Measurement of Atmospheric Neutrino Flux by Super-Kamiokande: energy spectra, geomagnetic effect, and solar modulation

Kimihiro Okumura
okumura@icrr.u-tokyo.ac.jp

Institute for Cosmic Ray Research (ICRR), University of Tokyo

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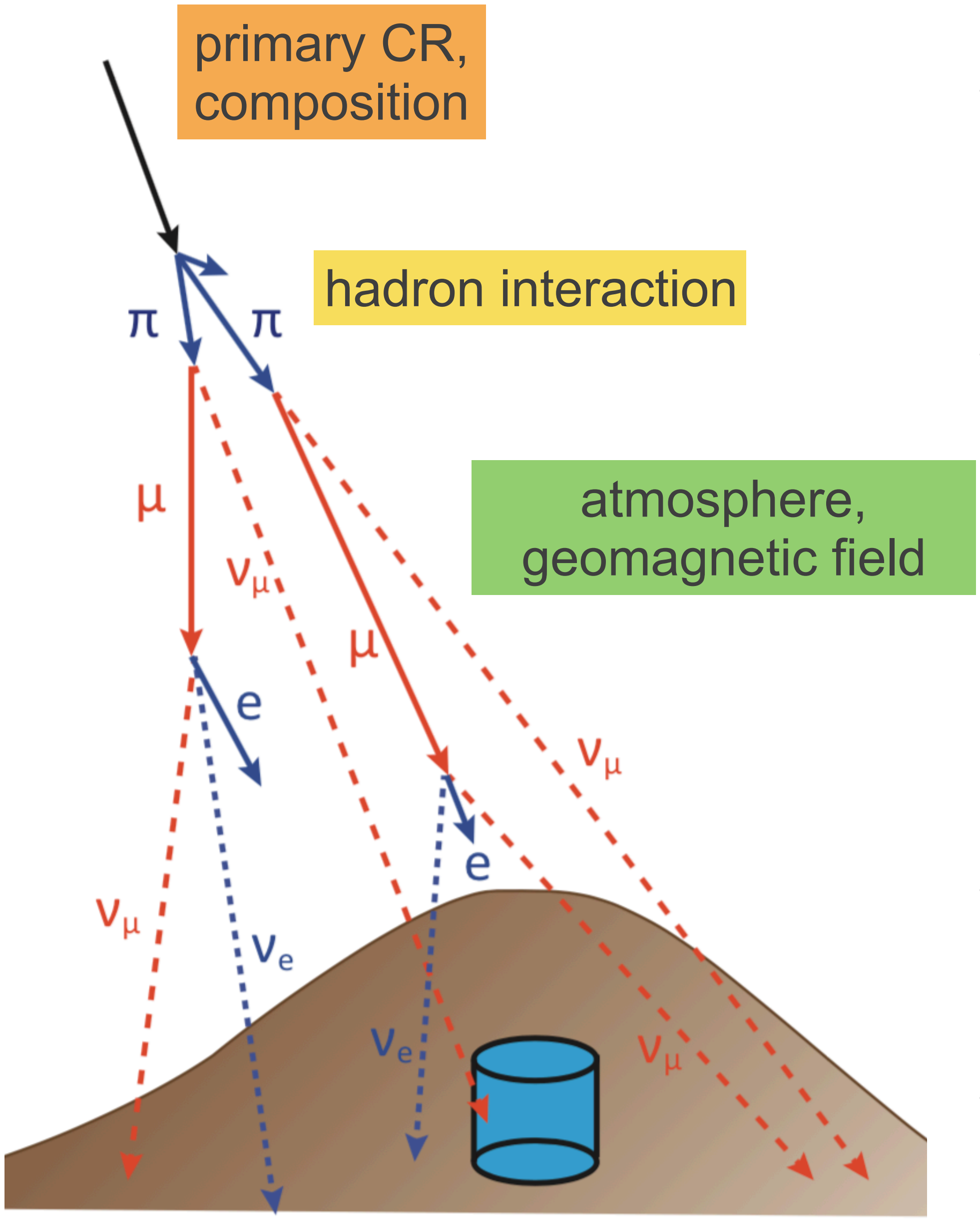
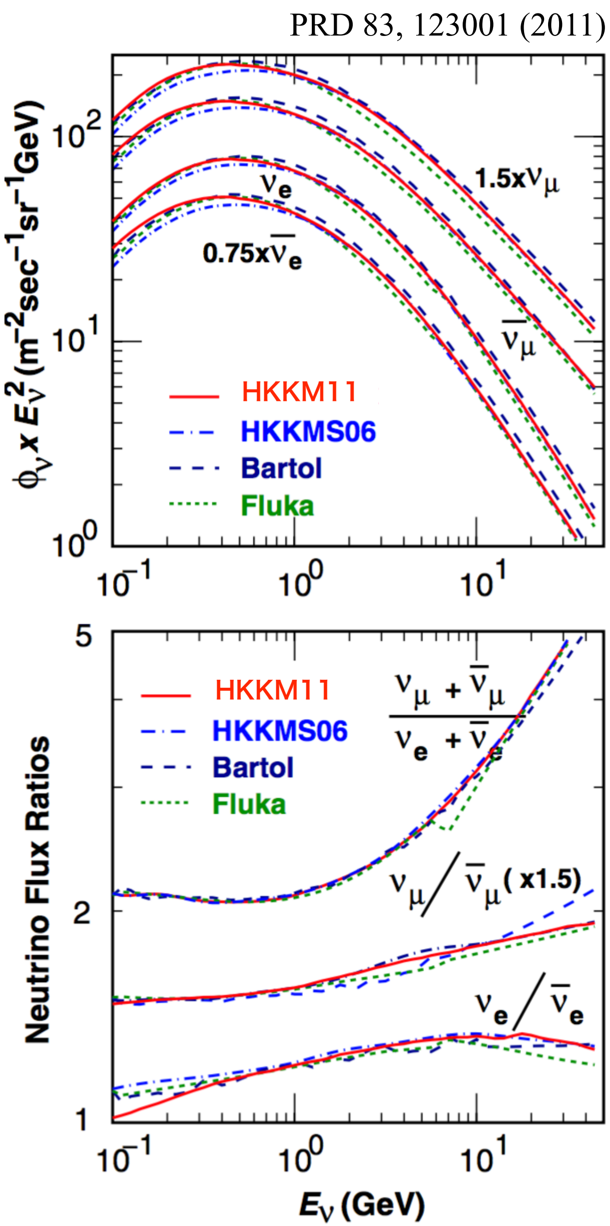
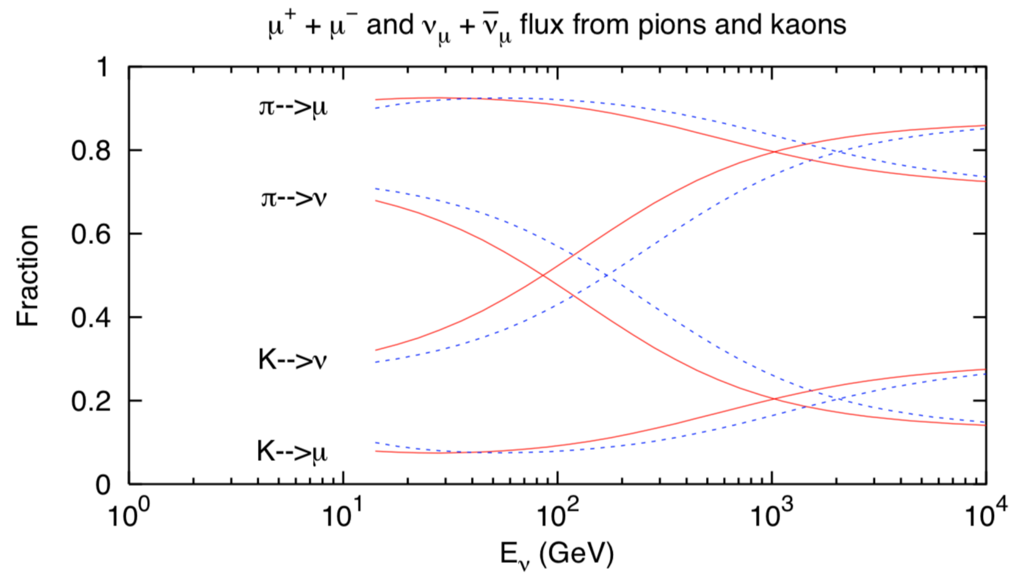
Introduction



- Atmospheric neutrino:
  end particle of cosmic ray interactions with atmosphere
- Neutrino flux affected by several factors:
  - primary CR flux, composition
  - hadron interaction
  - atmosphere model, seasonal variation, geomagnetic effect
- These effects are introduced in flux simulations precisely
- Can test flux prediction directly by flux measurement

