Poster #26

Measurement of charge ratio of cosmic-ray muon with the Super-Kamiokande detector

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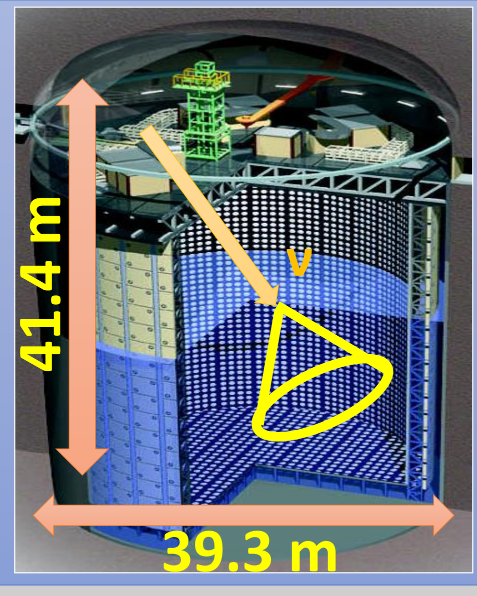
H. Kitagawa, T. Tada, Y. Koshio (Okayama university) for the Super-Kamiokande collaboration.

See detail: Pos (ICRC2021) 395, 360 (2022)

Unraveling the history of the universe and matter evolution with underground physics (UGAP2022)@Tokyo university of Science, 2022 June 13th-15th.



1. Introduction & Physics motivations

◆ Neutrino oscillation

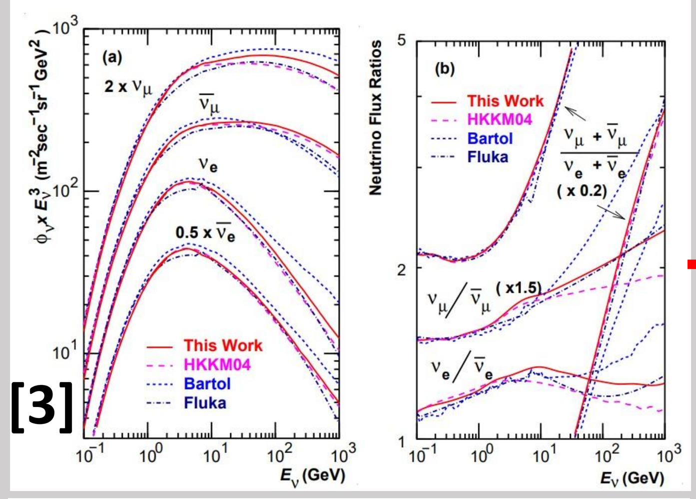
- The three-favor neutrino mixing, based on the PMNS matrix [1,2], is generally described by (1) three mixing angles, (2) two neutrino mass squared difference, and (3) one *CP*-violating phase.
  → mass hierarchy of Δm^2_{23}, octant of θ_{23}, and value of *CP*-violating phase are still unknown.

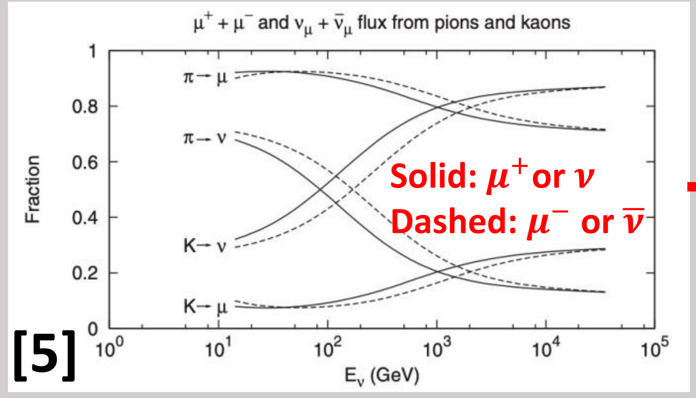
- Absolute fluxed of atmospheric neutrinos as well as their energy spectrum are precisely determined.
- $\nu/\bar{\nu}$ ratio basically depends on the absolute fluxes of muon, pion, and kaon (and their anti-particles).

