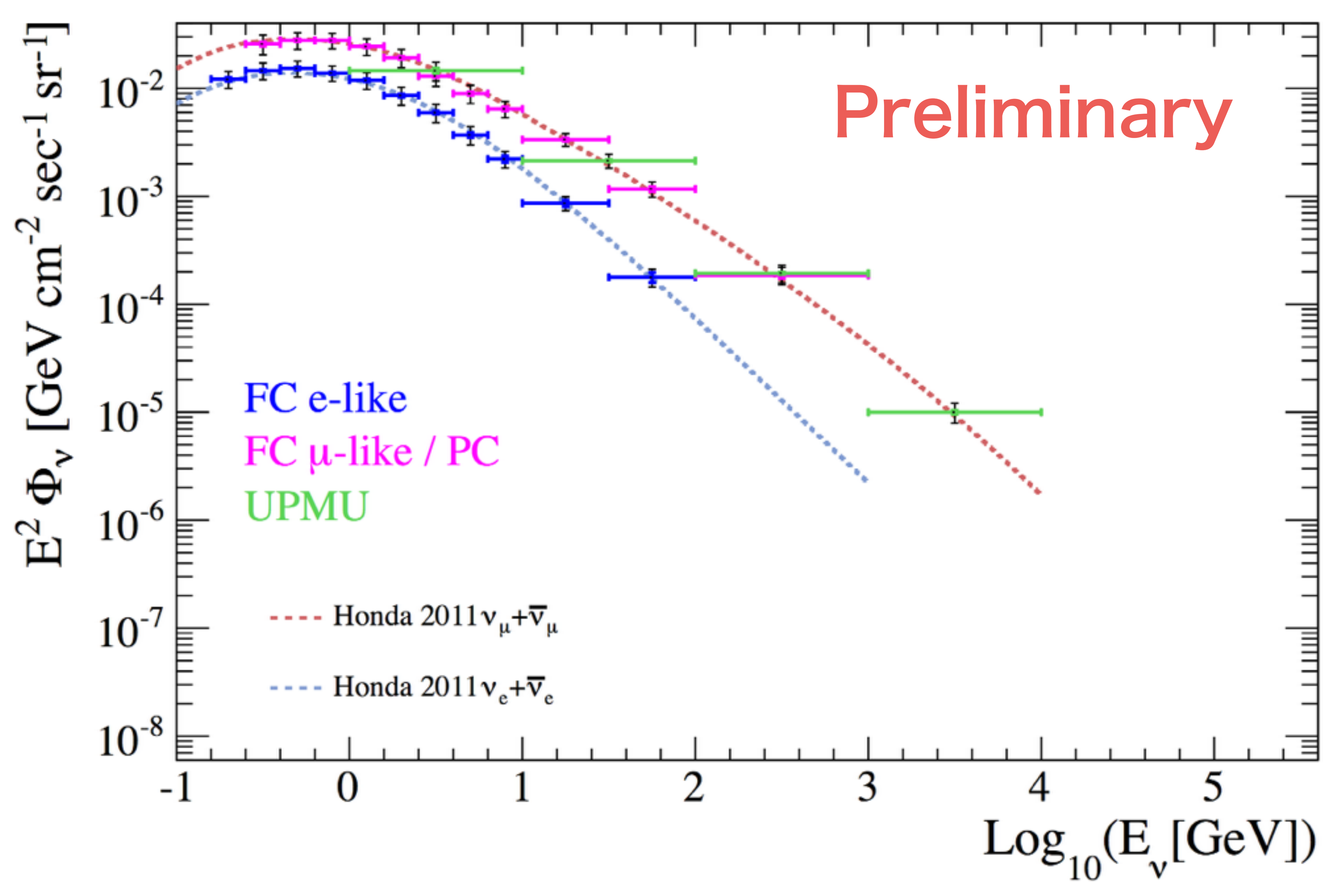
Atmospheric neutrino flux measurement by Super-Kamiokande

Kimihiro OKUMURA and Euan RICHARD (ICRR, Univ. of Tokyo) for Super-Kamiokande collaboration
Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo
okumura@icrr.u-tokyo.ac.jp richard@icrr.u-tokyo.ac.jp

Abstract

Directional-integated fluxes of atmospheric electron and muon neutrinos are measured in the energy range from sub-GeV to several TeV using Super-Kamiokande detector. Super-Kamiokande is the largest detector in the world which has sensitivity in this energy range, and excellent capabilities to distinguish ν_μ and ν_e by particle identification of out-going leptons. The energy spectrum is reconstructed using unfolding technique with the estimation of the systematic uncertainties, and compared with the existing flux calculation models.



