Classification of Super-Kamiokande atmospheric neutrino events by using neural network

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Abstract. We present a new event classification method based on neural network for multi-GeV multi-ring samples from Super-Kamiokande (SK) atmospheric neutrino observation. Identifications of neutrino flavors are more difficult for multi-ring events due to several hadrons generated in deep inelastic scattering. We employed neural network to optimize the classification from a combination of observed variables. Compared with the conventional method, significant improvements of the $\nu_e$ selection efficiency is confirmed with the comparable misidentification probabilities. Sensitivity to neutrino mass hierarchy can be improved with more statistics of $\nu_e$ samples.

1. Introduction
Existence of neutrino mass was discovered from observation of neutrino oscillation, while it is not determined yet whether mass hierarchy (MH) is normal ($m_1 < m_2 \ll m_3$) or inverted ($m_3 \ll m_1 < m_2$) although the normal hierarchy is indicated at 91.9%-94.5% confidence level by SK-T2K combined analysis [1]. Determination of MH is one of the most important subjects in particle physics.

Observation of atmospheric neutrinos has a sensitivity to the MH as the oscillation probability depends on it. Neutrino oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is enhanced in multi-GeV region because of matter effects if it is normal MH. On the other hand, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ is enhanced in case of inverted MH. Therefore, observation of $\nu_e$ and $\bar{\nu}_e$ events in multi-GeV region is a key to understand the neutrino MH. Neutrino flavor is identified by the outgoing charged lepton in quasi-elastic scattering for single ring events, typically in sub-GeV, while it is more difficult at higher energies where deep inelastic scattering becomes dominant. Current precision of MH study in Super-Kamionade is limited by the statistics in multi-GeV region, and hence improvement of neutrino event selection leads to enhancement of the sensitivity to MH.

2. Event classification by neural network
Super-Kamiokande is a large water Cherenkov detector located at Kamioka in Gifu Prefecture, Japan. 50 kton pure water is contained in a cylindrical water tank equipped with more than 11000 PMTs. Vertex positions and the directions of charged particles produced from neutrino interactions are reconstructed from the Cherenkov rings. In SK, particle types (electron or muon) are identified from the shape of Cherenkov ring image.
Currently, atmospheric neutrino events are classified by log likelihood (LL) method based on the variables reconstructed from the PMT hits. In order to improve event selection efficiencies, an alternative method based on neural network is being investigated. Neural network (NN) is one of machine learning methods. Recently, NN is actively developed and widely applied to various fields. Events are classified by the NN from the input variables based on the knowledge accumulated from the training samples.

We employed input variables listed in Table 1, following the current analysis based on LL method [1]. Multi-GeV multi-ring events of atmospheric neutrino are classified into 4 types: \( \nu_e \)-like, \( \bar{\nu}_e \)-like, \( \mu \)-like and others. \( \nu_e (\bar{\nu}_e) \)-like has \( \nu_e (\bar{\nu}_e) \) charged current interaction as correct class. \( \mu \)-like has \( \nu_\mu \) or \( \bar{\nu}_\mu \) charged current interaction as correct class as well. Neutral current interaction and tau neutrino events are included in “others”.

| Name      | Definition                                      |
|-----------|-------------------------------------------------|
| \( N_{\text{ring}} \) | Number of rings                                  |
| \( E_{\text{vis}} \) | Visible energy from total hit PMT               |
| \( T_{\text{mom}} \) | Transverse momentum \( /E_{\text{vis}} \)       |
| \( F_{\text{mom}} \) | Momentum of the most energetic ring \( /E_{\text{vis}} \) |
| \( N_{\text{decay e}} \) | Number of Michel electron                       |
| \( L_{\text{decay e}} \) | Distance between Michel \( e \) vertex and primary vertex |
| PID       | PID likelihood                                   |

The network architecture is shown in Figure 1. Batch normalization [2] is adopted before each activation. The efficiencies are not significantly improved with more layers.

The neural network is trained by 300 years atmospheric neutrino Monte-Carlo (MC) simulation. The performance is evaluated with respect to the efficiency and contamination by using 100 years MC which are independent from the training samples. Contamination is defined as the fraction of mis-identified events in each category.

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\text{inputs} \rightarrow \text{fc, 16} \rightarrow \text{relu} \rightarrow \text{fc, 32} \rightarrow \text{relu} \rightarrow \text{fc, 64}
\]

**Figure 1.** Neural network architecture used in the selection

3. **Results and discussion**

Results of the selection are shown in Table 2. Efficiencies of \( \nu_e \)-like, \( \bar{\nu}_e \)-like and \( \mu \)-like are increased with the comparable contamination. Compared to the LL method, \( \nu_e \) efficiency is increased by a factor 1.3 by the NN method. Sensitivity to MH will be improved with more statistics of \( \nu_e \) events if the systematic uncertainties can be controlled to the similar level to LL method.

Fig 2 shows \( \nu_e \) event distributions of transverse momentum \( T_{\text{mom}} \) and fraction of most energetic ring momentum \( F_{\text{mom}} \). These show that NN selected additional \( \nu_e \) events in high \( T_{\text{mom}} \) and low \( F_{\text{mom}} \) region with respect to LL method. This indicates that NN optimized to identify events with energetic hadrons improves \( \nu_e \) selection efficiency.

4. **Conclusions and perspective**

Observation of multi-GeV atmospheric neutrino is capable of resolving mass hierarchy. We investigated a classification of atmospheric neutrino events by using neural network. The
Table 2. Results of the selection by NN

|                  | Efficiency(%) | Contamination(%) |
|------------------|---------------|------------------|
|                  | LL            | NN               | LL               | NN               |
| $\nu_e$-like     | 34.4          | 46.7             | 54.0             | 52.8             |
| $\bar{\nu}_e$-like | 60.4          | 63.1             | 76.1             | 76.1             |
| $\mu$-like       | 77.0          | 85.9             | 7.6              | 8.9              |
| others           | 55.6          | 47.4             | 56.7             | 39.6             |

Figure 2. Distributions of transverse momentum (left) and fraction of most energetic ring momentum (right). Black line shows total $\nu_e$ CC events. Red and blue lines show the distributions of $\nu_e$-like events classified by the NN method and LL method respectively.

Tentative results indicate possible improvements with respect to the LL method. In order to evaluate the improvement of the analysis, evaluation of the systematic uncertainties is in progress.

References
[1] K. Abe et al. 2018 Phys. Rev. D97 072001
[2] S. Ioffe and C. Szegedy 2015 Proc. ICML 37 448