Poster #43

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

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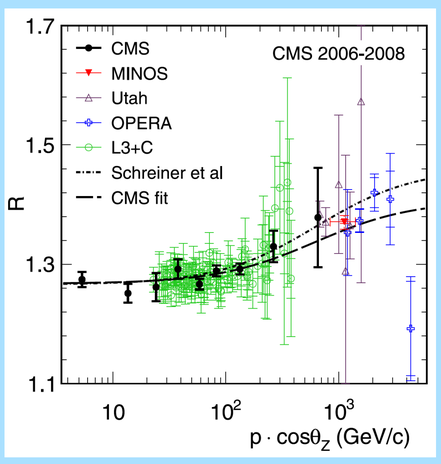
## 1. Introduction & Motivations

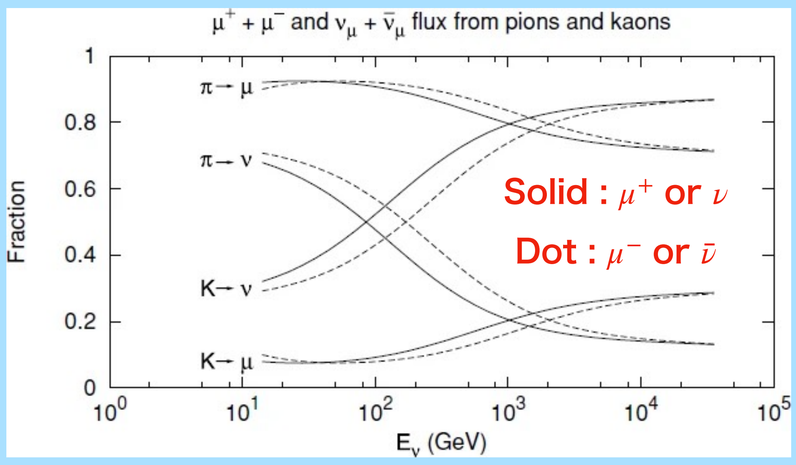
### Muon charge ratio $R$ $(\mu^+/\mu^-)$

- The muon charge ratio is the number of positive to negative atmospheric muons arriving at the Earth's surface.
- This value is about 1.27 below 200 GeV while it increases with higher momentum region. [1]
  → Muons from kaon decay tend to have large energy than those from pion. [2]

### Physics motivations

- We measured the muon charge ratio at muon energy of 1.3 TeV using Super-Kamiokande data.
  → Improve the atmospheric neutrino flux simulation.
  → Constrain the high energy hadronic interaction models.




## 2. Super-K & Reconstruction methods

### Super-K detector (SK)

- Water Cherenkov detector, located 1,000m underground.
- Containing 50 kton of ultra-pure water. [3]
- Separated into an inner detector (ID) and an outer detector (OD).
  → Gd-loaded water since July 2020 (SK-VI), and additional loading has been done on July 2022 (SK-VII). [4]
- Muons, whose energy is more than 1.3 TeV, enter the detector at 2 Hz.
  → About 2500 muons stop in the detector and decay into an electron (decay-e) per day. (less than 20 GeV)

| Phase | SK-I | SK-II | SK-III | SK-IV | SK-V | SK-VI | SK-VII |
|---|---|---|---|---|---|---|---|
| Period | 1996/04 ~ 2001/07 | 2002/10 ~ 2005/10 | 2006/07 ~ 2008/08 | 2008/09 ~ 2018/05 | 2019/01 ~ 2020/07 | 2020/07 ~ 2022/06 | 2022/06~ |
| Livetime | 1496 | 791 | 548 | 2970 | 379 | 454 | Running |
| ID PMTs | 11,146 | 5,182 | 11,129 | 11,129 | 11,129 | 11,129 | 11,129 |
| OD PMTs | 1,185 | 1,185 | 1,185 | 1,185 | 1,185 | 1,185 | 1,185 |