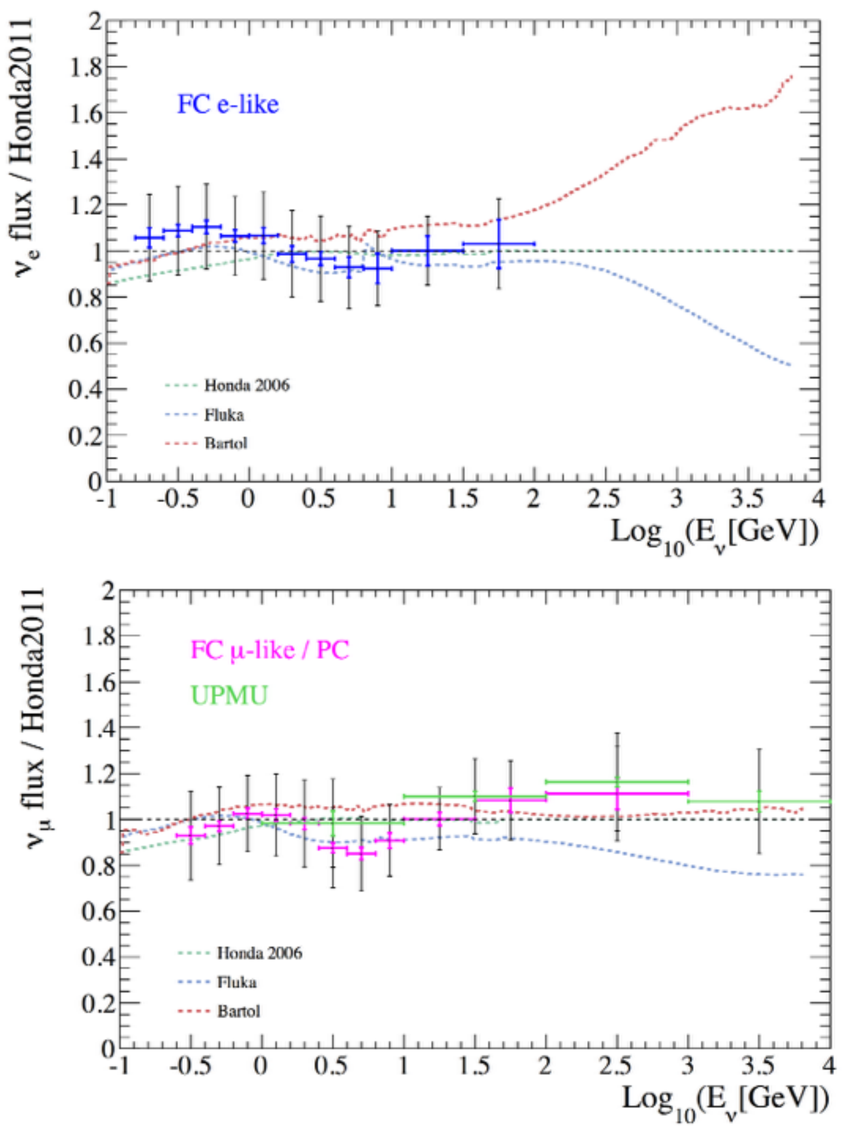


Figure 1 (left):
Directional-integrated ν_e (blue) and ν_μ (magenta and green) energy spectrum of atmospheric neutrino measured by Super-kamiokande detector.

