Measurements of the charge ratio and polarization of cosmic-ray muons with the Super-Kamiokande detector

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1. Introduction

➢ Muon charge ratio

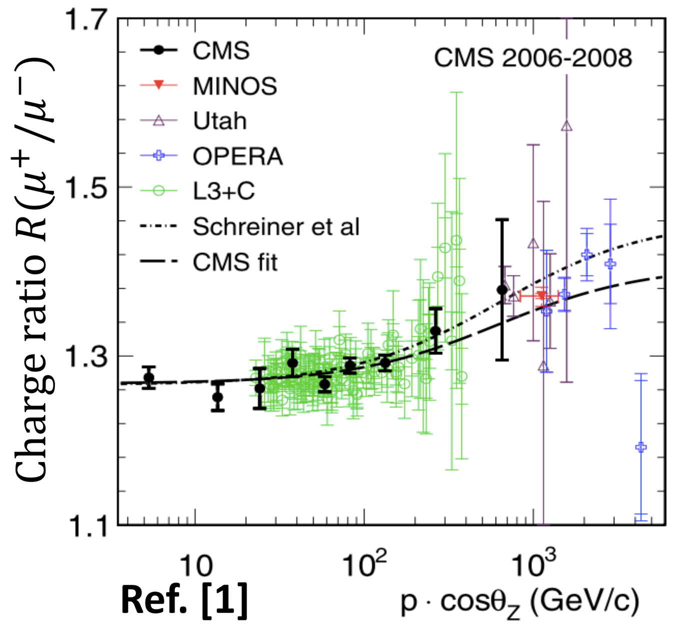
- The muon charge ratio is the ratio of the number of positive to negative atmospheric muons arriving at the Earth's surface.
  → Constrain models of high energy hadronic interactions and uncertainties of atmospheric neutrinos flux.
  → $R(\mu^+/\mu^-) \approx 1.27$ below 200 GeV/c and increases with higher momentum region[1],[2].

➢ Muon polarization

- The polarization directly reflects the K/π production ratio.
  → Contribute to the precise calculation of the atmospheric neutrino fluxes.

➢ Physics motivation

- In this study, we measured the muon charge ratio at muon energy of 1.3 TeV using the data of the Super-Kamiokande detector to improve physics models of cosmic-ray hadronic interactions.



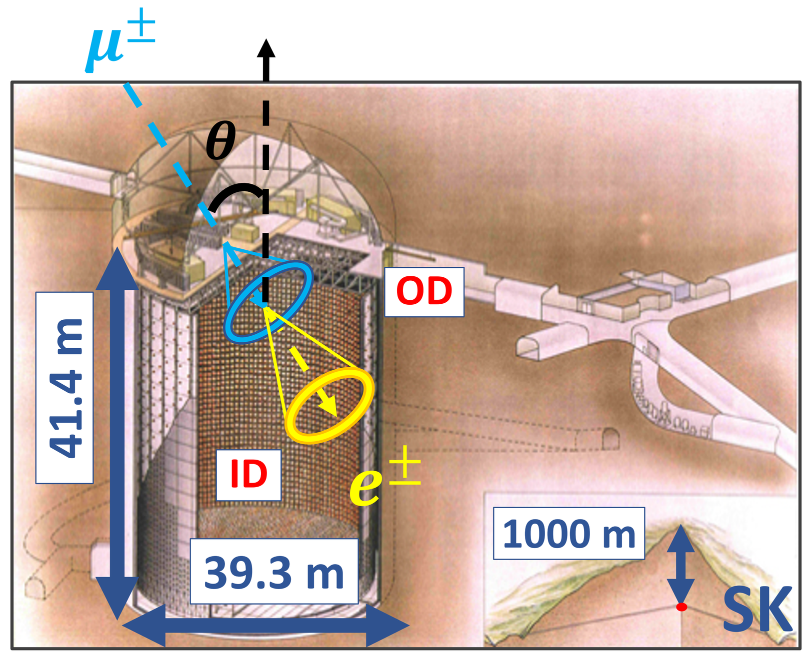
Ref. [1]