◆ Muon charge ratio $R\ (\mu^+/\mu^-)$

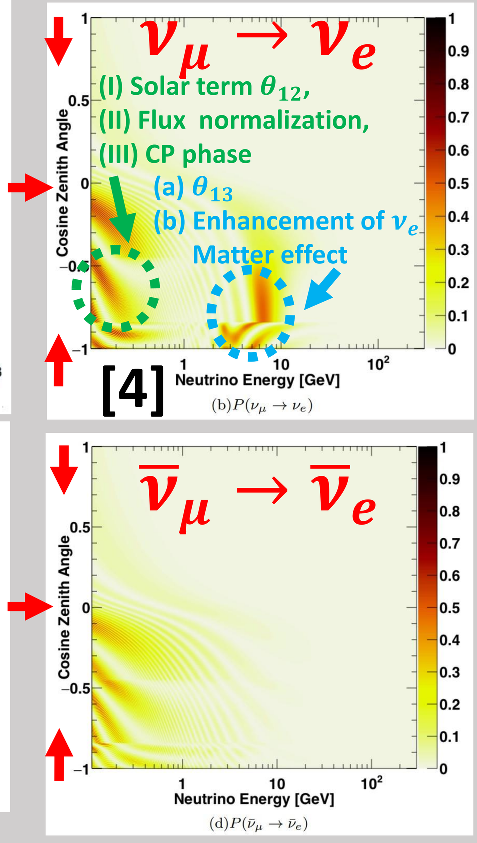
- The cosmic-ray muons dominantly come from the decay of mesons produced in the hadronic showers.
  → Muons from kaon decays tend to have larger energy than those from pion.
- Muon charge ratio $R\ (\mu^+/\mu^-)$ is about 1.27 below 200 GeV while it increases to about 1.4 above that energy.
  → New input for the atmospheric neutrino flux simulations, and the hadronic interaction model.

Atmospheric neutrino fluxes





Oscillation pattern zenith angle dep.

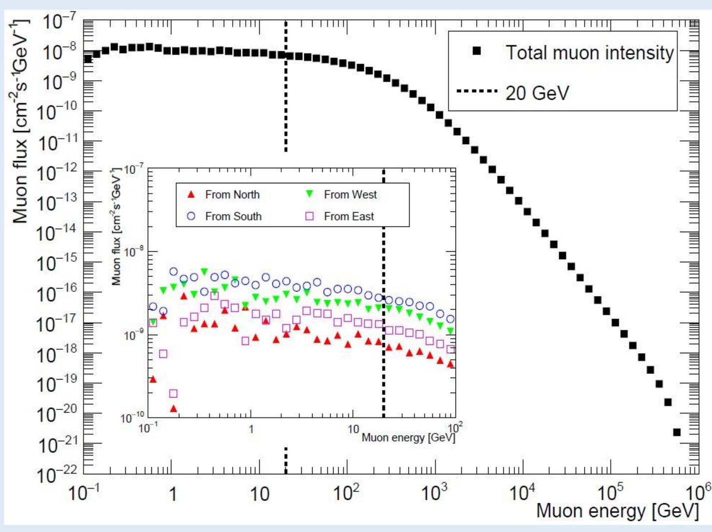


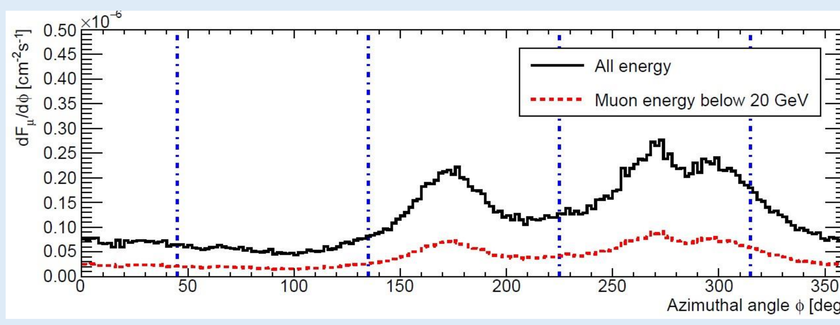
Normal hierarchy

2. Super-Kamiokande detector and reconstruction methods

◆ Detector

- Multi-purpose water Cherenkov detector, containing 50 kton of ultra-pure water [6].
  → Gd-loaded water since 2020 July and additional Gd-loading since 2022 June [7].
  (In this poster, the 2970-days data of SK-IV (pure-water phase) is presented.)
- Muons, whose energy is more than 1.3 TeV at the surface, enter the detector at 2 Hz.
  → About 2500 muons stop in the detector a day (less than 20 GeV).