Atmospheric Neutrino Flux in GeV-TeV



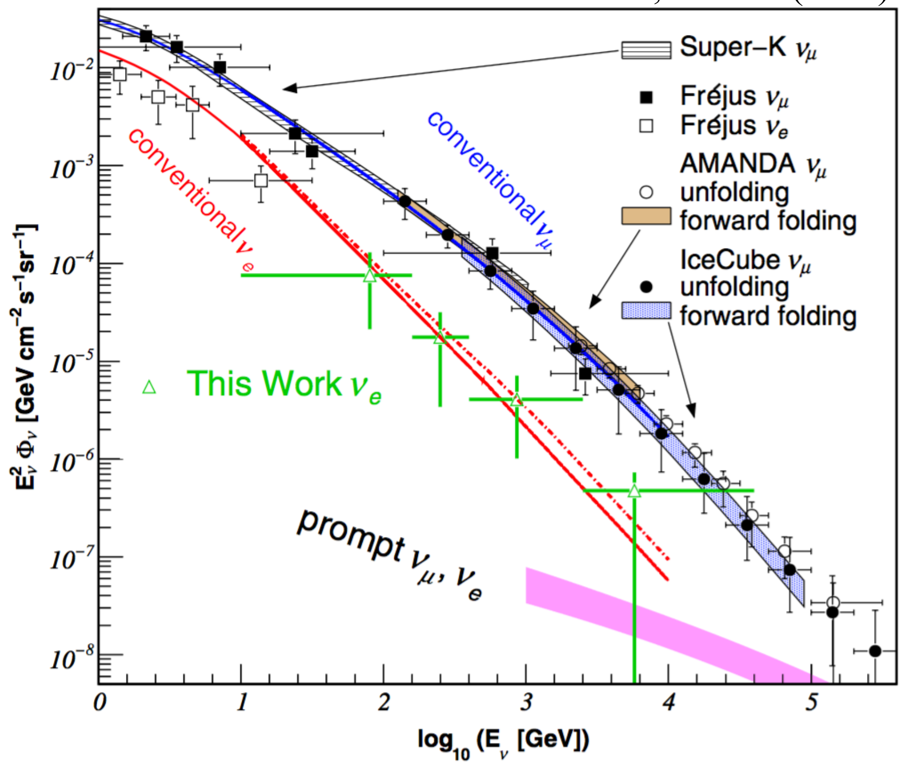


- Atmospheric neutrinos from π and K decays dominates below TeV energies (“conventional”)
- Nominal spectrum: $dN/dE \propto E^{-3.7}$ steeper for ν_e
- ν_μ/ν_e ~2 at GeV determined from π decay
- Larger kaon fraction as higher energies
  - Uncertainties due to π/K ratio

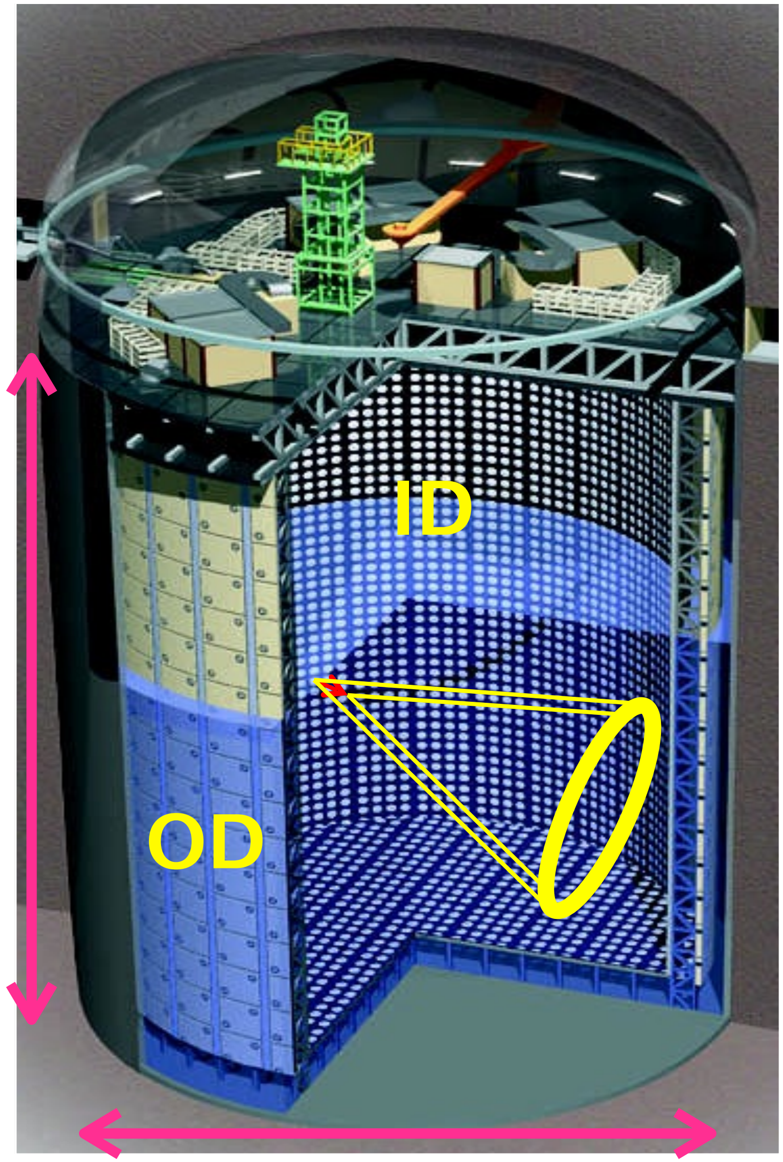
Motivations of This Study

- Accurate flux prediction is necessary as signal (oscillation analysis), and background (proton decay, DM, astro ν)
  - previous measurement by Frejus in 1995
  - recent detection of astrophysical neutrino by IceCube
- Comparison with recent improved flux calculations from various perspectives:
  - energy spectrum
  - geomagnetic effect
  - solar modulation effect
- This talk is based on *Physical Review D 94, 052001 (2016)*

PRL 110, 151105 (2013)



Super-K Detector



- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20” PMTs in inner detector (ID) for Cherenkov ring imaging
- 1885 8” PMTs for outer detector (OD)

Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~	

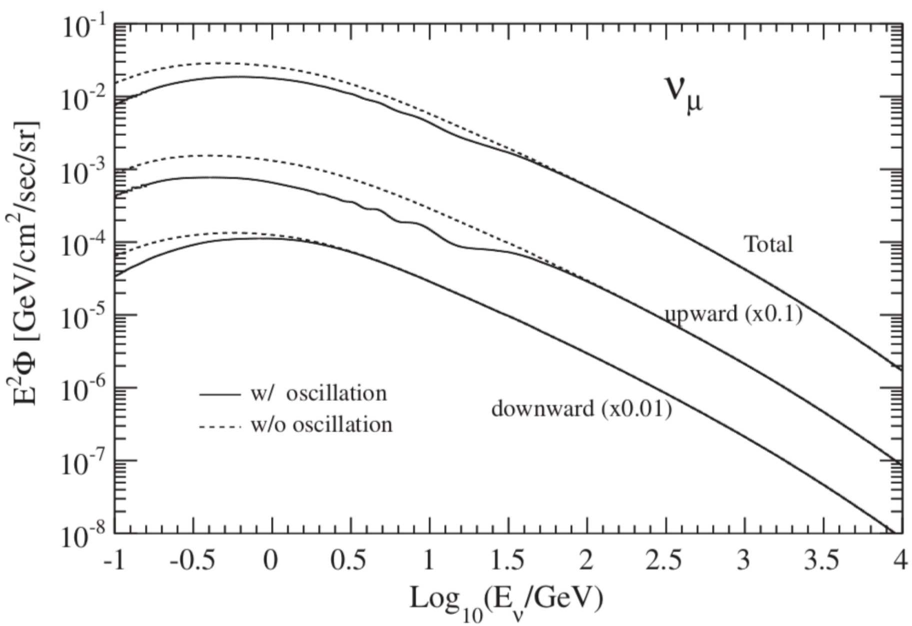
Energy Spectrum Analysis

Flux Measurement in Super-K

Flux — Cross section

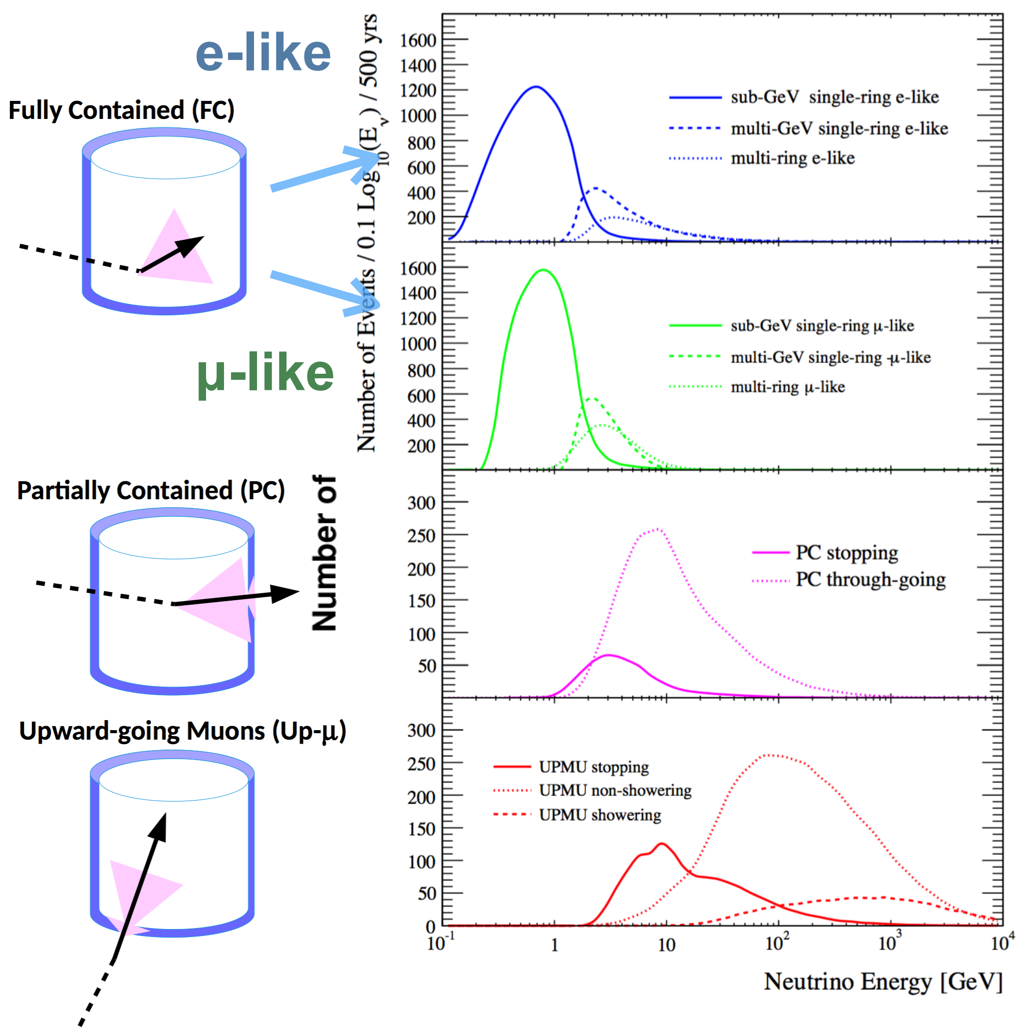
$$N = \Phi \otimes O \otimes \sigma \otimes \epsilon$$

Oscillation — Efficiency

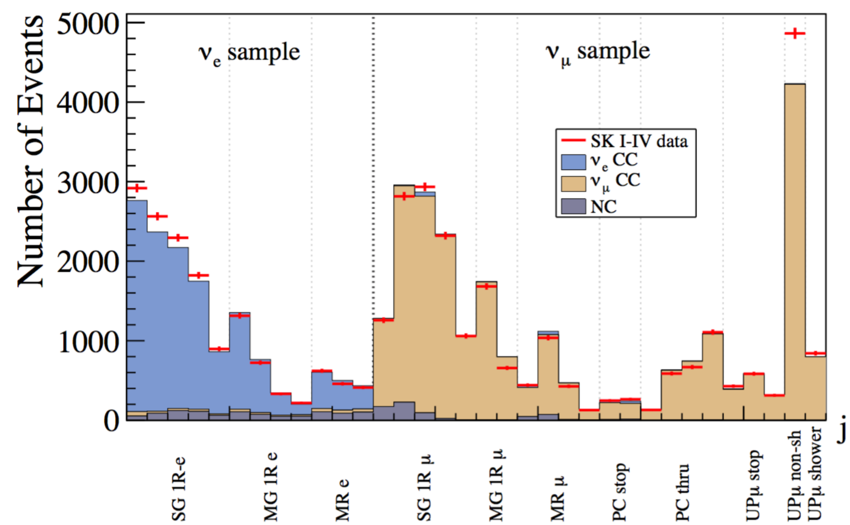


- Neutrino oscillation affects flux and energy spectrum, especially for ν_μ
- Atmospheric neutrino is utilized to measure neutrino oscillation
  - input: *N, Φ, σ, ε*
  - output: *O*
- Flux measurement
  - using estimated *O* from external measurement, we can measure flux (*Φ*)

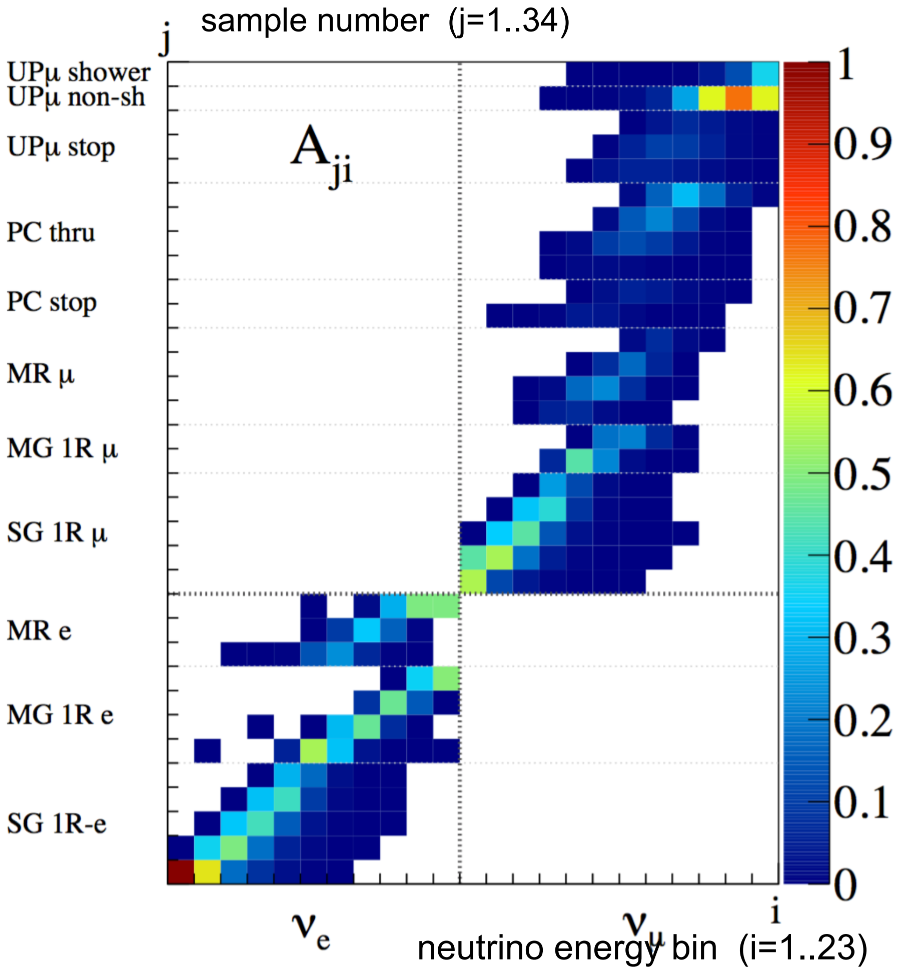
Data Sample, Neutrino Energy



- Three event topologies: FC, PC, UPμ
- Covers from sub-GeV up to 100 GeV (10 TeV) for ν_e (ν_μ)
- Provide high purity ν_e and ν_μ sample thanks to excellent particle identification and NC background abilities
- Caveat: slightly different sample selection from that of Super-K oscillation analysis