2. Super-Kamiokande (SK)

➢ SK detector

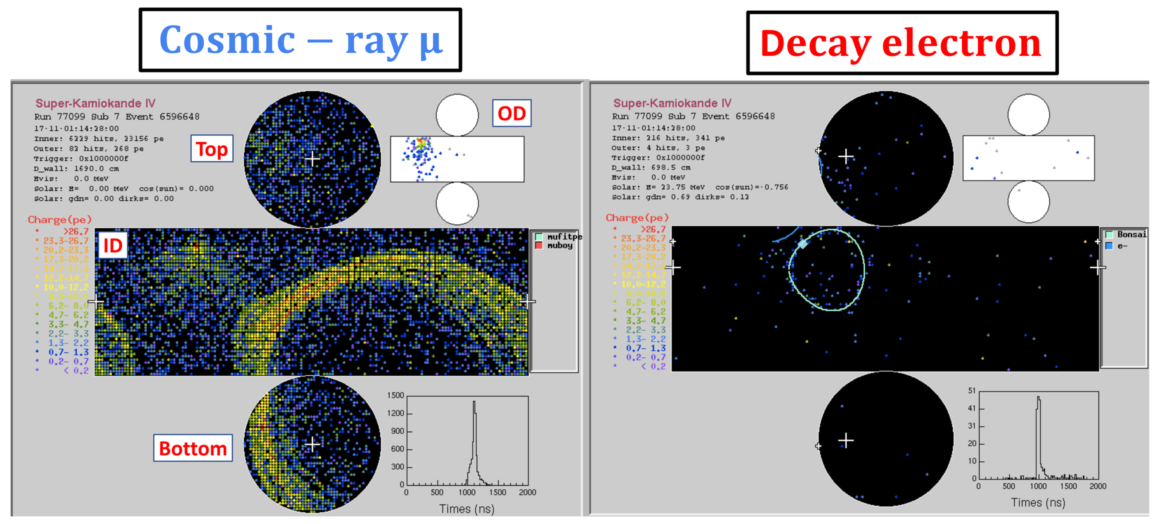
- SK is a water Cherenkov detector, located 1,000 m underground (2,700 m water equivalent)[3].
- The tank contains 50 kton pure water and separated into an inner detector (ID) and an outer detector (OD).
- 11,129 20-inch PMTs are installed in the ID.
  → In this analysis, data of SK-IV is used.

Phase	SKI	SK-II	SK-III	SK-IV	SK-V	SK-VI
Period	1996/04 ~2001/07	2002/10 ~2005/10	2006/07 ~2008/08	2008/09 ~2018/05	2019/01 ~2020/07	2020/07~
Livetime [days]	1496	791	548	2970	379	Running
ID PMTs	11,146	5,182	11,129	11,129	11,129	11,129
OD PMTs	1,885	1,885	1,885	1,885	1,885	1,885
PMT coverage[%]	40	19	40	40	40	40



➢ Event reconstruction

- Approximately 2,000 $\mu - e$ decay events stop in the ID in a day.
- Direction of muons are reconstructed with;
  ・Time information of hit PMT, etc.
- Vertex position and energy of electrons are reconstructed with;
  ・Time information and position of hit PMT, etc.



Reference:
[1] V. Khachatryan, et al.: *Phys. Lett.* B 692, 83 (2010). [2] N. Agafonova, et al.: *Eur. Phys. J.* C 67, 25 (2010) .
[3] S. Fukuda, et al.: *Nucl. Instrum. Meth.* A 501, 418 (2003). [4] T. Suzuki, D.F. Measday, and J.P. Roalsvig, *Phys. Rev.* C 35, 2212 (1987).
[5] M. Yamada, et al.: *Phys. Rev. D* 44, 617 (1991).

