Measurement of the Charge Ratio of Cosmic-Ray Muons in Super-Kamiokande

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Contents

- Cosmic-ray muons
- Muon charge ratio
- Super-Kamiokande (SK)
- $\mu - e$ decay
- Muon charge ratio in SK-IV
- Summary

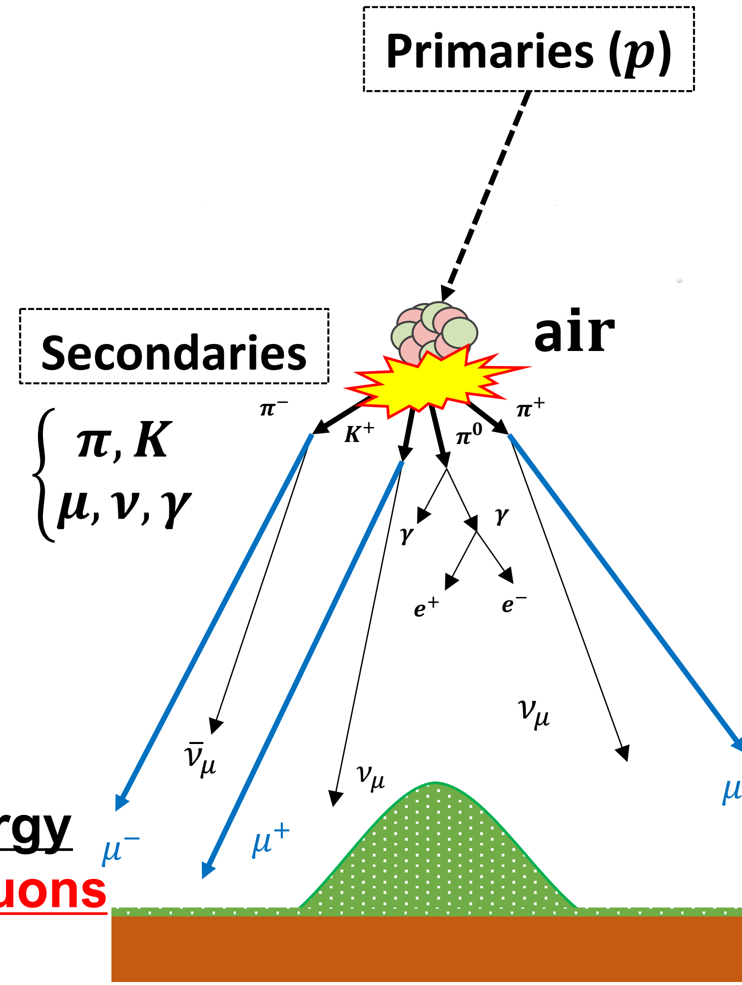
Cosmic–ray muons

Primary cosmic-rays interact with atmospheric nuclei and produce secondaries

$$p + air \rightarrow X + \pi^{\pm}(K^{\pm})$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$\mu^{\pm}$ carry the secondary production information



<u>Probing particle interactions in the high-energy region through observation of cosmic-ray muons</u>

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Muon charge ratio

Physics motivation

The precise estimation of hadron productions and the atmospheric neutrino flux is required
→ uncertainties of μ, π, K fluxes and their charge ratio