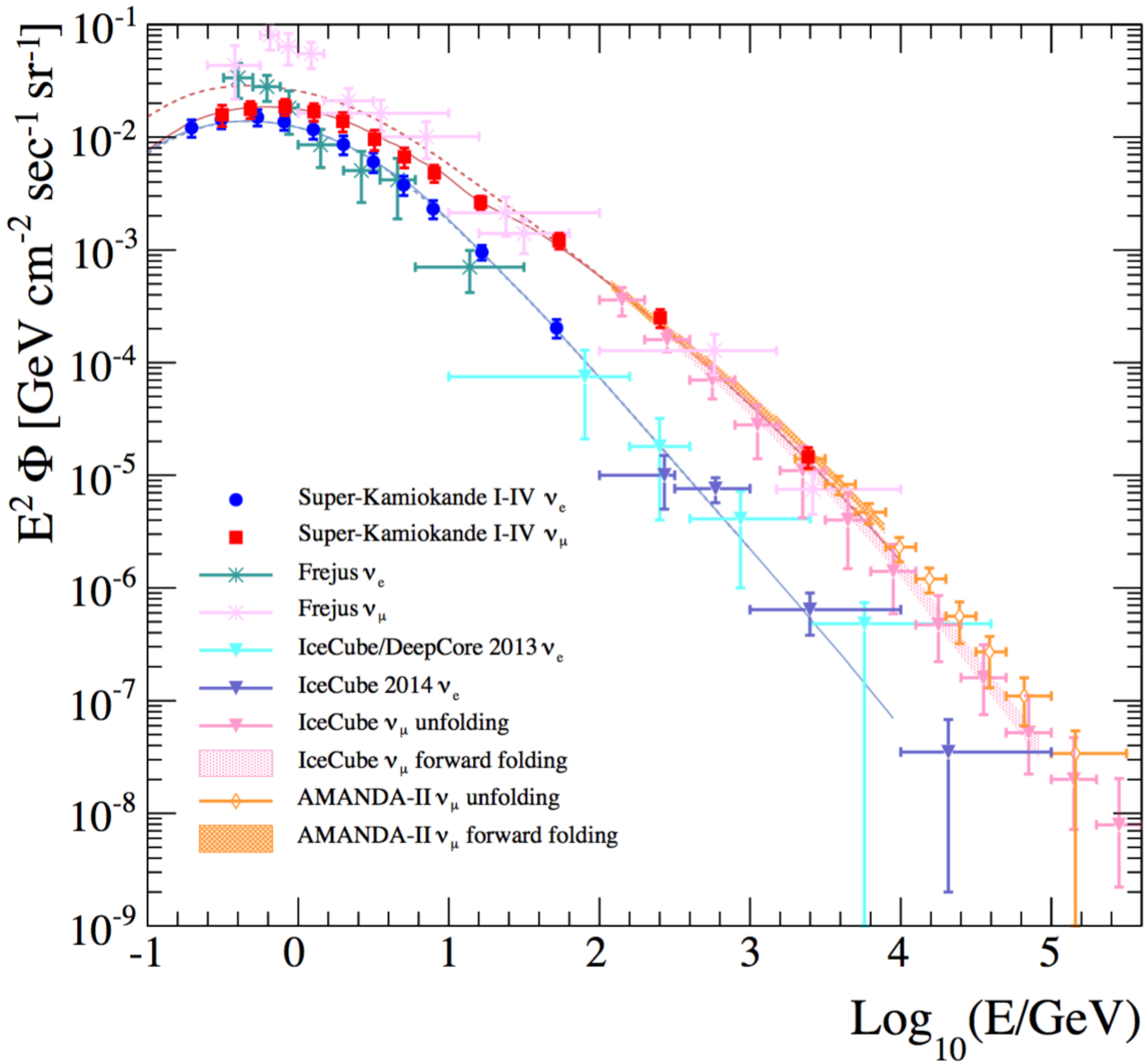
Flux Unfolding



- Adopt iterated Bayesian method for flux unfolding
- Response matrix constructed from MC events.
- Unfold number of events in neutrino energy bin, and then convert to flux value by applying normalization factor estimated with MC

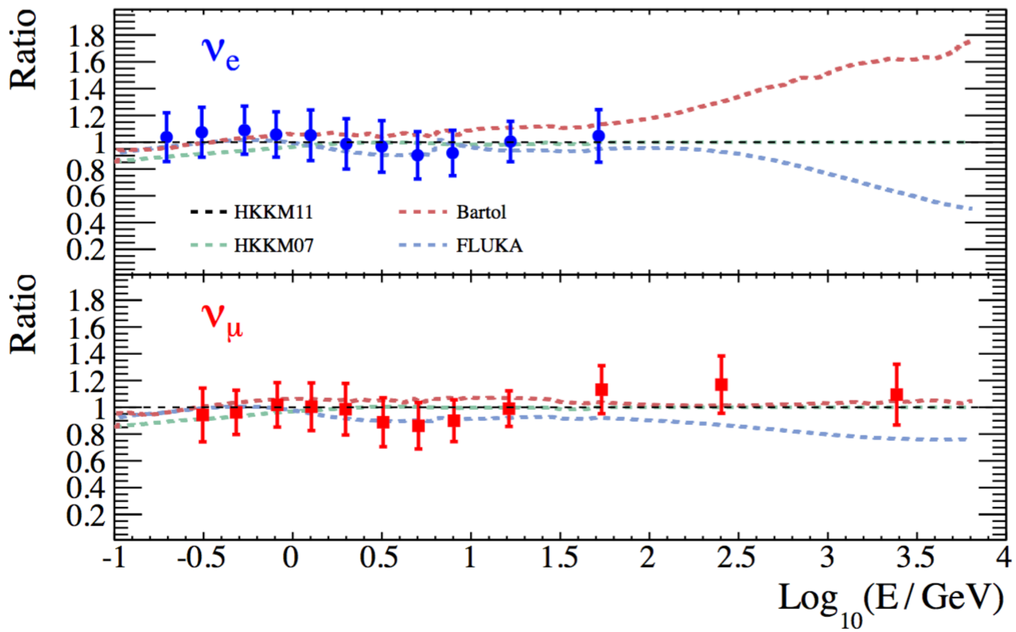
(*) G. D'Agostini, NIM A 362, 487 (1995)

Super-K Measured Energy Spectrum



- Provide significantly improved flux measurement below 100 GeV
- Extended to lower energies down to ~100 MeV
- Overlap in high energy with AMANDA and IceCube regions
- Caveat: larger flux expected at Frejus site due to lower rigidity cutoff

Comparison With Flux Models

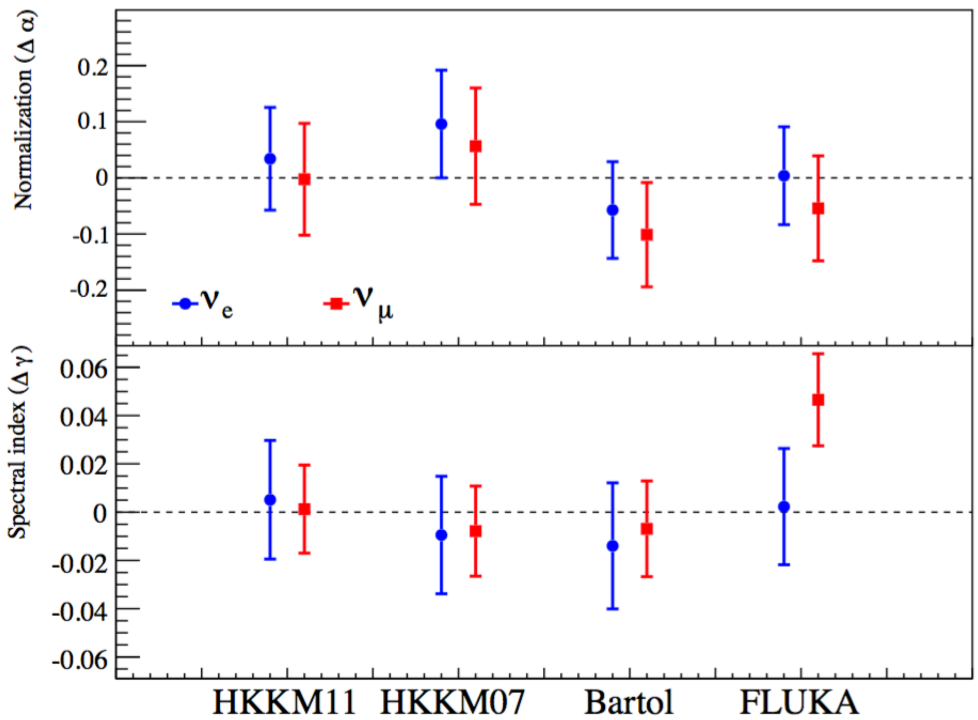


Flux model	χ^2 ν_e and ν_μ	ν_e only	ν_μ only
HKKM11 [21]	21.8	4.9	10.3
HKKM07 [20]	22.2	6.2	10.0
Bartol [23]	30.7	7.1	14.7
FLUKA [22]	25.6	5.4	11.4
(DOF	23	11	12)

$$\chi^2 = \sum_i^N \sum_j^N (\Phi_i - \Phi_{MC,i})^T C_{ij}^{-1} (\Phi_j - \Phi_{MC,j})$$

