Atmospheric neutrinos with Super-Kamiokande

S.Mine (University of California, Irvine)
for Super-Kamiokande collaboration

An artist's impression of a cosmic ray interacting with the Earth's atmosphere. Jamie Yang

Neutrino oscillation

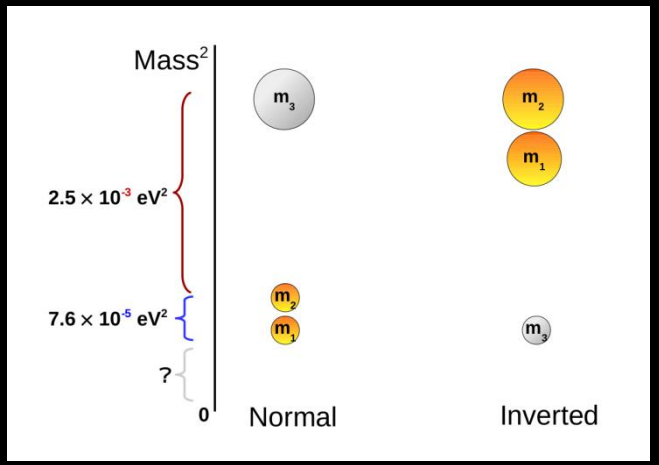
Three-neutrino mixing paradigm based on PMNS matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- 3 mixing angles, 2 mass splittings, 1 CP violating phase

- Remain unknown parameters
  - CP violation phase?
    - imbalance between matter and antimatter might be developed due to CPV on νs
  - Mass hierarchy?
    - unification of forces
    - determine whether neutrino is Majorana

http://www.hyper-k.org/en/physics/phys-hierarchy.html

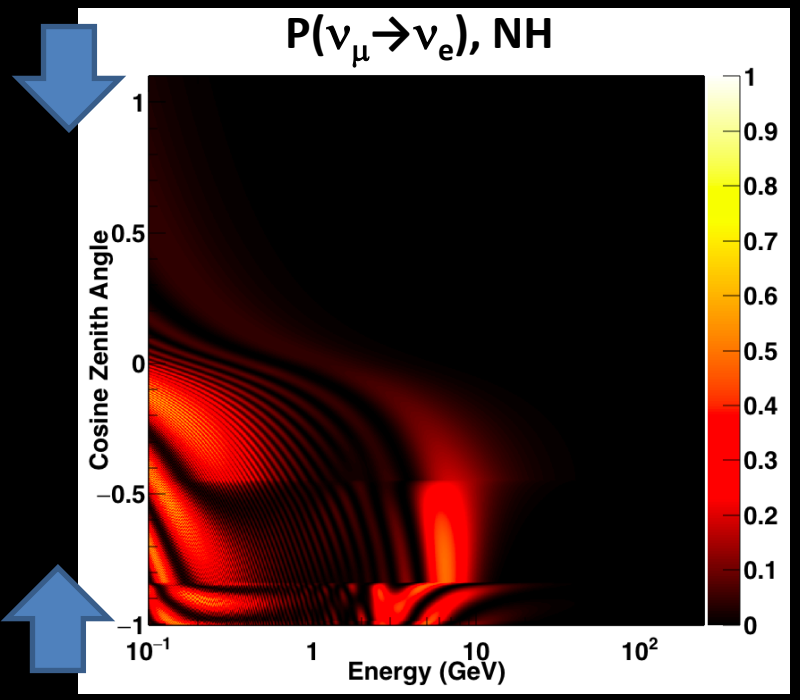


"NH" "IH"

See Carlo and Asaka-san's talks for detail

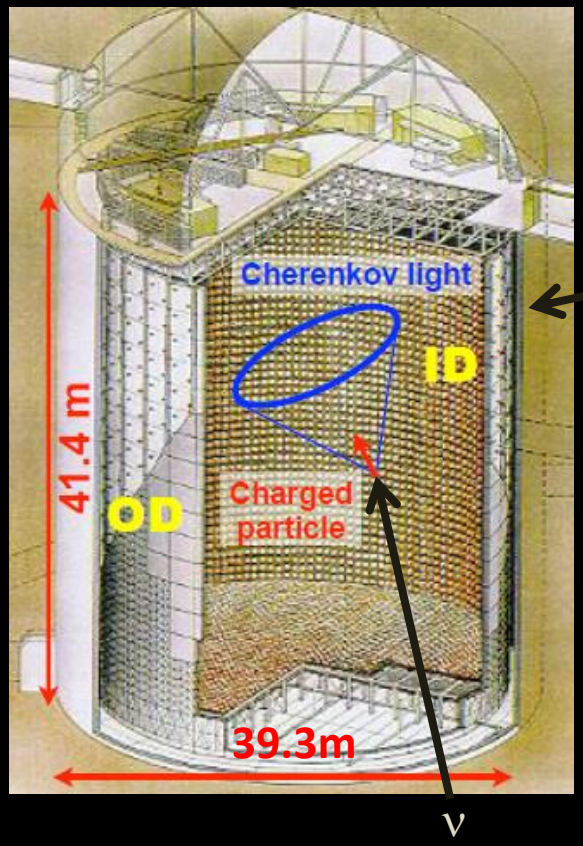
Atm.-ν oscillation analysis

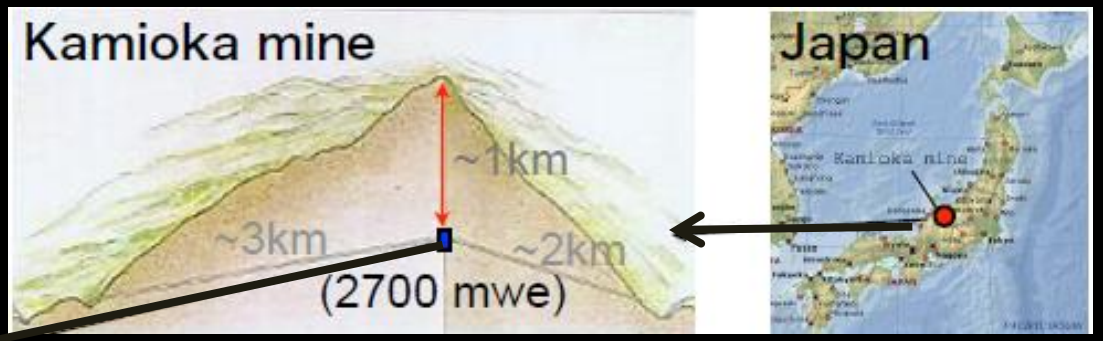
- Sensitive to unknown parameters of PMNS formalism
  - presence of neutrinos and antineutrinos
  - effects of matter
  - wide variety of energies and pathlengths
- Measurement of mass hierarchy
  - upward-going excess of either ν_e (NH) or anti-ν_e (IH) by θ_{13}-induced matter effects between 2 and 10 GeV
  - determining mass hierarchy and θ_{23} play important role to establish CPV
- This talk: *(paper in preparation)*
  - three-flavor ν oscillation analysis with external constraints
  - tau neutrino appearance
  - on-going studies for oscillation analyses



(for IH, matter effects appear in anti-ν)

Super-Kamiokande (SK)





Nucl. Instr.&Meth, A 737C(2014)

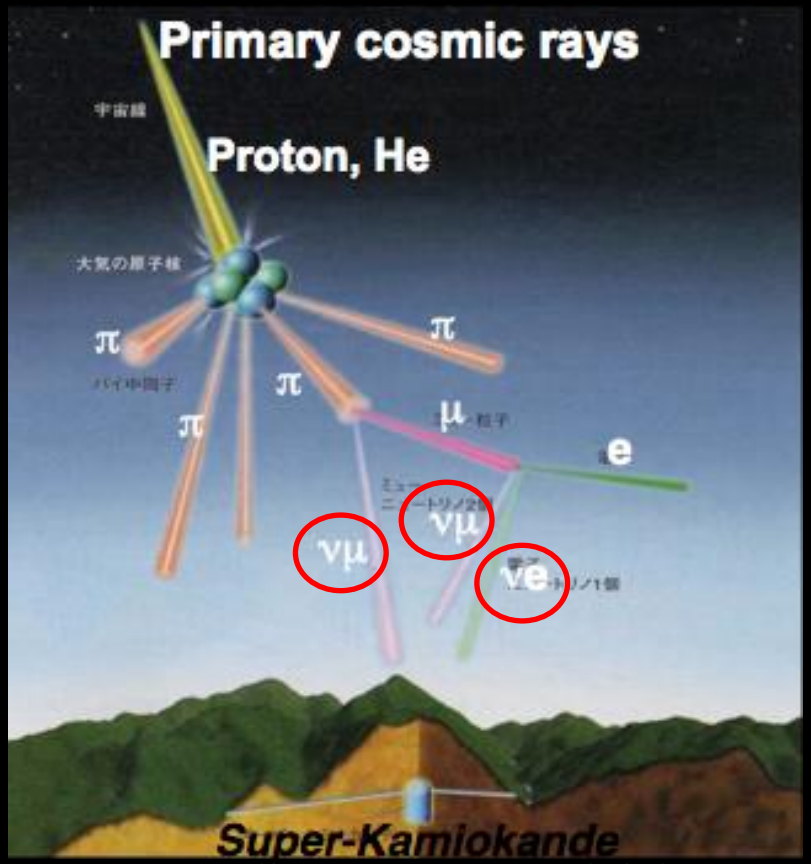
Phase		SK-I	SK-II	SK-III	SK-IV
Period	start	1996 Apr.	2002 Oct.	2006 Jul.	2008 Sep.
	end	2001 Jul.	2005 Oct.	2008 Sep.	(running)
Number of PMTs	ID (photo-coverage)	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)
	OD	1885			
Anti-implosion container		no	yes	yes	yes
OD segmentation		no	no	yes	yes
Front-end electronics		ATM (ID) OD QTC (OD)			QBEE

- SK total ~ 20 years

SK collaboration

- ~160 people
- ~40 institutes
- Japan, U.S., Korea, China, Poland, Spain, Canada, U.K., Italy, France

