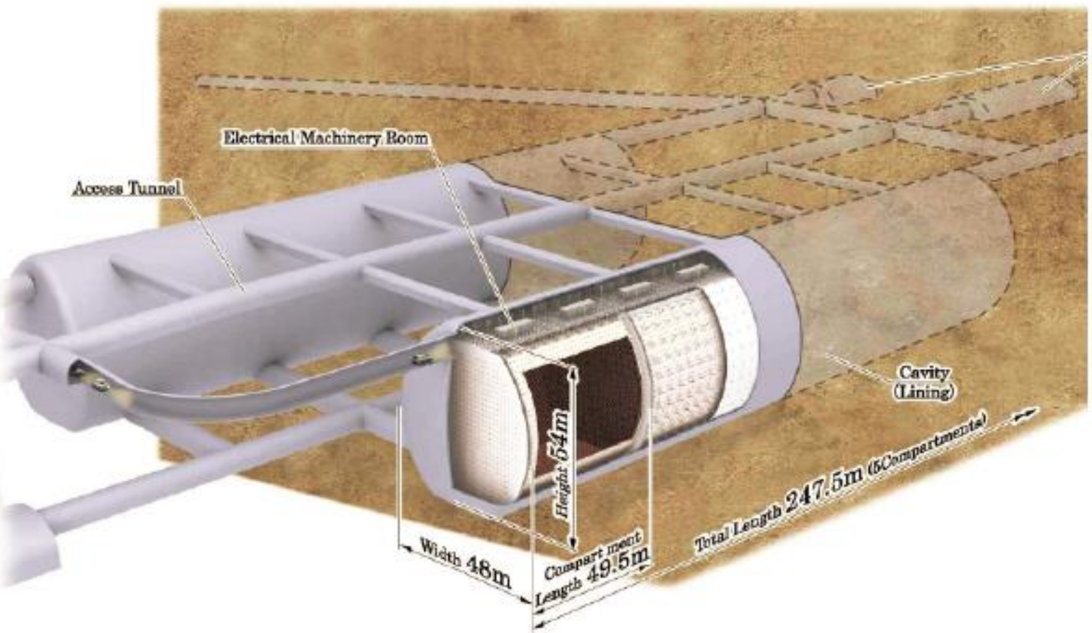


- **PINGU: determine MH at ~ 3σ level with ~3 years of data**
- **ORCA: similar**

Future experiment: HyperK

- **Water Cerenkov detector: 0.99 Mt in two caverns and 10 compartments**
- **Fiducial Volume: 0.56 Mt(0.056×10 compartments)**
- **99000 20” PMT for inner detector, 20% coverage**
- **25008 8” PMT for outer detector**

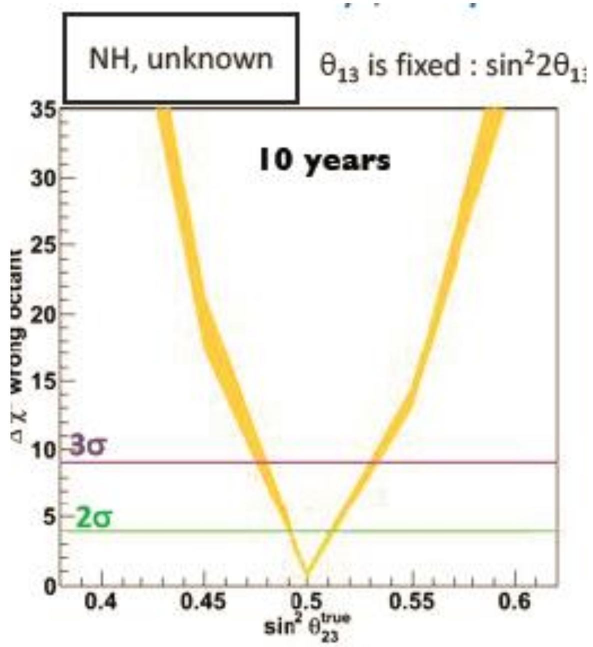
× 25 larger ν target & proton decay sources
× 50 for νCP to T2K

