Constraint on the atmospheric neutrino flux models using the cosmic-ray muon data in the Super-Kamiokande

Poster #325

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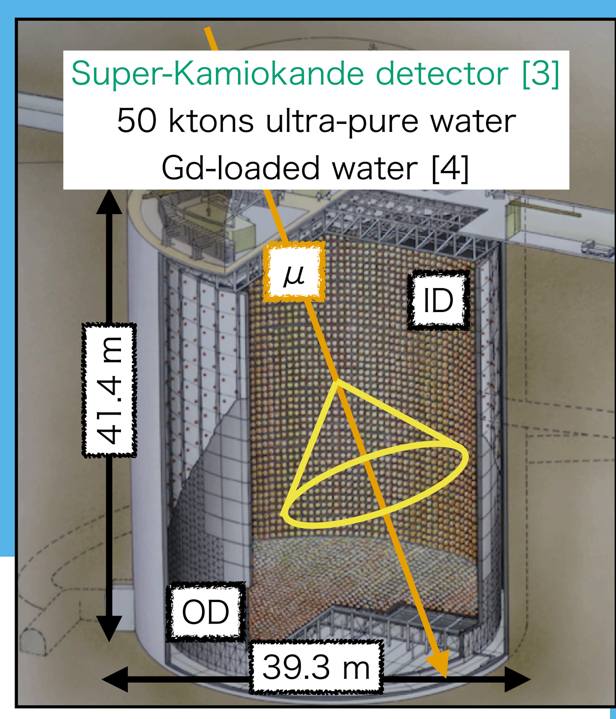
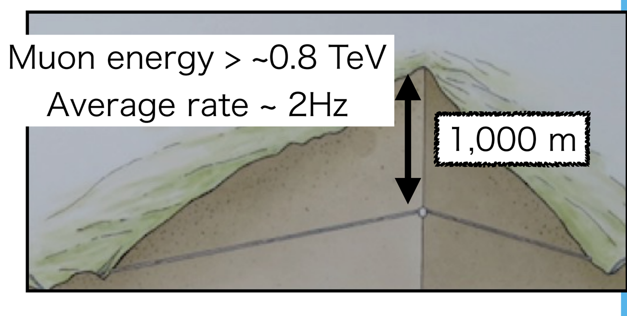
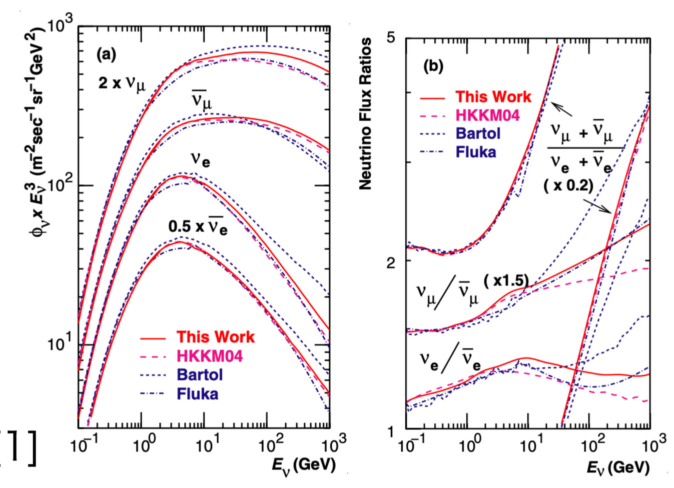


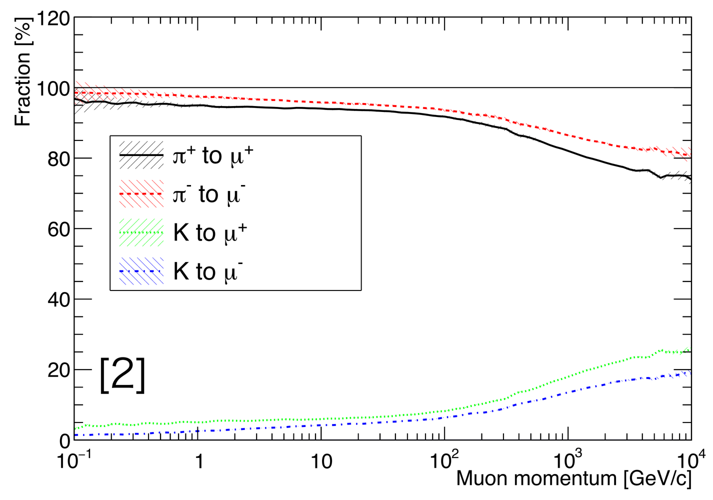


Introduction & physics motivations



[1]