Atmospheric neutrinos

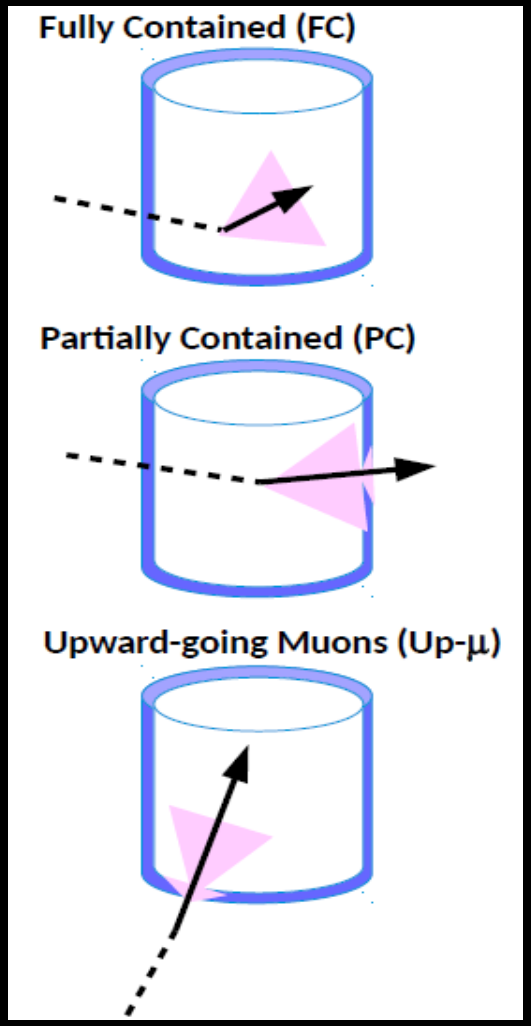


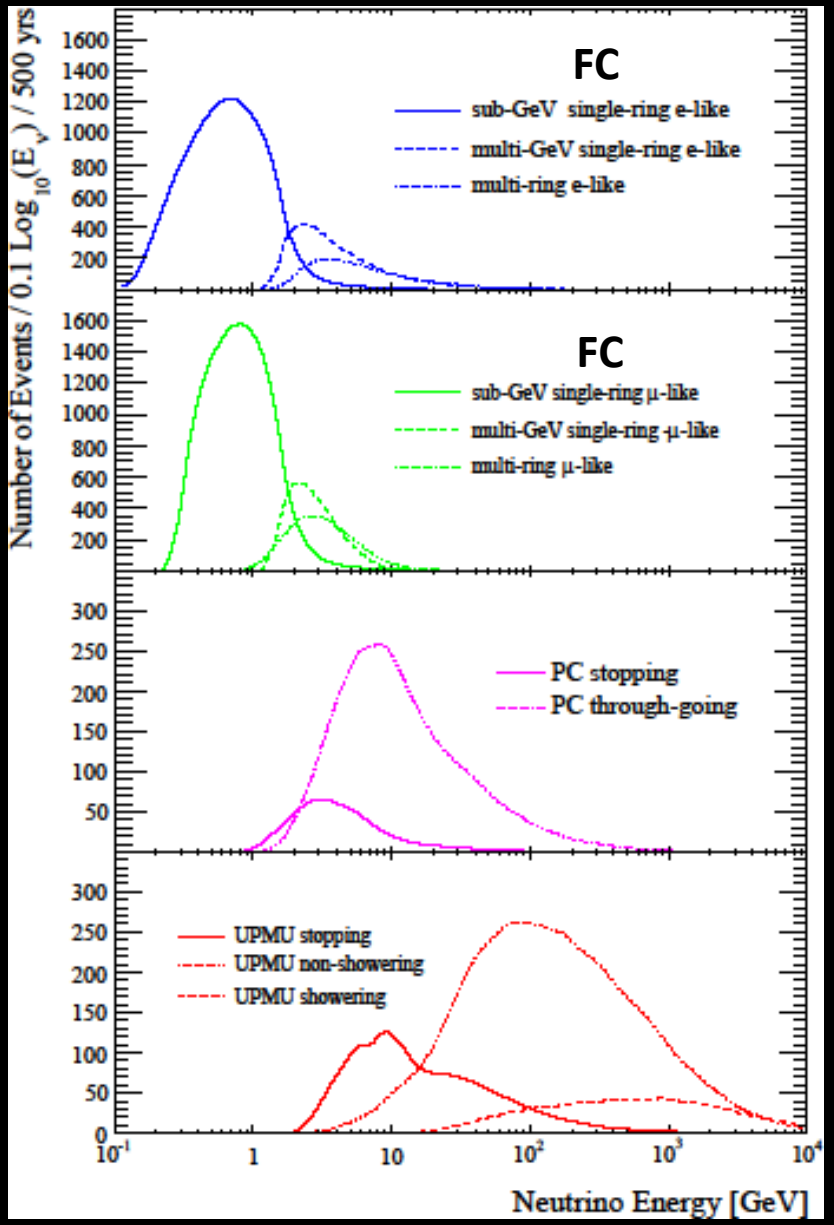
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/atmos.html

- Cosmic rays strike air nuclei and decay of hadrons gives νs
- νs travel length: 10-10,000km
- νs energy: 100MeV-10TeV
- Both νs and anti-νs

excellent tool for broad studies of neutrino oscillations

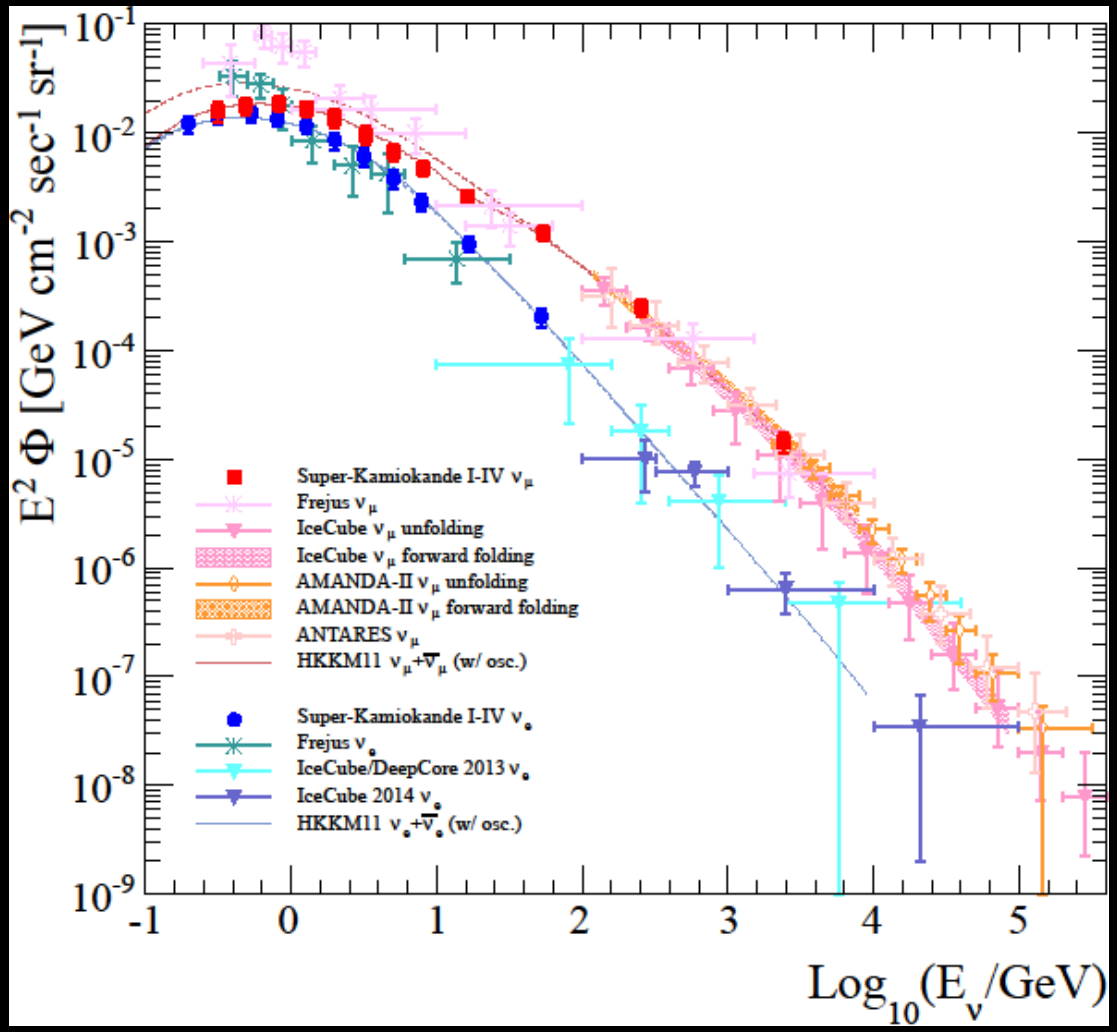
Neutrino true-energy for each subsample





Measured energy spectra of atm.-ν by SK

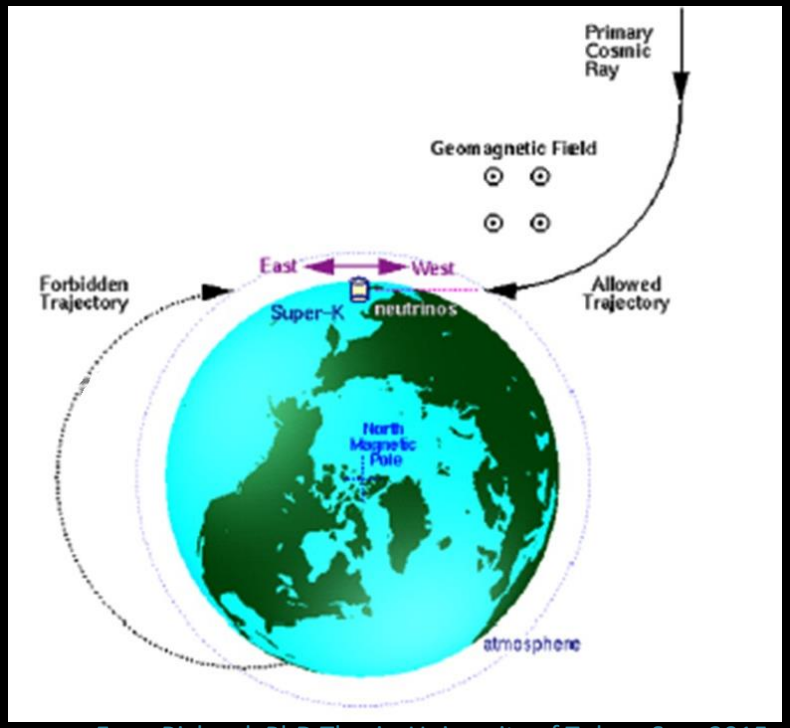
Phys. Rev. D94, 052001 (2016)



