Measurement of the charge ratio and the spin polarization of the cosmic-ray muons with the Super-Kamiokande

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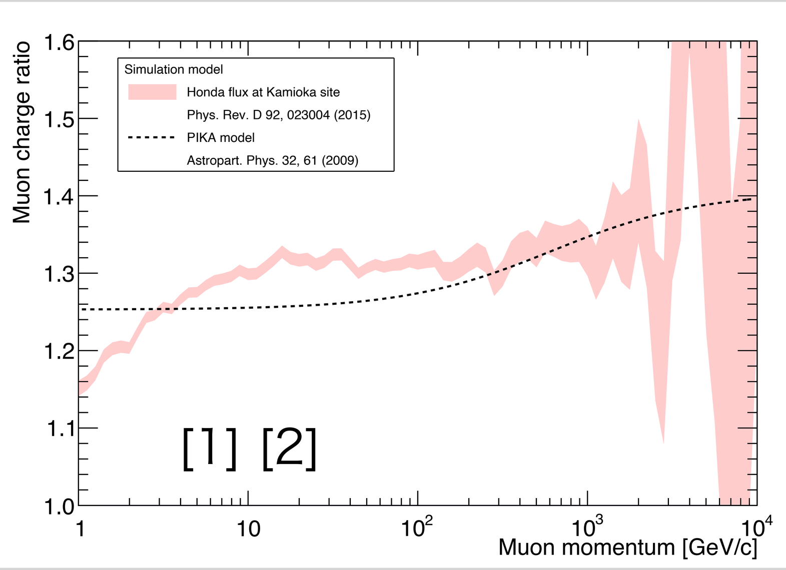
1. Introduction

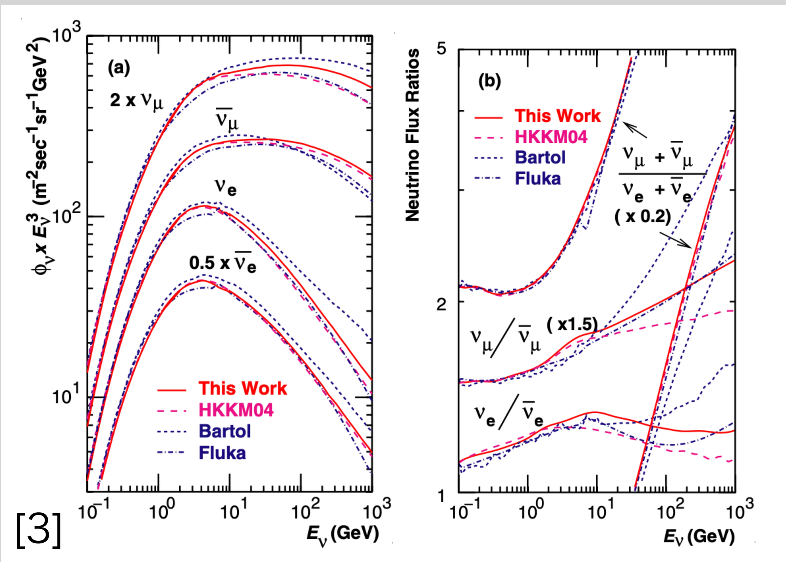
Muon charge ratio R (μ^+/μ^-)

- The ratio of positive to negative atmospheric muons arriving at the experimental site.
- It increases with higher momentum region. [1] [2]

Physics motivations

- Super-K can measure the muon charge ratio at momentum more than ~TeV.
  - Reduce the uncertainty of atmospheric neutrino flux. [3]
    → Accurate atmospheric neutrino simulation.
  - Constrain the high energy hadronic interaction models.





2. Super-K & Reconstruction methods

Super-K detector (SK)

- Water Cherenkov detector, located 1,000m underground. (2700 m.w.e.)
- Contain 50 kton of ultra-pure water. [4]
  → Gd-loaded water since July 2020. [5]
- Separated into an inner detector (ID) and an outer detector (OD).
- Muons, whose energy is more than ~TeV at Earth's surface, enter the detector at 2 Hz.