- Compared with flux models and test agreement by χ^2
- Not strongly inconsistent
  - p-value: 0.53, 0.32, 0.13 for HKKM11, FLUKA, Bartol, respectively

Fit with Variable Normalization and Spectral Index

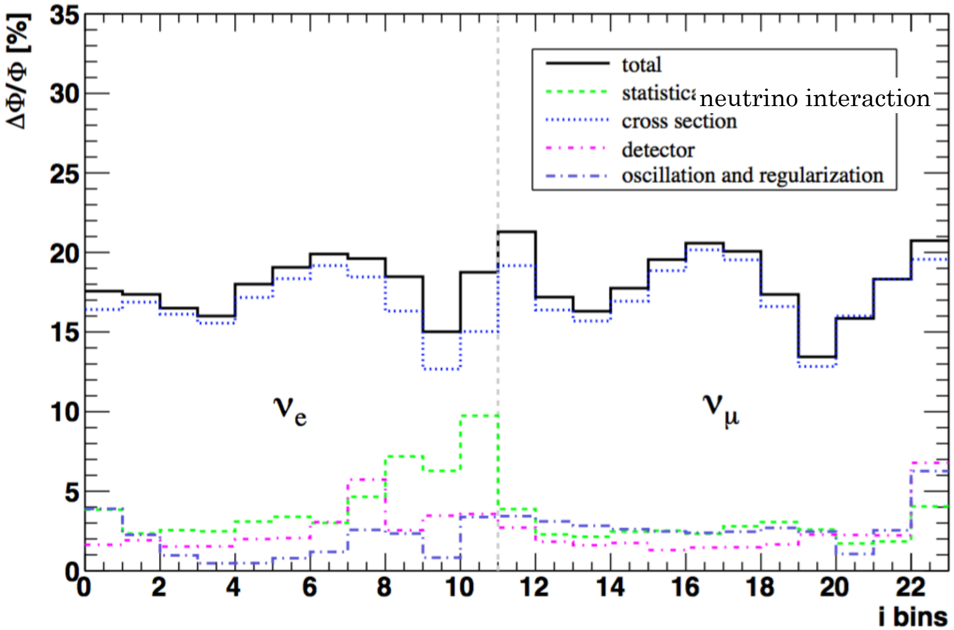


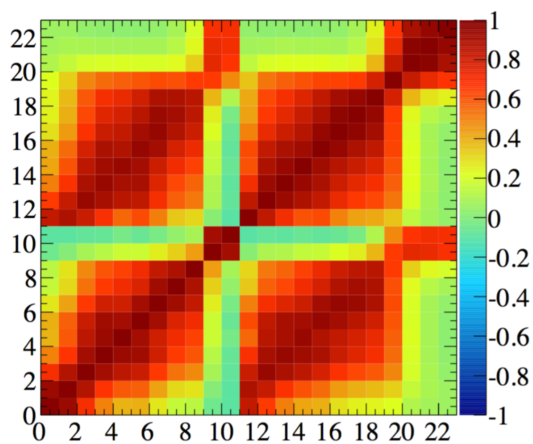
- Fit data and models with variable normalization (Δα) and spectral index (Δγ) parameters

$$\Phi'_{MC,i} = (1 + \Delta\alpha) \left(\frac{\bar{E}_i}{1\ \mathrm{GeV}} \right)^{\Delta\gamma} \Phi_{MC,i}$$

- Agrees within 1σ except from FLUKA ν_μ spectrum (2.4σ)

Systematic Uncertainty





- Utilize same systematic error estimation as used in oscillation analysis
- For calculation of error propagation, Toy MC method is adopted
  - Repeat Toy MC throw and flux unfolding by 2000 times. Variance of unfolded fluxes is taken as error
- Approximately 20% error estimated in total
- Neutrino interaction error is dominant

error coefficient

$$\tilde{M}_j(\mathbf{g}) = M_{MC,j} \times \left(1 + \sum_{k}^{N_{\rm sys}} f_{jk} g_k\right) \qquad (3.10)$$

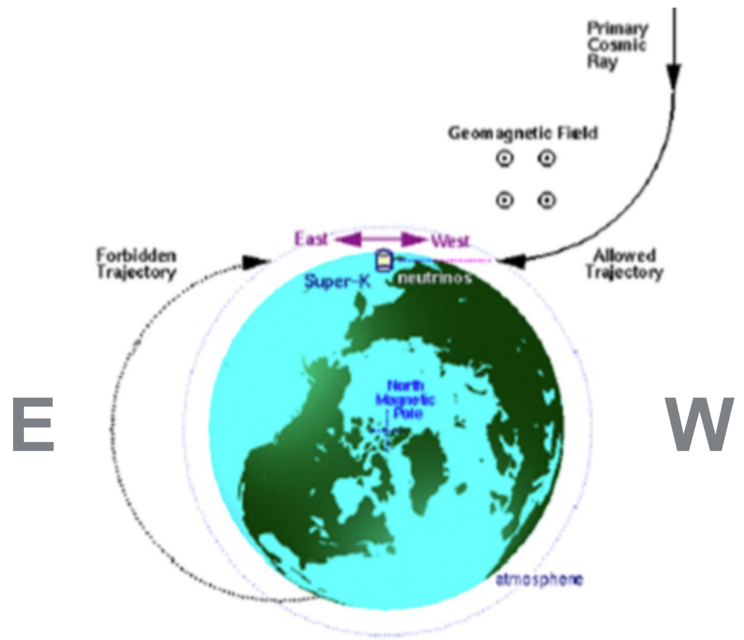
nominal MC

random Gauss.

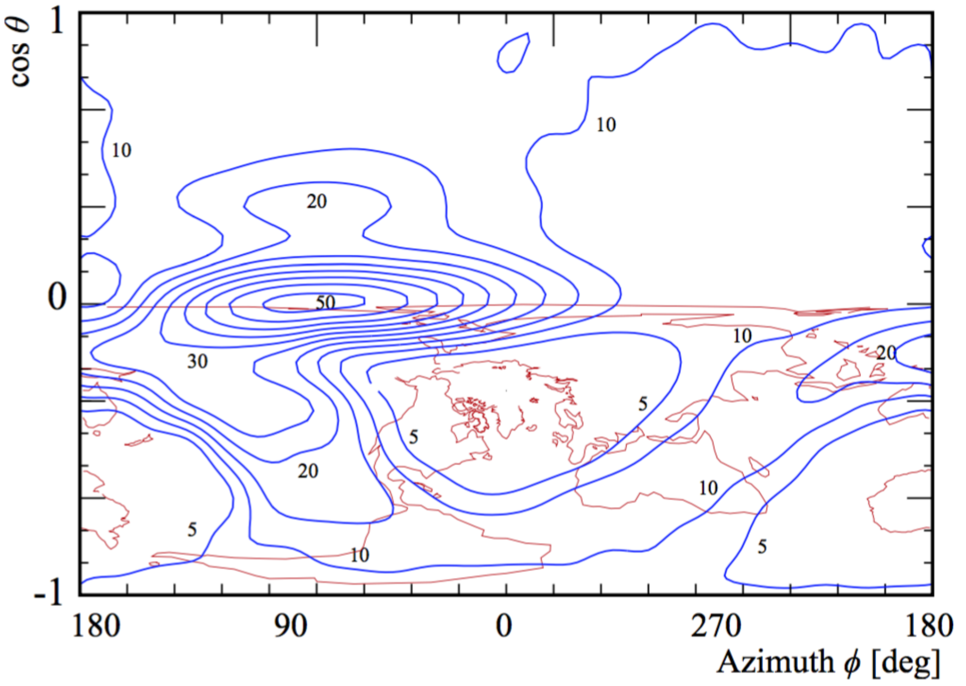
Azimuthal Spectrum Analysis

Geomagnetic Effect

- "East-West effect" in azimuthal direction is well-known on cosmic ray flux, such as dipole asymmetry
- Rigidity cutoff due to geomagnetic field depends on position and direction at Earth's surface
- Can test for such asymmetries by using Super-K neutrino data