- Neutrino oscillation
  - Mass hierarchy, octant of θ_{23}, and the value of CP-violating phase are still unknown.
  - For further precise measurements, we should reduce uncertainties due to atmospheric neutrino; absolute flux, $\nu/\bar{\nu}$ ratio, and energy spectrum.
- Cosmic-ray muon
  - Come from the decay of mesons produced in the hadronic showers as the pair of the atmospheric neutrinos.
  - We can indirectly obtain information about atmospheric neutrinos by measuring cosmic-ray muons.
- Muon charge ratio, spin polarization, and parent meson ratio
  - Muons from kaon decays tend to have larger energy and polarization than those from pion decays.
  - Measurement of charge ratio and polarization are directly related to $\nu/\bar{\nu}$ ratio and neutrino energy spectrum.
  - As muon energy increases, the contribution of kaon decay increases.
  - → Constrain the hadronic interaction model and new input for improving the atmospheric neutrino flux simulation.



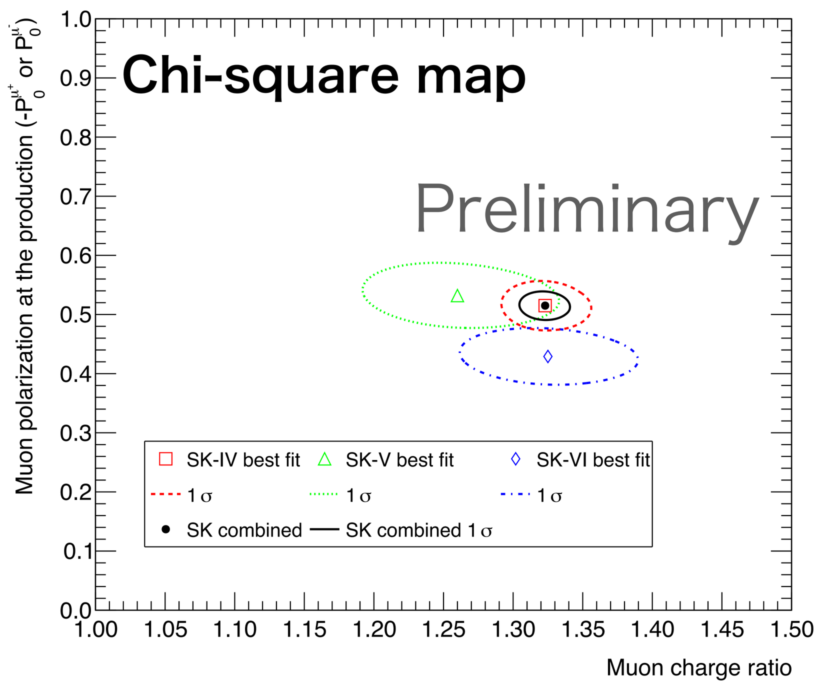
[2]

Measurement of charge ratio and polarization

- Use the pair event of the stopping muon in the detector and the decay electron.
  - Charge ratio : Determined using the decay time of stopping muon.
  - Polarization : Determined using opening angle between muon and decay electron.
- Data-set : 2008 Sep. - 2022 Dec.
- Analysis
  - Observed data was analyzed and compared with the MC simulation, which generated muon decay in water.
- MC simulation for decay electron
  - Considered muon charge, and their decay process with polarization.
    - → Nuclear capture of negative muon that affects the energy spectrum of decay electron.
    - → De-polarization mechanisms in water. (Different between positive and negative muon)
- Results
  - To determine them, chi-square is evaluated by fitting three distributions.
    - → Decay time, Opening angle ($\cos\theta$), Energy spectrum of decay electron.

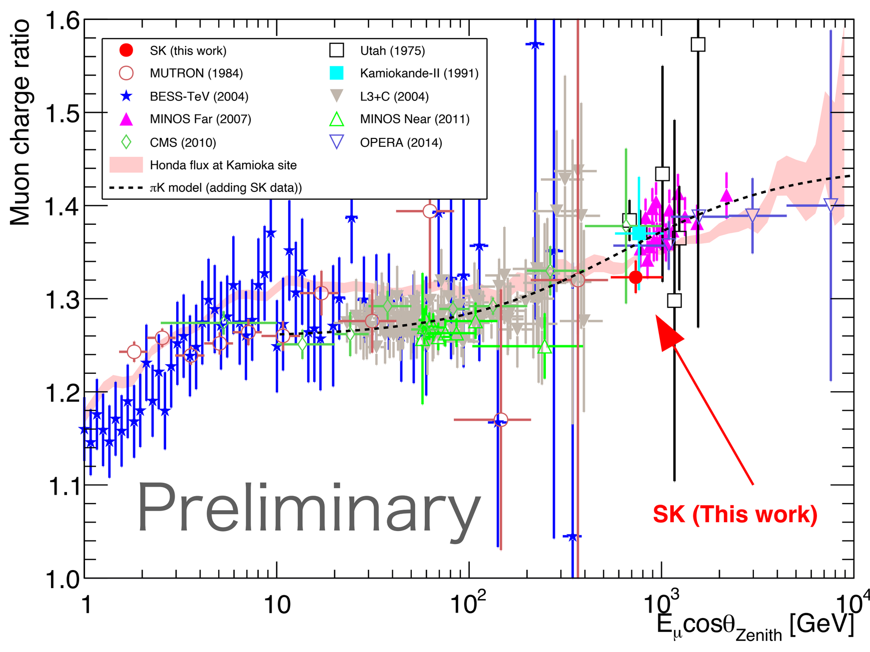
$$\chi^2_{\rm Total}(R, P_0^{\mu}) = \chi^2_{\rm Time} + \chi^2_{\rm Energy} + \chi^2_{\cos\theta}$$