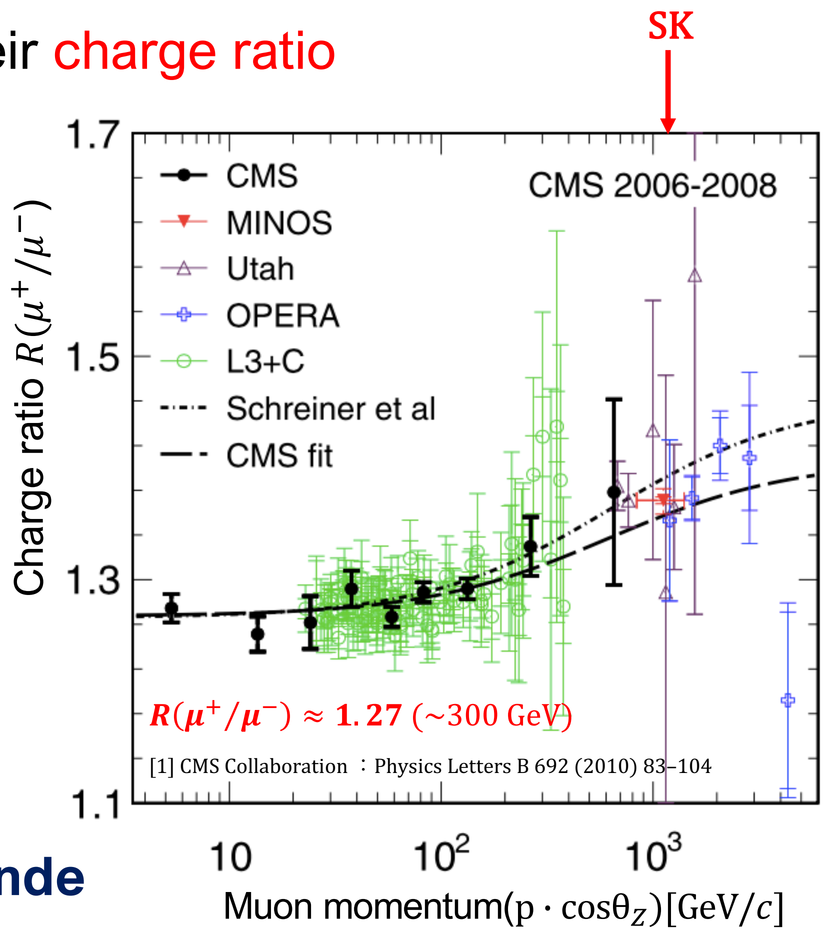
Muon charge ratio $R(\mu^+/\mu^-)$

- π/K production dependency
- K contribution to TeV energy region

$$p + air \rightarrow \Lambda^0 + K^+ + \text{anything}$$

Further measurement in the TeV region for the precise $R(\mu^+/\mu^-)$ prediction

→ can be measured in **Super-Kamiokande**



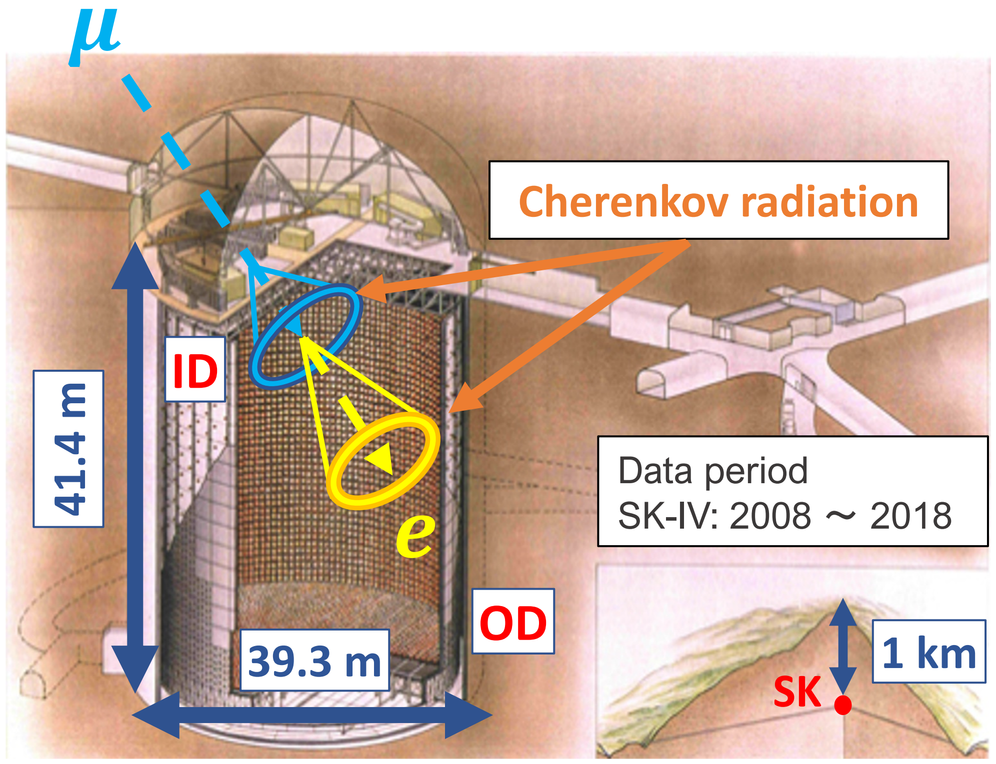
Super-Kamiokande (SK)

■ Super-Kamiokande detector

- Water Cherenkov detector
  → located 1,000 m underground in Kamioka mine (Japan)

- 50 kton water tank
  → Inner Detector (ID),
  Outer Detector (OD)

- PMTs installed in ID and OD
  → event reconstruction



High-energy muons
penetrate underground (~1.3 TeV)