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
Detector	Pure water	Pure water	Pure water	Pure water	Pure water	Gd loaded (0.01%)	Gd loaded (0.03%)

- In this analysis, we measure the charge ratio using the SK-IV data (2970 days : Pure water phase).

Reconstruction methods

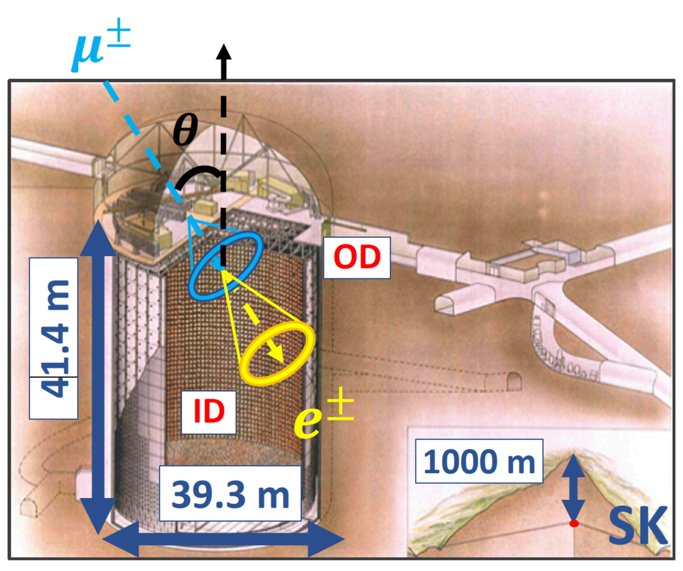
- Decay-e is tagged within [-5, +35] μsec window after muon event.
- μ- e event happens about 2,500 times per day.

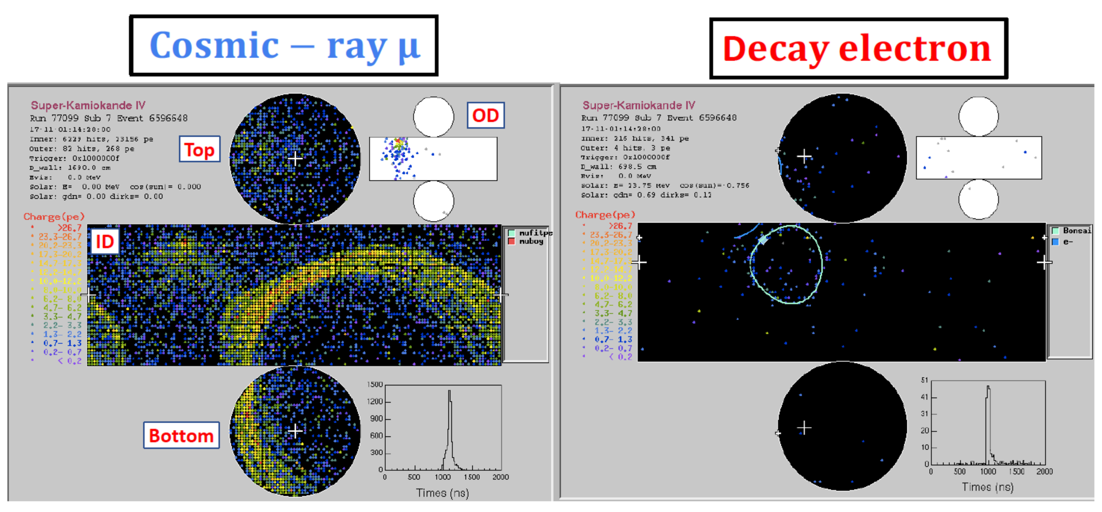
[Muon]

- Track and direction : Timing and charge information of ID PMTs.
- Stopping position : Enter position, direction, and track length. [6]

[Decay-e]

- Vertex : The residual timing of hit PMTs.
- Direction : Cherenkov ring pattern.
- Energy : Based on the number of PMT hits. [7]