- In this poster, we analyzed the SK-IV data. (SK-IV : Pure water phase)

### Reconstruction methods

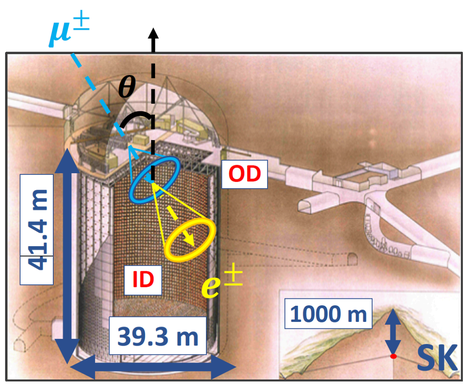
- Pair of muon and decay-e is tagged within [-5, +35] $\mu$sec window.

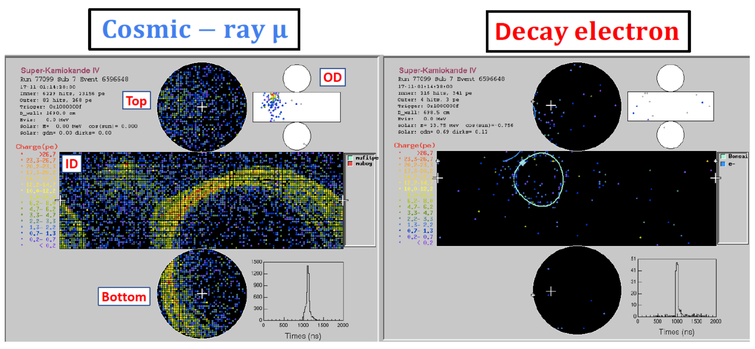
**[Muon]**

- Track(s) and direction(s) : Timing information of ID PMTs.
- Stopping position : dE/dx of the muon track. [5]

**[Decay-e]**

- Vertex : The residual timing of hit PMTs.
- Direction : Locations of hit PMTs.
- Energy : The number of hit PMTs after corrections by many factors. [6]




## 3. Analysis

### Selection cuts

**[Muon]**

- Down going muons stopped inside the ID are selected.

**[Decay-e]**

- Time difference between muon stop and decay-e generation (tdiff) is 1.3 $\mu$sec < tdiff < 30 $\mu$sec.
- The reconstructed decay-e energy is greater than 8 MeV.
- Position difference between muon stop position and vertex of decay-e is less than 300 cm.
  → After these cuts, **2,000,000 pairs of muon and decay-e** are selected.

### Negative muon capture

- Negative muon tends to be captured on Oxygen in water.
  → As a result, negative muon lifetime is shorter. (About 1.8 $\mu$sec)
- 18.4% of negative muons produce Nitrogen-14 & -15, which emit $\gamma$-rays soon. [7, 8]
  → Need to correct the number of the negative muons.
  → Correction factor : $\Lambda_c = 0.184 \pm 0.001$

### Measurement of the muon charge ratio

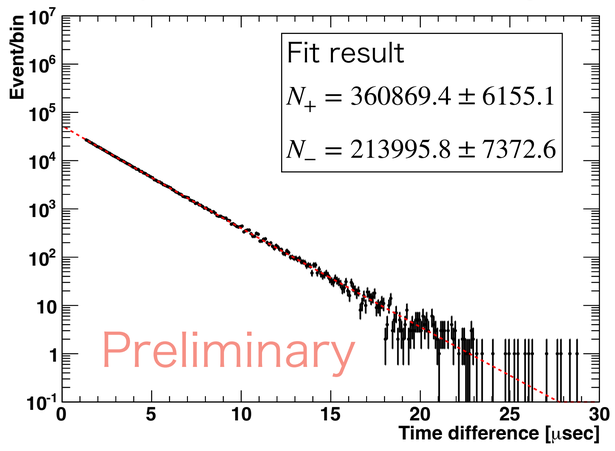
- Counting the number of positive and negative muons by fitting the decay curve.