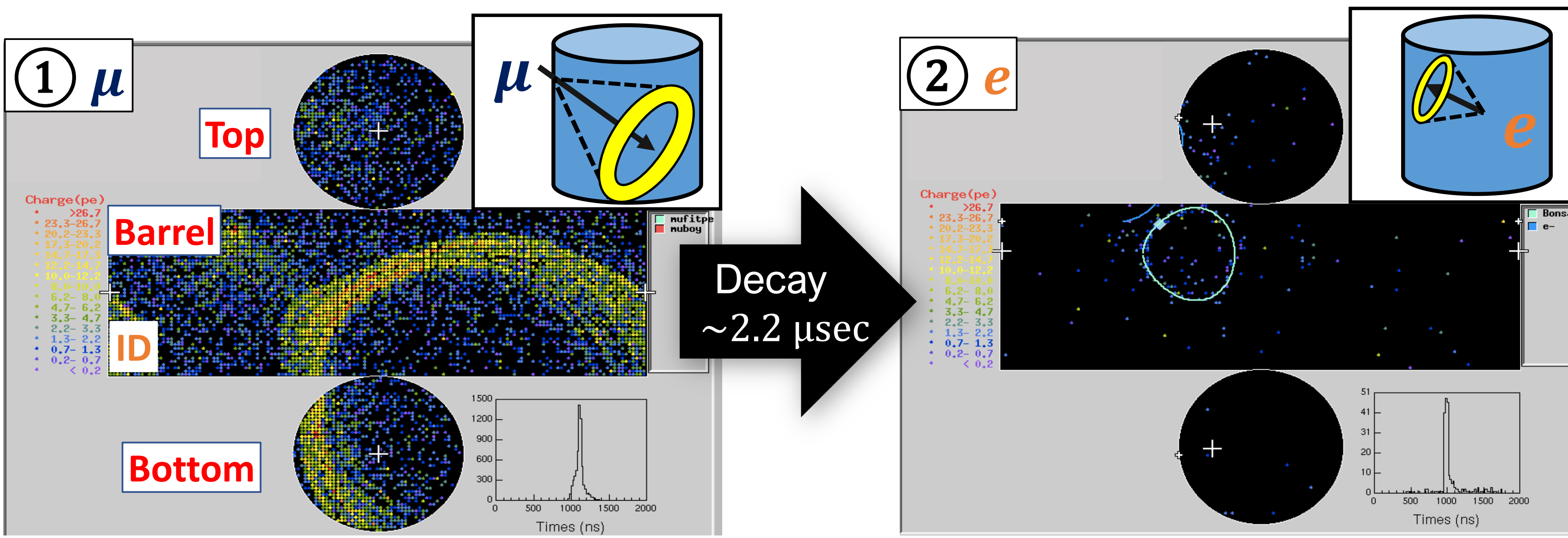
→ measure the charge ratio using μ − e decay

$\mu - e$ decay event

Muon-decay electron signal

$\mu^{\pm} \rightarrow e^{\pm} + \nu_e\ (\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$ (Lifetime: τ_{μ}~2.2 μsec)

- Number of hit PMTs → μ (e) emit a lot (few) of Cherenkov photons
  → energy reconstruction for e
- Timing information of hit PMTs → direction & vertex reconstruction
- Observe 2,000 events/day



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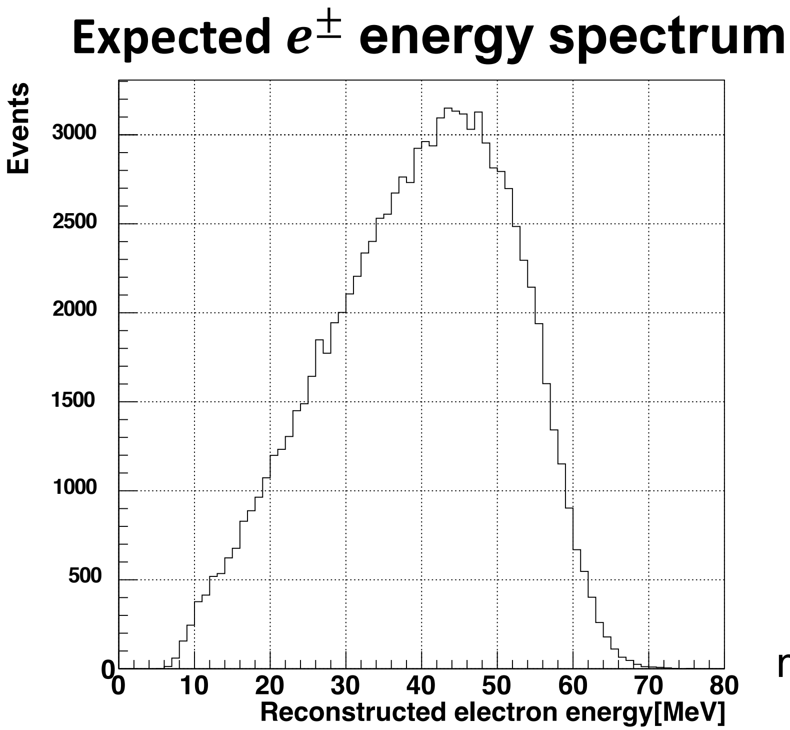
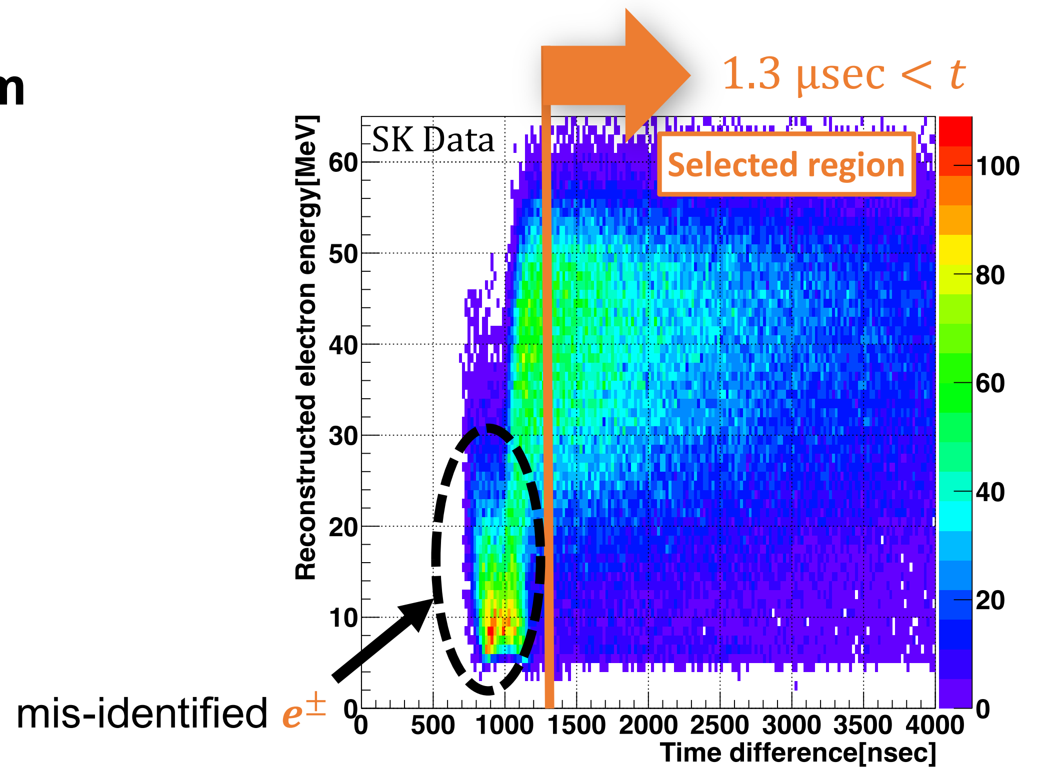
$\mu - e$ decay search