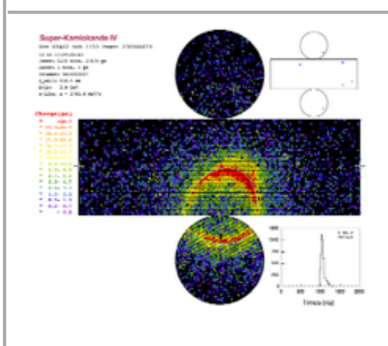
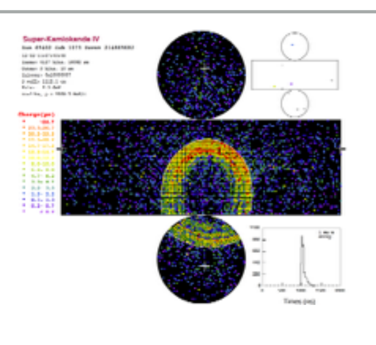
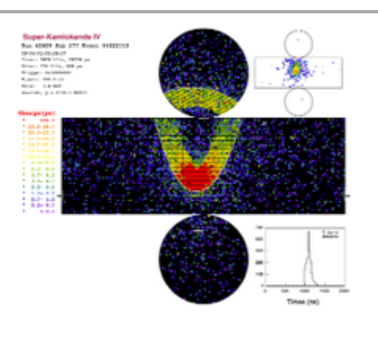
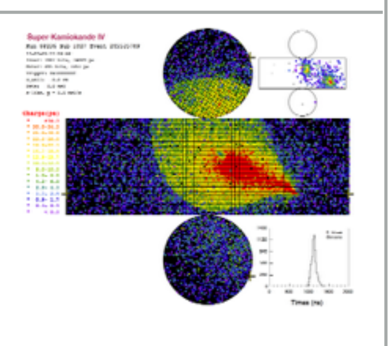
Figure 2 (right):
Ratio between measured flux and Honda 2011 calculation [1]. Colored and thick error bar shows statistical error, and black and thin error bar shows systematic error. Other flux models (Honda 2006 [2], Bartol [3], Fluka [4]) are also shown for comparison. Large difference in high energy electron neutrino flux is due to kaon production uncertainty.

Motivation

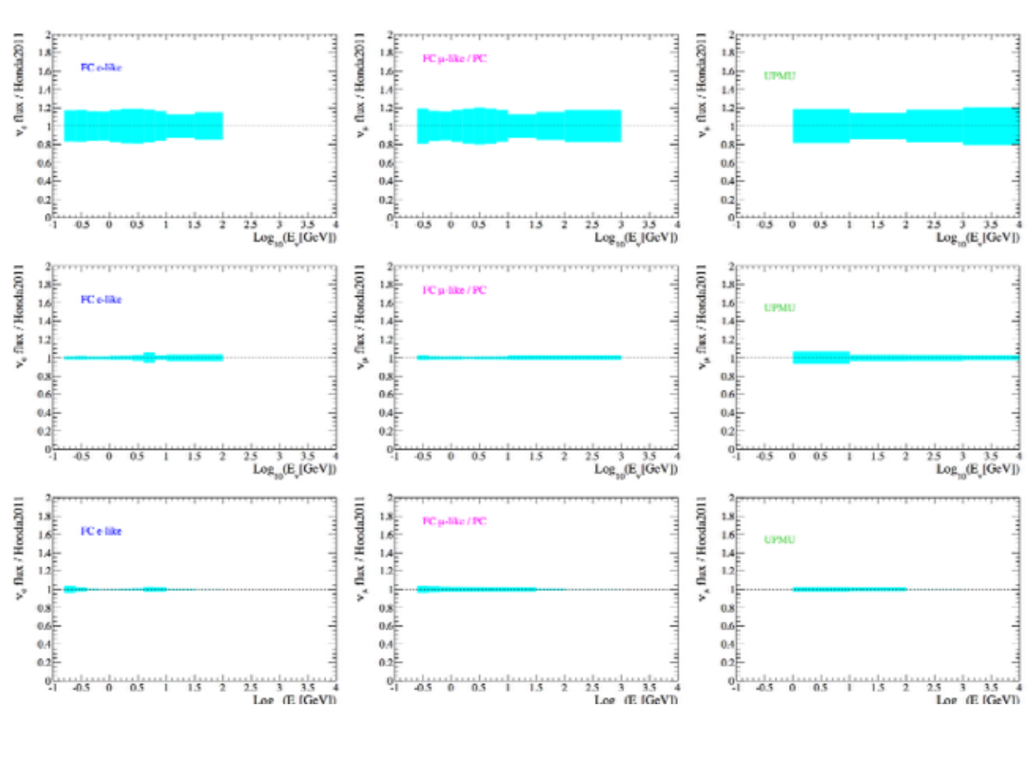
- Quantify neutrino flux with current understanding uncertainties and compare existing flux model.
- Give constraint on flux uncertainties due to kaon production.
- Scientific requirements in astroparticle physics (ex. HE astronomical ν).