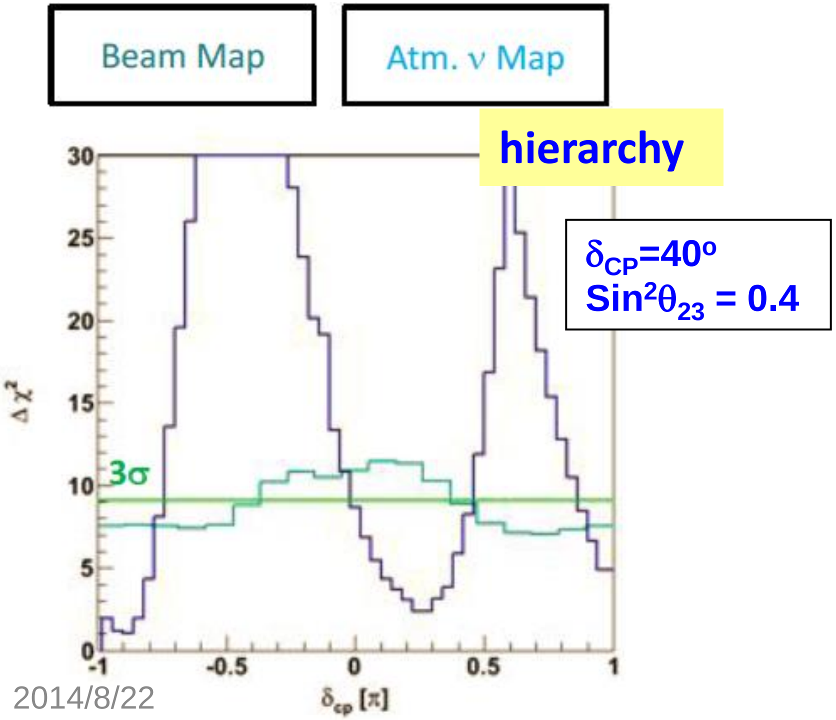


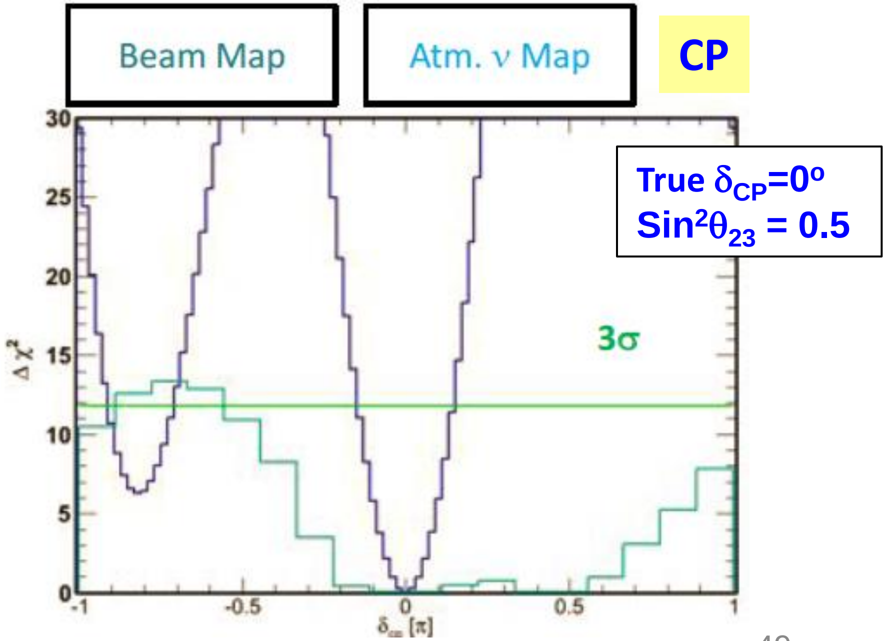
Wendell@HyperK open meeting 2012

Neutrino Physics

- Octant issue: $\Delta \sin^2\theta_{23}$ < 1%
- Mass hierarchy: ~ 3 σ for 10 years but T2HK much better