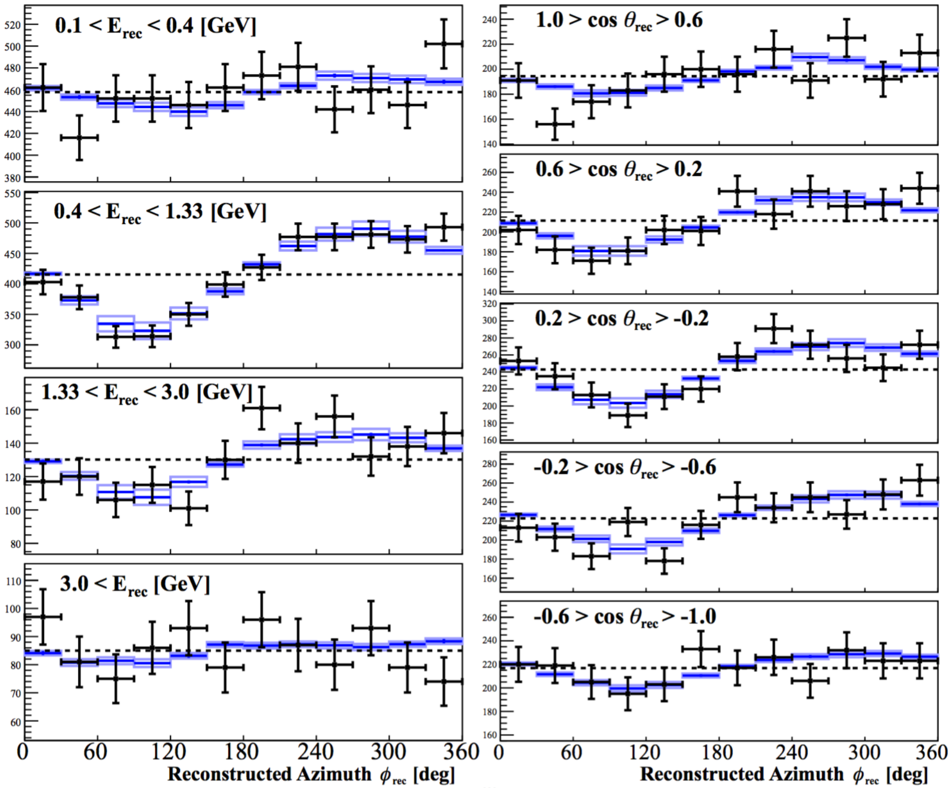


Rigidity cutoff seen from Super-K

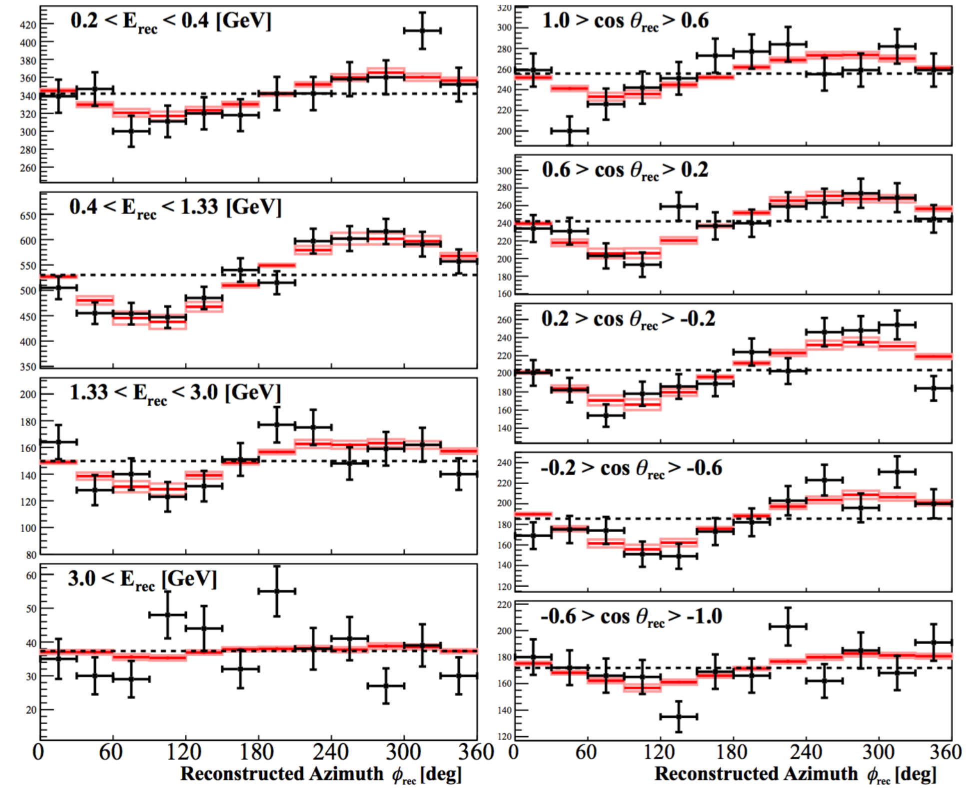


Azimuthal Distributions

electron-like

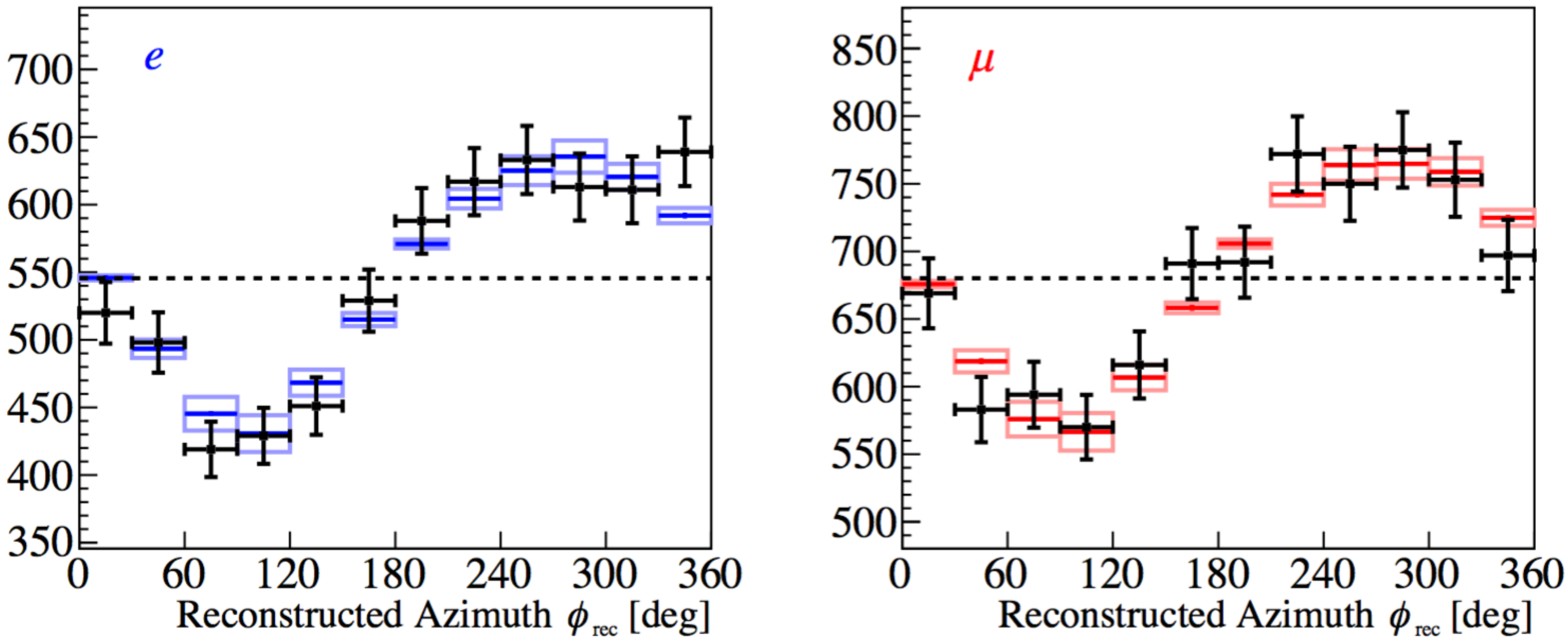


muon-like



- “East-west” effect becomes larger for lower energies and horizontal direction
- Modulation becomes small in lowest energy below E<0.4GeV because directional information is lost due to large lepton scattering angle