Selection criteria for $\mu - e$ candidates

1. $\mu - e$ decay time difference : $1.3\ \mu\text{sec} < t$
   → remove mis-identify hit PMTs from the muon longer tail hits in $t \leq 1.3\ \mu\text{sec}$





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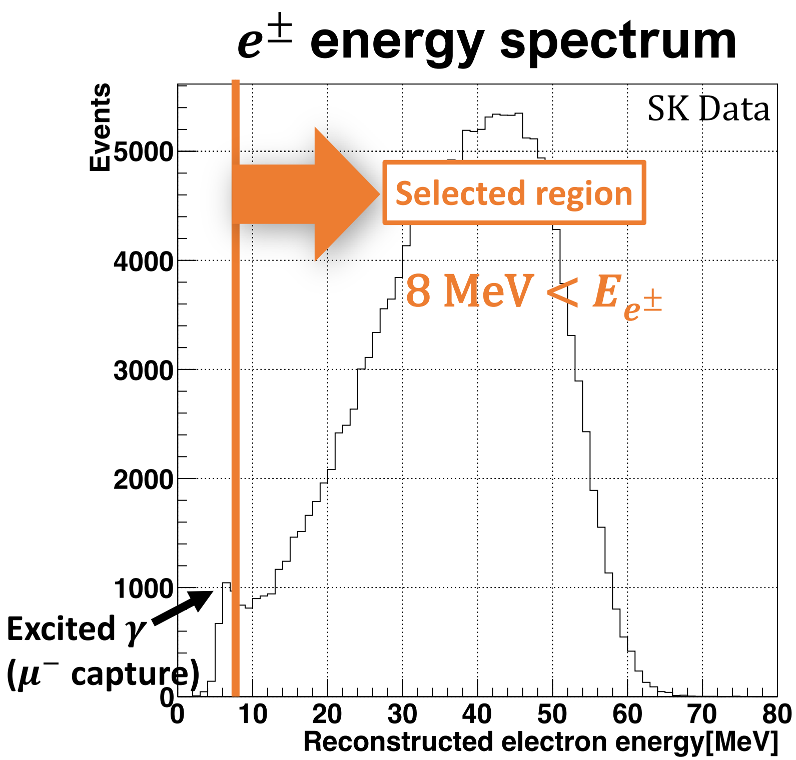
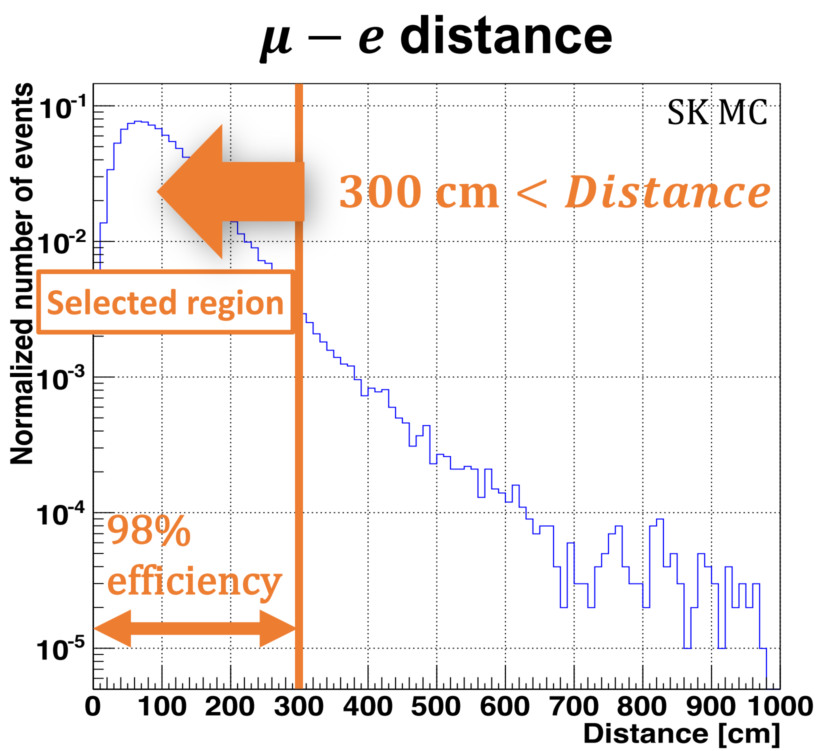
$\mu - e$ decay search