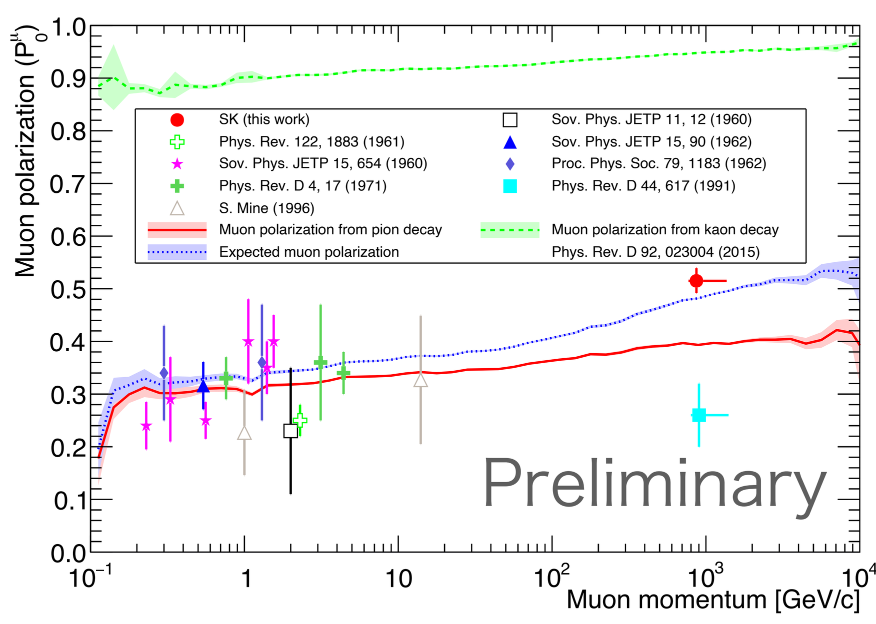
$$\begin{cases} \chi^2_{\rm Time} = \sum_i^{n_{\rm Time}} \frac{(N_i^{\rm Data} - N_i^{\rm MC})^2}{(\sigma_i^{\rm Data})^2 + (\sigma_i^{\rm MC})^2 + (\sigma_i^{\rm Syst.})^2} \\ \chi^2_{\cos\theta} = \sum_i^{n_{\cos\theta}} \frac{(N_i^{\rm Data} - N_i^{\rm MC})^2}{(\sigma_i^{\rm Data})^2 + (\sigma_i^{\rm MC})^2 + (\sigma_i^{\rm Syst.})^2} \\ \chi^2_{\rm Energy} = \sum_i^{n_{\rm Energy}} \frac{(N_i^{\rm Data} - N_i^{\rm MC})^2}{(\sigma_i^{\rm Data})^2 + (\sigma_i^{\rm MC})^2} + \left(\frac{1-p}{\sigma^{\rm E\text{-}scale}}\right)^2 \end{cases}$$



$R = 1.32 \pm 0.02$ (stat. + syst.) $P_0 = 0.52 \pm 0.02$ (stat. + syst.)

  - Charge ratio is compared with two models (Honda flux [2], πK model [5]).
    - → Consistent with Honda flux (< 1 σ).
    - → 1.9 σ tension from the πK model.
  - Polarization has 1.6 σ tension from Honda flux expectation [2].
  - This result provide new input to the neutrino flux simulation to constraint atmospheric neutrino production.