Event sample

- Three sample (fully-contained, partially-contained, upward-going muons) are utilized.
- FC are separated into electron-like and muon-like by particle identification algorithm.
- PC and UPMU are categorized by ν_μ sample, but ν_μ flux by UPMU are separately calculated due to different acceptance of solid angle.
- Eliminate neutral current enriched sub-sample to enhance flux sensitivity.

ν_e flux	ν_μ flux		
Fully-contained (FC) electron-like	Fully-contained (FC) muon-like	Partially-contained (PC)	Upward-going muon (UPMU)
			
0.15 ~ 100 GeV	0.25 GeV ~ 1 TeV		1 GeV ~ 1 TeV
4π	4π		2π

Uncertainties in measured flux



- Statistical and systematic uncertainties are estimated by toy calculation.
- Cross section, detector, neutrino oscillation uncertainties are considered.
- Uncertainties in oscillation parameters are based on PDG 2013.
- About 20% of cross section uncertainties are dominated in flux measurement.

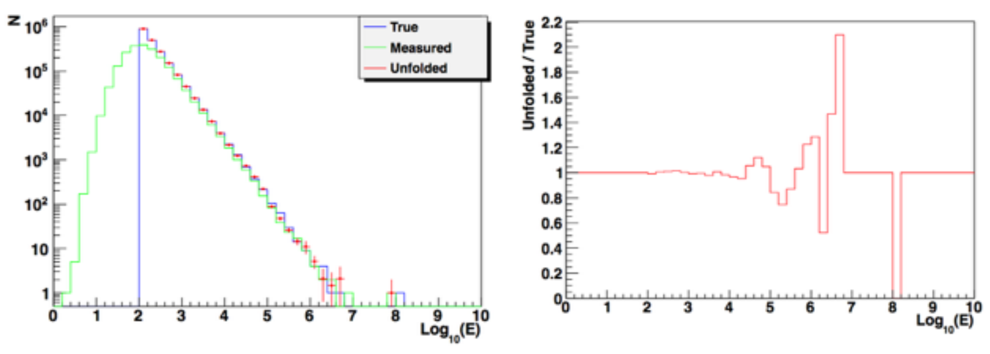
Figure 6 (left) : Breakdown of each systematic error sources (top: cross section, middle: detector-related, bottom: neutrino oscillation).

Flux reconstruction

Bayes unfolding:

We adopt iterated Bayes unfolding [5] (implemented in RooUnfold) to convert from observable to neutrino energy spectrum.

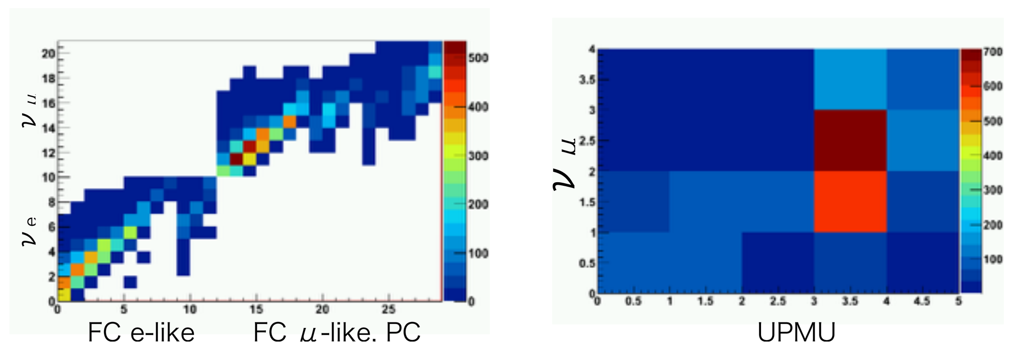
Figure 3 (right) : one example by toy simulation to demonstrate performance of Bayes unfolding method. Power-law spectrum of $E^{-3.0}$ is nicely reconstructed.