Selection criteria for $\mu - e$ candidates

1. $\mu - e$ decay time difference : $1.3\ \mu\text{sec} < t$
2. Reduction of low energy backgrounds : $8\ \text{MeV} < E_{e^{\pm}}$
3. Distance between $\mu - e$ position : $300\ \text{cm} < Distance$





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Muon lifetime in medium

μ^- capture in nuclei

μ^- lifetime becomes shorter in the medium due to the nuclear capture

μ^- in medium

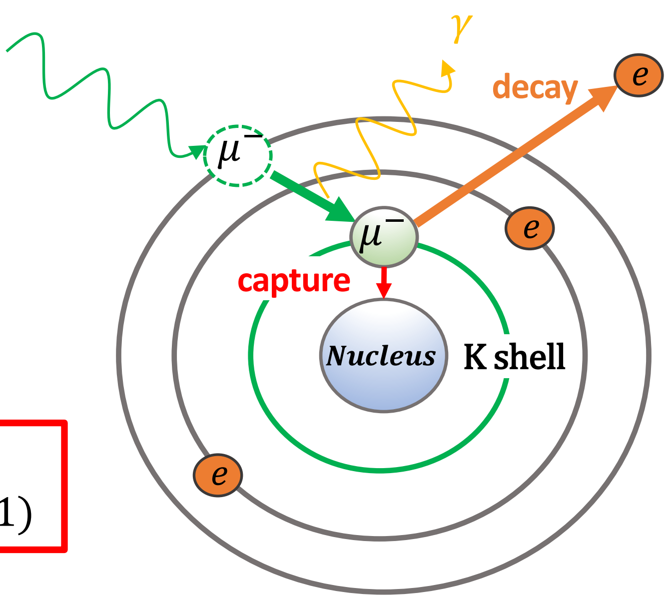
↓

Binding in nuclear orbit
(Coulomb interaction)

↓

Decay in orbit (free decay)
$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$

Nuclear capture (capture)
$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$



Total decay rate Γ_{Total} $[1/s]$:

$$\Gamma_{\mathrm{Total}} = \Gamma_{\mathrm{Free\ decay}} + \Gamma_{\mathrm{Capture}} = \frac{1}{\tau_{\mu^-}} > \frac{1}{\tau_{\mu^+}}$$

Lifetime in water (^{16}O)[2], [3]

τ_{μ^-}	τ_{μ^+}
1.795 μsec	2.196 μsec

[2] P. A. Zyla,et al.: (Particle Data Group), Prog.Theor.Exp.Phys.2020, 083C01 (2020)
[3] T. Suzuki, D.F. Measday, and J.P. Roalsvig, Phys. Rev. C 35, 2212 (1987)

