Measurements of the atmospheric neutrino by Super-Kamiokande: energy spectrum, geomagnetic effects, and solar modulation

Kimihiro Okumura
Institute for Cosmic Ray Research, The university of Tokyo
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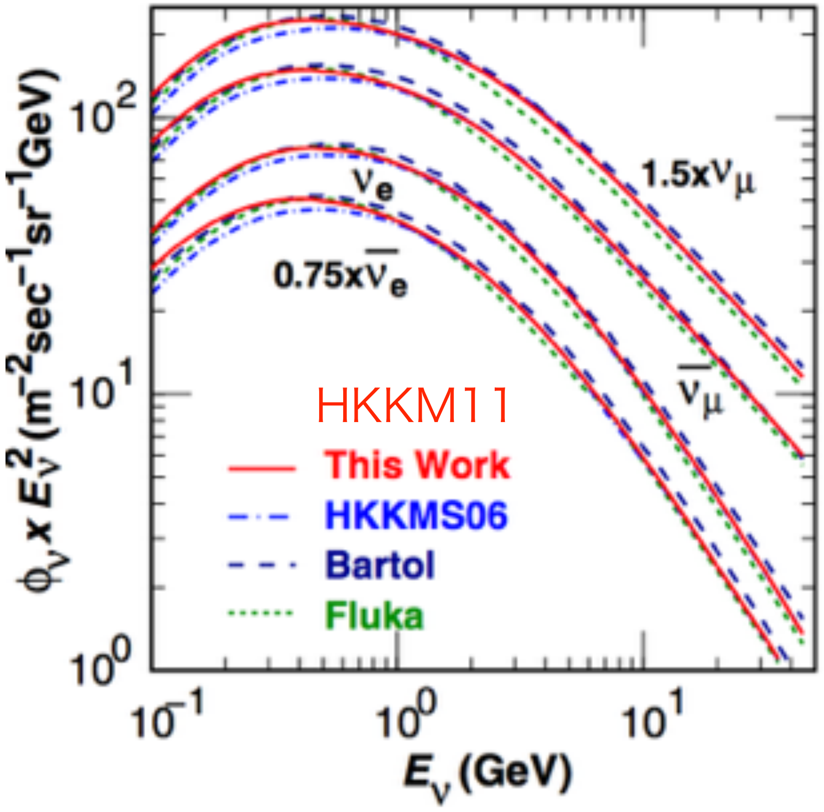
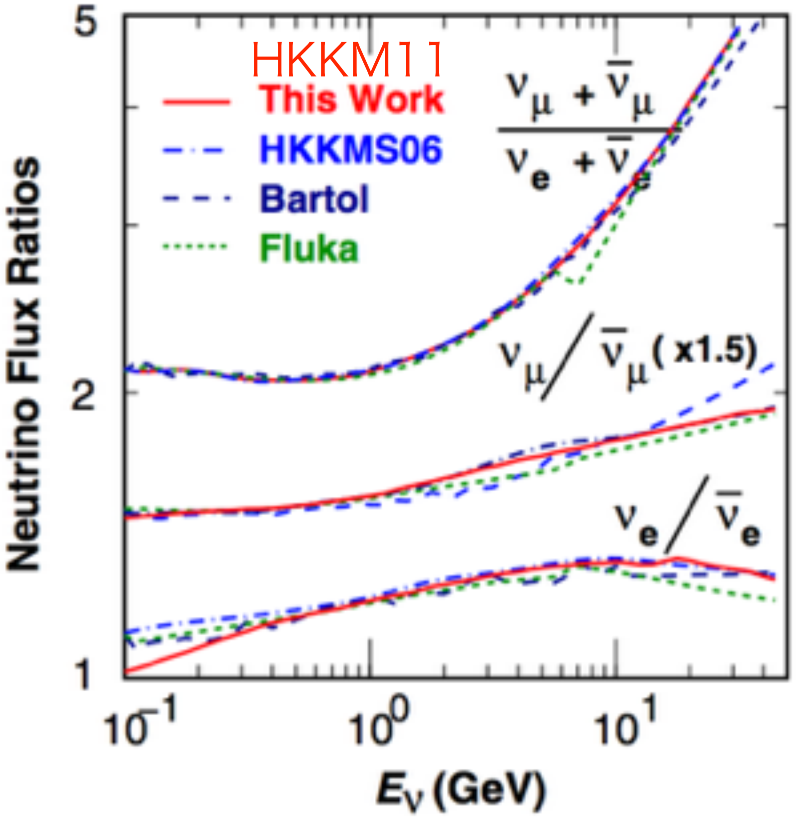
Atmospheric Neutrinos

- Mostly produced from pion and K decay below TeV
- Rigidity cutoff below several GeV due to geomagnetic effect
- Accuracy of flux calculation has been improved because of better simulation and more precise CR and hadron cross section meas.



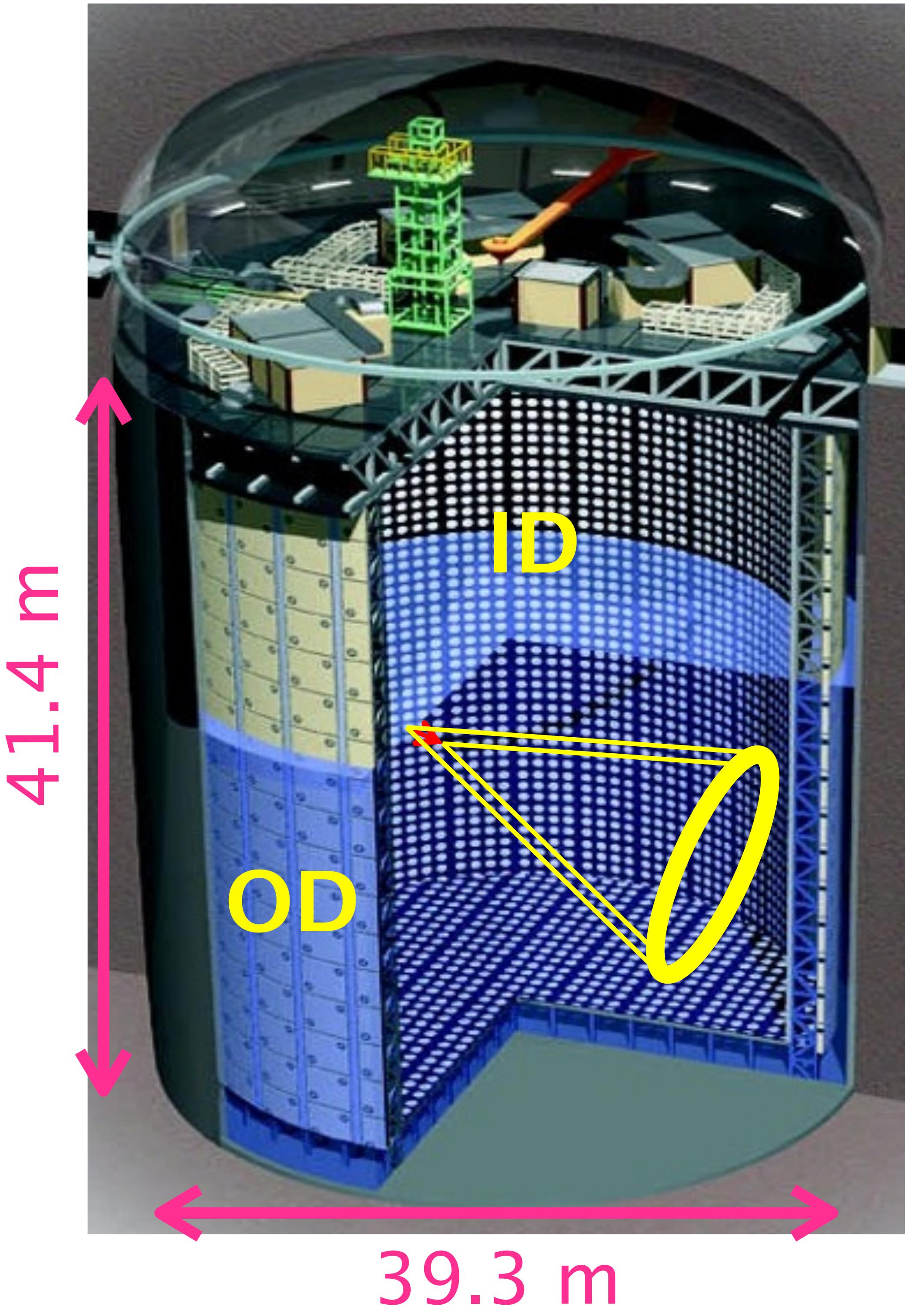
PHYSICAL REVIEW D **83**, 123001 (2011)



Motivation of This Analysis

- Accurate flux prediction is necessary as signal (oscillation analysis), and background (proton decay, DM, astrophysical ν)
  - Previous measurement by Frejus in 1995
  - Recent detection of astrophysical neutrino by IceCube
- Comparison with recent improved flux calculations in various aspects:
  - Energy spectrum
  - Geomagnetic effect
  - Solar modulation effect

Super-K Detector

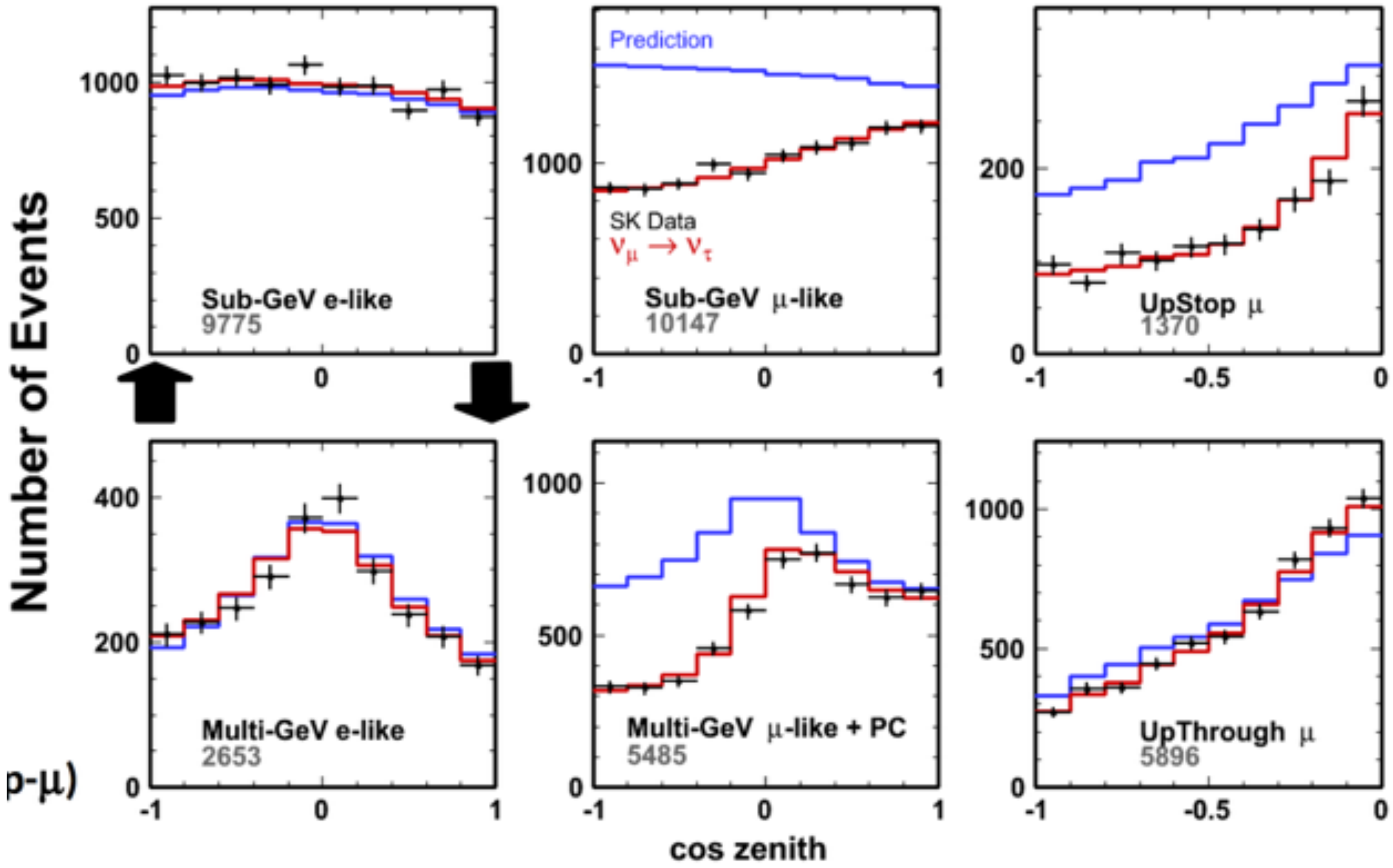


- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20” PMTs in inner detector (ID) for Cherenkov ring imaging
- 1885 8” PMTs for outer detector (OD)