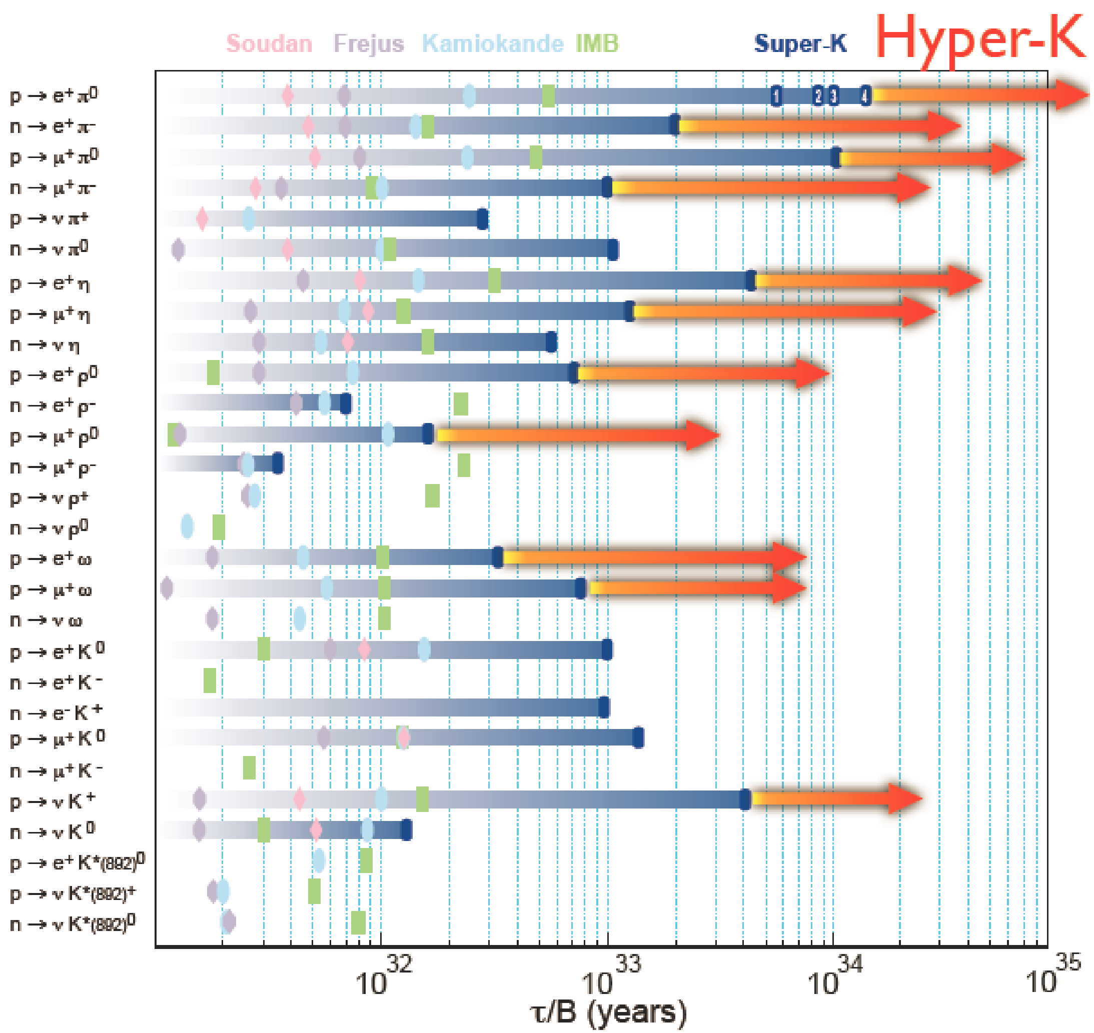






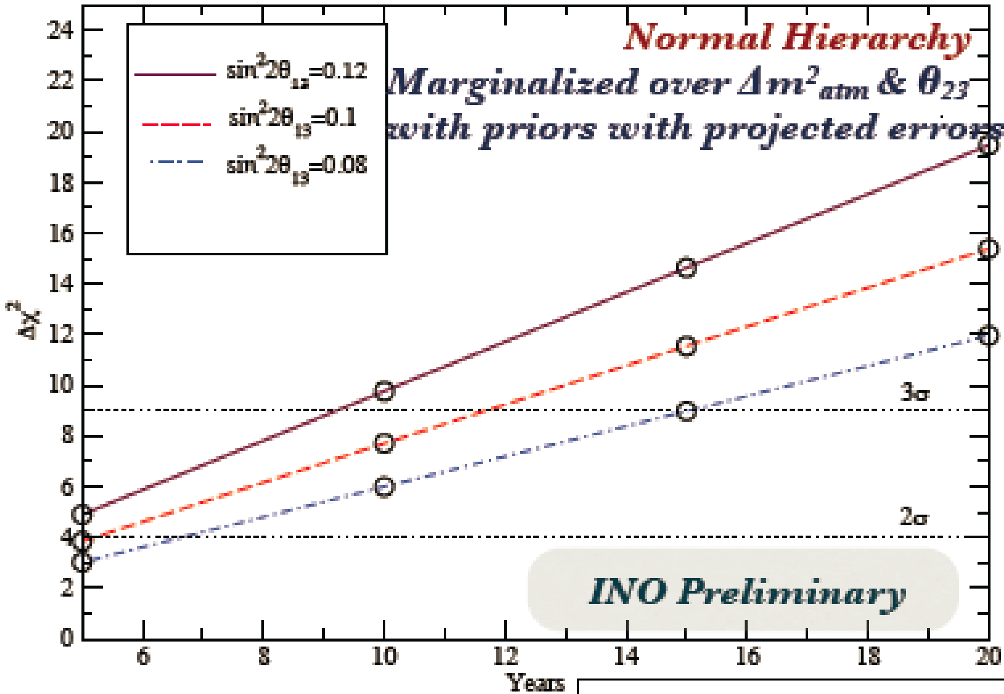
Other Physics at HyperK

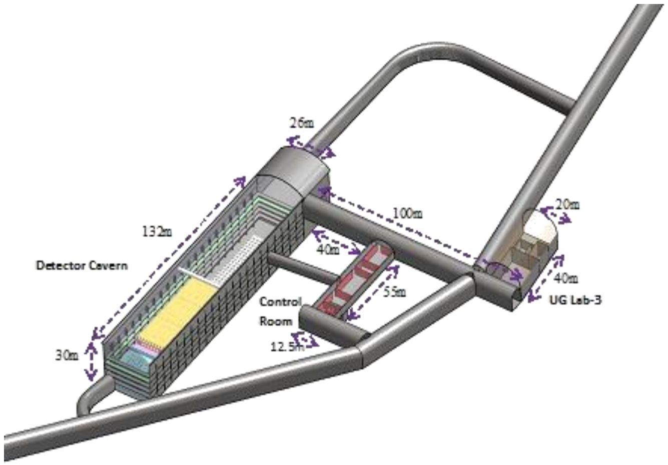
- **Supernova neutrinos**
  - ~ 200,000 events for SN@ 10 kpc
  - Relic SN neutrinos: several hundreds
- **Solar neutrinos**
- **Proton decays**
  - ~ 10 times better than SuperK
  - For example, P → $e^+ + \pi^0$: ~ 5.7×10^{34} years

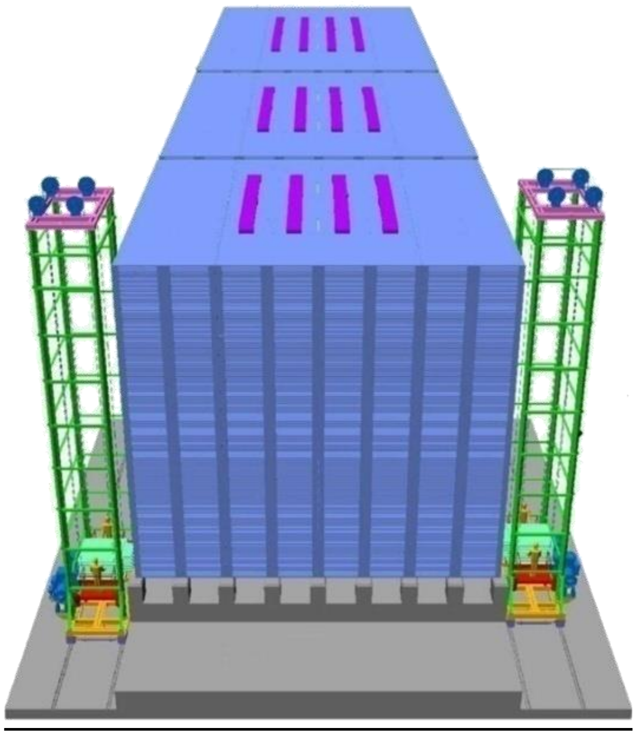


Future Experiment: INO

- INO(India-based Neutrino Observatory): 50kt magnetized iron plates interleaved with RPCs: **Sign sensitive**
- Construction started, operational: 2018
- Sensitivity to mass hierarchy: ~3σ after 10 years running







Choubey@neutrino'12

Summary

- Atmospheric neutrinos lead to the discovery of neutrino oscillation
- Neutrino mixing parameters, θ_{23} and ΔM^2_{32}, are determined by the SuperK, T2K & MINOS.
- IceCube is catching up
- Many future experiments for
  - Mass hierarchy
  - θ_{23}
  - CP phase
  - And proton decays, Supernova neutrinos, etc.