3. Data analysis ($\mu - e$ decay)

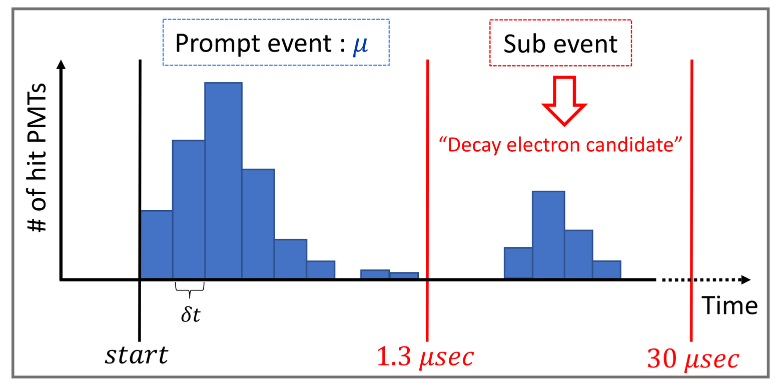
The selection criteria for $\mu - e$ decay was evaluated by using the SK detector simulation.

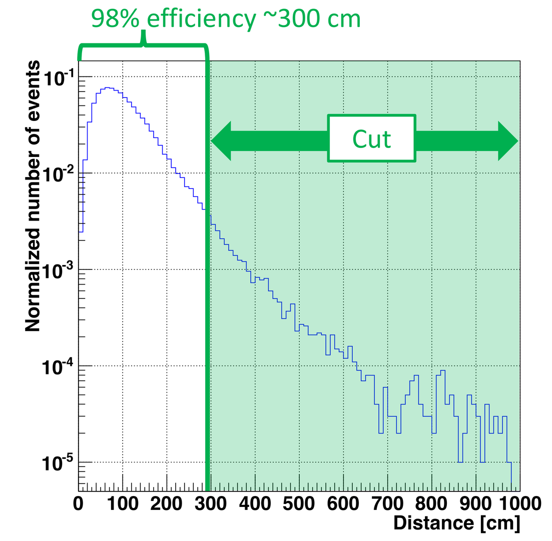
➢ Cosmic-ray muons

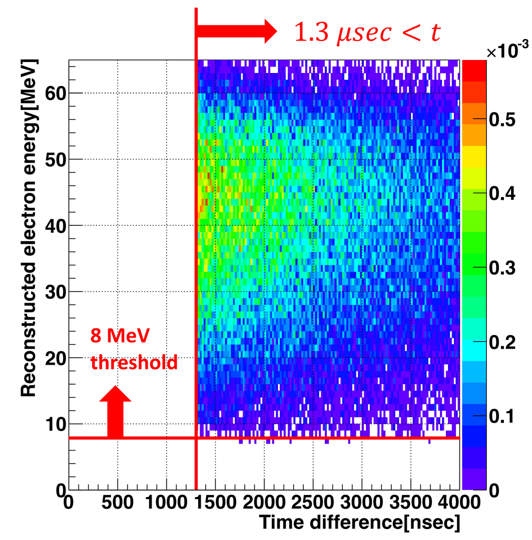
- Down going muons with the zenith angle $\theta < 90°$ which stopped inside the ID are selected.

➢ Decay electrons

- The time interval should satisfy, $1.3\ \mu sec < t < 30\ \mu sec$.
  → Distinguish the delayed signal from the primary event with broad time information.
- The reconstructed decay electron energy is greater than 8 MeV.
  → To remove low energy backgrounds from nuclear capture.
- The reconstructed distance between the stop position of the muon and vertex position of the decay electron is less than 300 cm.