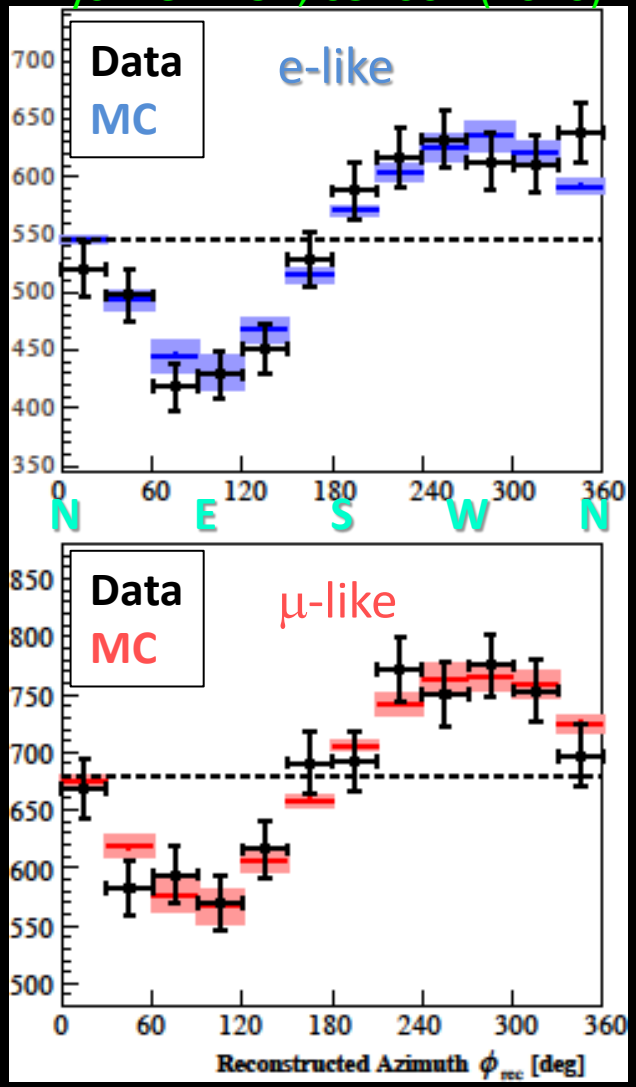
- PDG values of oscillation parameters as input

Measured azimuthal distributions of atm.-ν by SK

Phys. Rev. D94, 052001 (2016)

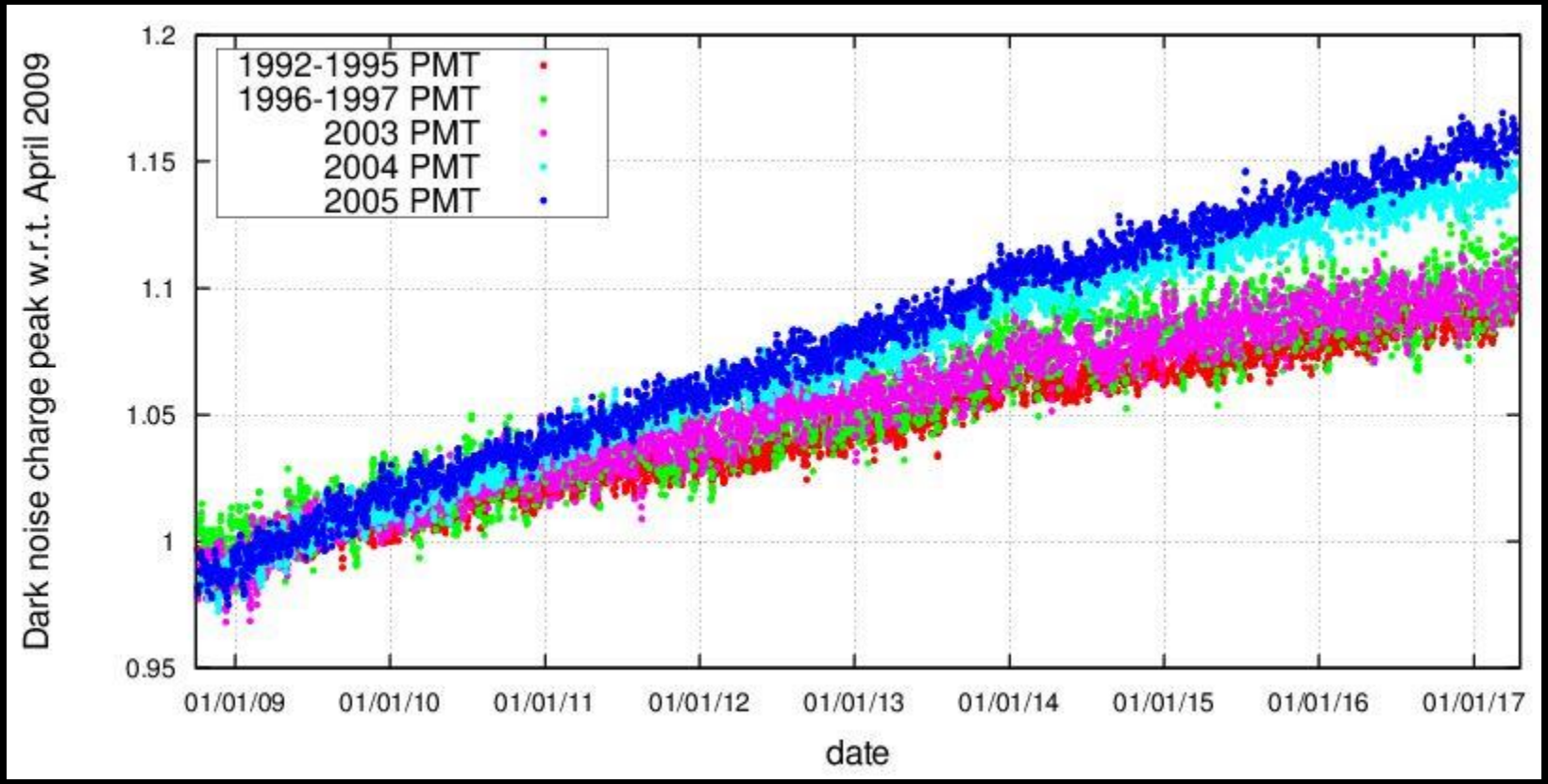


Euan Richard, PhD Thesis, University of Tokyo, Sep. 2015



(0.4<E_{rec}<3.0GeV, |cosθ_{rec}|<0.6)