Observed $\mu^{\pm}$ events

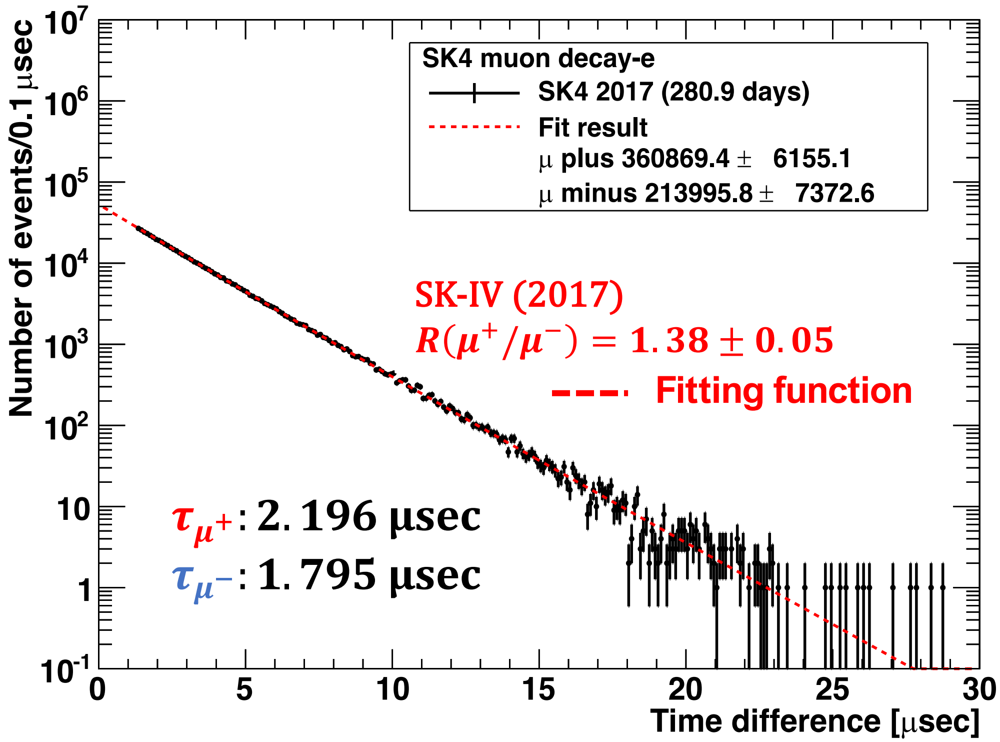
Decay curve of stopping muon

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

μ^{+} μ^{-}

Fixed parameters $\tau_{\mu^{+}}$, $\tau_{\mu^{-}}$ in water

$\rightarrow$ optimize N_{+}, N_{-} respectively



Muon charge ratio

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

Λ_{c}: μ^{-} capture rate (18.4%)

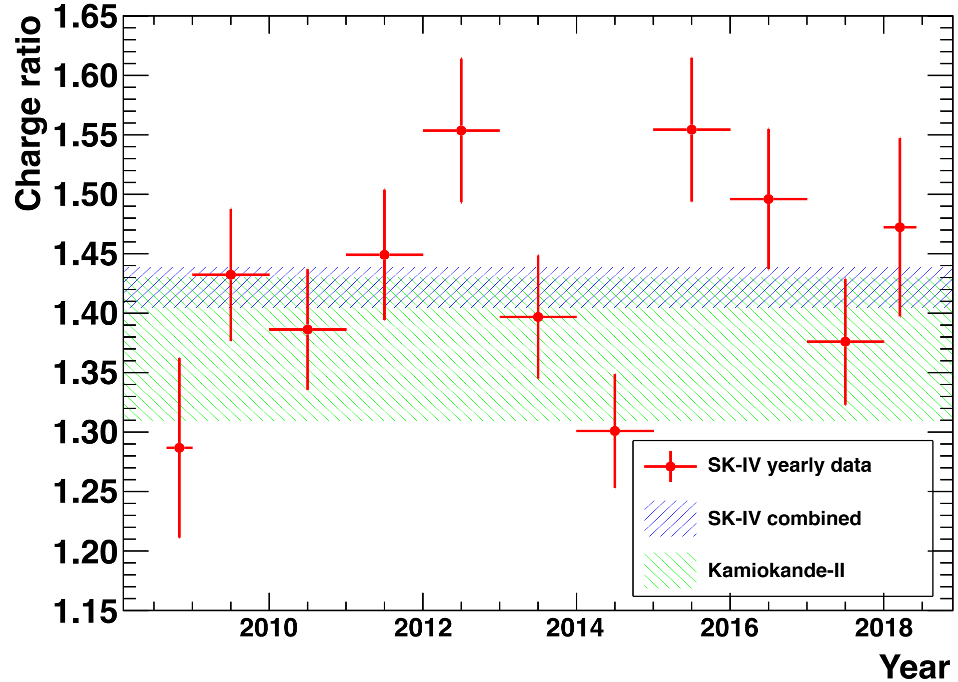
Muon charge ratio in SK-IV

Yearly variation of the charge ratio in SK-IV $(2008 \sim 2018)$
Averaged charge ratio in SK-IV $\Longrightarrow R(\mu^+/\mu^-) = 1.42 \pm 0.02$

■ π/K production

K production contribute to the charge ratio in TeV region
$\rightarrow$ increase from $R(\mu^+/\mu^-) \approx 1.27$ $(10 \sim 300\ \text{GeV})$

$$p + air \rightarrow \Lambda^0 + K^+ + \text{anything}$$



π/K production dominates in the energy region up to TeV
$\rightarrow$ can improve π/K ratio prediction in the TeV scale

Summary

- Investigate hadronic interaction in atmosphere and prediction for atmospheric neutrino flux:
  → $R(\mu^+/\mu^-)$ measurement is required

- Measured $R(\mu^+/\mu^-)$ using SK detector:
  → search for $\mu - e$ decay candidates
  → counting total $N_\pm$ considering lifetime $\boldsymbol{\tau_{\mu^\pm}}$ difference in water