4. Results

➢ Measurement of the charge ratio

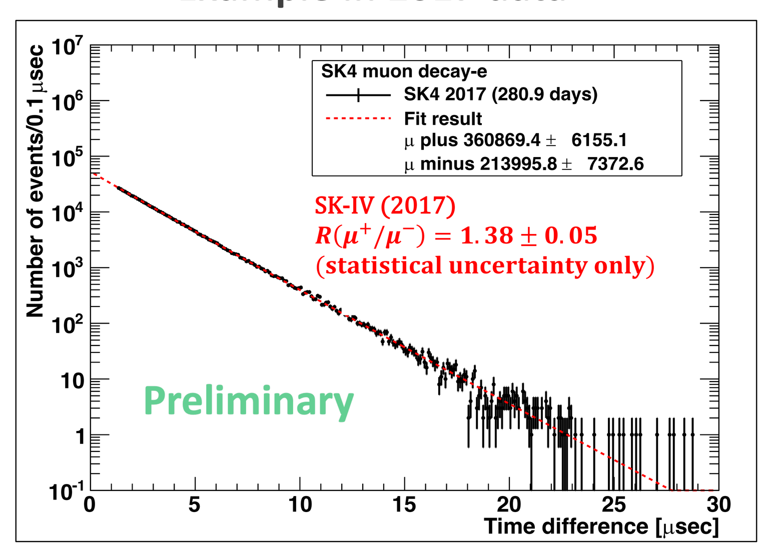
Charge ratio can be measured by counting N_+ and N_- from decay curve of stopping muons.

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

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

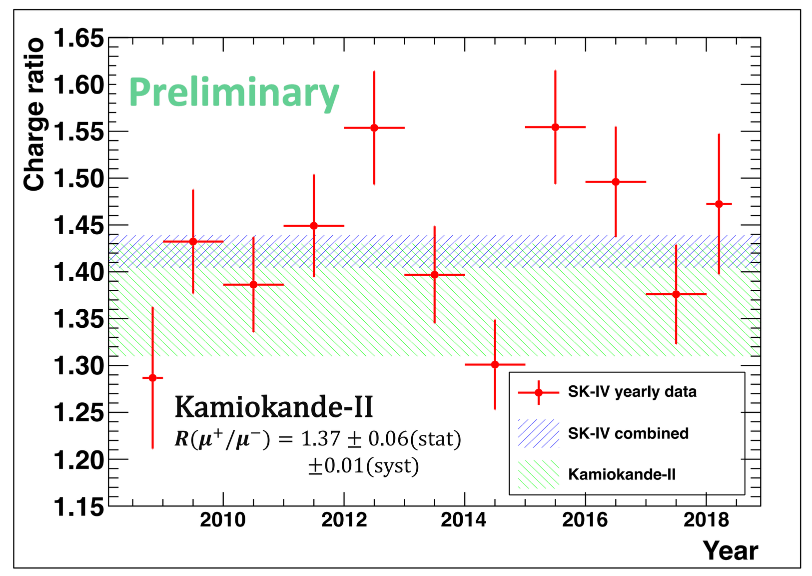
N_+	:	# of positive muons
N_-	:	# of negative muons
Δt	:	Binning width (0.1 μsec)
τ_{μ^+}	:	Lifetime of positive muon ($2.1969811 \pm 0.0000022\ \mu sec$)
τ_{μ^-}	:	Lifetime of negative muon in water ($1.7954 \pm 0.020\ \mu sec$)[4]
Λ_c	:	0.184 ± 0.001, nuclear capture fraction for negative muons in water[4]

Example in 2017 data



➢ The charge ratio in SK-IV

- Yearly variation of the charge ratio in data period of SK-IV (2008 ~ 2018).
- The charge ratio in SK-IV at the energy of 1.3 TeV
  $\Rightarrow R(\mu^+/\mu^-) = 1.42 \pm 0.02$ (statistical uncertainty only)
- The result is in agreement with Kamiokande-II[5] within their uncertainties.



5. Summary & Prospects

- Using the data of SK-IV, the charge ratio was measured to be 1.42 ± 0.02 (statistical uncertainty only).
- The SK-IV result is consistent with the Kamiokande-II's result within their uncertainties.
- Analysis for polarization of cosmic-ray muons is also on-going.

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