East-West Asymmetry

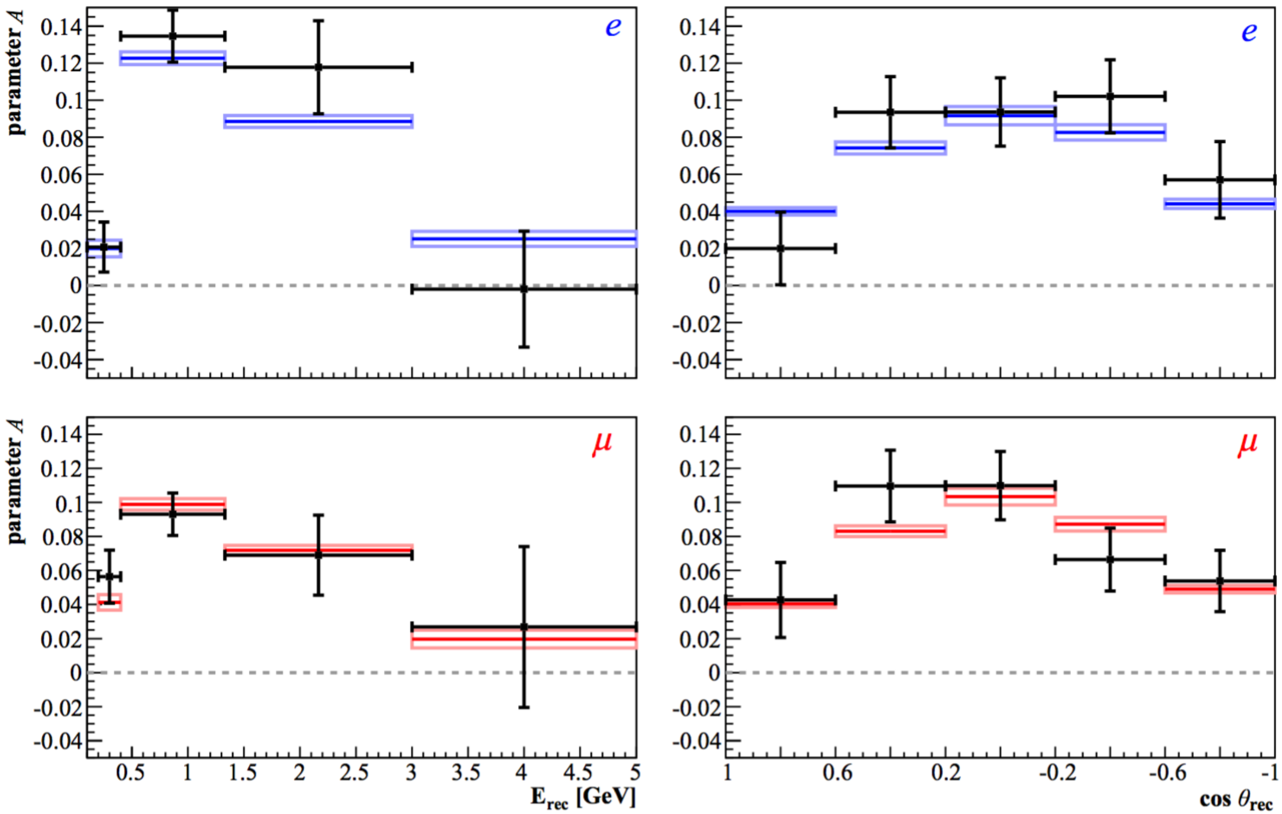


- Select events by $|\cos\theta|<0.6$ and $0.4<E_{rec}<1.33$ GeV to optimize significance
- Clear asymmetries are seen and significance level
  - 6.0σ (8.0σ) for μ-like and e-like

$$A_\mu = 0.108 \pm 0.014(\text{stat}) \pm 0.004(\text{syst})$$
$$A_e = 0.153 \pm 0.015(\text{stat}) \pm 0.004(\text{syst})$$

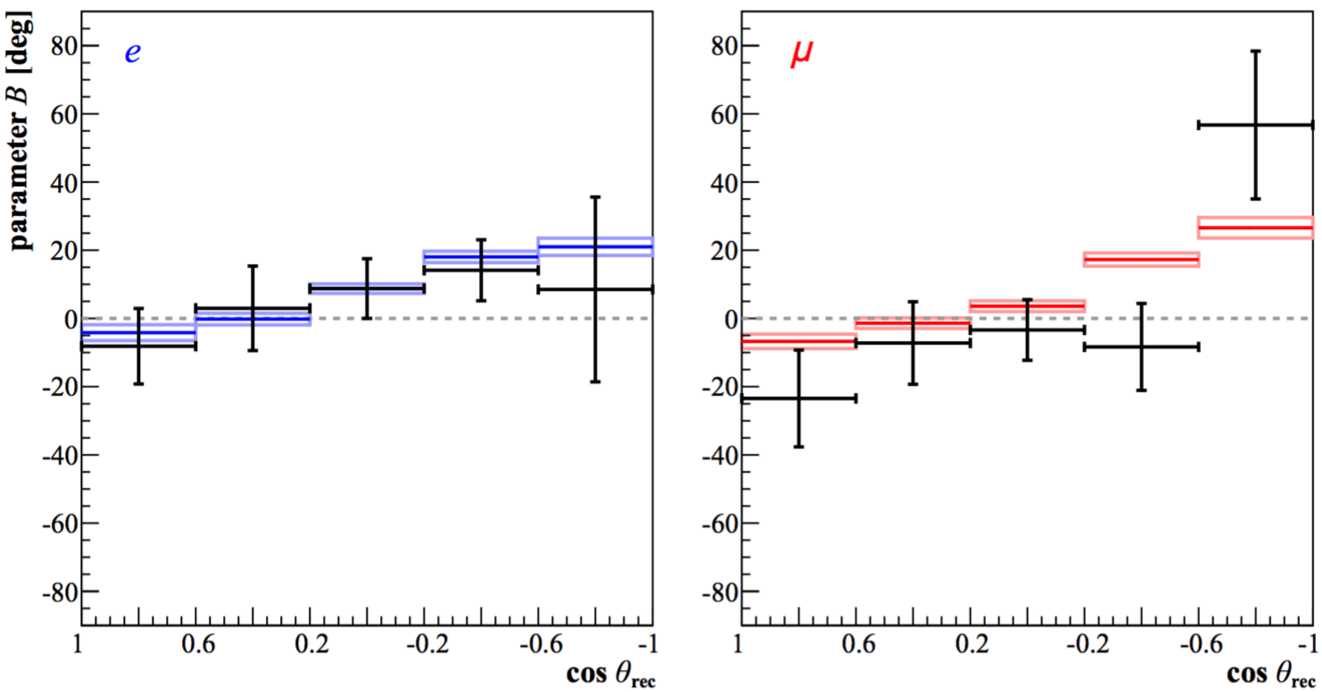
$$A = \frac{n_{\text{east}} - n_{\text{west}}}{n_{\text{east}} + n_{\text{west}}}$$

Energy and Zenith Dependence



- Test for in each energy and zenith angle with asymmetry parameter, *A*
- Agrees with expectation within statistical uncertainties

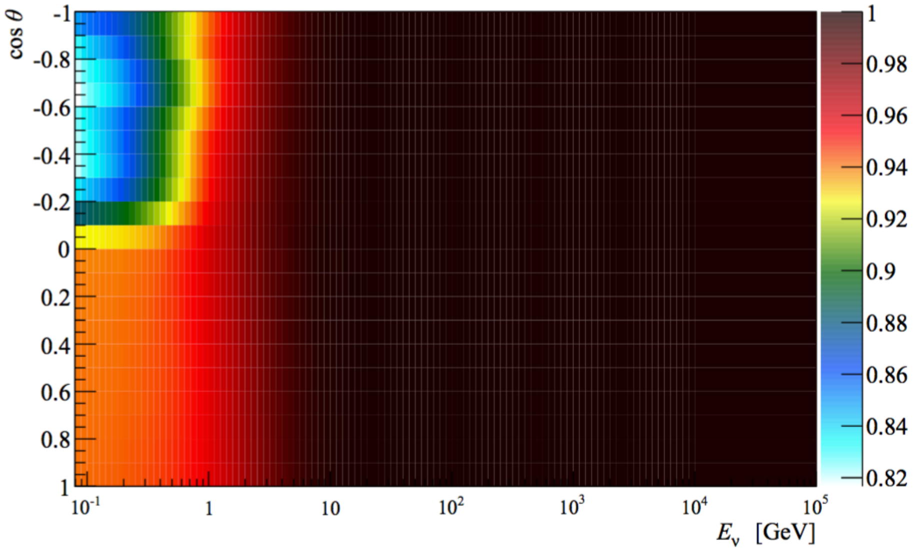
Azimuthal modulation phase

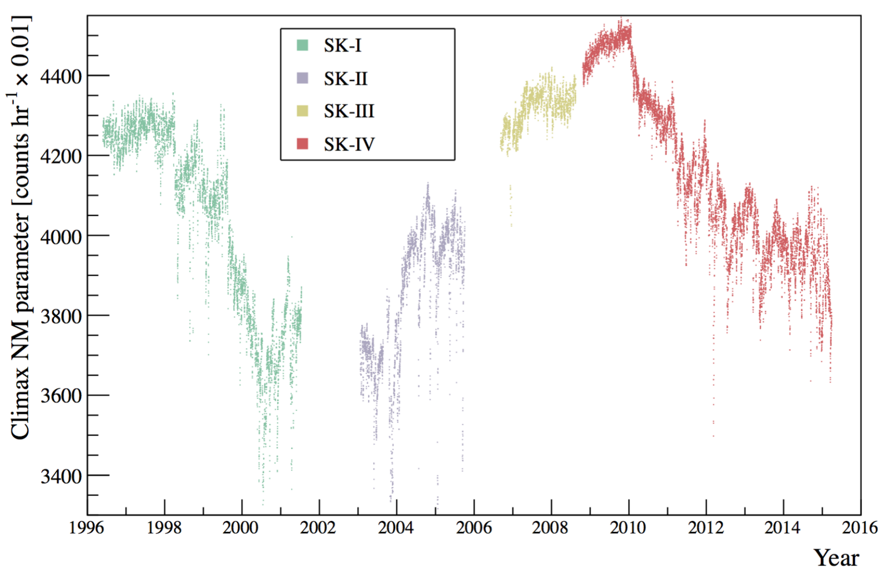


- Investigate phase shift of azimuthal modulation by fitting sine curve:
  $k_2 \times \sin(\varphi + B) + k_1$
- Zenith dependence is seen with 2.2σ significance, and consistent between data and MC
- HKKM11 calculation models reproduced geomagnetic effect