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 ~	

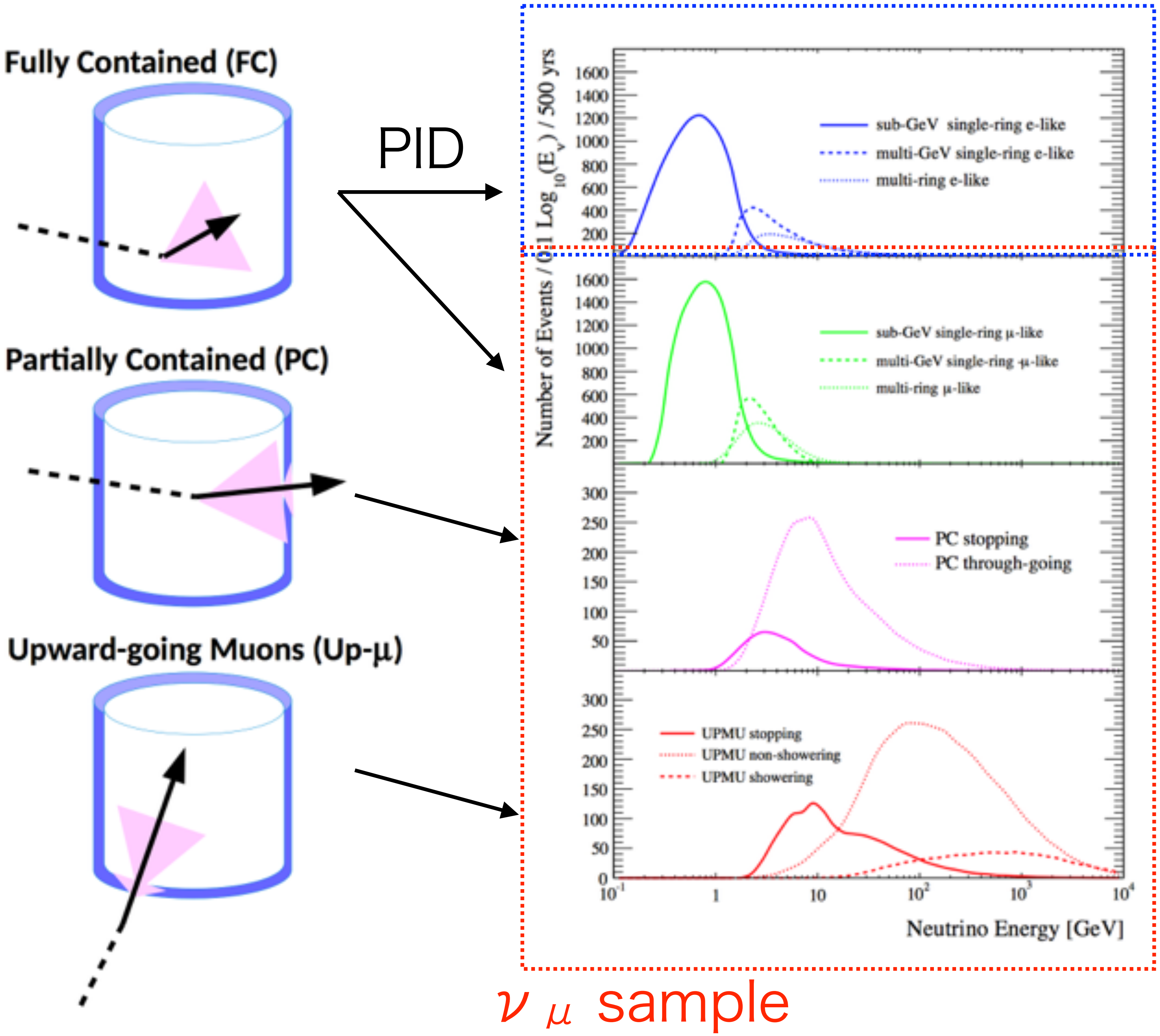
Flux Measurement in Super-K

- Neutrino oscillation has been studied with calculated neutrino flux value and error
- This analysis: neutrino flux is measured considering oscillation using PDG parameters
- ν and ν̄ are difficult to be separated in SuperK;
  ν means ν + ν̄ in this presentation



Energy Spectrum Analysis

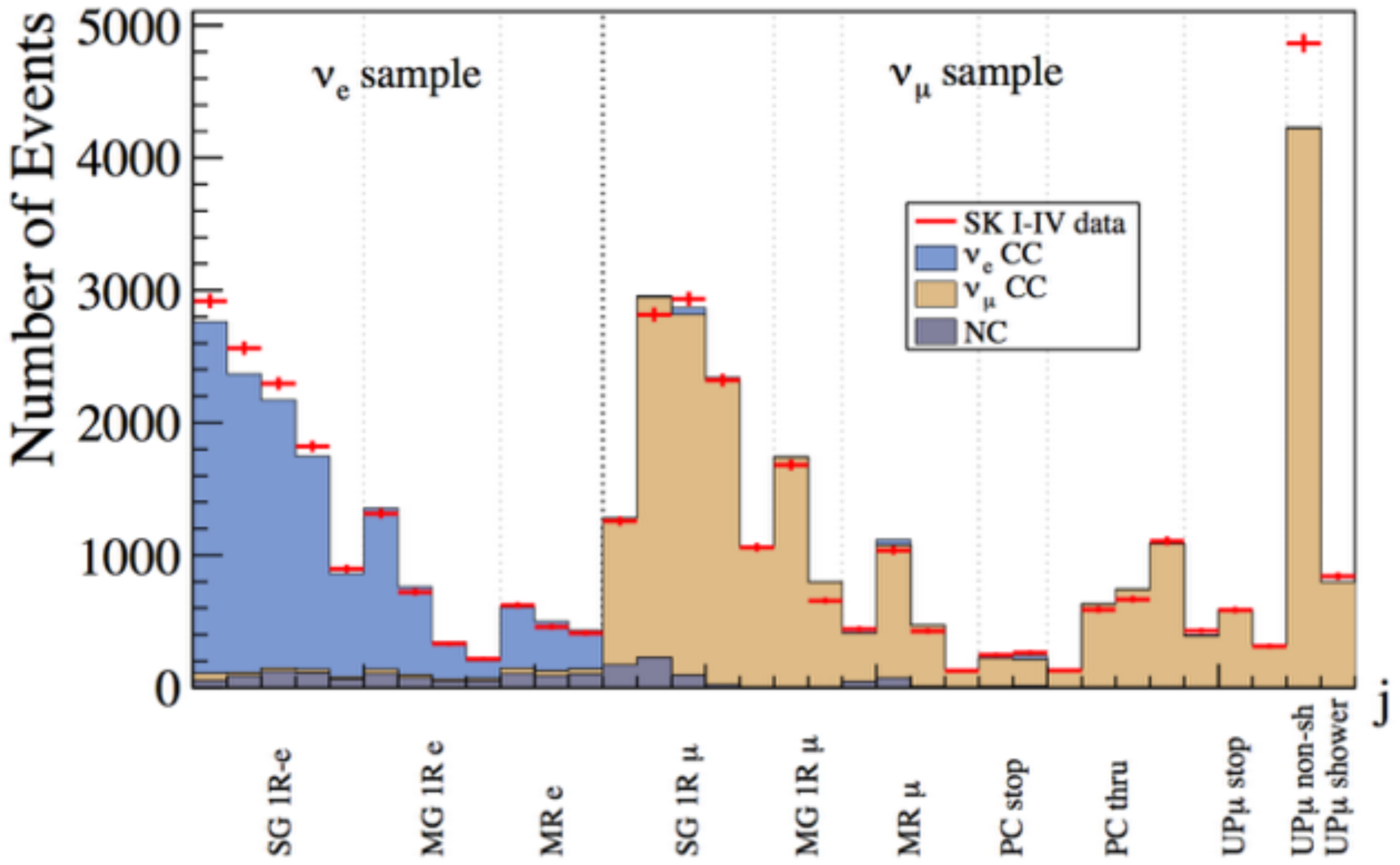
Data Sample, Neutrino Energy



- Three event types (FC, PC, UPμ)
- FC events separated to e-like and μ-like by PID
- Also divided by event topology (e.g. single/ multi-ring, stopping/ through)
- Different event sample has different energy response
- νe (νμ) sample covers up to 100 GeV (10 TeV)

Data Sample, Neutrino Energy

- Signal: correct flavor CC events. BG: wrong flavor CC and NC
- Expectation with HKKM11 flux, NEUT, PDG2014 osc. parameters
- High purity (>73 %); NC reduction applied in e-like sample



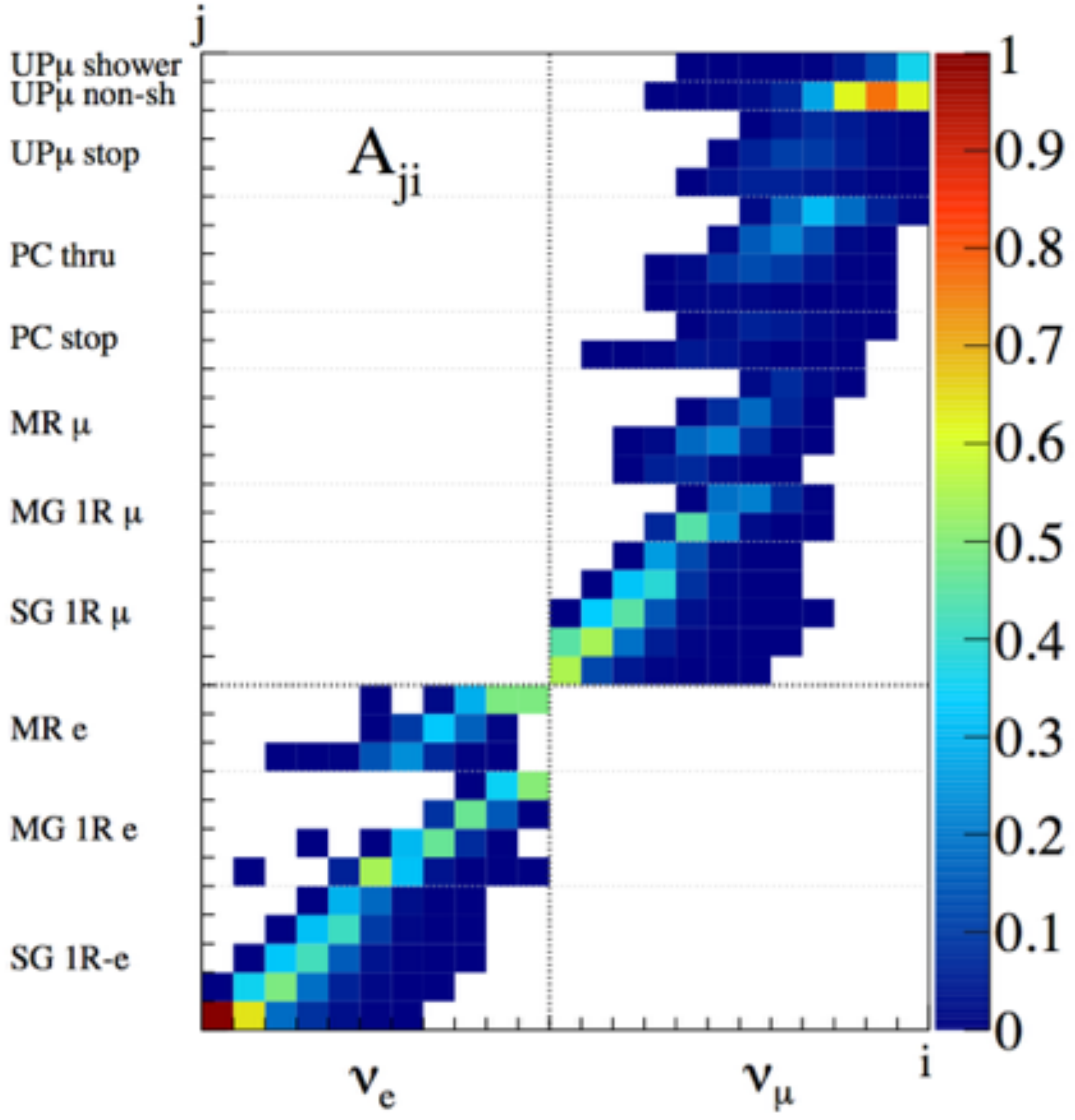
Sample bins
(j=1..34)

Flux Unfolding

- Iterated Bayesean method(*) was adopted to obtain energy spectrum
  - model independent, simple, fast, theoretically robust
- Response matrix obtained from MC events
  - BG subtraction is considered
- Unfold # of events in neutrino energy bin
  - normalization, estimated from MC, is applied to convert to flux value

Sample bins (j=1..34)