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

$N_+$ : # of positive muons
$N_-$ : # of negative muons
$\Delta t$ : Binning width (0.1 $\mu$sec)
$\tau_{\mu^+}$ : Lifetime of positive muon
2.1969811 ± 0.0000022 $\mu$sec
$\tau_{\mu^-}$ : Lifetime of negative muon in water
1.7954 ± 0.020 $\mu$sec

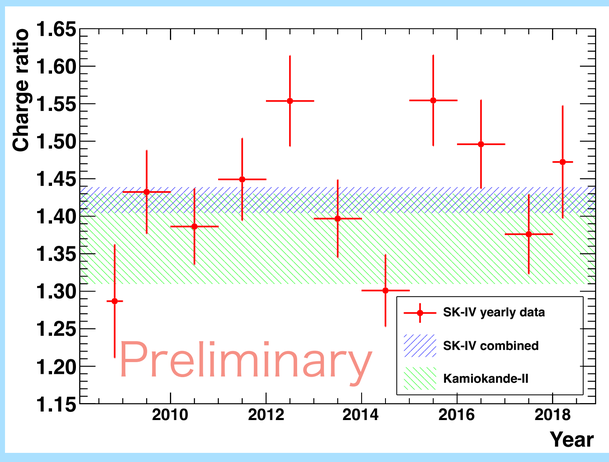
$$R(\mu^+/\mu^-) = \frac{N_+}{N_-/(1-\Lambda_c)}$$

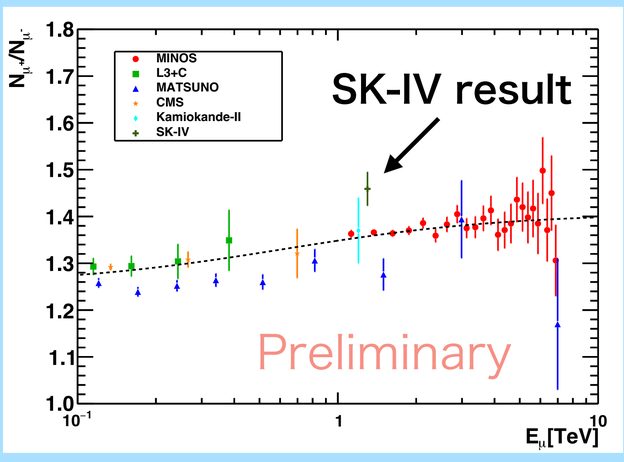
Example in 2017 data (280.9 days)




## 4. Results

- The charge ratio : $R(\mu^+/\mu^-) = 1.42 \pm 0.02$(stat.)
  → Consistent with Kamiokande- II [9]
- The yearly variation of the charge ratio in SK-IV is not significant.
- This result is higher than the expected value based on the theoretical model. [10]




## 5. Summary & Prospects

- Determine the muon charge ratio by measuring the lifetime of decay electrons in Super-Kamiokande.
  → $R(\mu^+/\mu^-) = 1.42 \pm 0.02$ (only statistical uncertainty)
  → Estimation of systematic uncertainties will be completed soon.
- The study of the polarization of the cosmic-ray muons is now ongoing.
  → Evaluate the angle between the direction of muon and decay-e.

### References

[1] *Pays. Lett. B* 692, 83 (2010). [2] *Earth, Planet and Space* 62, 195-199 (2010).
[3] *Nucl. Inst. Meth. A* 501, 418 (2003). [4] *Nucl. Inst. Meth. A* 1027, 166248 (2022).
[5] *Phys. Rev. D* 93, 012004 (2016). [6] *Phys. Rev. D* 94, 052010 (2016). [7] Phys. Rev. C 35, 2212 (1987).
[8] Physics Reports 354, 243-409 (2001). [9] *Phys. Rev. D* 44, 617 (1991). [10] *Astropart. Phys.* 32, 61(2009).