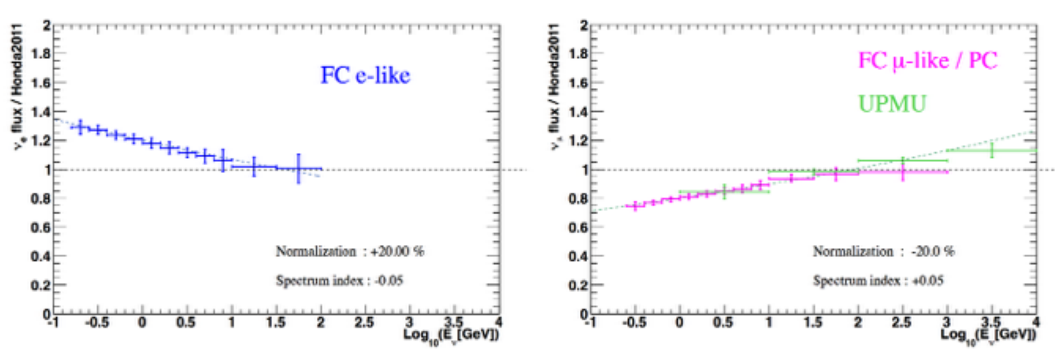


Response function:

and provide for each Super-K period (SK1-4) respectively.

Figure 4 (right) : response function between observable (FC, PC, UPMU) to neutrino spectrum (ne, nm) used in SK4.





Bias check:

Reproducibility of energy spectrum is checked by bias study using Monte-Carlo sample.

Figure 5 (left) : reconstructed (data) and input (dashed line) spectra by bias study. input spectrum is modified for normalization and spectral index from nominal MC.

FC/PC
$$\int d\Omega\, \Phi_i = \int d\Omega\, \Phi_i^{MC} \cdot \frac{N_i^{CC}}{\int d\Omega \int dE\, \Phi^{MC}(E)\, O(E)\, \sigma(E)\, \epsilon^{CC}(E)\, VT}$$

UPMU
$$\int d\Omega\, \Phi_i = \int d\Omega\, \Phi_i^{MC} \cdot \frac{N_i^{CC}}{\int d\Omega \int dE\, \Phi^{MC}(E)\, O(E)\, A(E)\, T}$$

Flux calculation:

Flux values are calculated using reconstructed number of CC events and Monte-Calro expectations according to these formula.

Conclusions and discussions

- Atmospheric neutrino flux is measured from sub-GeV to 100 GeV and 10 TeV for ν_e and ν_μ, respectively, by Super-Kamiokande. Bayes unfolding method is utilized and energy spectrum reproducibility is checked by bias check. Statistical and systematic uncertainties are estimated by toy calculation, and about 20% uncertainties are derived. Calculated fluxes agree with existing flux models within systematic uncertainties.
- As shown in Figure 2, measurement of wider energy range with km³ size detector would lead better understanding of atmospheric neutrino spectrum, and also could constraint uncertainty due to kaon production by combined analysis.

Reference

[1] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D 83, 123001 (2011).
[2] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D 75, 043006 (2007).
[3] G. D. Barr, T. K. Gaisser, P. Lipari, S. Robbins, and T. Stanev, Phys. Rev. D 70, 023006 (2004).
[4] G. Battistoni, A. Ferrari, T. Montaruli, and P.R. Sala, Astropart. Phys. 19, 269 (2003).
[5] Nuclear Instr. and Methods A 362 (1995) 487-498