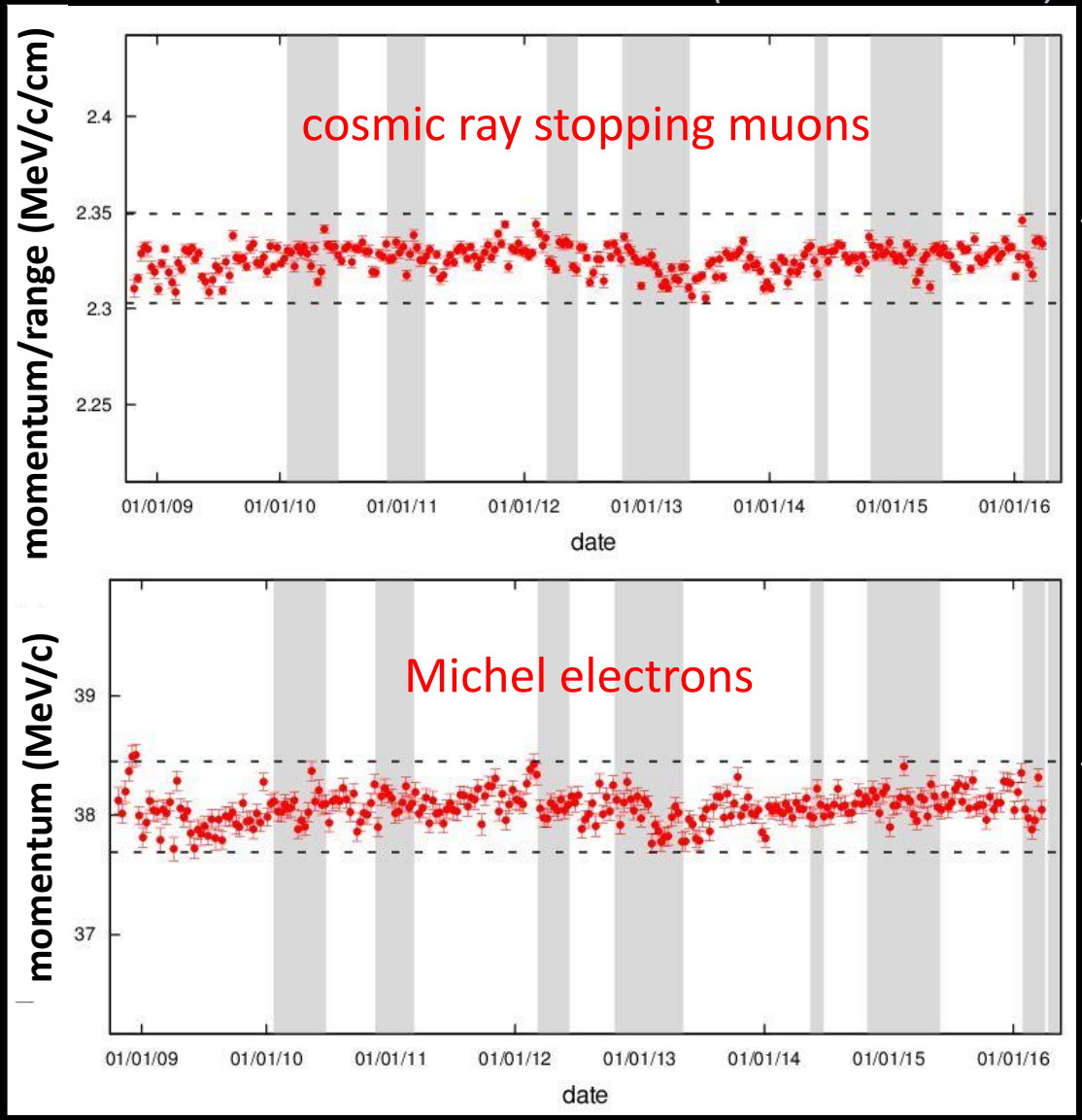
PMT gain time variation in SK-IV



- PMT production dependence implemented in event reconstruction in SK-IV

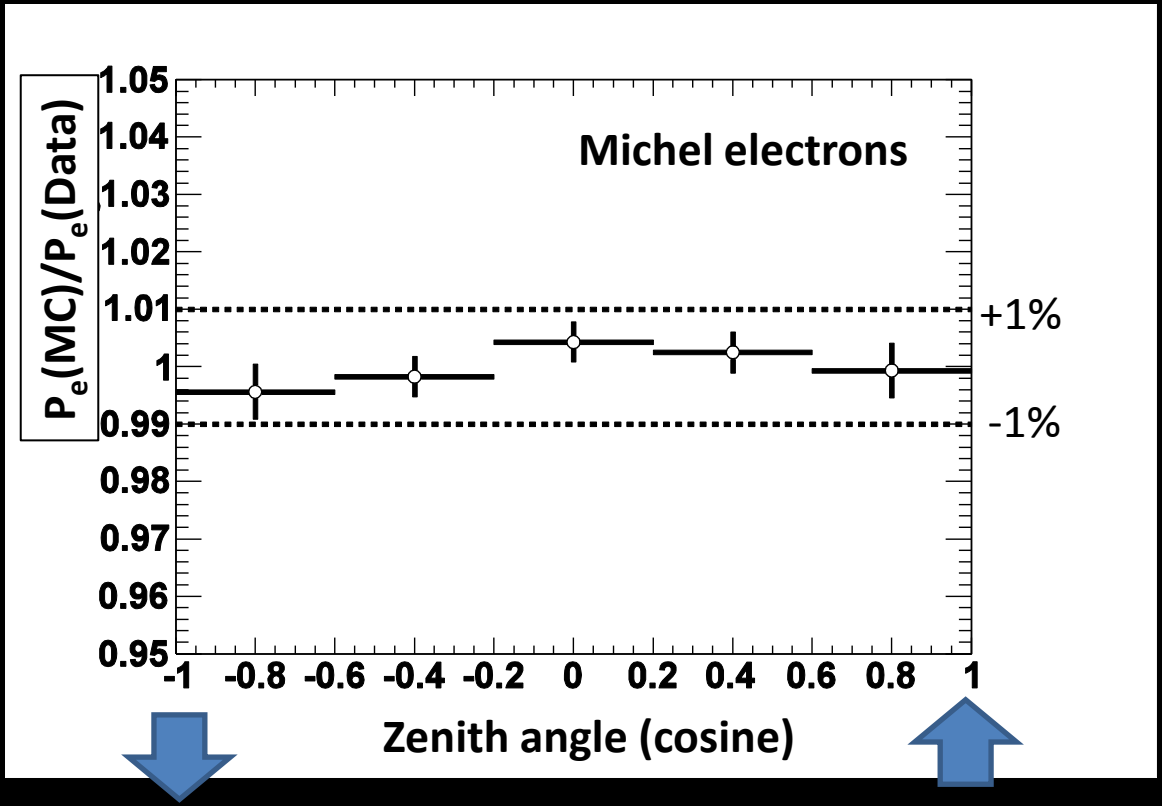
Momentum time variation in SK-IV

(bands: T2K ν beam)



- RMS/Mean: 0.36%

Momentum directional dependence in SK-IV



- largest deviation: 0.49%

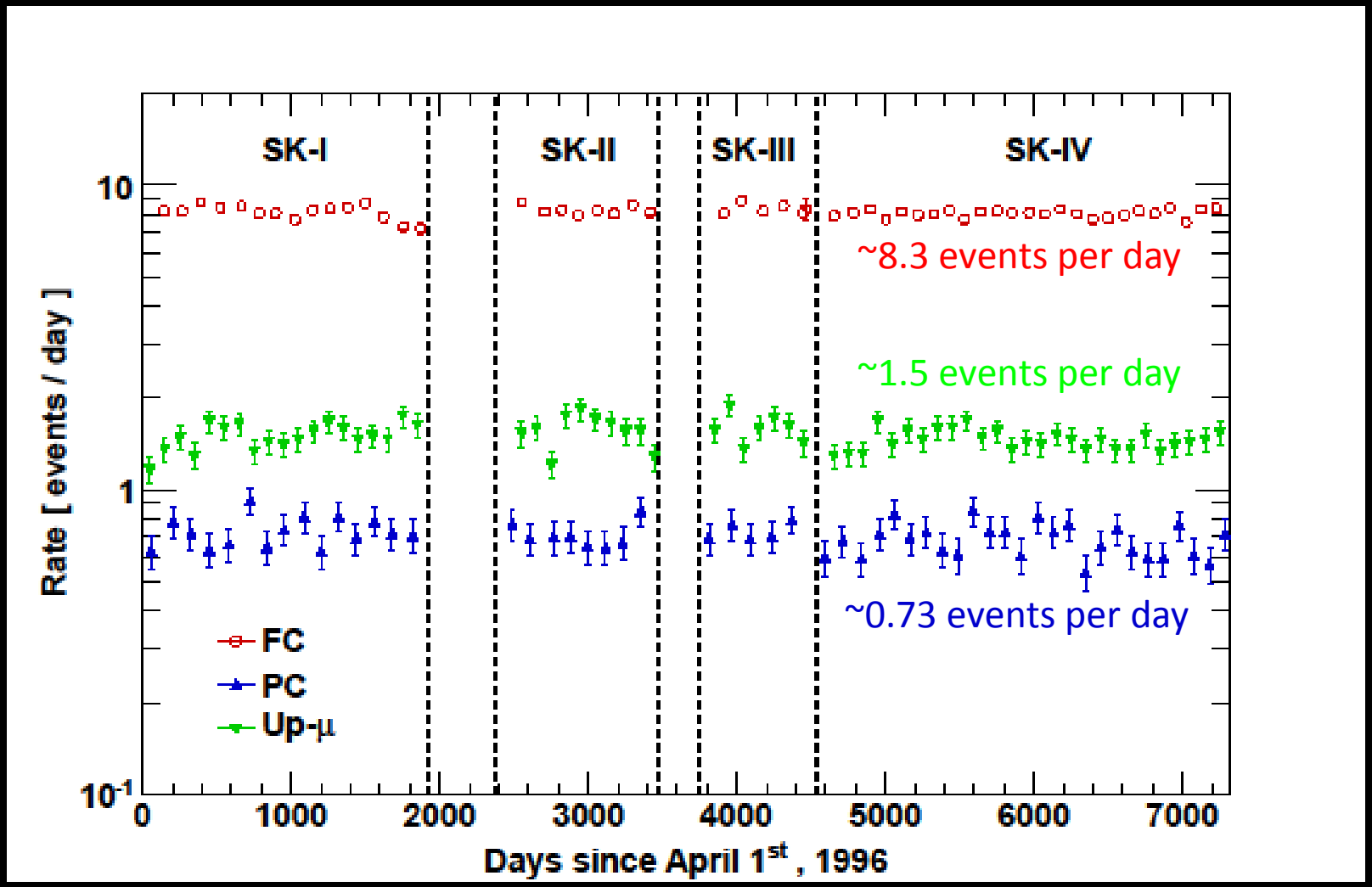
Energy scale error
(unit: %)

	SK-I	SK-II	SK-III	SK-IV
Absolute scale	3.13	2.70	1.62	2.08
Time variation	0.90	0.56	1.81	0.36
Total	3.26	2.76	2.42	2.11