3. Analysis

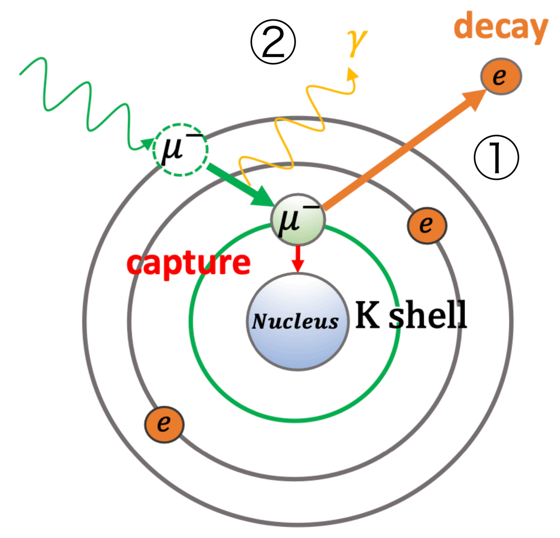
Event selection

[Muon]

- Down-going muons and stopped inside the ID are selected.

[Decay-e]

- Time difference between muon and decay-e
  1.3usec < Time difference < 30usec.
- Position difference between muon stop position and decay-e vertex is less than 300cm.



Negative muon capture

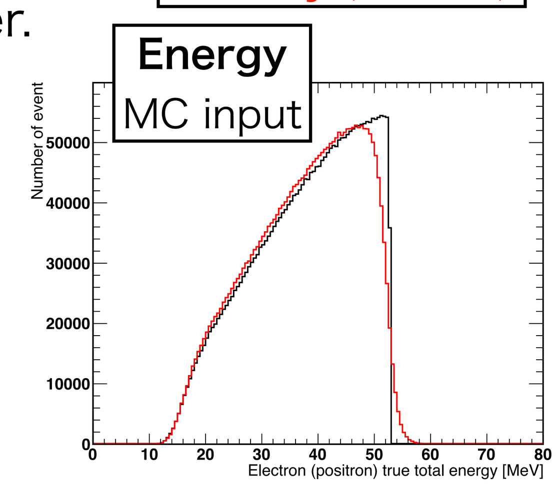
Negative muon capture

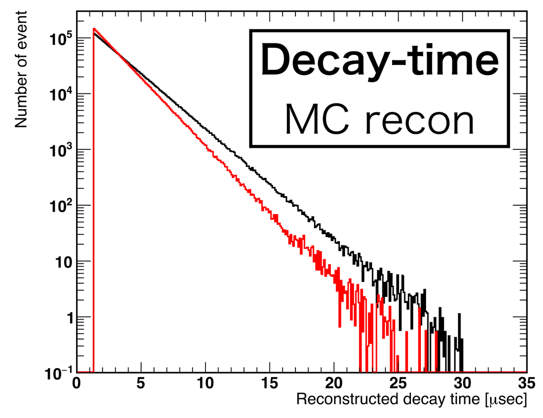
- Negative muon is captured on Oxygen in water.
  → Cause either process ① or ②
  ① Decay into electron in orbit.
  ② Absorbed in the nucleus and emits γ - rays.

Variables used for measurement

- Energy of decay-e
  - Energy spectrum of positron is Michel spectrum.
  - Energy spectrum of electron is distorted by process ①.
- Decay time
  - Negative muon has a shorter decay time by competition between ① and ②.

μ+ only (P = +1)
μ- only (P = +1)





