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Stop-μ Analysis for Atmospheric $\nu_\mu/\bar{\nu}_\mu$ Separation in Super-Kamiokande

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We study μ^+/μ^- separation using decay electron information in a cosmic ray stopping muon sample in order to separate atmospheric $\nu_\mu/\bar{\nu}_\mu$. We discuss event selection method defined for cosmic ray MC and data sample to identify decay electrons and apply it to atmospheric neutrino MC. Adding this selection, we obtained average muon decay time by fitting the muon decay time distribution. These results are consistent with the previously reported values. Therefore, we confirmed that this selection worked well. In future prospect, we will make distributions of the difference of log likelihood in atmospheric neutrino MC using presented results in order to develop event-by-event separation.

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[*] Speaker.

1. Introduction

When primary cosmic rays interact with Earth atmosphere, they produce the neutrinos:

$$\begin{aligned}
\pi^+ &\to \mu^+ + \nu_\mu, \\
\pi^- &\to \mu^- + \bar{\nu}_\mu, \\
\mu^+ &\to e^+ + \nu_e + \bar{\nu}_\mu, \\
\mu^- &\to e^- + \bar{\nu}_e + \nu_\mu.
\end{aligned}$$

Those coming below the horizon cause neutrino oscillation that have undergone matter effects inside the Earth. In matter, neutrino oscillation probability is different between normal hierarchy(NH) ($m_1 < m_2 \ll m_3$) and inverted hierarchy(IH) ($m_3 \ll m_1 < m_2$) [1]. As shown in Fig.1, NH and IH enhance appearance (disapperance) of neutrino and antineutrino, respectively. Therefore, we can see difference between NH and IH, if we separate neutrinos and antineutrinos. So far, neutrino oscillation taking matter effects into account has been measured using $\nu_e/\bar{\nu}_e$ separation [2]. In this study, we developed a new method to separate atmospheric $\nu_\mu/\bar{\nu}_\mu$ event-by-event using a likelihood function to improve oscillation analysis. The details of three flavor atmospheric neutrino oscillation analysis in Super-Kamiokande was reported [3]. We studied μ^+/μ^- separation using decay electron information such as energy and decay time distributions in a cosmic ray stopping muon sample. First, we studied a tagging method for a decay electron in the cosmic ray MC/data, and applied it to atmospheric neutrino MC.

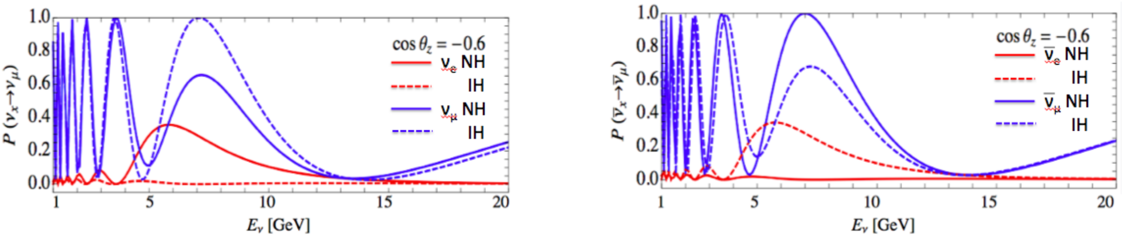

Figure 1: Difference of oscillation probability in ν_e NH, ν_e IH, ν_μ NH and ν_μ IH (left) [1]. Also shown those for $\bar{\nu}_e$ and $\bar{\nu}_\mu$ (right).

2. Decay electron tagging method

We used cosmic ray stopping muon and data and MC samples to determine criteria for decay electron tagging. We also used 1-ring charged current quasi-elastic events in atmospheric neutrino MC to verify the criteria. We selected events which fulfilled the following criteria.