Response matrix

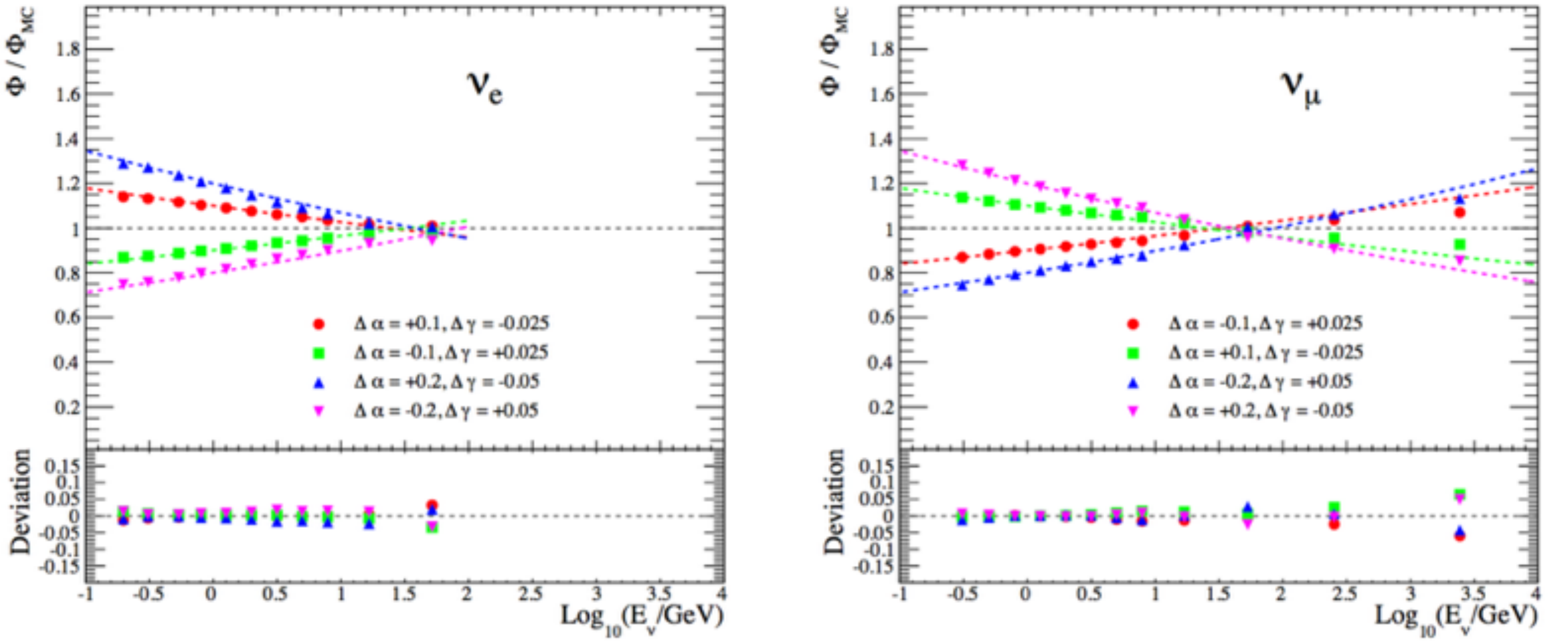


Neut. energy bin (i=1..23)

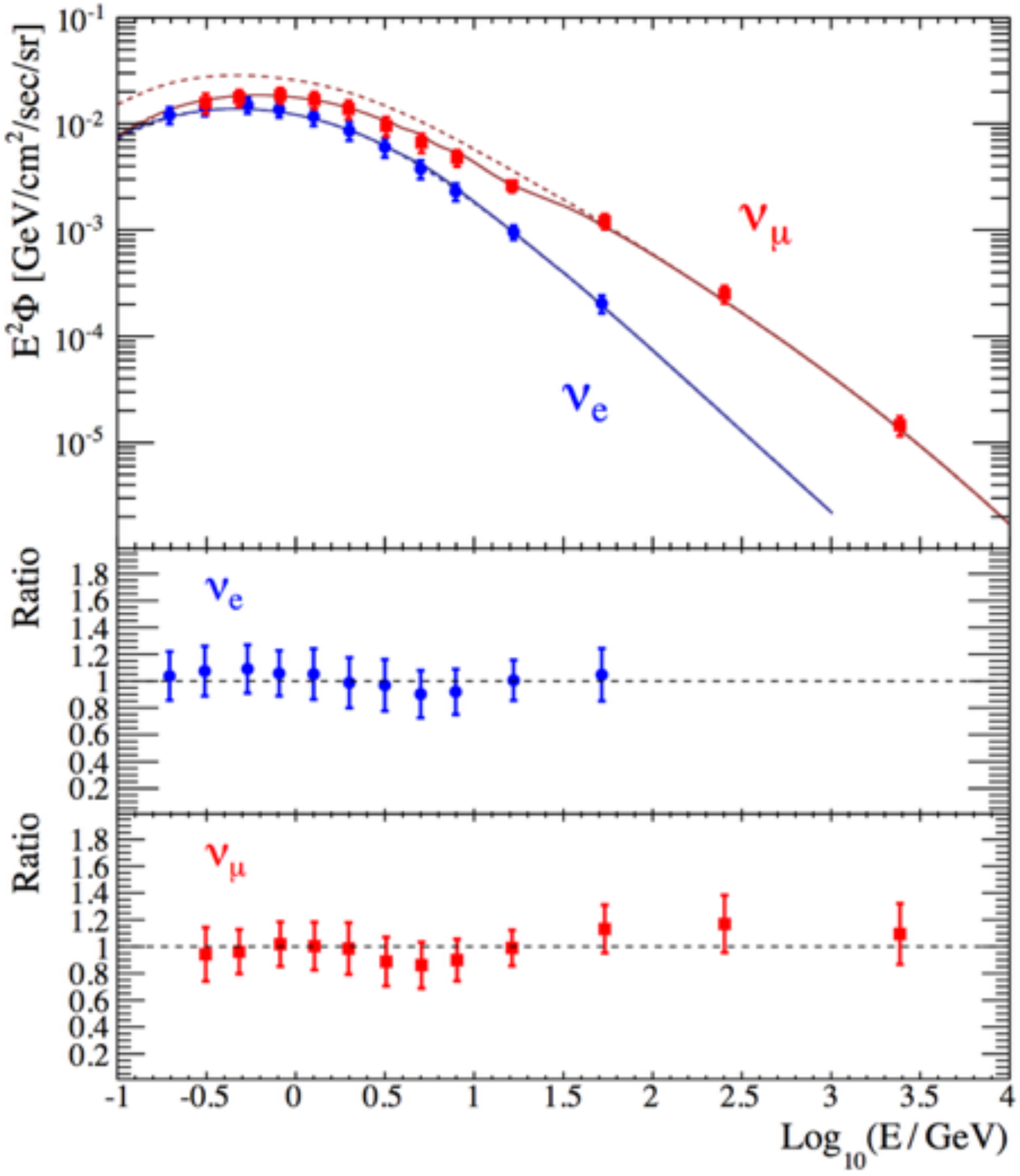
(*) G. D'Agostini, NIM A 362, 487 (1995)

Unfolding Test with MC

- Test unfolding method using modified MC data with different norm. and spectrum index
- reasonably good performance
- Incompleteness is considered in systematic error



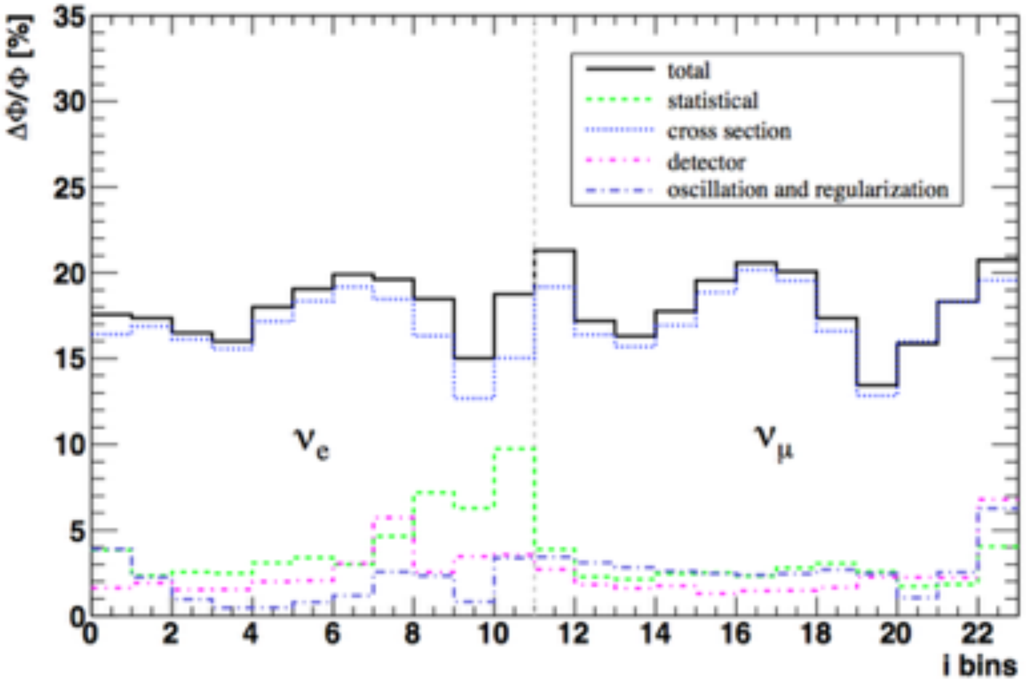
Unfolded Energy Spectrum



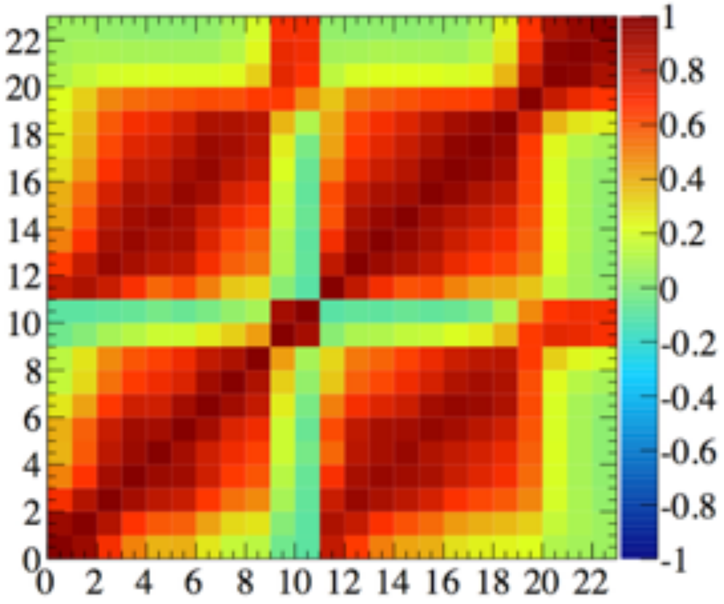
- Dotted line: HKKM11 w/o oscillation
- Solid line: HKKM w/ oscllation
- Error bar includes both statistical and systematic uncertainties
- Measured energy spectrum agrees with the oscillated HKKM11 flux within estimated uncertainties

Systematic Uncertainty

Error size (%)



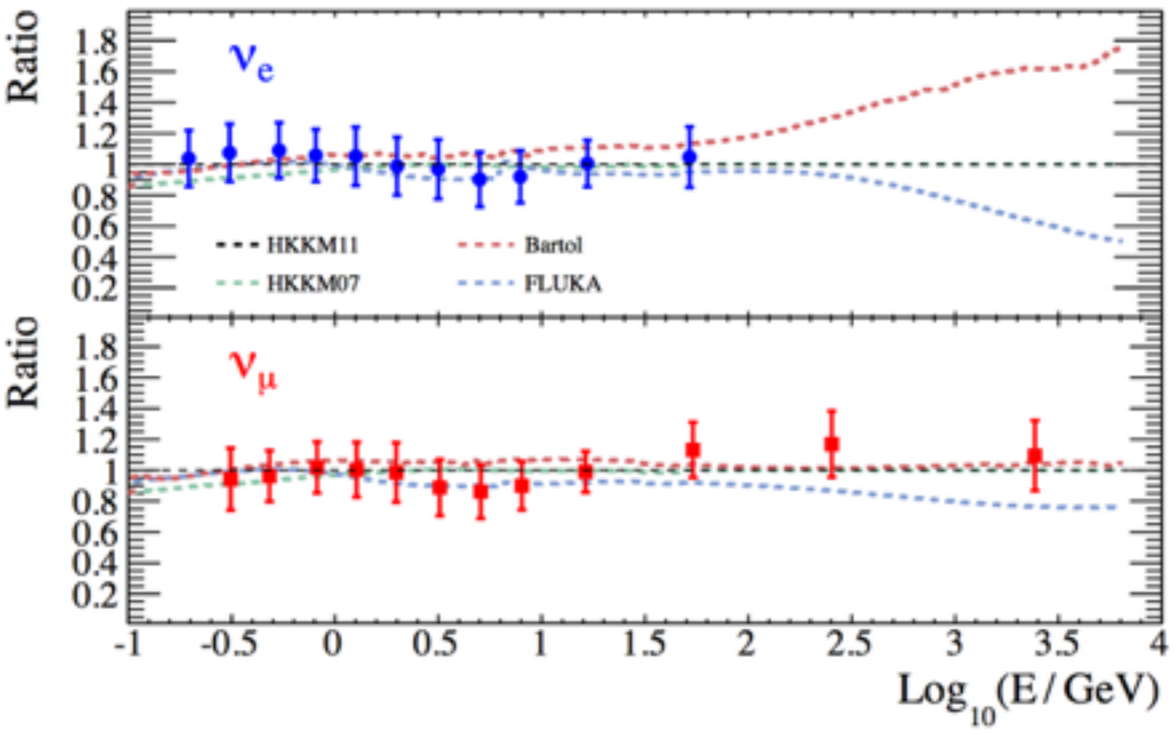
Correlation matrix

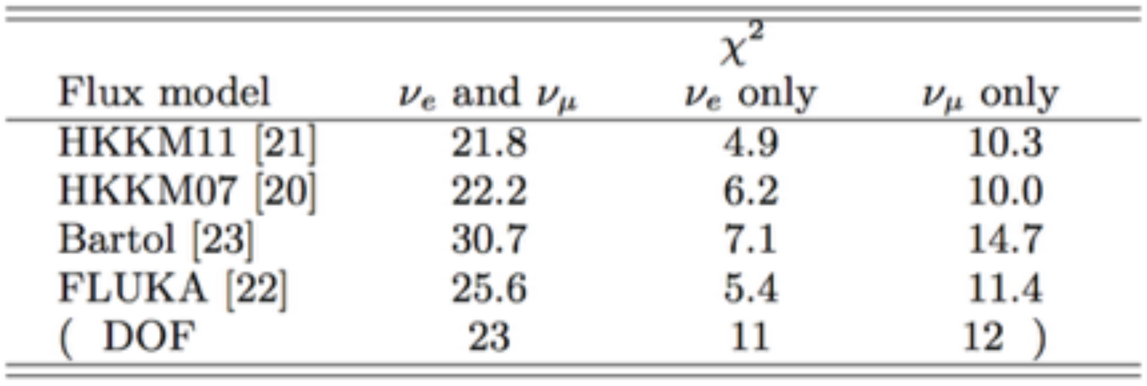


- Utilize almost same systematic error used in oscillation analysis (except for flux related)
- For error propagation to flux value, Toy MC method is adopted
- Toy MC data are calculated by (3.10) with random Gaussian g_k and error coefficient f_{jk}
- Unfold 2000 sets of Toy MC data, and calculated variance and correlation
- About 20% error estimated in total; cross section error dominant

$$\tilde{M}_j(\mathbf{g}) = \underset{\underset{\text{nominal MC}}{\uparrow}}{M_{MC,j}} \times \left(1 + \sum_{k}^{N_{sys}} \overset{\overset{\text{error coefficient}}{\swarrow}}{f_{jk}} \underset{\underset{\text{random Gauss.}}{\uparrow}}{g_k}\right) \qquad (3.10)$$