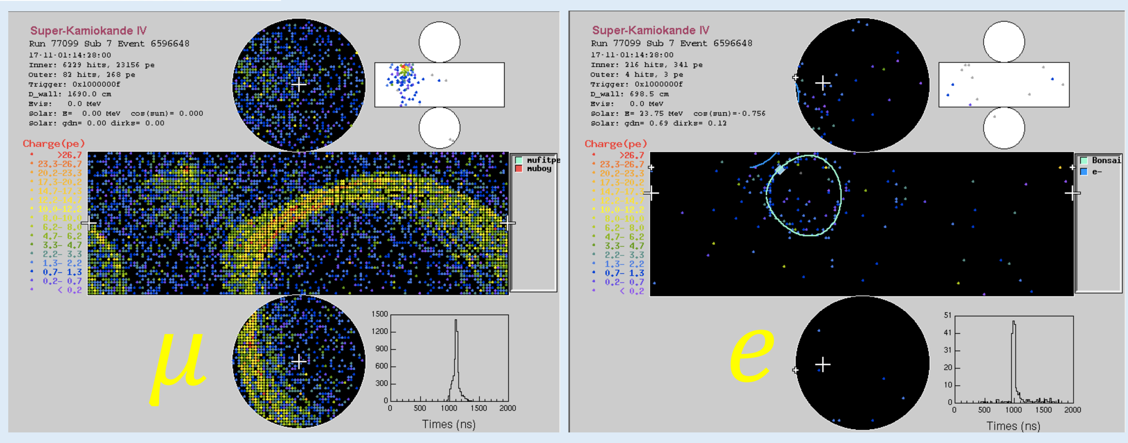


Directional dependence of muon flux at SK site based on MUSIC simulation [8]

See also poster #22 by M. Shinoki
Measurement of cosmogenic neutron in Super-Kamiokande

◆ Reconstruction methods

- Pair of muon and decay-e is tagged within [-5, +35] micro-sec window by the front-end electronics [9].
  [Muon] Muon track(s) with direction(s) based on timing of ID PMTs, and stopping position based on dE/dx of muon track [10].
  [Decay-e] Vertex bases on the time residual of hit PMTs timing, direction based on the hit PMTs locations, and energy based on the number of hit PMTs after corrections by water transparency, angle of incoming photon, dark rate, and so on [11].



3. Analysis and results

Parameter	Lifetime [micro-sec]
Positive τ_{μ^+}	2.1969811 ± 0.0000022
Negative τ_{μ^-}	1.7954 ± 0.0020

◆ Measurement of muon charge ratio

- Negative muon tends to be captured on Oxygen in water and this process results in the shorter lifetime (2.2 micro-sec → 1.8 micro-sec).
  → Time difference between the stop muon and the decay-e reflects the ratio of positive and negative muons.
  → 18.4% of negative muons produce Nitrogen-14 and -15, which emit γ-rays soon after their production [12, 13].

$$\Lambda_c = 0.184 \pm 0.001$$

- Selection cuts: energy, vertex, goodness of reconstruction, time difference less than 1.3 micro-sec (due to after pulse, reflection/scattered photons).
  → After these cuts, 2,000,000 pairs of muon and decay-e are selected.

- Counting the number of positive and negative muons by fitting the decay curve.
  → Correcting the number of negative muon due to nuclear capture reaction.

$$N(t-(t+\Delta t)) = N_+\left\{1-\exp\left(-\frac{\Delta t}{\tau_{\mu^+}}\right)\right\}\exp\left(-\frac{t}{\tau_{\mu^+}}\right) + N_-\left\{1-\exp\left(-\frac{\Delta t}{\tau_{\mu^-}}\right)\right\}\exp\left(-\frac{t}{\tau_{\mu^-}}\right)$$