- Muon decay time > 1.2 [micro sec.]
- Total charge of muon > 1000 [p.e.]
- Number of decay electron = 1

- Decay electron type = sub-event type
- Goodness of fit for electron vertex reconstruction > 0.5 (Max:1)
- Elimination of the events near the wall (2m from the wall)

Here “sub-event” is an event triggered within 100 μs after the parent event. We used 17,467 events, 59,626 events, and 26,801 events in cosmic ray MC, data and atmospheric neutrino MC, respectively. Figure 2 shows correlation between muon range and muon momentum. By fitting this correlation with a linear function, a constant of momentum/range was obtained in each momentum range. In the range from 0 to 400, from 400 to 1000, and from 1000 to 4000 [cm], momentum/range constants are 2.76, 2.35, and 2.42 [MeV/c/cm], respectively. In this way, a muon range can be estimated from the momentum. Using these constants, the distribution of distance between the reconstructed decay electron and the expected stop position of muon was obtained (Fig. 3). First, we used the cosmic ray MC and the data in each range, and decided the cut $d < 150$ cm. Then the same procedure was applied to the atmospheric neutrino MC, and validity of the cuts was confirmed.

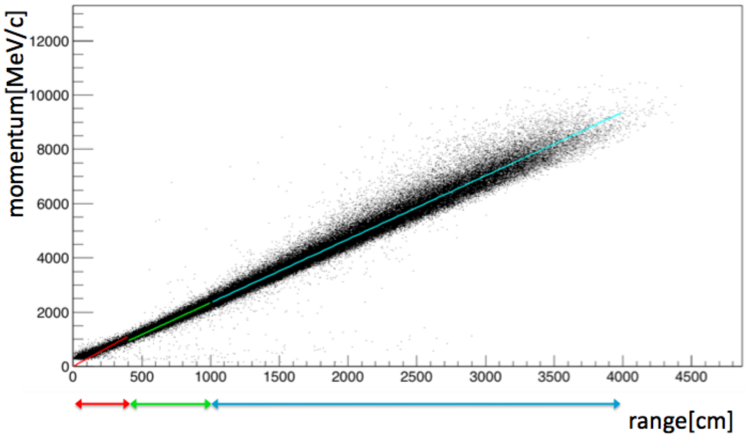

Figure 2: Correlation between muon range and muon momentum. Red, green, and blue lines show the ranges from 0 to 400, from 400 to 1000, and from 1000 to 4000 cm, respectively.

3. Results for selected decay electrons

We made the distributions of energy (N50) and decay time as shown in Fig.4 which were used for μ^+/μ^- separation likelihood. Here, N50 is the maximum number of PMT hits in a 50 ns sliding timing window for a decay electron. This is used to estimate energy. We can clearly see the peak in the N50 spectra due to gamma rays from muon capture in the ν_μ sample produced as below:

$$\mu^- + {}^{16}\mathrm{O} \rightarrow \nu_\mu + \mathrm{n} + {}^{15}\mathrm{N}^*,$$
$$ {}^{15}\mathrm{N}^* \rightarrow {}^{15}\mathrm{N} + \gamma.$$