Solar Modulation Analysis

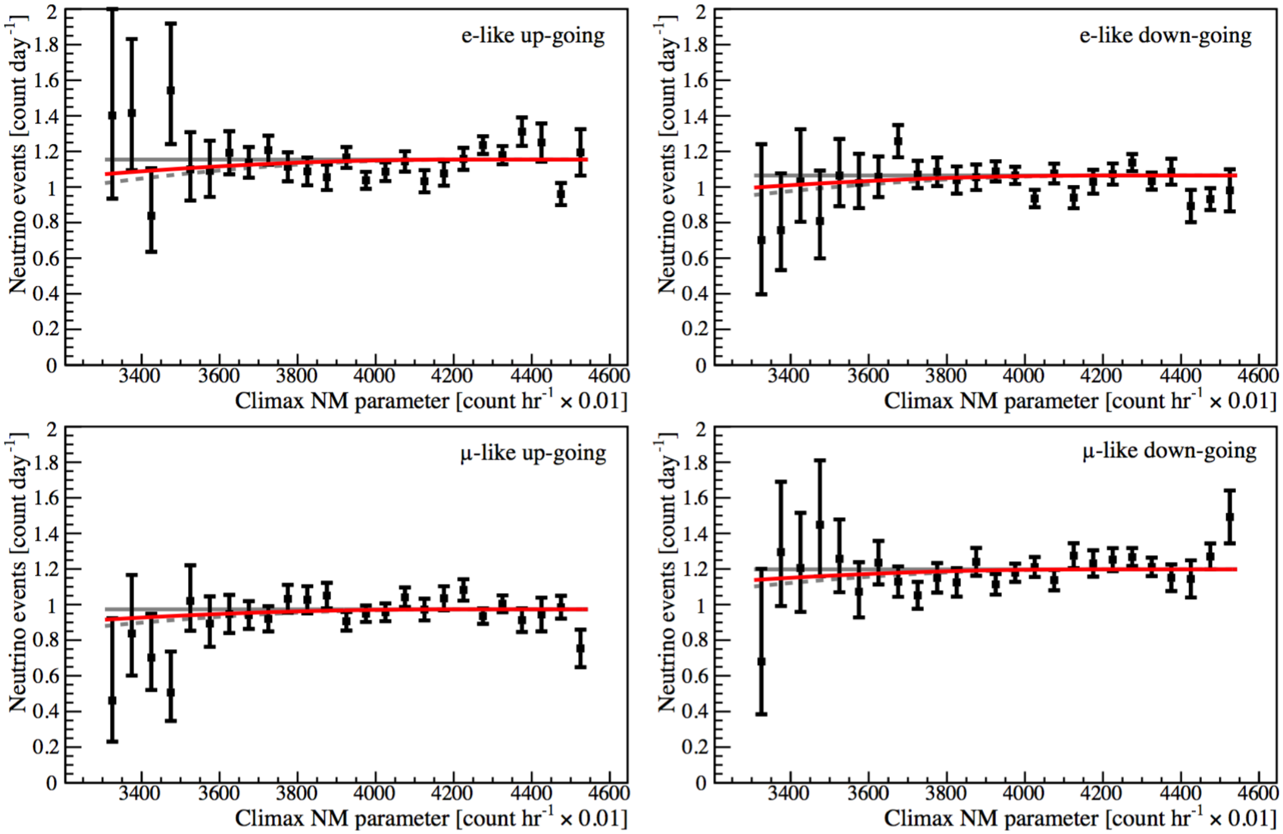
Modulation Effect of Solar Activity





- Atmospheric neutrino flux will be affected by solar activity below 1 GeV
  - Solar wind scatter off CR
- Larger effect for upward direction coming from polar regions, where solar effect is larger
- SuperK data covers more than one and half solar cycles
- Test correlation with solar modulation by event rate change

Correlation with Solar Modulation



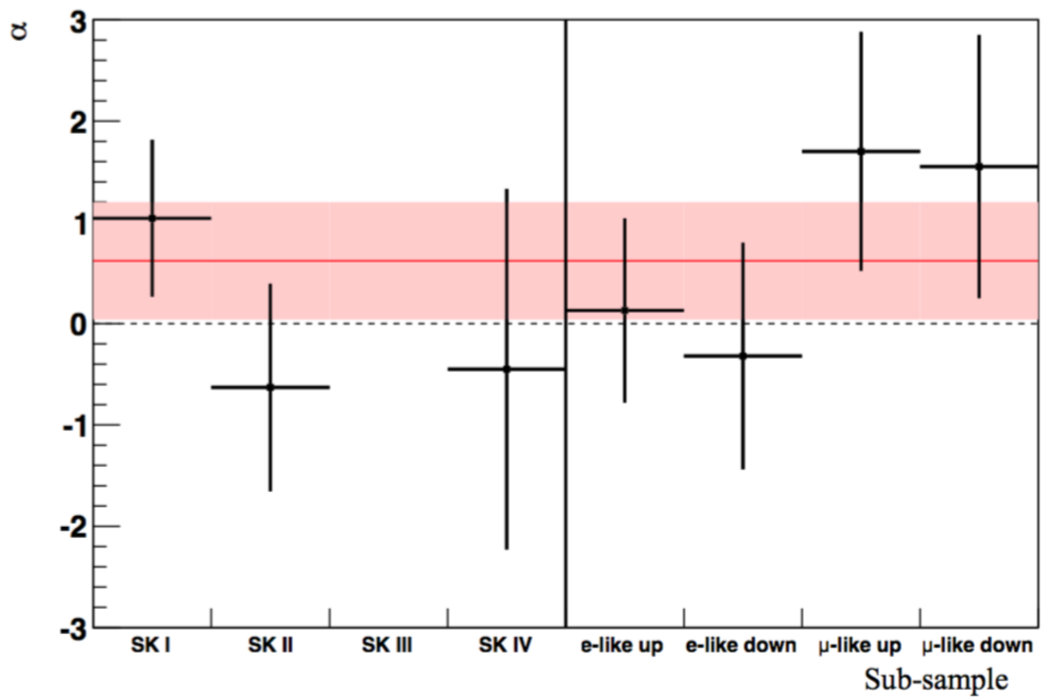
Best fit

Prediction (α=1)

No correlation (α=0)

- Correlations between sub-GeV event rate vs neutron monitor are investigated
- Effect is small and difficult to see:
  - directional information is lost by neutrino scattering
- Estimate correlation by one parameter fitting (α)
- Best fit : α = 0.62 ± 0.58 (1.06 σ)

Fitting to Sub-samples



- Also apply fitting for sub-sample (e-like / μ-like, upward / downward)
- No SK-III result since observation time is too short to cover solar cycle
- Prefer no correlation for e-like, but not statistically significant
- Not inconsistent with overall result

Summary

- A comprehensive study on the atmospheric neutrino flux in the energy region from sub-GeV to TeV using SuperK was performed
- ν_e and ν_μ energy spectra are measured with higher accuracy from 100 MeV up to 10 TeV, and consistent with flux models.
- Azimuthal spectrum of data and MC agrees well confirming implementation of geomagnetic field in flux calculation
  - Geomagnetic effect in azimuthal distribution is seen at 6σ (8σ) for ν_μ (ν_e).
  - An indication that the angle of the dipole asymmetry shifts depending on the zenith angle was found at the 2.2 σ level
- Expected correlation between neutrino flux and solar activity was studied using sub-GeV sample
  - Predicted effect is found to be relatively small (62% of expected), and a weak preference is seen at 1.1σ level