Comparison With Flux Models





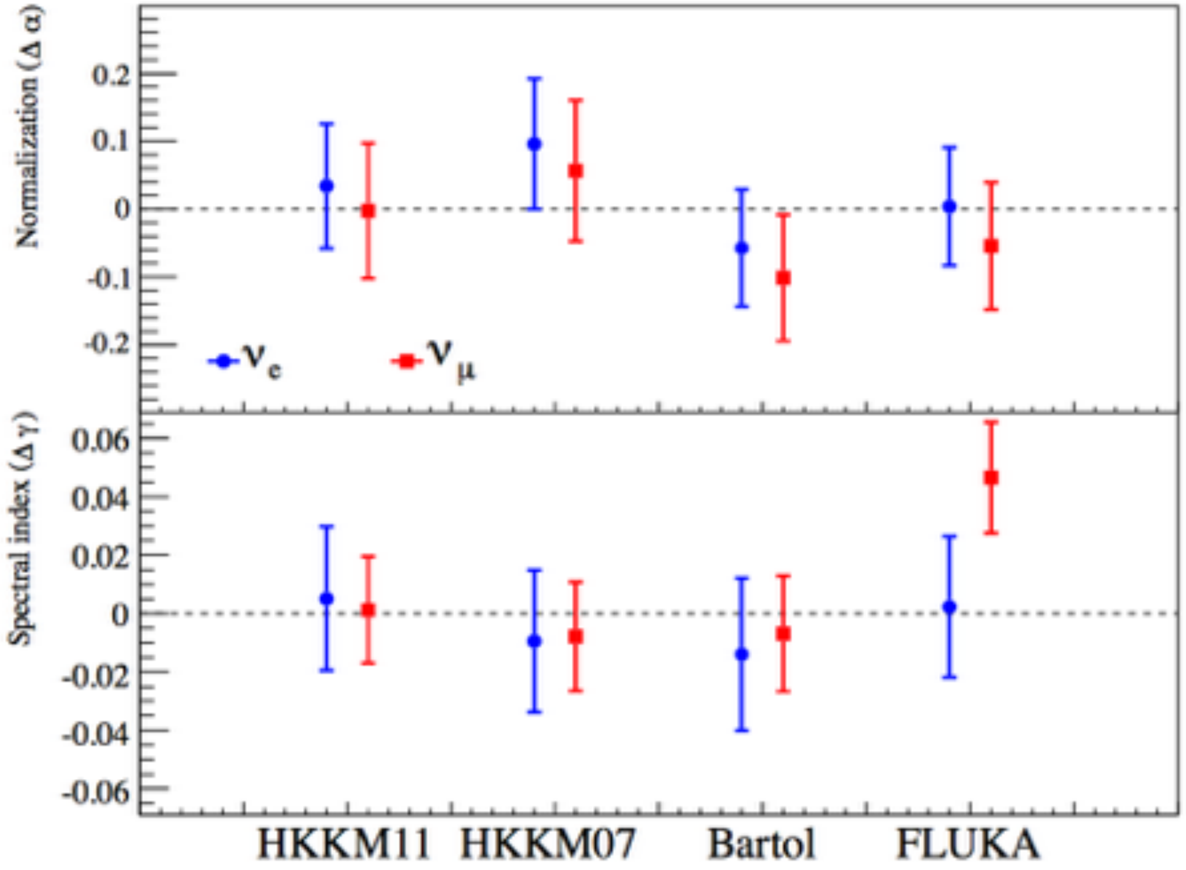
		χ^2	
Flux model	ν_e and ν_μ	ν_e only	ν_μ only
HKKM11 [21]	21.8	4.9	10.3
HKKM07 [20]	22.2	6.2	10.0
Bartol [23]	30.7	7.1	14.7
FLUKA [22]	25.6	5.4	11.4
(DOF	23	11	12)

- Test agreement with several flux models by χ^2 value including error correlation
- Not strongly inconsistent
- p-value: 0.53, 0.32, 0.13 for HKKM11, FLUKA, Bartol, respectively

$$\chi^2 = \sum_i^N \sum_j^N (\Phi_i - \Phi_{MC,i})^T C_{ij}^{-1} (\Phi_j - \Phi_{MC,j}) \quad (3.12)$$

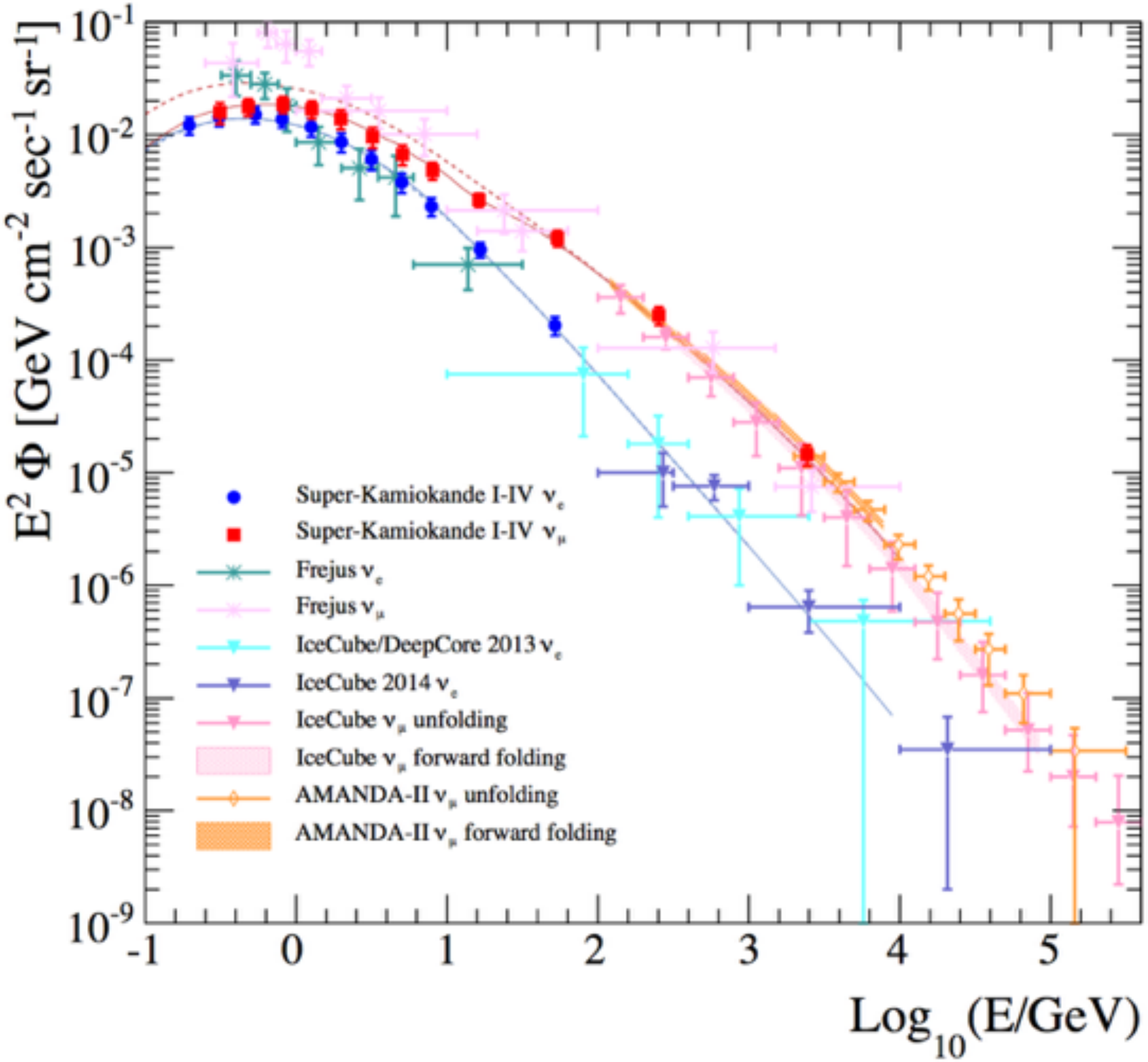
Fit with Variable Normalization and Spectral Index

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



- Fit data and models with variable normalization ($\Delta\alpha$) and spectral index ($\Delta\gamma$) parameters
- Agrees within 1σ except form FLUKA ν_μ spectrum (2.4σ)