	SK-I	SK-II	SK-III	SK-IV
Directional dependence	0.6	0.6	1.3	0.49

- Improved in SK-IV thanks to new PMT gain correction

Atm.-ν event rate

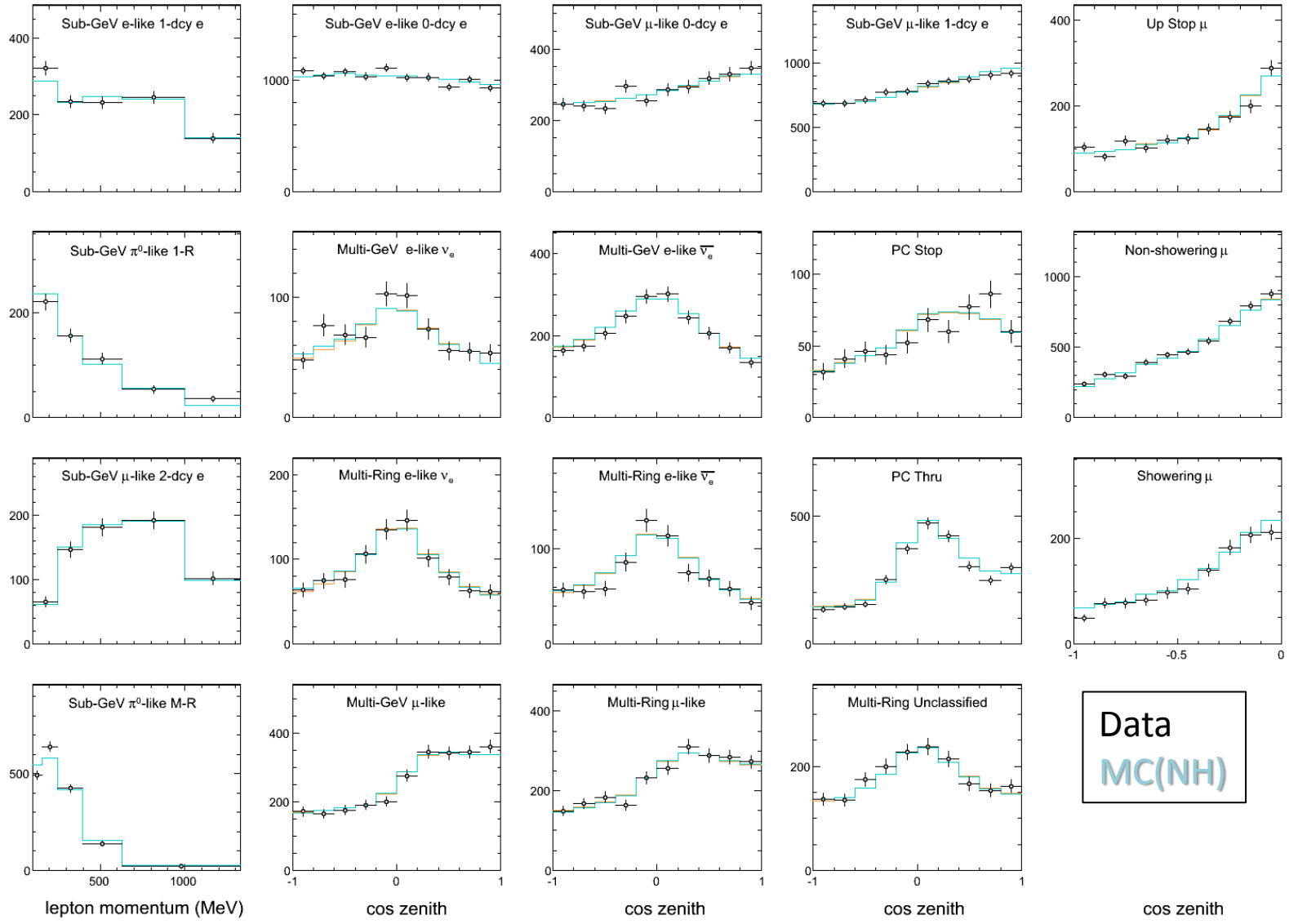


Zenith angle and momentum distributions

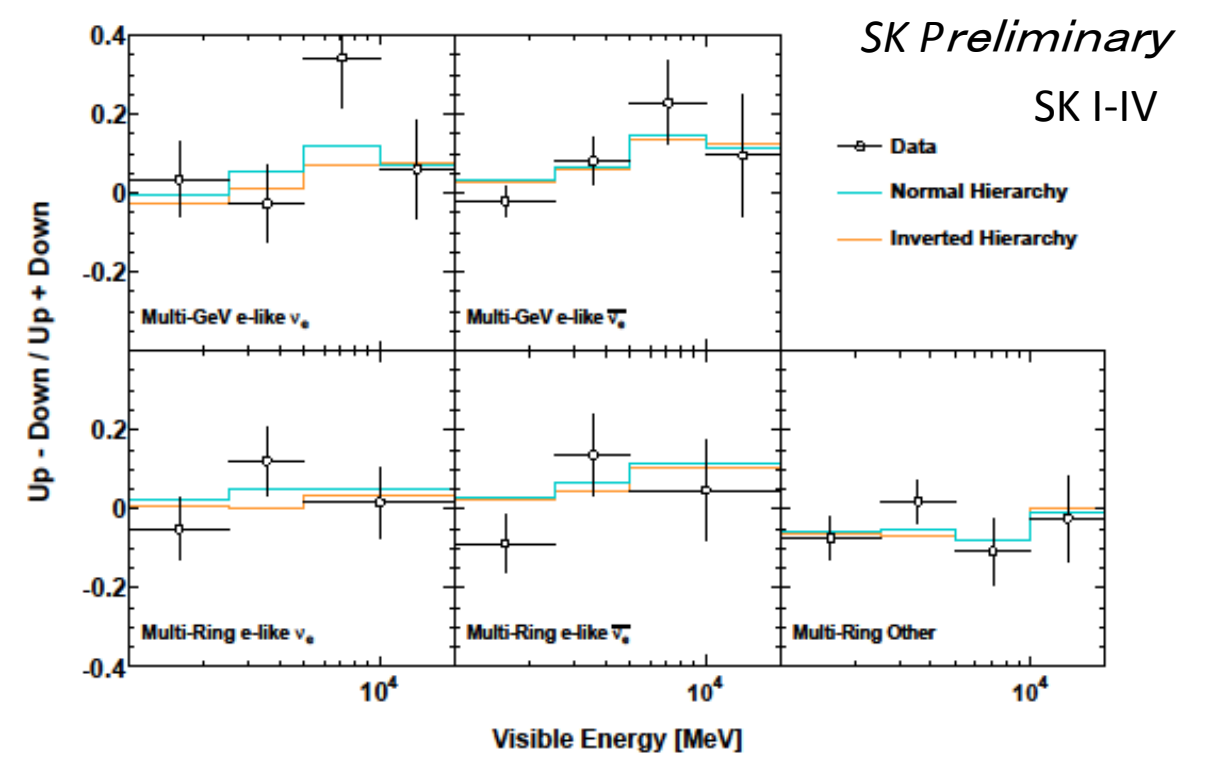
SK I-IV

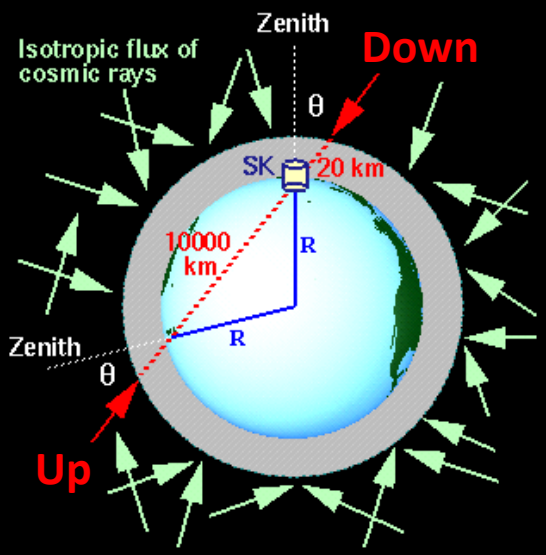
(19 analysis samples for 3-ν oscillation analysis)

SK Preliminary



Up ($\cos\theta<-0.4$) to Down ($\cos\theta>0.4$) ratio





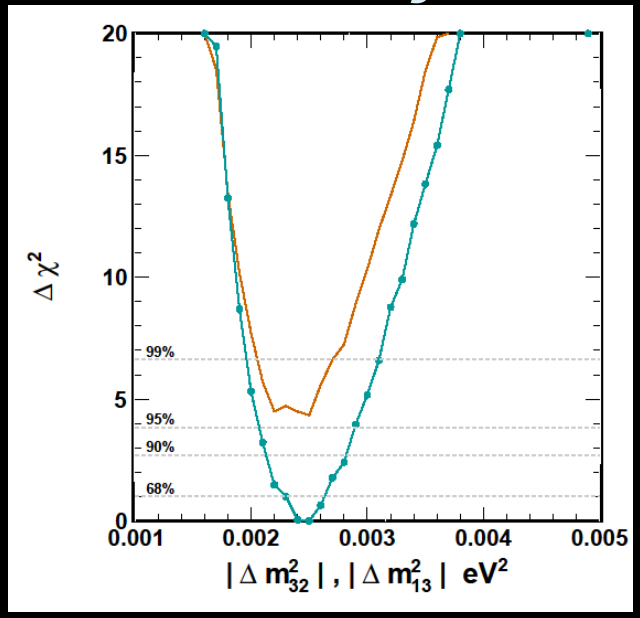
http://hep.bu.edu/~superk/atmnu/

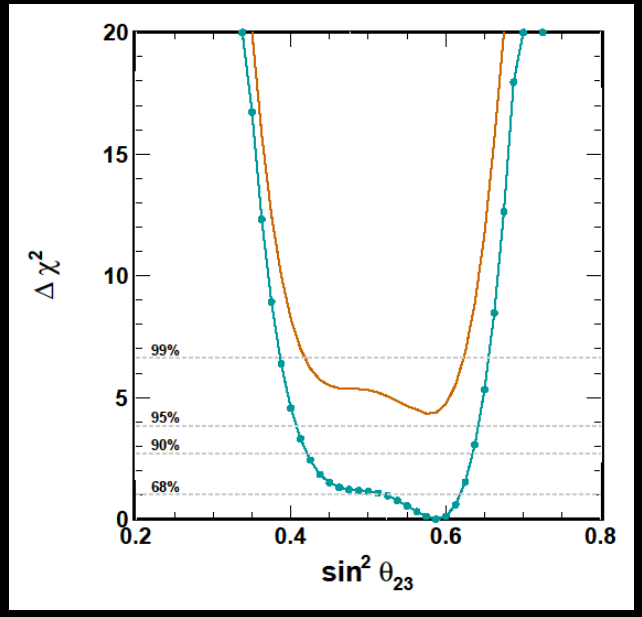
Constraints on ν oscillation parameters

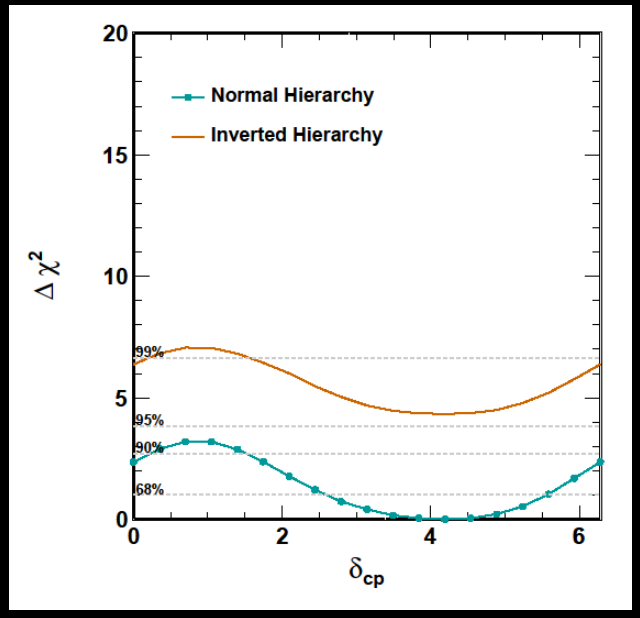
($\sin^2\theta_{13}$=0.219)