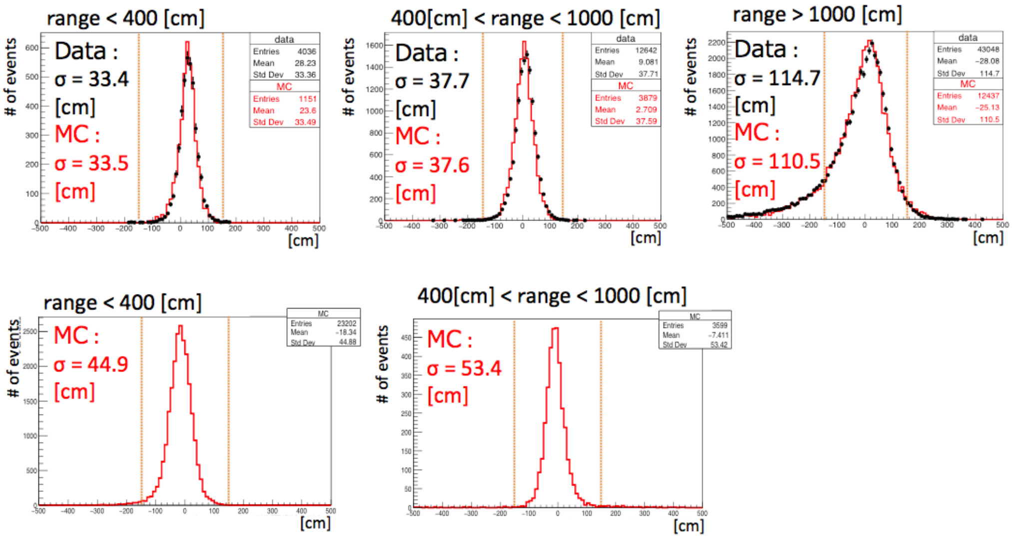

Figure 3: Distributions of distance between the reconstructed decay electron and the expected stop position of muon. The top plots show cosmic ray muon MC and data. The bottom plots show atmospheric neutrino MC. The black points and the red histgrams show data and MC, respectively.

By fitting the distribution of decay time, the average decay time was calculated. As result, those for the cosmic ray stopping muon data and MC were 2.057±0.009 μs and 2.042±0.009 μs, respectively. In atmospheric neutrino MC, those for $\mu^-(\nu_\mu)$ and $\mu^+(\bar{\nu}_\mu)$ were 1.786±0.013 μs and 2.210±0.022 μs, respectively. These are consistent with the previously reported values. (μ^- and μ^+ have 1.7954±0.020 μs and 2.19703±0.00004 μs, respectively [4, 5].) Therefore, we confirmed that our decay electron selection worked well.

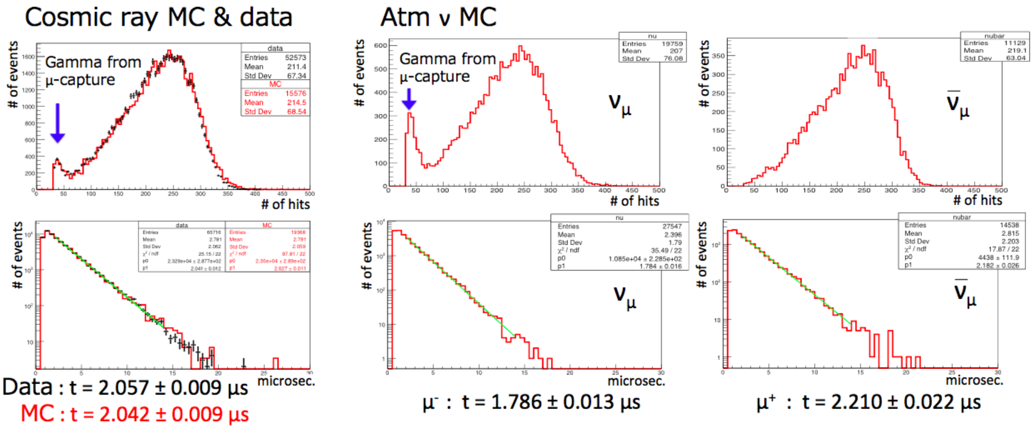

Figure 4: Distributions of N50 (top) and decay time (bottom) in the cosmic ray and the atmospheric neutrino samples. In the bottom figures, the green histograms show the fit range (1.2-12 microsec).

4. Conclusion and future prospect

We have developed a method of tagging decay electron. As a next step, we will develop event-by-event $\nu_\mu/\bar{\nu}_\mu$ separation using difference of log likelihood in atmospheric neutrino MC. Log likelihood difference ΔL can be constructed as below:

$$\mathrm{P}^{\nu_\mu} = \mathrm{P}^{\nu_\mu}(\text{Decay time}) \times \mathrm{P}^{\nu_\mu}(\text{N50}),$$
$$\mathrm{P}^{\bar{\nu}_\mu} = \mathrm{P}^{\bar{\nu}_\mu}(\text{Decay time}) \times \mathrm{P}^{\bar{\nu}_\mu}(\text{N50}), \text{and}$$
$$\Delta \mathrm{L} = \log \mathrm{P}^{\nu_\mu} - \log \mathrm{P}^{\bar{\nu}_\mu}.$$

Here P means a probability density function using the decay time and the N50 distributions for decay electrons in an atmospheric neutrino sample. Finally, we will apply it to atmospheric neutrino data and introduce into atmospheric neutrino oscillation analysis in Super-Kamiokande.

References

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