Comparison to Other Experiments

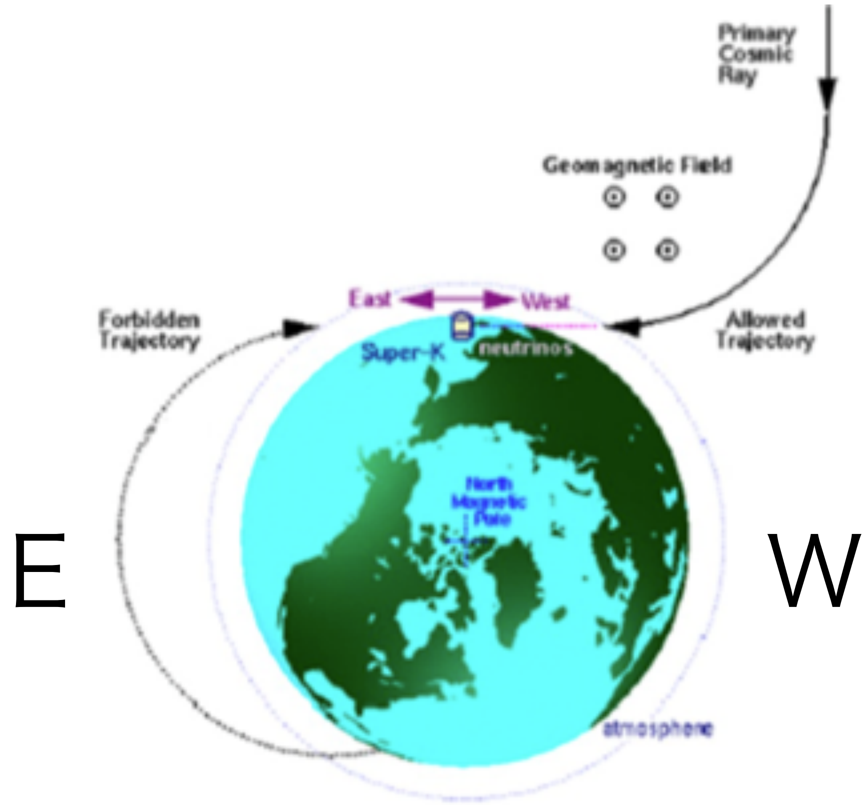


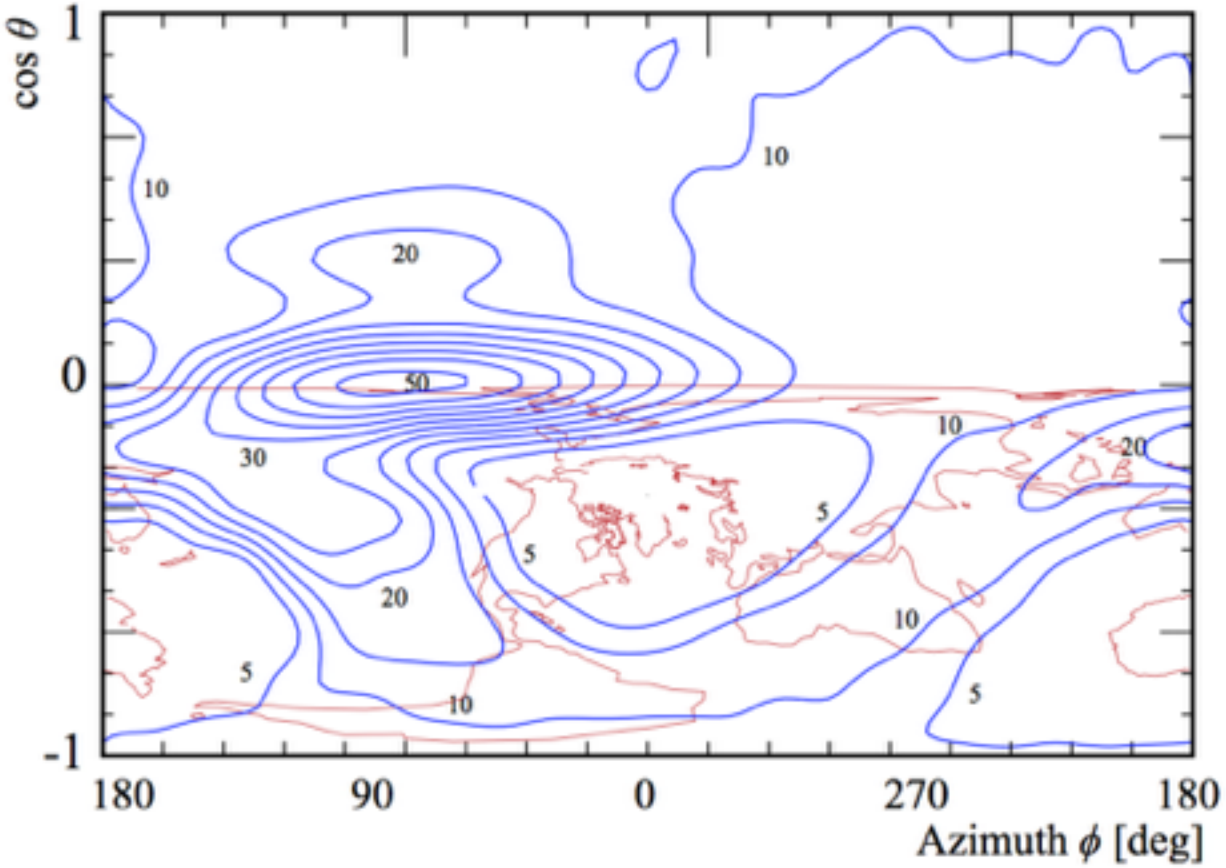
- Our measured data provide significantly improved below 100 GeV
- Extended to lower energies down to ~100 MeV
- Overlap in high energy with AMANDA and IceCube regions

Azimuthal Spectrum Analysis

Geomagnetic Effect

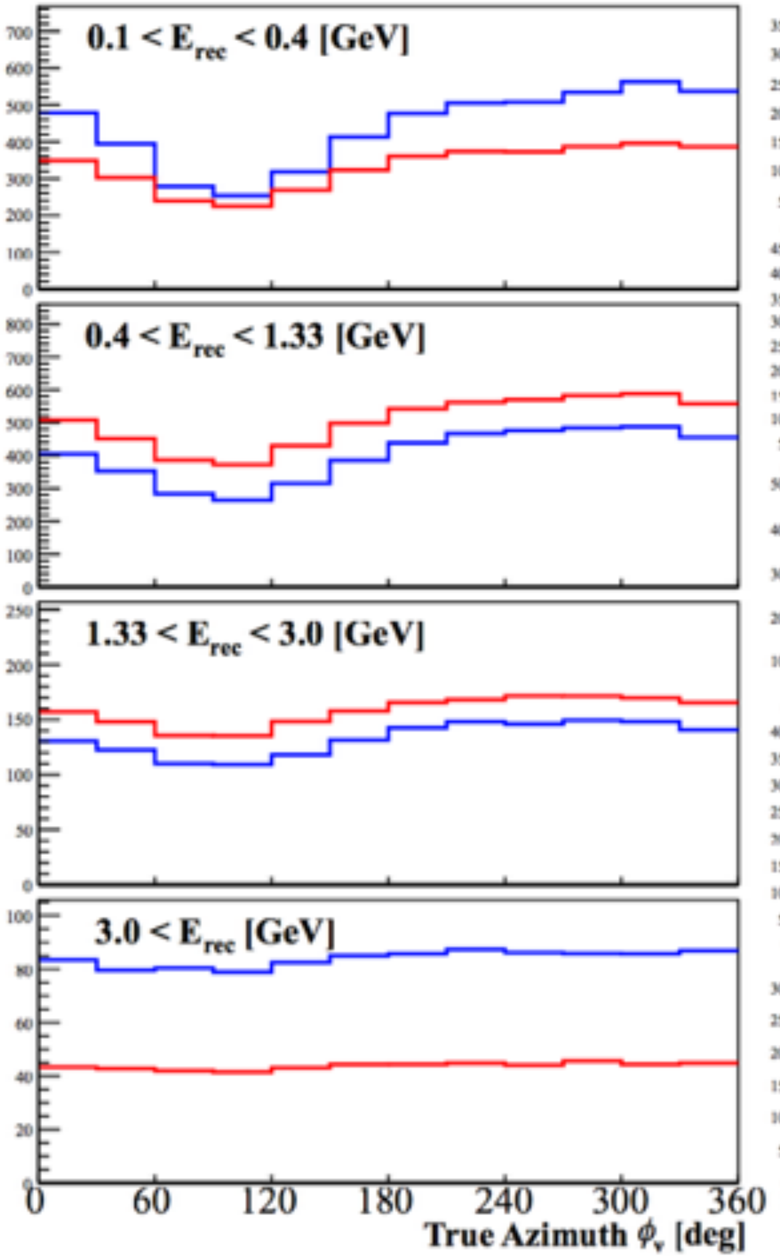
- Rigidity cutoff due to geomagnetic field depends on position and direction at Earth’s surface
- Well-known effects on cosmic ray flux, such as “east-west effect” dipole asymmetry
- Can test for such asymmetries by using neutrino



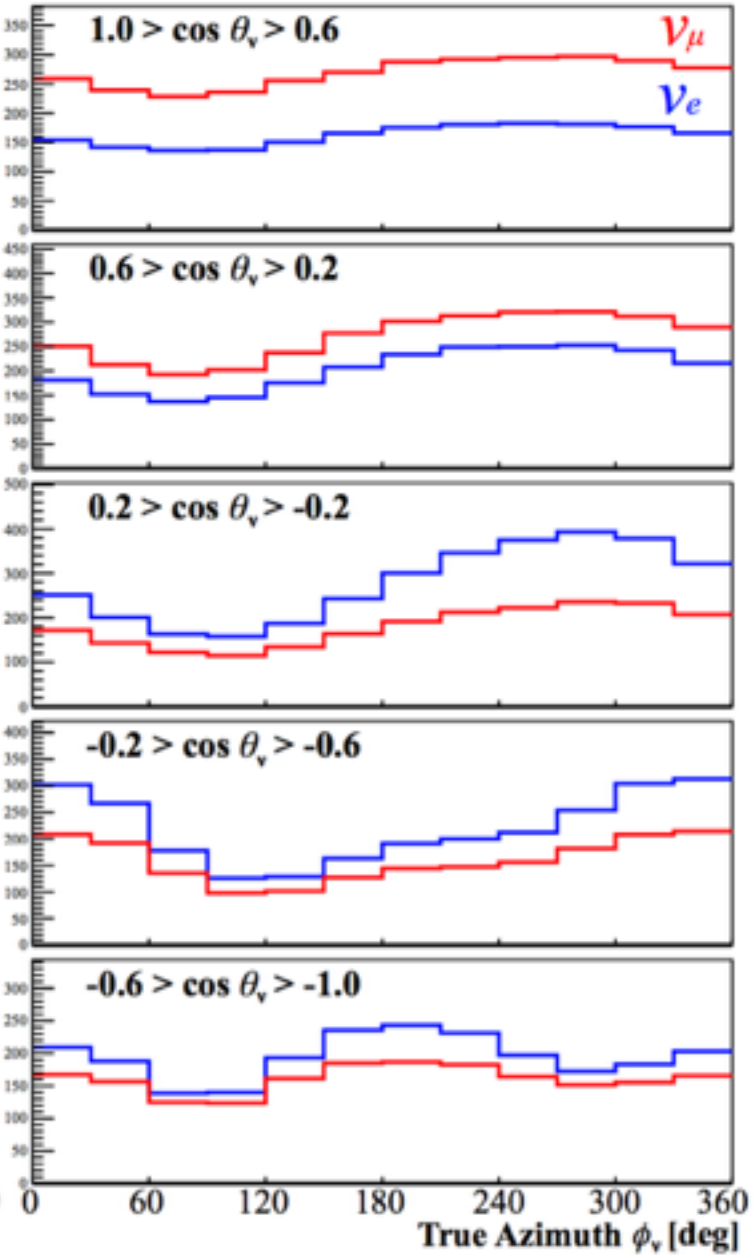


Azimuthal Distributions (True)

Energy-dependent



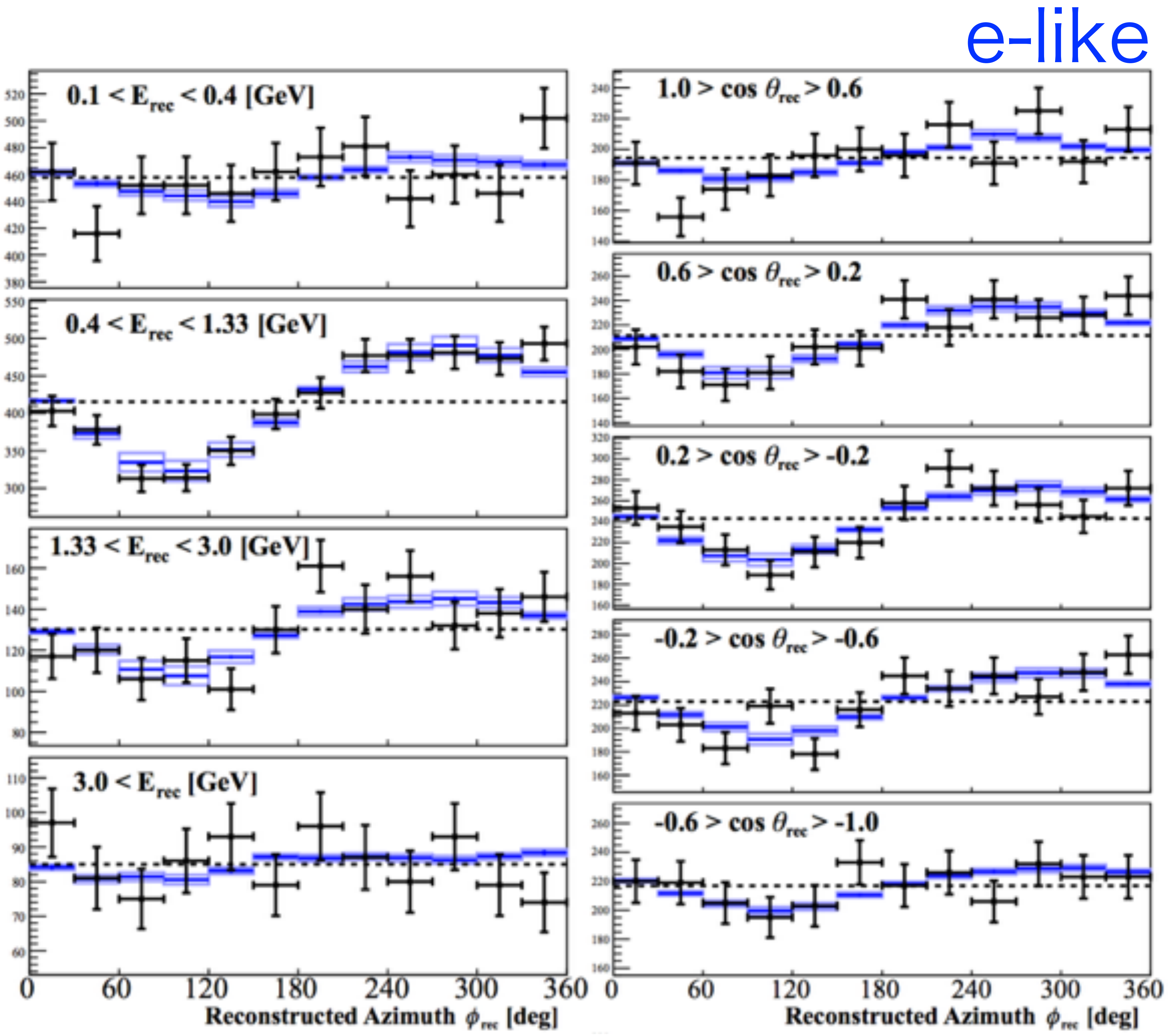
Zenith-dependent



S W N E

- Sample: fully-contained single-ring events
- True neutrino direction and reconst. energy
- Asymmetry becomes larger for lower energies and near horizontal direction