Evaluation of the charge ratio

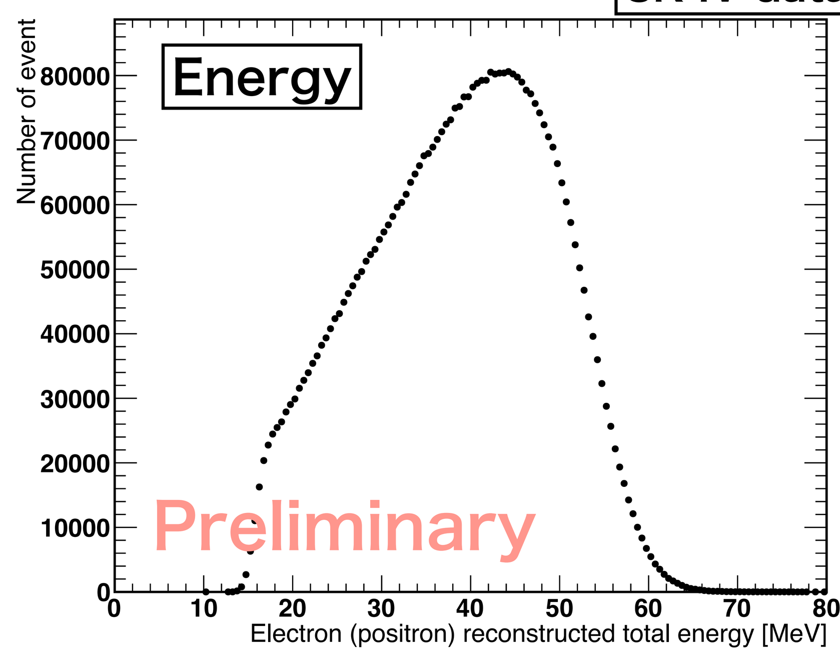
- Create MC with various charge ratio.
- Calculate the χ^2 in each variable.

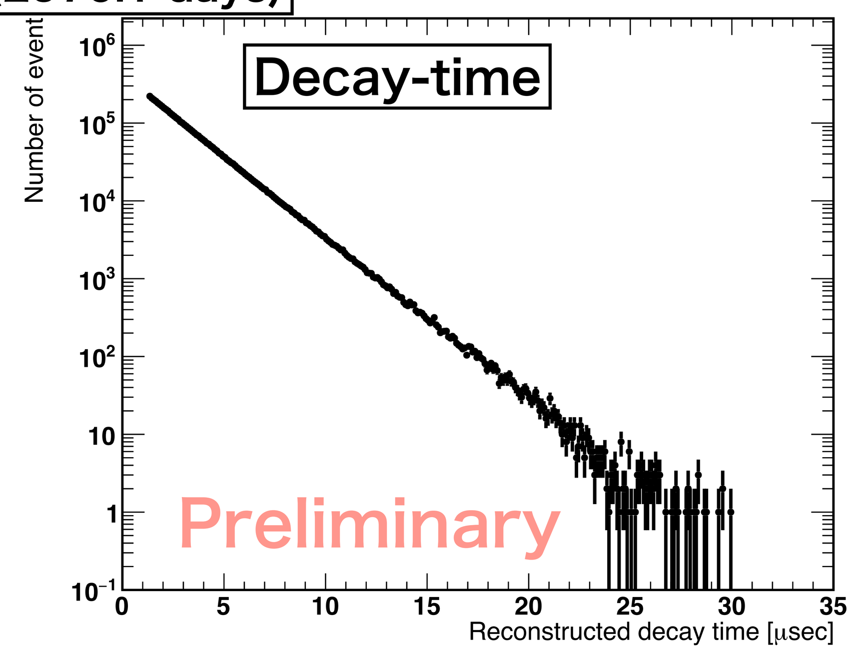
$$\chi^2 = \sum_i^{nbins} \frac{(N_i^{Data} - N_i^{MC})^2}{(Error_i^{Data})^2 + (Error_i^{MC})^2 + (Systematic_i)^2}$$

$$\chi^2_{sum} = \chi^2_{Energy} + \chi^2_{Decay-time}$$

Determine R that minimizes the χ^2

SK-IV data (2970.1 days)