SK I-IV

SK Preliminary







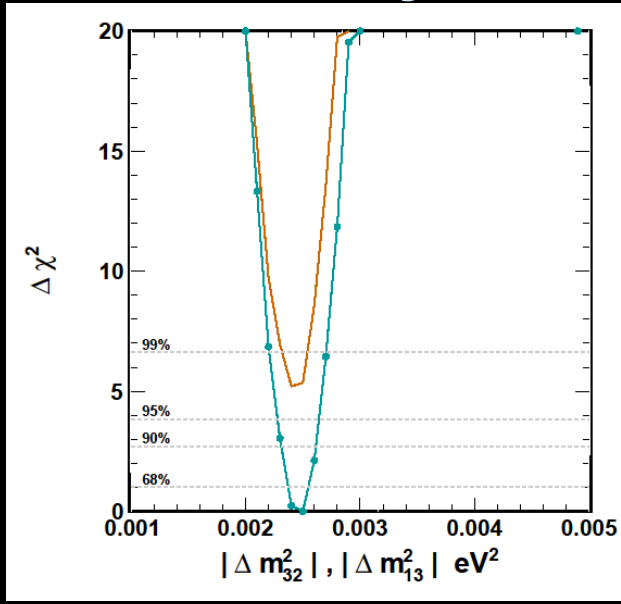
- $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$
- Under IH hypothesis, probability to obtain $\Delta\chi^2$ of -4.3 or less is 3.1%($\sin^2\theta_{23}$=0.6) and 0.7%($\sin^2\theta_{23}$=0.4). Under NH hypothesis, probability is 45%($\sin^2\theta_{23}$=0.6)

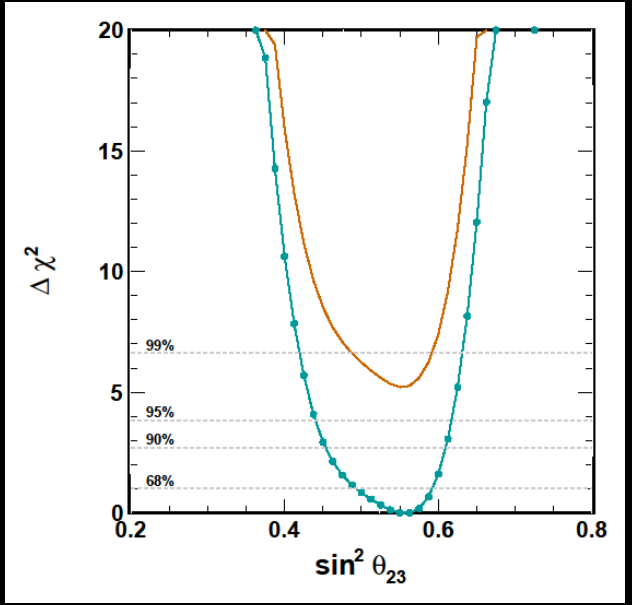
Constraints on ν oscillation parameters

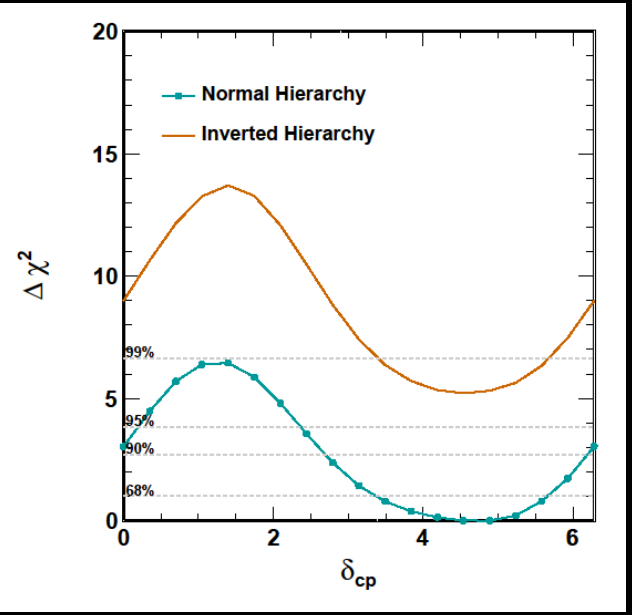
(sin²θ$_{13}$=0.219 and combined fit of SK and T2K)

SK I-IV

SK Preliminary







- SK has used *publicly available* information to model and fit T2K experiment* together with atmospheric neutrinos

*6.57x10^{20}pot(ν)

- $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$
- Under IH hypothesis, probability is 2.4%(sin²θ$_{23}$=0.6) and 0.1%(sin²θ$_{23}$=0.4). Under NH hypothesis, probability is 43%(sin²θ$_{23}$=0.6)

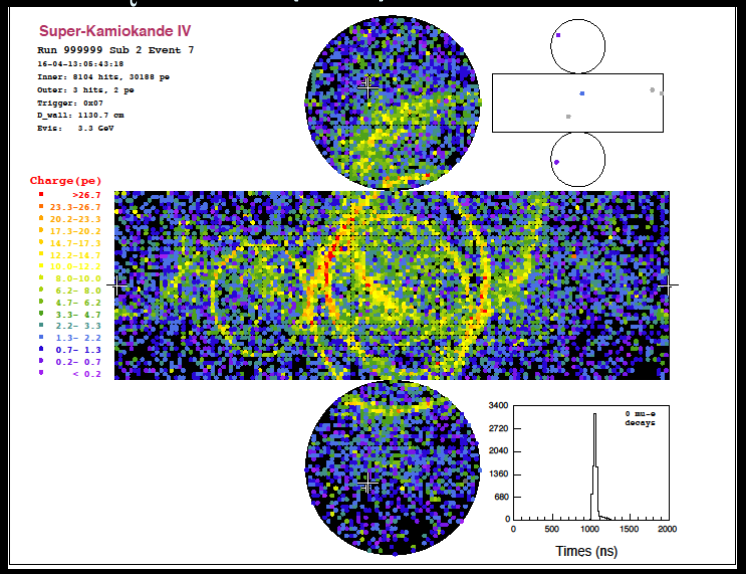
Measurement of atm.-ν_τ appearance

- Direct detection of ν_τs for confirmation of three-flavor oscillations
- Energy thre. for CC ν_τ int.: 3.5GeV
- Not possible to directly detect τs due to short life time
- Difficult to distinguish multi-ring BKG events (multi-π/DIS) from τ signal
- We apply multivariate method to statistically identify CC ν_τ events. Inputs:
  - visible energy
  - # Michel electrons
  - etc.

τ decay modes

Decay mode	Branching ratio (%)
$e^-\bar{\nu}_e\nu_\tau$	17.83
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41
$\pi^-\nu_\tau$	10.83
$\pi^-\pi^0\nu_\tau$	25.52
$3\pi\nu_\tau$	18.29
others	10.12

CC ν_τ event (MC)

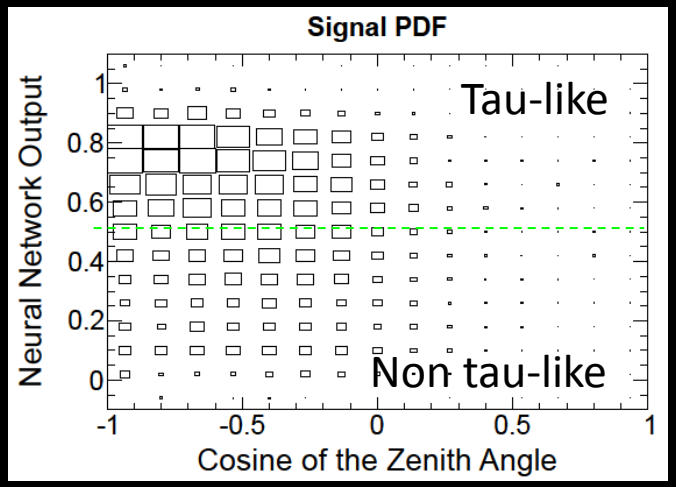


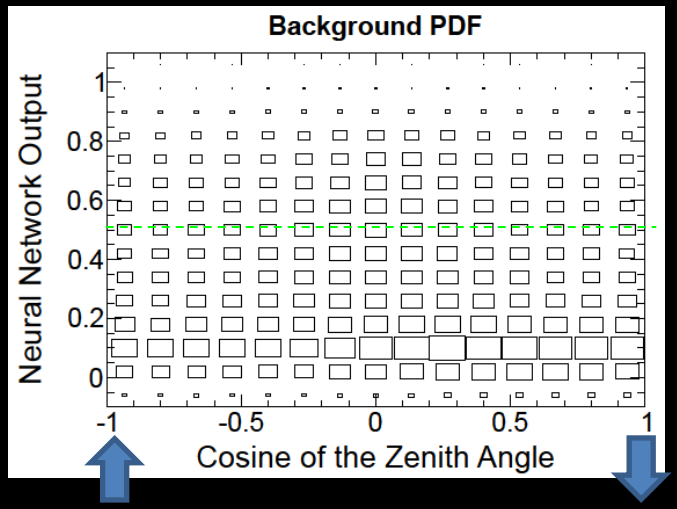
$$Data = PDF_{BG} + \alpha \times PDF_{tau} + \sum \epsilon_i \times PDF_i$$