- Result of SK-IV (10 years) averaged data:
  → $R(\mu^+/\mu^-) = 1.42 \pm 0.02$ (~ 1.3 TeV region)
  → K production enhance, $R(\mu^+/\mu^-) \approx 1.27$ ($10 \sim 300$ GeV)

- Improvement of muon charge ratio prediction:
  → can estimate π/K production ratio in TeV scale

Back up

Research activities

- **CERN, Switzerland (Apr. 2022 – Present)**
  Measurement of the Hadron Production for T2K Experiment at NA61/SHINE CERN

- **Okayama University, Japan (Apr. 2019 – Mar. 2022)**
  Master Thesis: Measurement of the Charge Ratio of Cosmic-Ray Muons in Super-Kamiokande

- **CERN, Switzerland (Online) (Jun. 2020 – Aug. 2021)**
  1) Searching for ALPs in Light-by-light Scattering in pp Collisions Using AFP Proton Tagging with the ATLAS Detector (DPG Spring Meeting)

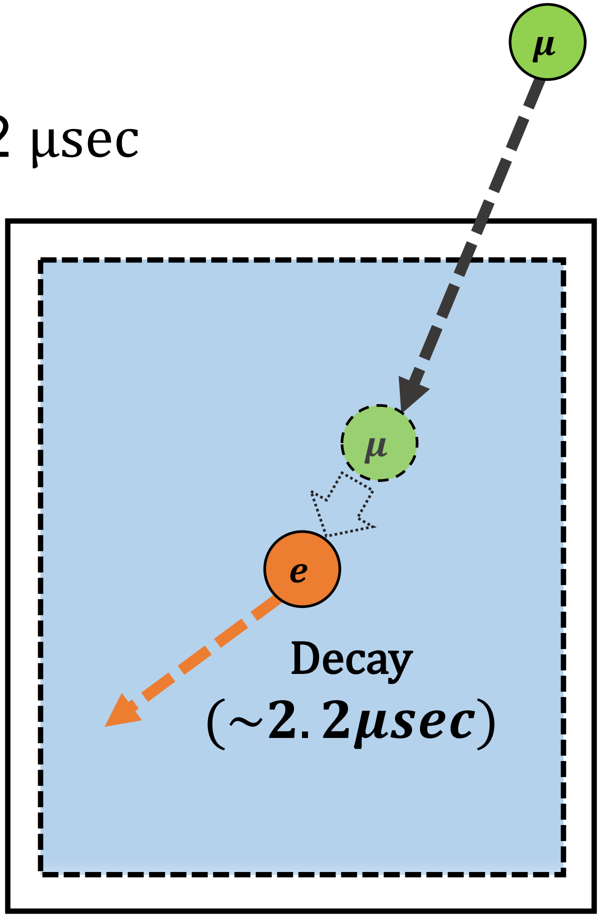
  2) Study of Jets for an Axion-Like Particle Search with the ATLAS Detector (Report)

  3) Optimization of Diphoton Acoplanarity Selection for an Axion-Like Particle Search with the ATLAS Detector (Report)