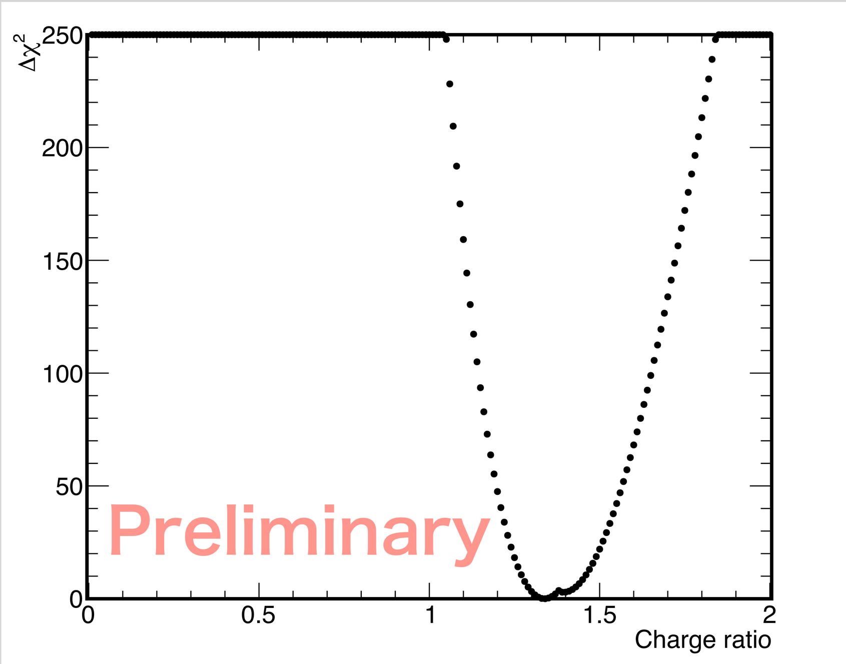


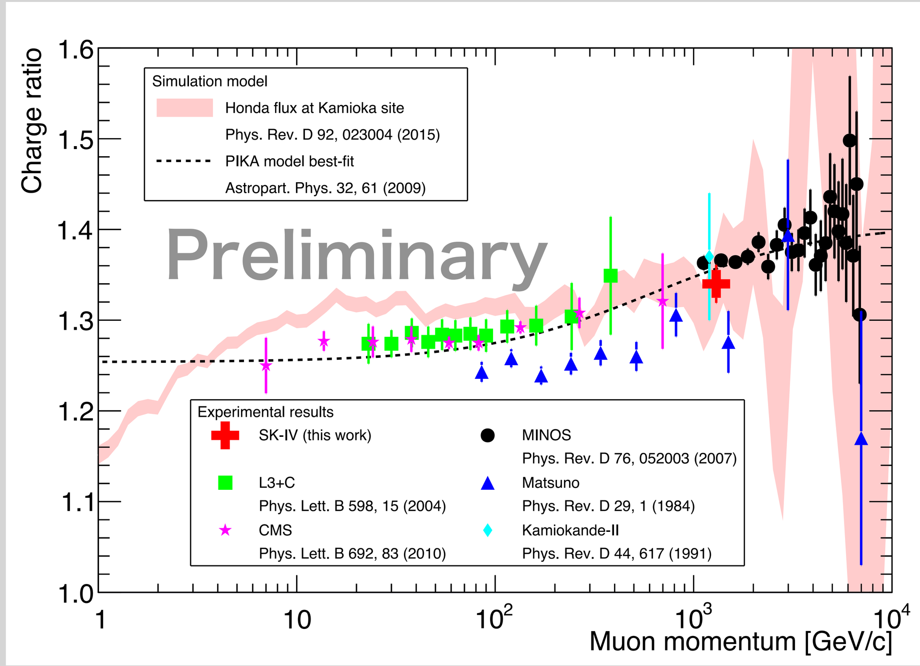
4. Results

R = 1.34 ± 0.02 (stat. + syst.)

Minimum χ^2/ndf = 315.250/267 = 1.181

- The charge ratio agrees with predicted value within 1 σ.





5. Summary and plan

- The detailed understanding of the muon charge ratio can reduce the uncertainty of atmospheric ν flux.
- Measure the muon charge ratio by evaluating the χ^2 of SK-IV (2970 days) data and MC in Super-Kamiokande.
  → R = 1.34 ± 0.02 (stat. + syst.),
- Measurement of the spin polarization using the angle between muon and decay-e is on-going.

References

[1] *Phys. Rev. D* 92, 023004 (2015). [2] *Astropart. Phys.* 32, 61 (2009).
[3] *Phys. Rev. D* 75, 043006 (2007). [4] *Nucl. Inst. Meth. A* 501, 418 (2003).
[5] *Nucl. Inst. Meth. A* 1027, 166248 (2022). [6] *Phys. Rev. D* 93, 012004 (2016).
[7] *Phys. Rev. D* 94, 052010 (2016).