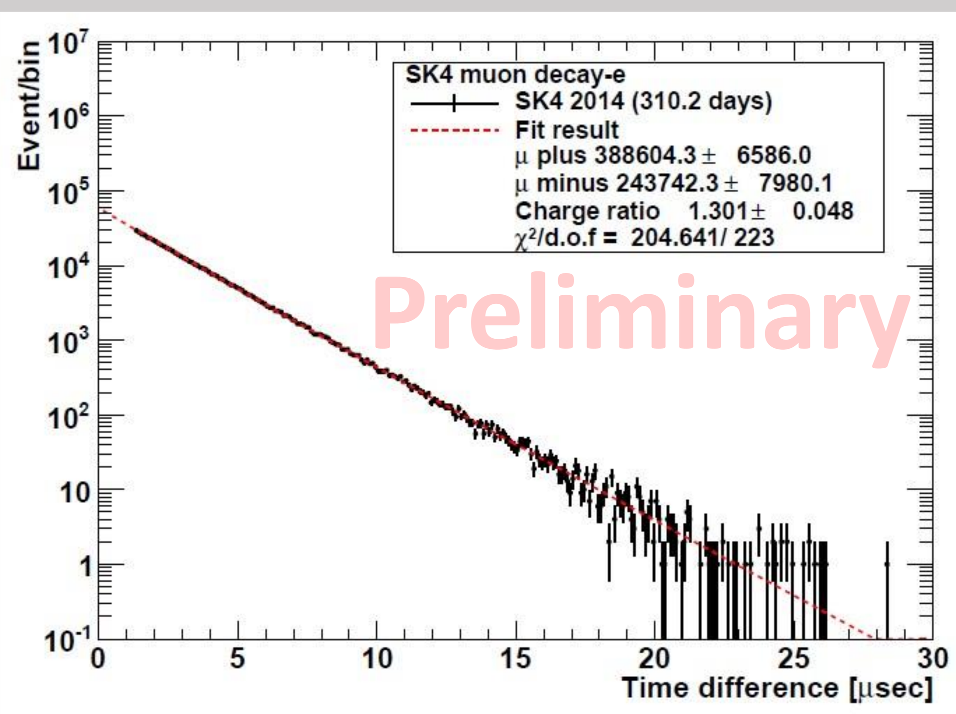
$$R(\mu^+/\mu^-) = \frac{N_+}{N_-/(1-\Lambda_c)}$$