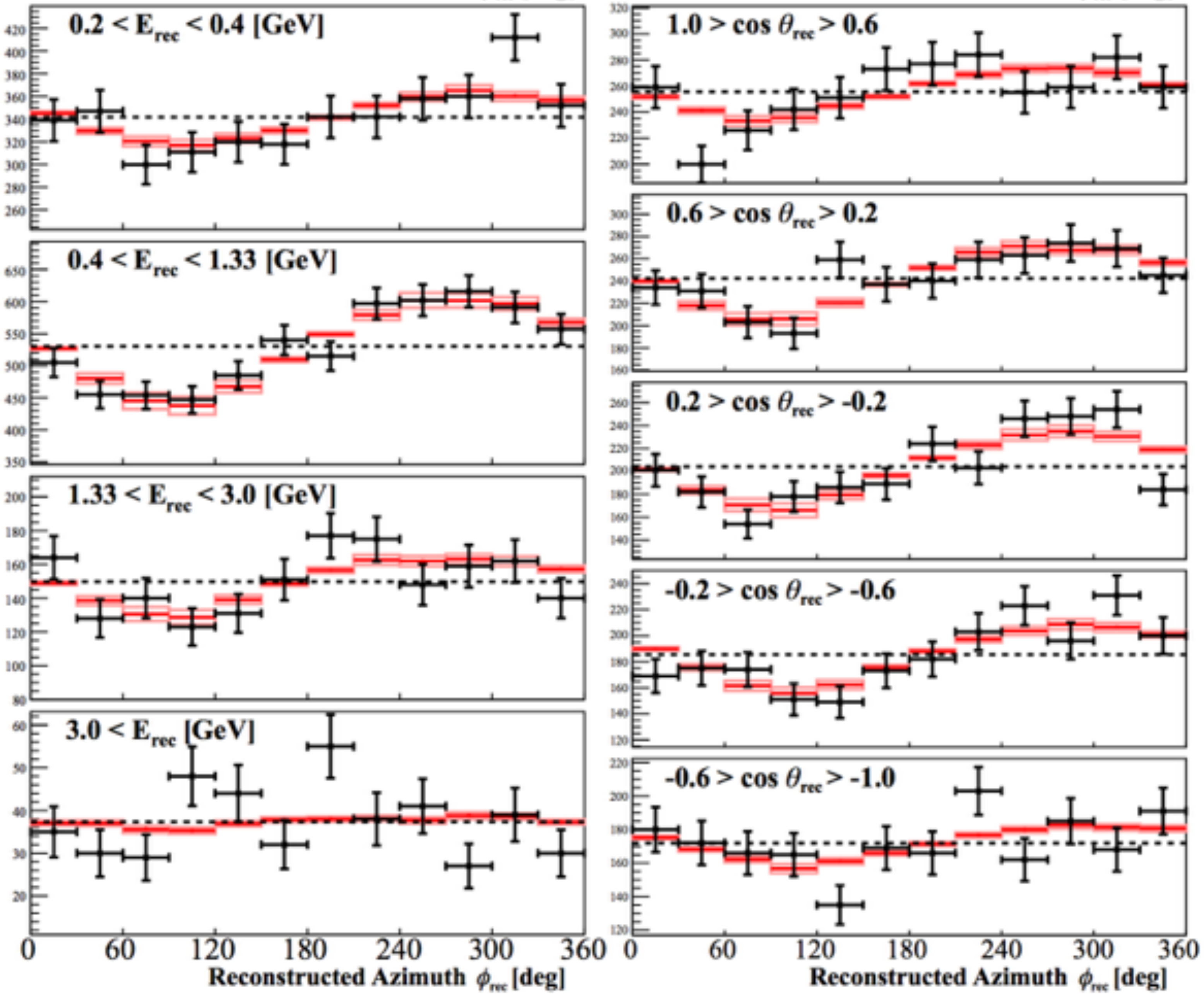
Azimuthal Distributions (Reconst.)



- Reconst.: scattered lepton direction
- Large scattering in sub-GeV energy
- Asymmetry effect smear out in E<0.4 GeV due to larger scattering of lepton
- Asymmetry still visible in E>0.4 GeV

Azimuthal Distributions (Reconst.)

μ-like

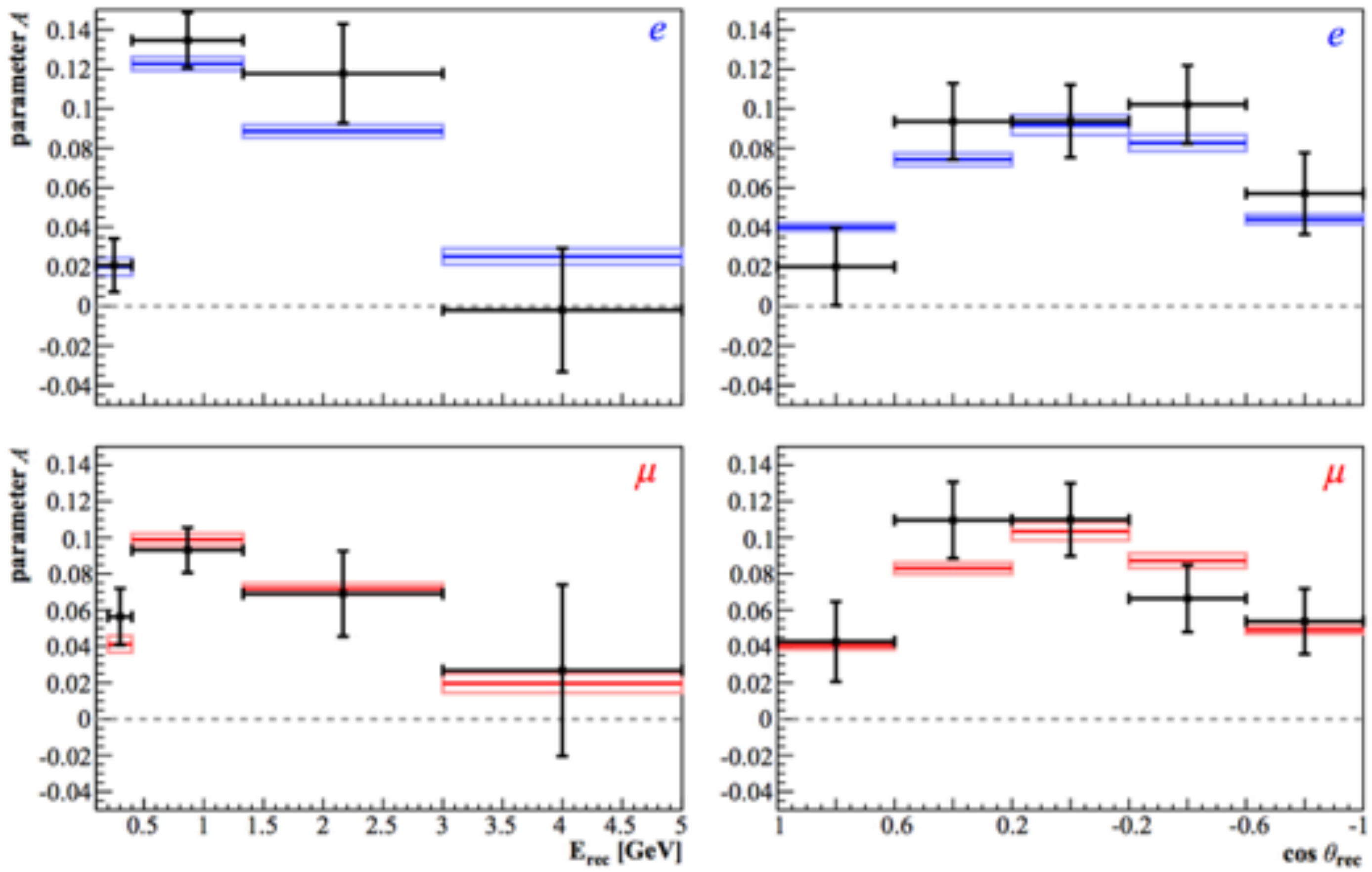


- Reconst.: scattered lepton direction
- Large scattering in sub-GeV energy
- Asymmetry effect smear out in E<0.4 GeV due to larger scattering of lepton
- Asymmetry still visible in E>0.4 GeV

Energy and Zenith Dependence

- Test for in each energy and zenith angle with asymmetry
- N_{east} (N_{west}) are number of east (west) going events
- Agrees with expectation within statistical uncertainties
- HKKM11 calculation models geomagnetic effect well

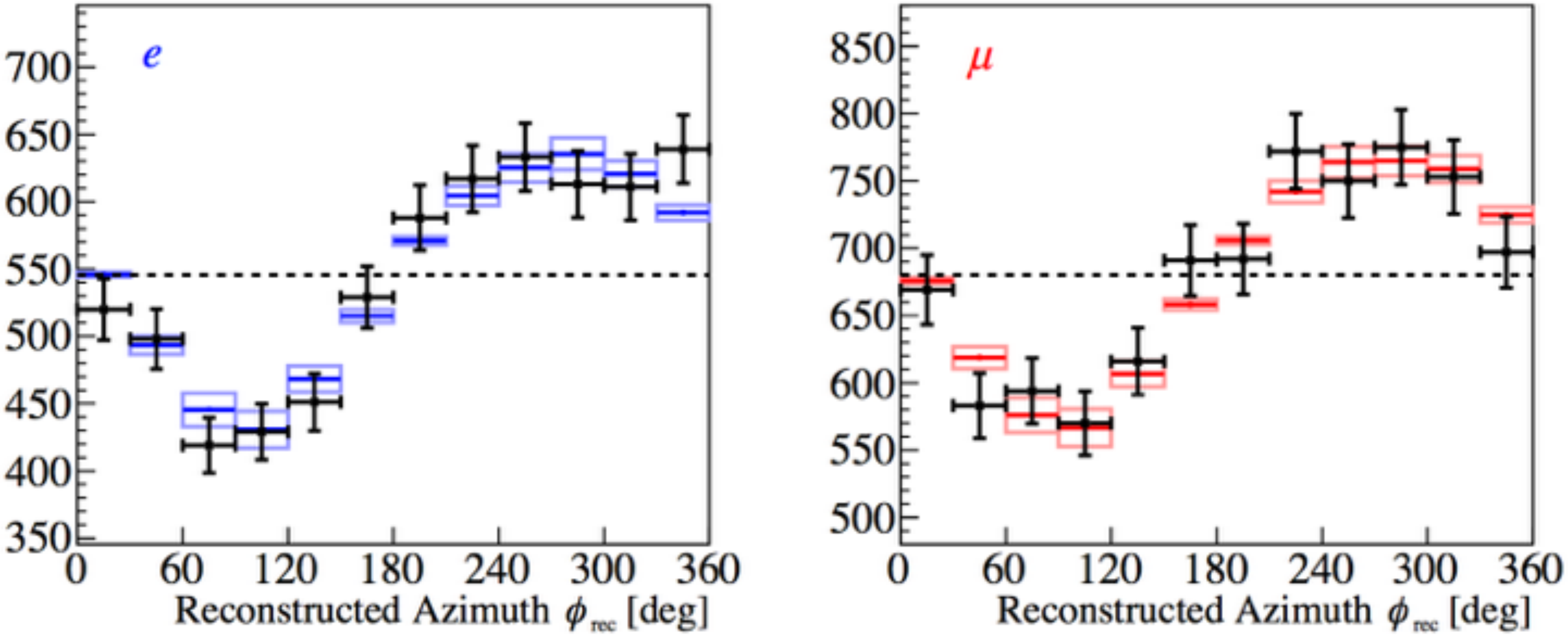
$$A = \frac{n_{\text{east}} - n_{\text{west}}}{n_{\text{east}} + n_{\text{west}}}$$



East-West Asymmetry

- Select sub-sample by |cosθ|<0.6 and 0.4<Erec<1.33 GeV to optimize significance of asymmetry
- Clear asymmetries are seen and significance level is 6.0σ (8.0σ) for μ-like and e-like