Measurement of the atmospheric meson ratio

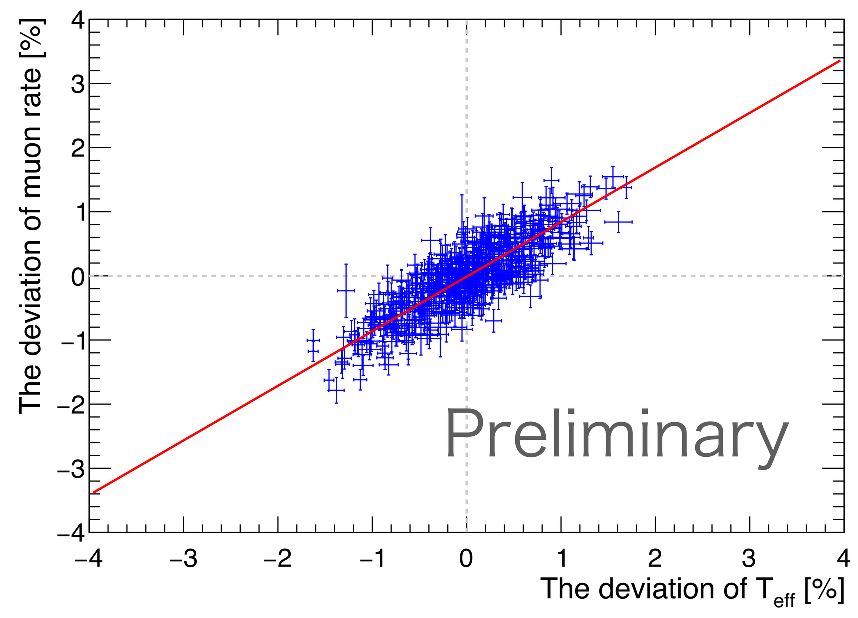
- Use the through going muon in the detector
- Data-set : 2008 Sep. - 2018 May.
- Analysis
  - The correlation between the variation of muon rate (R_{μ}) and the variation of atmospheric temperature ($T_{\rm eff}$).
    - R_{μ} is the number of muon events that are normalized by its lifetime.
    - $T_{\rm eff}$ is the temperature weighted by the muon production intensity at different altitudes in the atmosphere [6].
      - → Atmospheric temperature data-set is provided by the Japan Meteorological Agency [7].
- Results
  - Correlation coefficient $\alpha_{\rm T}$ is obtained by fitting with linear function.

$\alpha_{\rm T} = 0.85 \pm 0.01$ (stat.)

  - We can calculate the atmospheric meson ratio $r_{K/\pi}$ using the correlation coefficient $\alpha_{\rm T}$.
    - → Kaon and pion are affected differently due to the variation of the atmospheric temperature.

$r_{\rm K/\pi} = 0.12 \pm 0.03$ (stat.)

  - This result is important information to improve the prediction of the atmospheric neutrino flux.



The calculation of the atmospheric meson ratio $r_{K/\pi}$

- Theoretical function of $\alpha_{\rm T}$ is depend on $r_{K/\pi}$ [6].

$$\alpha_{\rm T} = \frac{1}{D_\pi}\frac{1/\epsilon_{\rm K} + (0.365 \times r_{\rm K/\pi})(D_\pi/D_{\rm K})^2/\epsilon_\pi}{1/\epsilon_{\rm K} + (0.365 \times r_{\rm K/\pi})(D_\pi/D_{\rm K})/\epsilon_\pi}$$

$$D_{\pi,\rm K} \equiv \frac{\gamma}{\gamma+1}\frac{\epsilon_{\pi,\rm K}}{1.1\langle E_{\rm thr}\cos\theta\rangle} + 1$$

$$\epsilon_\pi = (114 \pm 3)\ {\rm GeV},\ \epsilon_{\rm K} = (851 \pm 14)\ {\rm GeV}$$

→ The energies in which decay and interaction occur with equal probability

Summary

- For further precise measurement of neutrino oscillation, it is important to understand the atmospheric neutrino precisely.
  - Muon charge ratio reflects the ratio of neutrinos and anti-neutrinos.
  - Muon polarization and the atmospheric meson ratio affects the shape of neutrino energy spectrum.

$R = 1.32 \pm 0.02$ (stat. + syst.) $P_0 = 0.52 \pm 0.02$ (stat. + syst.) $r_{\rm K/\pi} = 0.12 \pm 0.03$ (stat.)

- These results are consistent with Honda flux expectation within 2 σ (charge ratio and polarization).
- Especially for P_0 and $r_{K/\pi}$, provide the unique input to improve the atmospheric neutrino simulation.

[1] *Phys. Rev. D.* **75**, 043006 (2007). [2] *Phys. Rev. D* **92**, 023004 (2015). [3] *Nucl. Inst. Meth. A* **501**, 418 (2003). [4] *Nucl. Inst. Meth. A* **1027**, 166248 (2022). [5] *Astropart. Phys.* **32**, 61 (2009). [6] *Astropart. Phys.* **33**, 140 (2010). [7] *J. Meteor. Soc. Japan. Ser. II* **96**, 269 (2016).