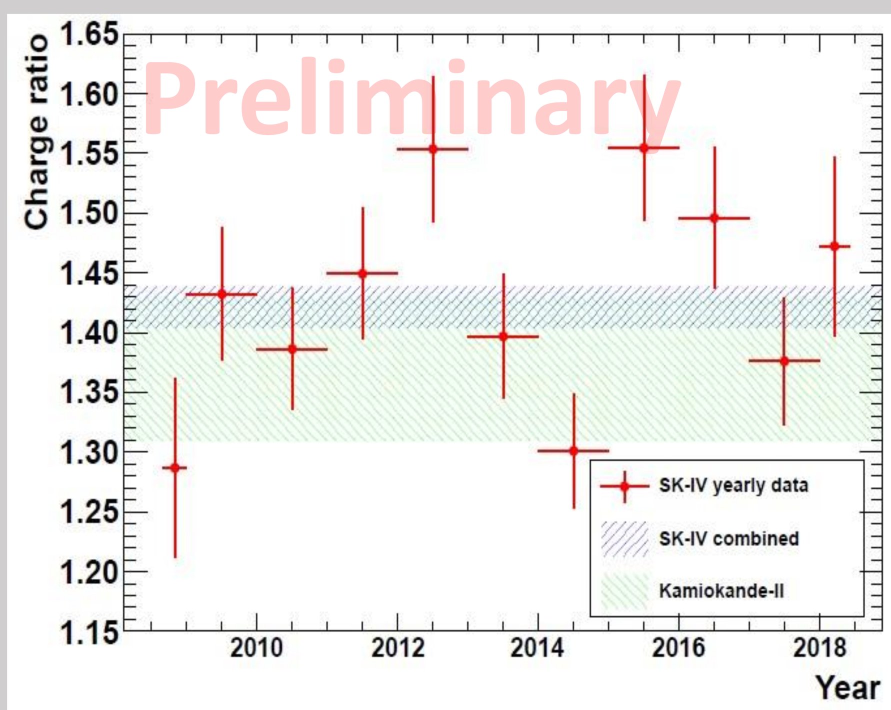
◆ Results

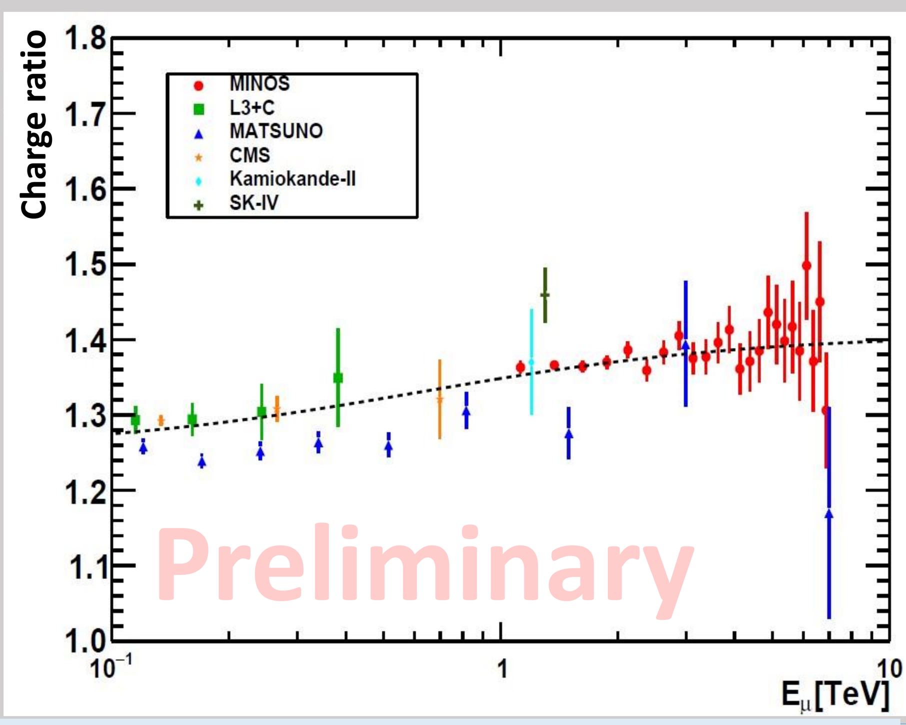
- Charge ratio is measured to be $R\ (\mu^+/\mu^-) = 1.42 \pm 0.02$ (stat.)
  → Consistent with Kamiokande-II [14].

- No significant time variation.
- Slightly higher than expected value based on the theoretical model [15].

  → New input for interaction model, and neutrino flux simulation.

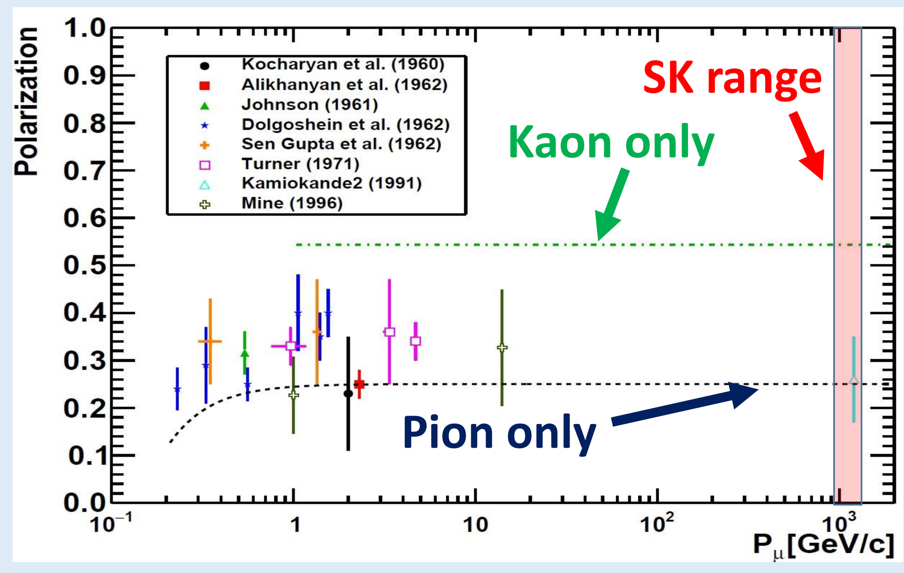






4. Summary and future prospect

- Neutrino oscillation parameters should be precisely measured to understand the properties of neutrinos.
- Muon charge ratio reflects the absolute atmospheric neutrino flux and the ratio of neutrinos and anti-neutrinos.
- Determine the muon charge ratio by measuring the lifetime of decay electrons in the Super-Kamiokande.
  → $R\ (\mu^+/\mu^-) = 1.42 \pm 0.02$ (stat.), systematic uncertainties are evaluating now.
- Study of the polarization of the comic-ray muon by evaluating the angle between muon and decay-e is on-going.
  → Energy spectrum of atmospheric neutrinos from muon/pion/kaon decays depends on their polarization.



Reference: [1] *Prog. Theor. Phys.* 28, 870 (1962). [2] *Zh. Eksp. Teor. Fiz.* 53, 1717 (1967). [3] *Phys. Rev. D 75*, 043006 (2007). [4] *Phys. Rev. D* 97, 072001 (2018).
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