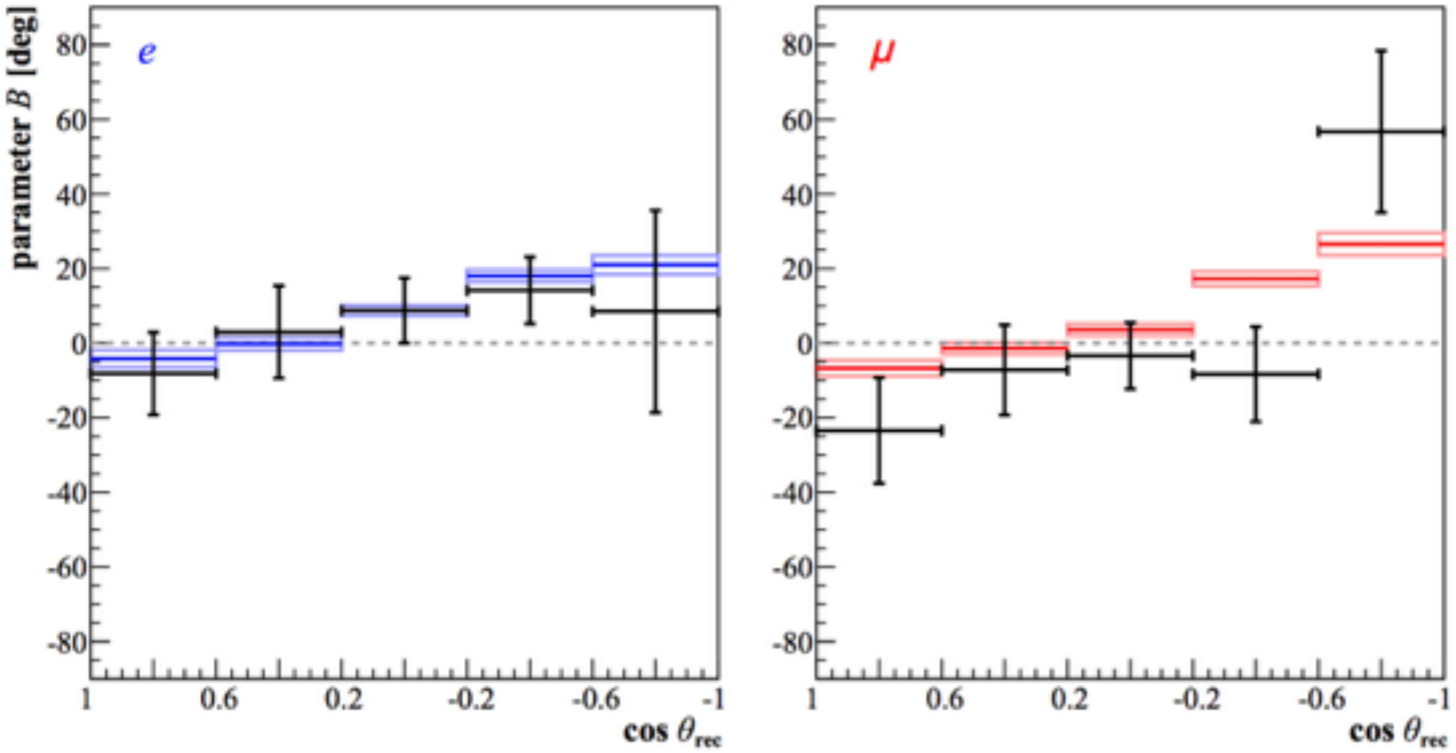
$$A_\mu = 0.108 \pm 0.014(\text{stat}) \pm 0.004(\text{syst})$$
$$A_e = 0.153 \pm 0.015(\text{stat}) \pm 0.004(\text{syst})$$



Zenith Dependence of Asymmetry

- Actually the geomagnetic structure is more complicated
- Check zenith dependence of asymmetry by fitting azimuth distribution in each zenith bin by

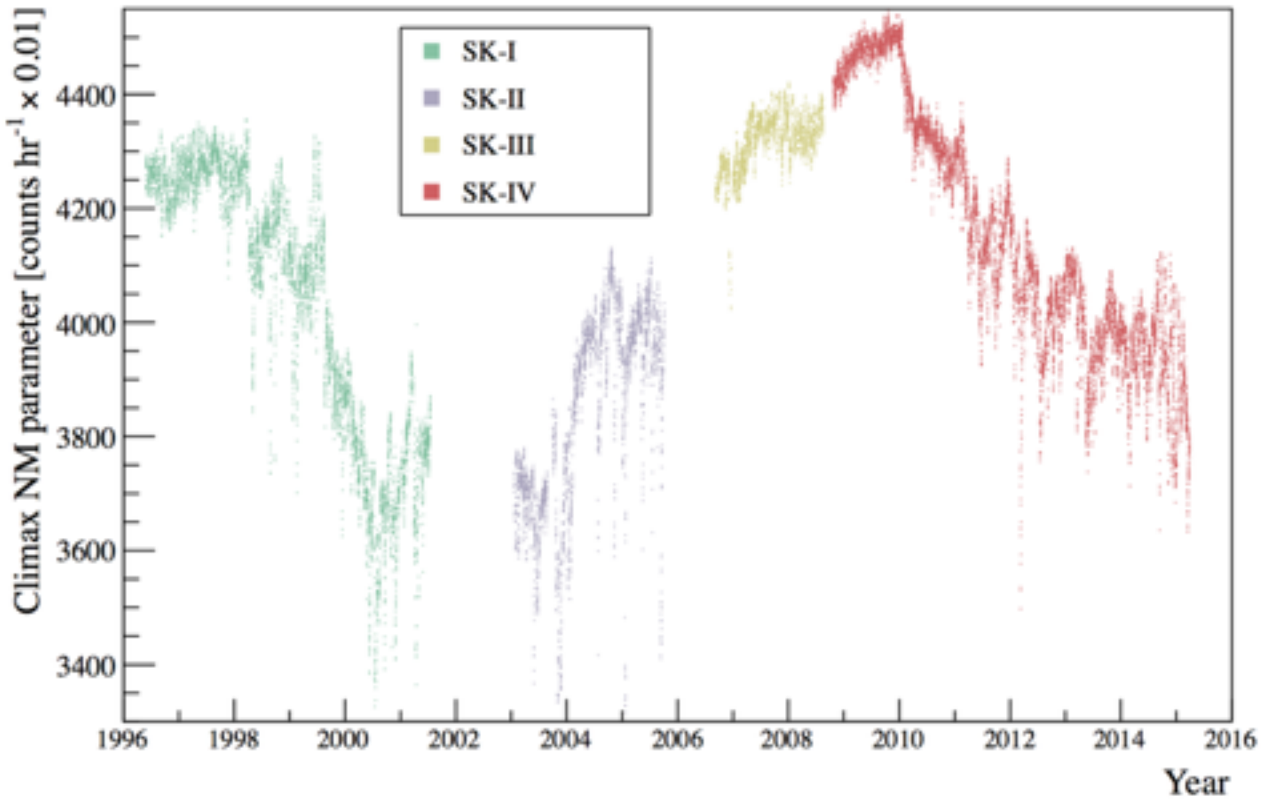
  $k_2 \times \sin(\varphi+B) + k_1$
- Dependence is seen with 2.2σ significance, and consistent between data and MC prediction



Solar Modulation Analysis

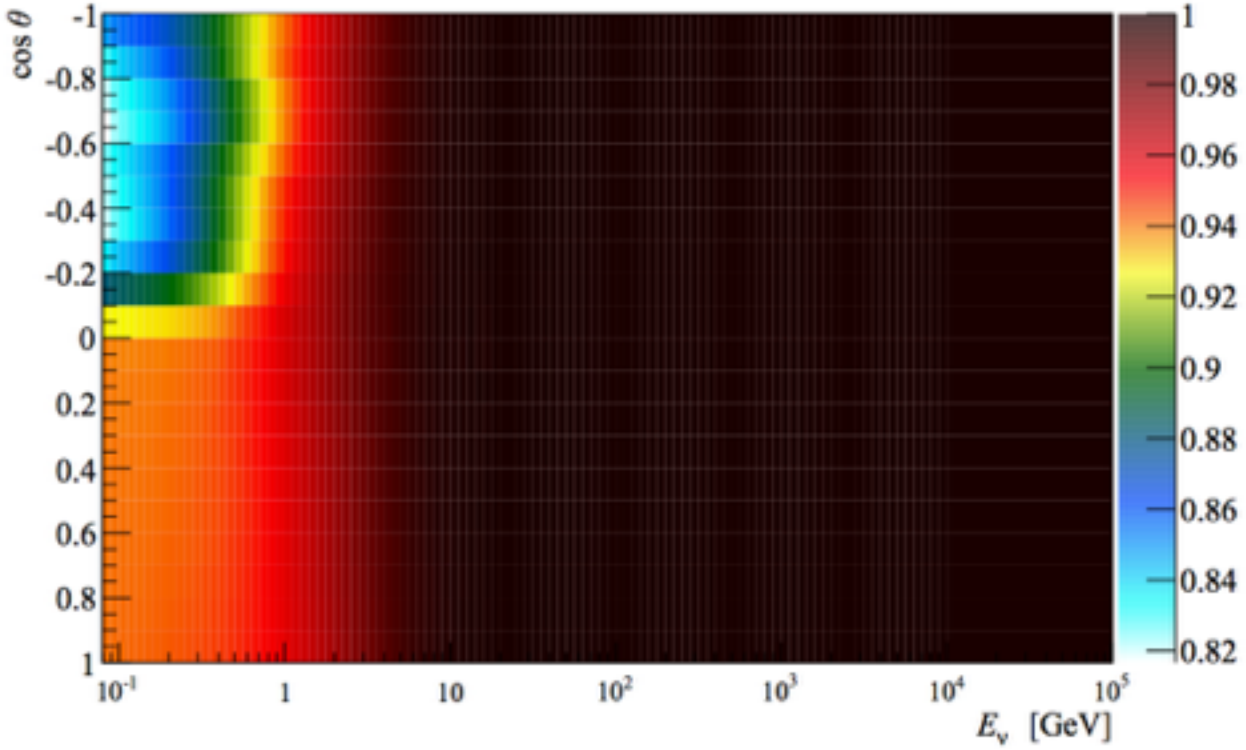
Solar Activity and Neutron Monitors

- CR flux is known to be anti-correlated with solar activity since solar wind scatters out CRs
- Test to see if neutrino flux is similarly correlated.
- SuperK data covers more than one and half solar cycles
- Use neutron monitor (NM) at Earth's surface as estimator of solar activity and modulation of CR flux

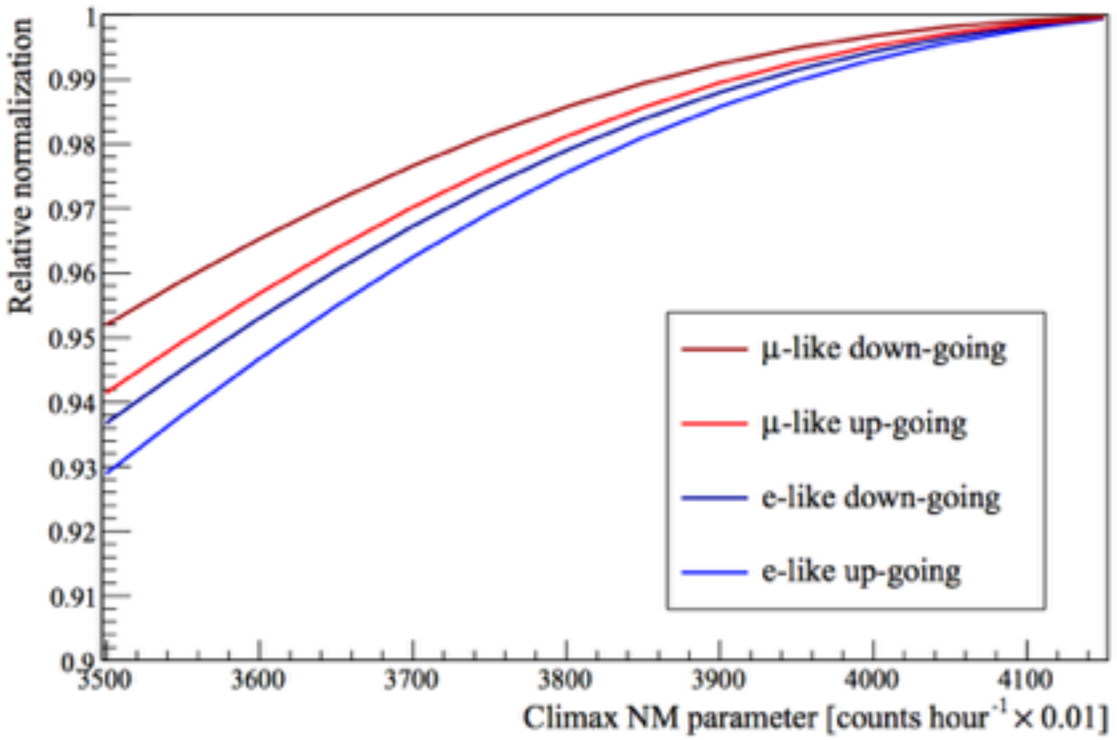


Modulation Effect in Flux Prediction

- In HKKM flux model, solar effect of flux prediction is implemented as a function of energy, neutrino direction and NM count
- Effect is larger for upward direction since polar regions, where solar effect is larger, are below horizon