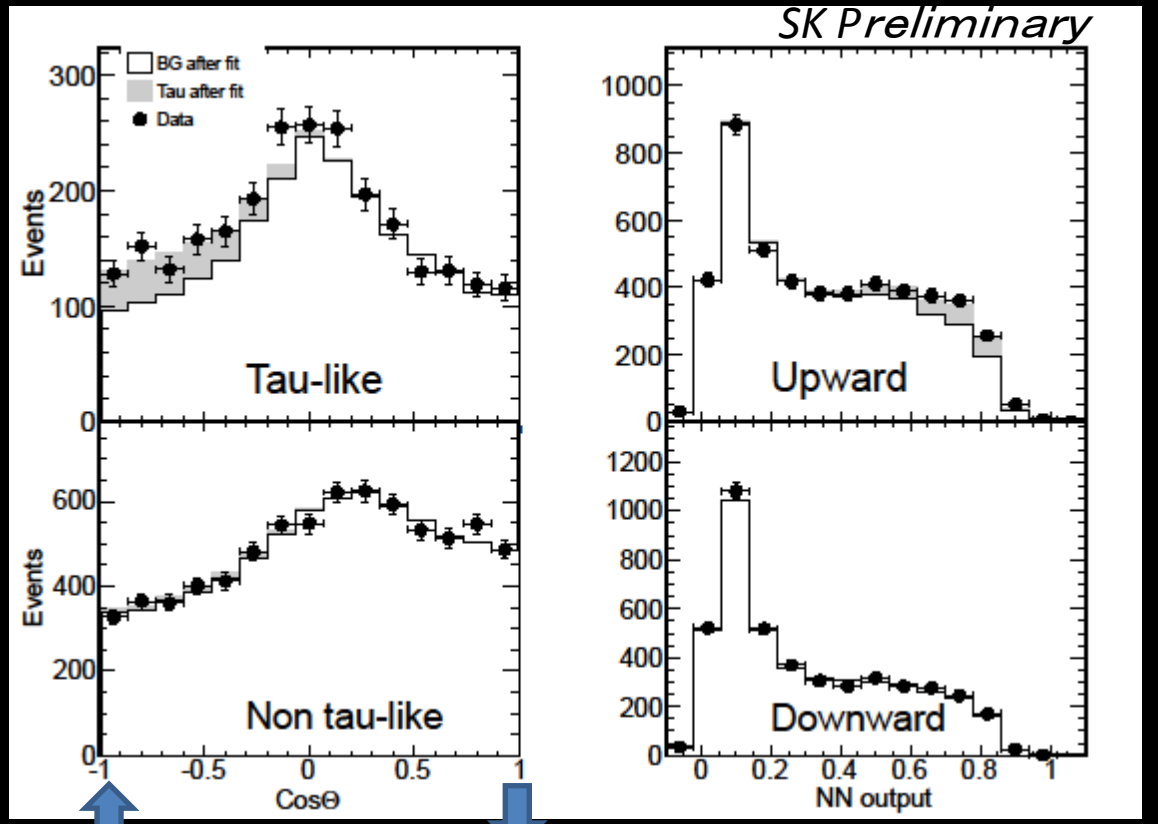
α = 1.47±0.32(stat.+syst.)

SK I-IV: 5,326d
(SK-IV: 2,520d)

- 4.6σ of rejection hypothesis of no τ appearance
- dominated by statistical uncertainty



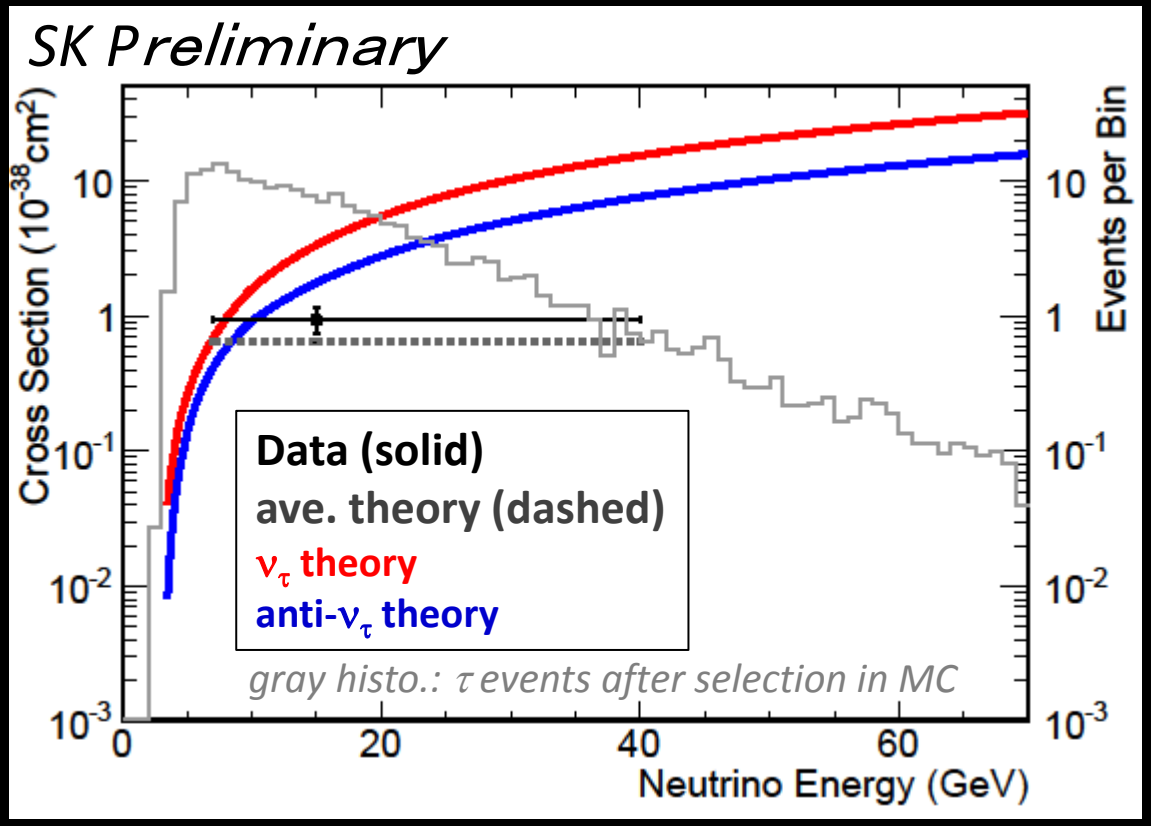




- suppressing τ background would improve hierarchy measurement

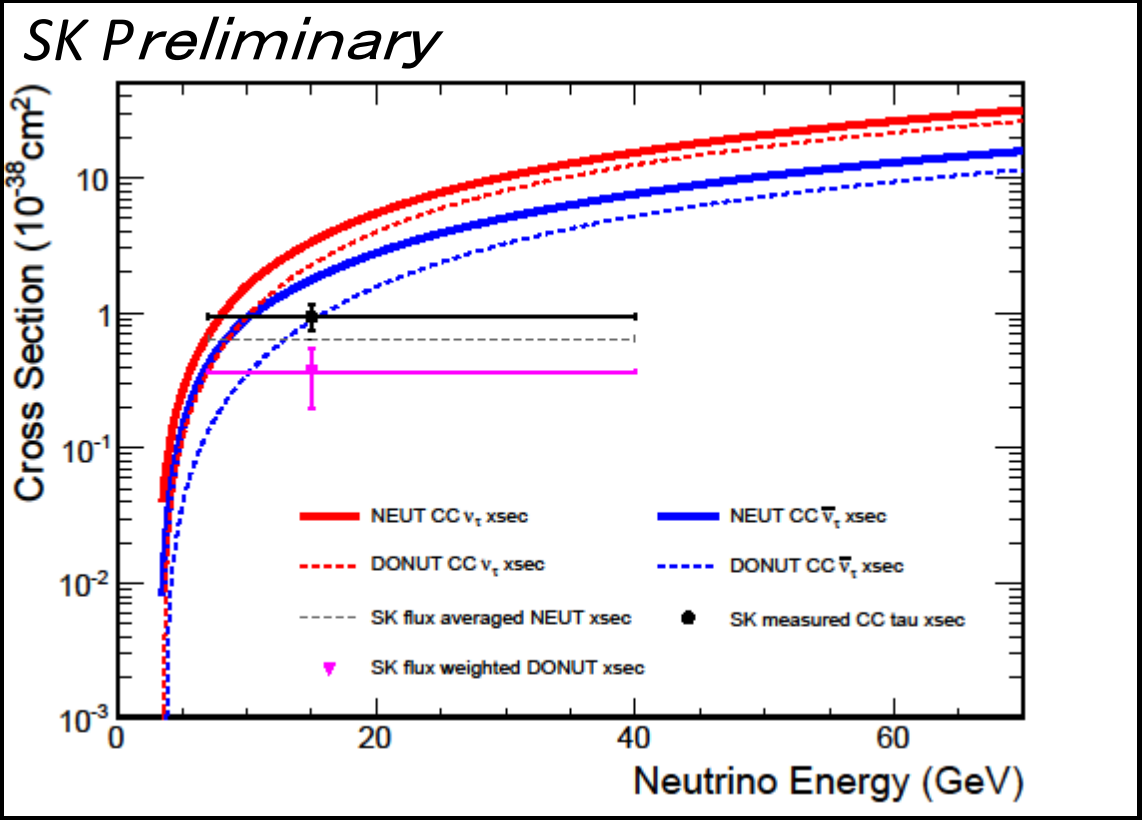
Measured fluxed averaged CC ν_τ cross section

$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$



- $(0.94 \pm 0.20) \times 10^{-38}$cm^2 for ν energy at 3.5-70GeV

Comparison with DONUT



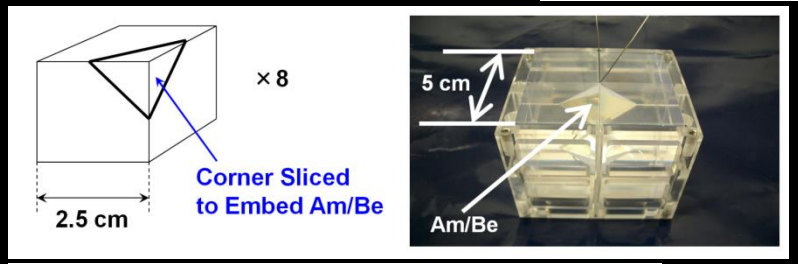
DONUT results converted to differential cross section and weighted by SK flux

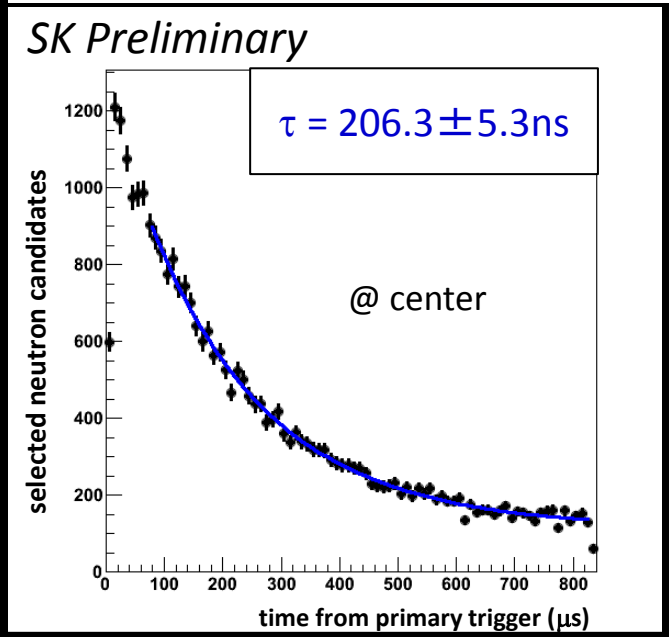
- SK result is larger than DONUT because of difference in ν energies
  - DONUT measured DIS cross section
  - CCQE & CC coherent production contribute to SK

Neutron tag in SK-IV

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*} + n$$
$${}^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma\ (4.43\ \mathrm{MeV})$$
or
$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$$

- Atm.-ν interactions frequently accompanied by n production
- n + p → d + γ(2.2MeV)
- γ hit search enabled by QBEE
  - signal ε: 20.5% *(~80% with Gd)*
- Already implemented in nucleon decay searches
  ex.) ~50% BKG rejection for $p \rightarrow e\pi^0$ search
- Studies on-going to improve sensitivities on ν oscillation analyses with n-tag

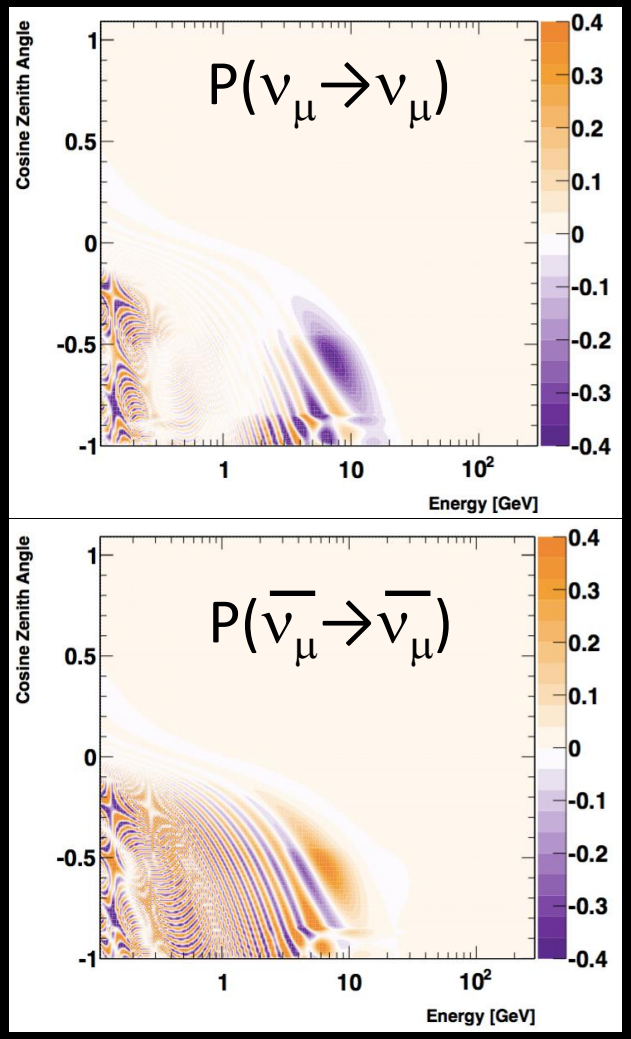




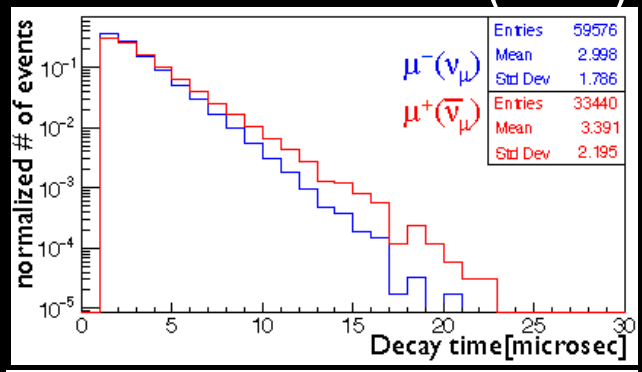
$\nu_\mu/\bar{\nu}_\mu$ separation

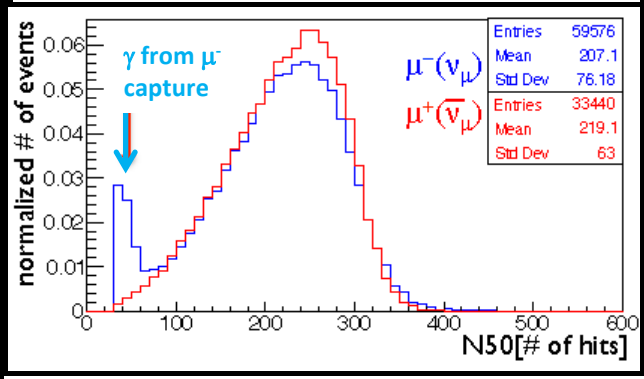
(on-going study)

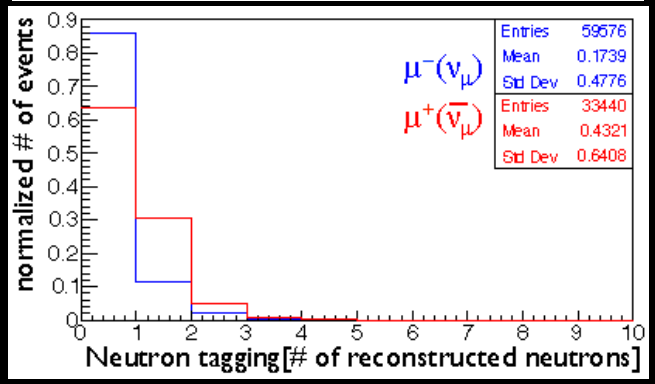
NH - IH



Atm.-ν MC (SK-IV)



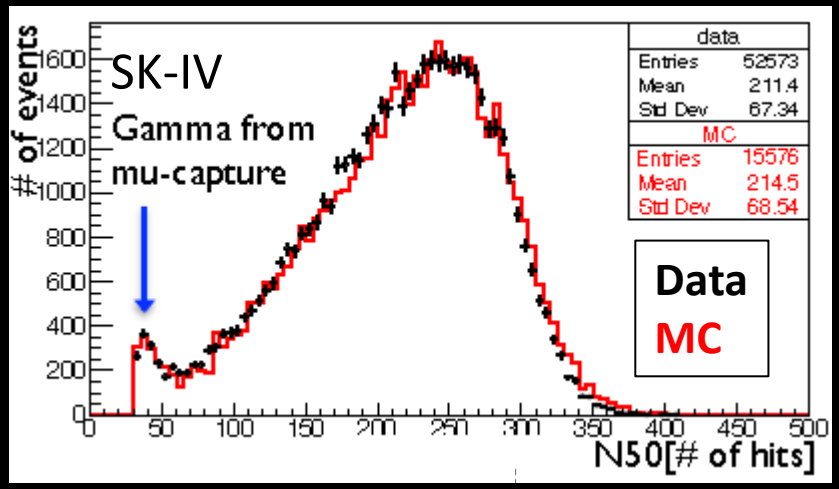




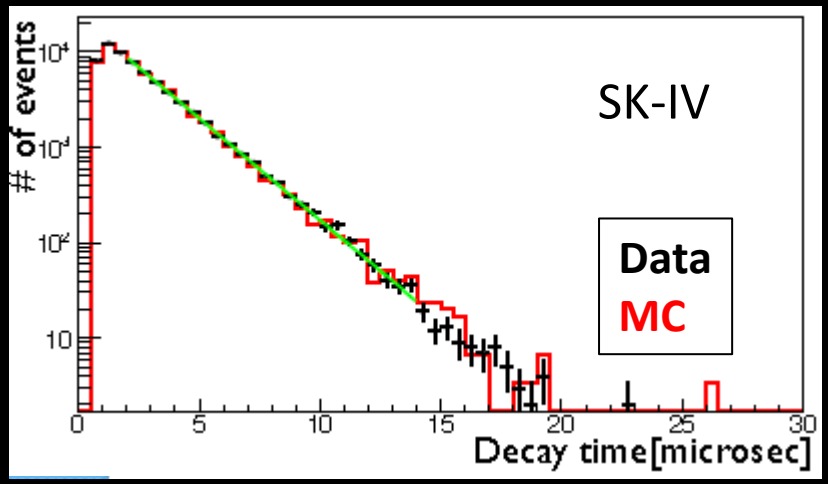
(N50: #hits in 50ns sliding window. NOT momentum)

Michel electrons from cosmic ray muons

SK Preliminary



(N50: #hits in 50ns sliding window. NOT momentum)



τ = { 2.057±0.009μs (Data)
2.042±0.009μs (MC)

(μ^+/μ^- = 1.37 @ Kamioka)

Summary

- Atmospheric neutrino oscillation analyses
  - weakly favoring normal hierarchy
    - χ^2(NH)-χ^2(IH)=-4.3(SK,θ_{13} fix), -5.2(SK+T2K,θ_{13} fix)
  - tau neutrino appearance: significance of signal 4.6σ
    - CC ν_τ cross section: (0.94±0.20)×10^{-38}cm^2 at 3.5-70GeV

(paper in preparation)

- Prospects
  - updated constraints from T2K
  - neutron tag
  - incorporate tau likelihood
  - μ^+/μ^- likelihood
  - other analysis improvements