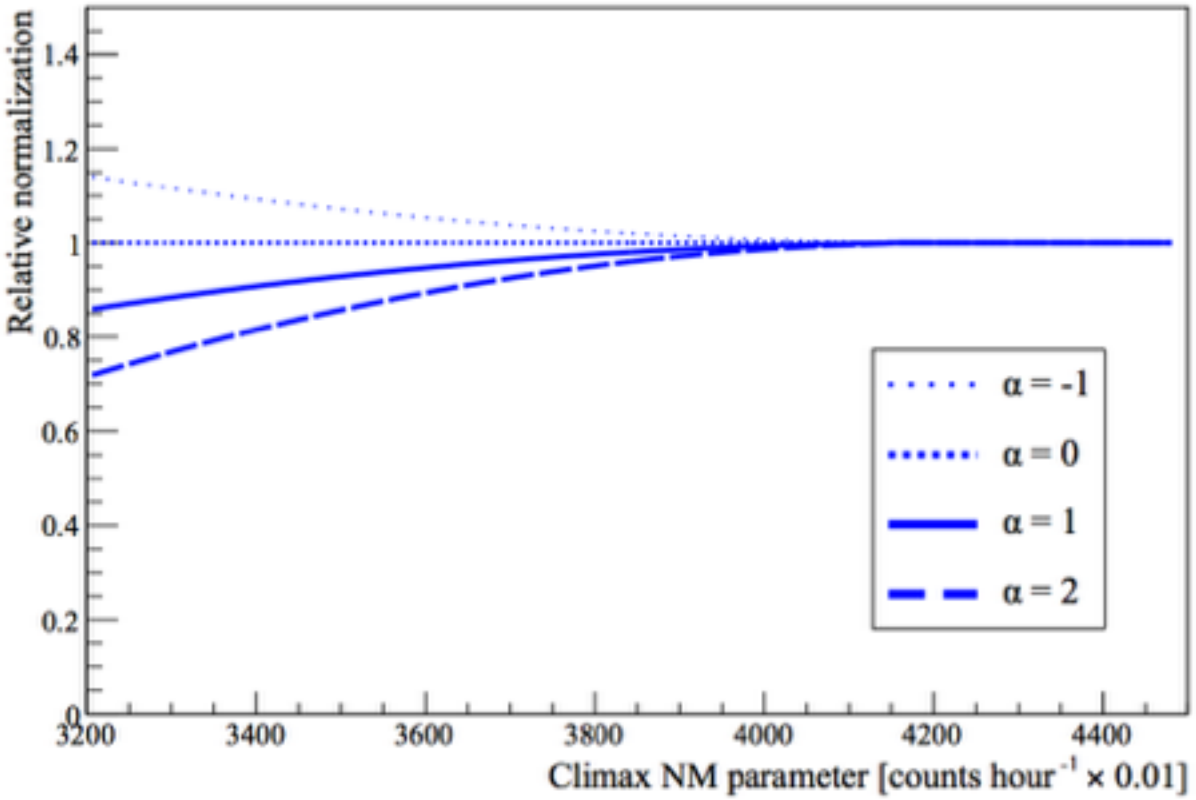
expected change of ν_e flux



relative normalization change

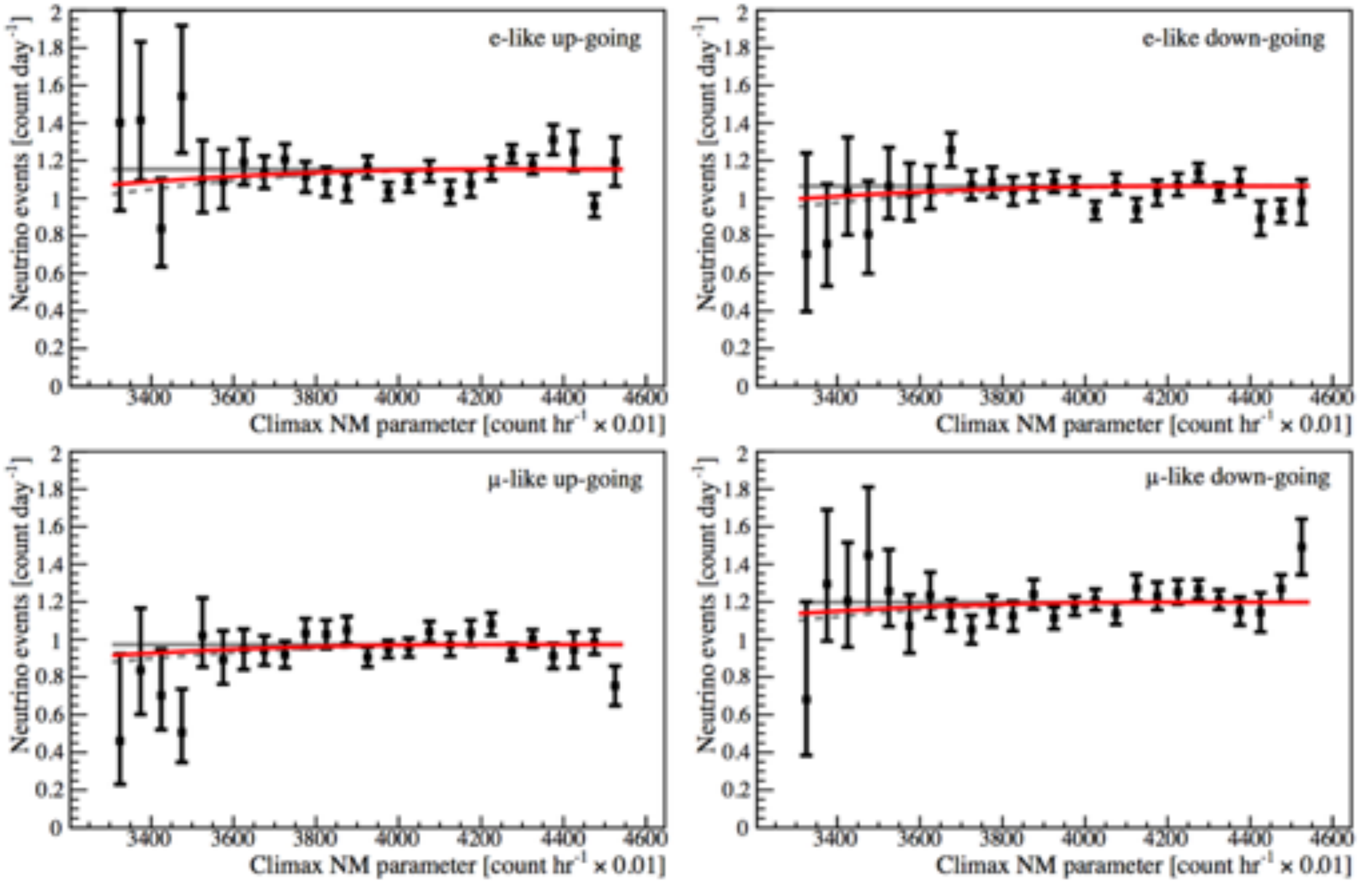
Correlation Parameter

- To estimate correlation between neutrino and NM, α parameter is introduced (=0: no correlation, =1:expected correlation)
- Estimate by fitting data and prediction with varying α



Fitting Result

- Single-ring sub-GeV events (Evis<1.33GeV) are used for anlysis
- sample are divided into SK phase, e-like / μ-like, upward/ downward
- Best fit: α = 0.62 +- 0.58. significance: 1.06 σ



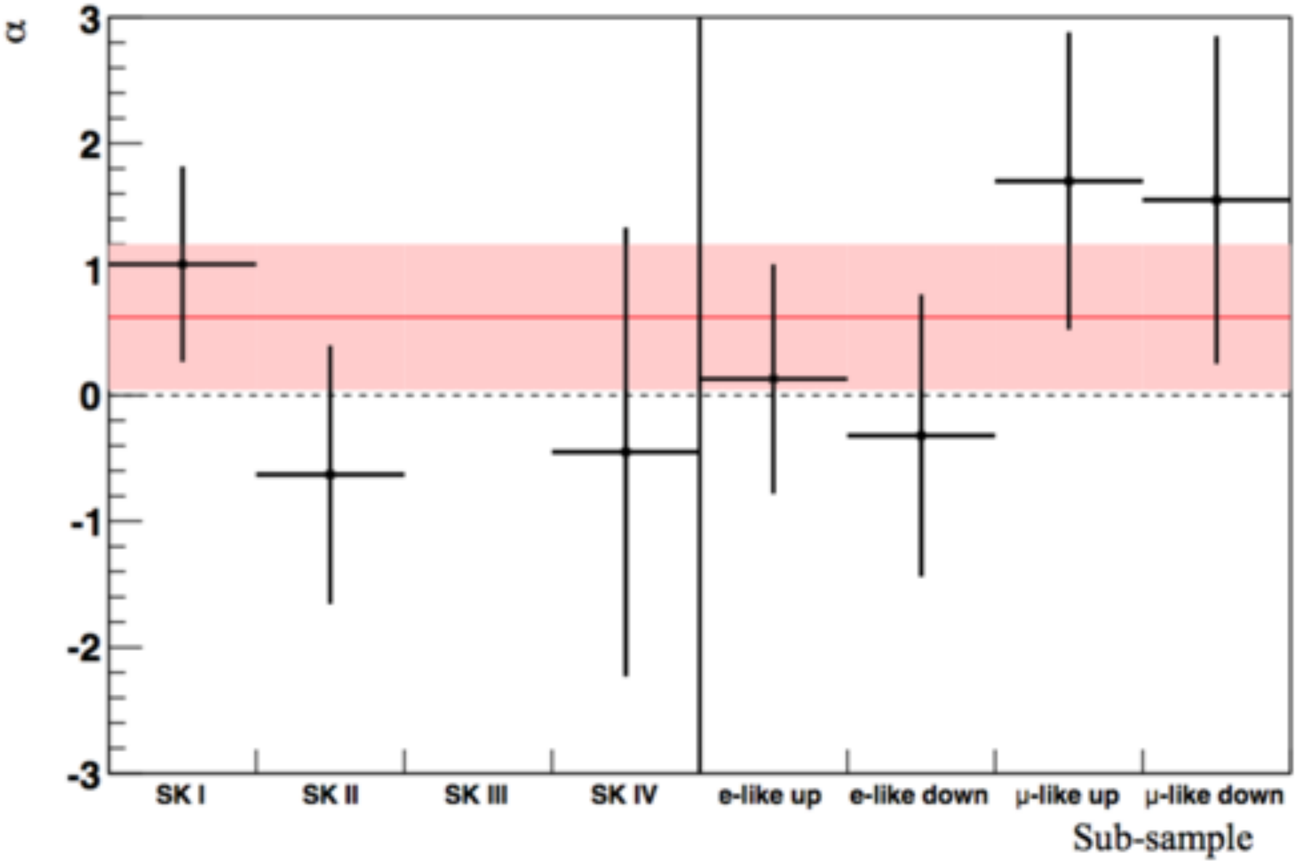
red solid: best fit

grey dashed: predicted

grey solid: no correlation

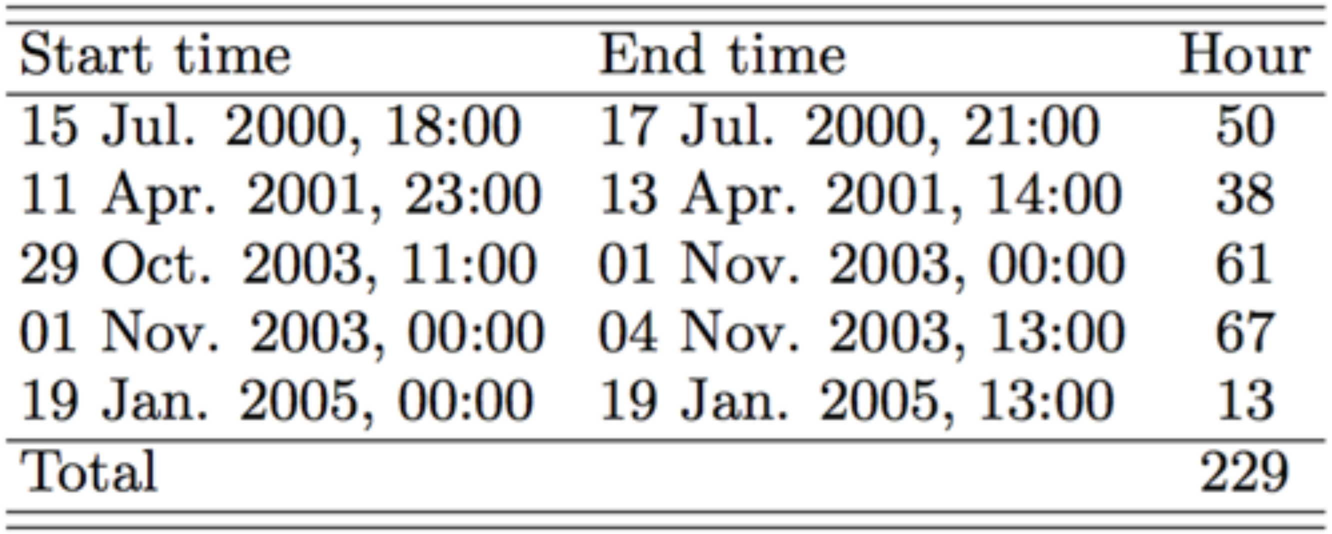
Fitting Result

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



Study of Forbrush Events

- For very high solar activity (NM < 330,000 hr^{-1}), so called “Forbrush period”, no prediction is available, but expect decrease of neutrino events
- 7.1 days of “Forbrush period” data has analyzed, and found
  20 events observed
- 32.80 +- 0.17 events expected in case of no correlation
- p-value to observe 20 or less: 0.017
- 98.3% (2.38σ) rejection of no-correlation hypothesis



Start time	End time	Hour
15 Jul. 2000, 18:00	17 Jul. 2000, 21:00	50
11 Apr. 2001, 23:00	13 Apr. 2001, 14:00	38
29 Oct. 2003, 11:00	01 Nov. 2003, 00:00	61
01 Nov. 2003, 00:00	04 Nov. 2003, 13:00	67
19 Jan. 2005, 00:00	19 Jan. 2005, 13:00	13
Total		229

Period of NM>330,000 hr^{-1}
during SK I-IV

Summary (1)

- 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 $2.2\ \sigma$ level

Summary (2)

- Expected correlation between neutrino flux and solar activity was studied using sub-GeV sample
  - Predicted effect is found to be relatively small, and an indication is seen at 1.1σ level
  - A decrease of neutrino flux was seen at 2.4σ level during particularly intense solar activity period

Backup