Muon-decay

(1) Single muon enter and stop inside the tank

(2) Decay electrons are generated at around 2.2 μsec



Search for $\mu - e$ decay events

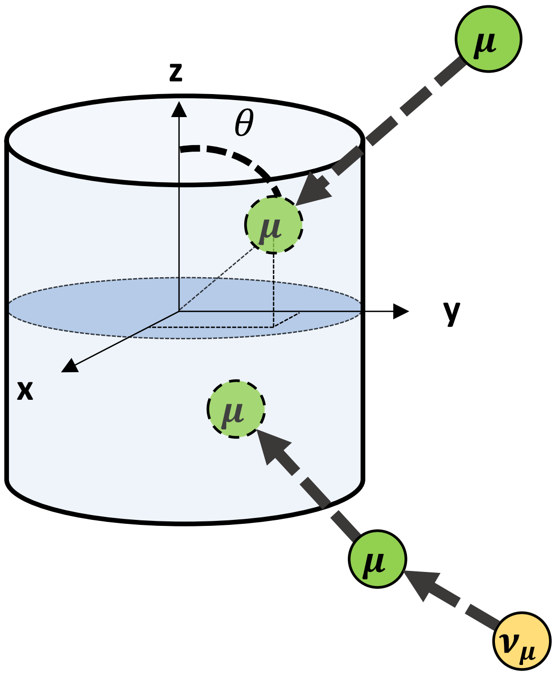
Data contains background events

Identify from the typical characteristics of $\mu - e$ decay events

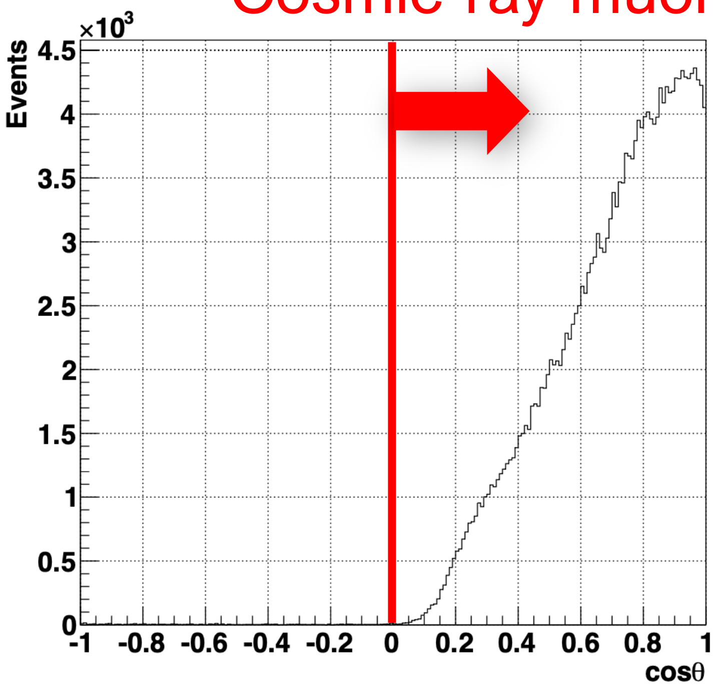
Muon zenith angle dependency

■ Zenith angle distribution of stopping muons

Cosmic-ray muons ($\theta < 90^{\circ}$)



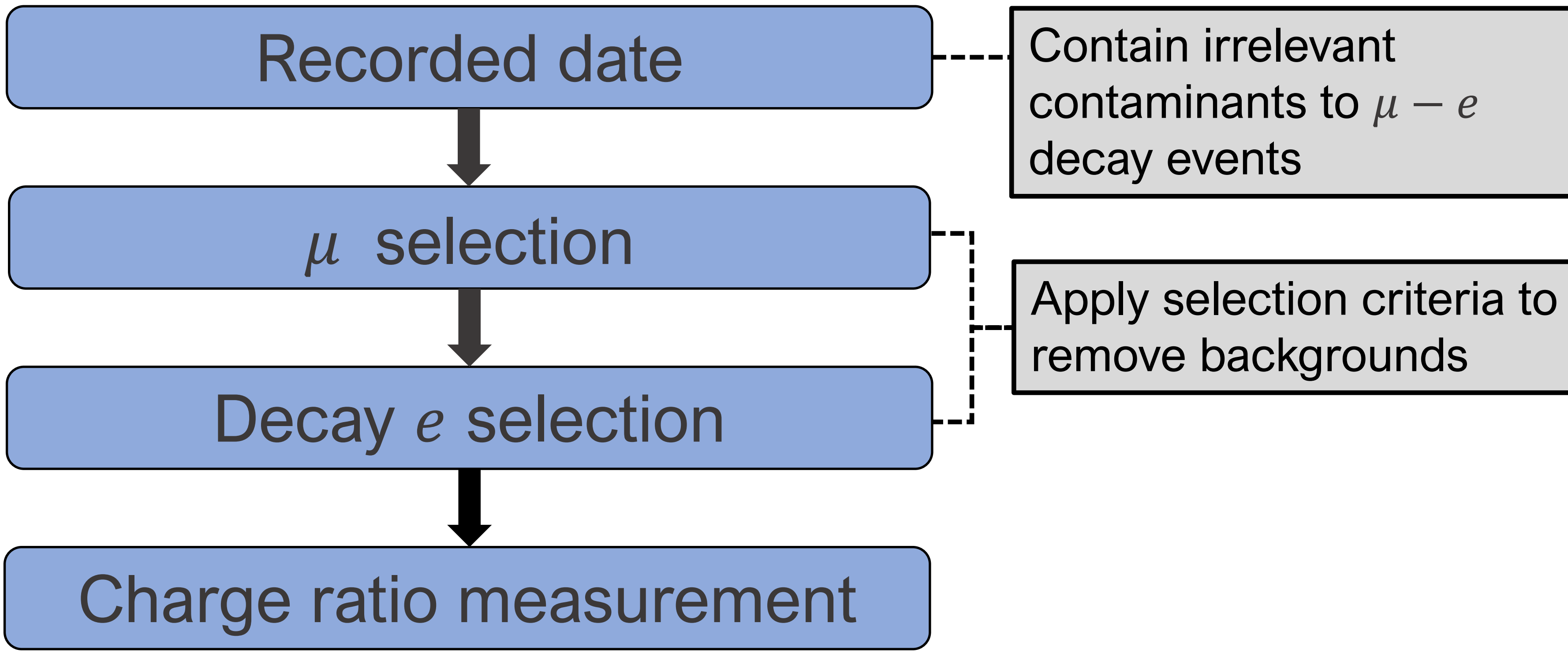
Cosmic-ray muons



upward-going muon induced from neutrino interaction ($\theta > 90^{\circ}$)

➡ Upward-going direction region ($\cos\theta < 0$) are rejected

Analysis flow chart



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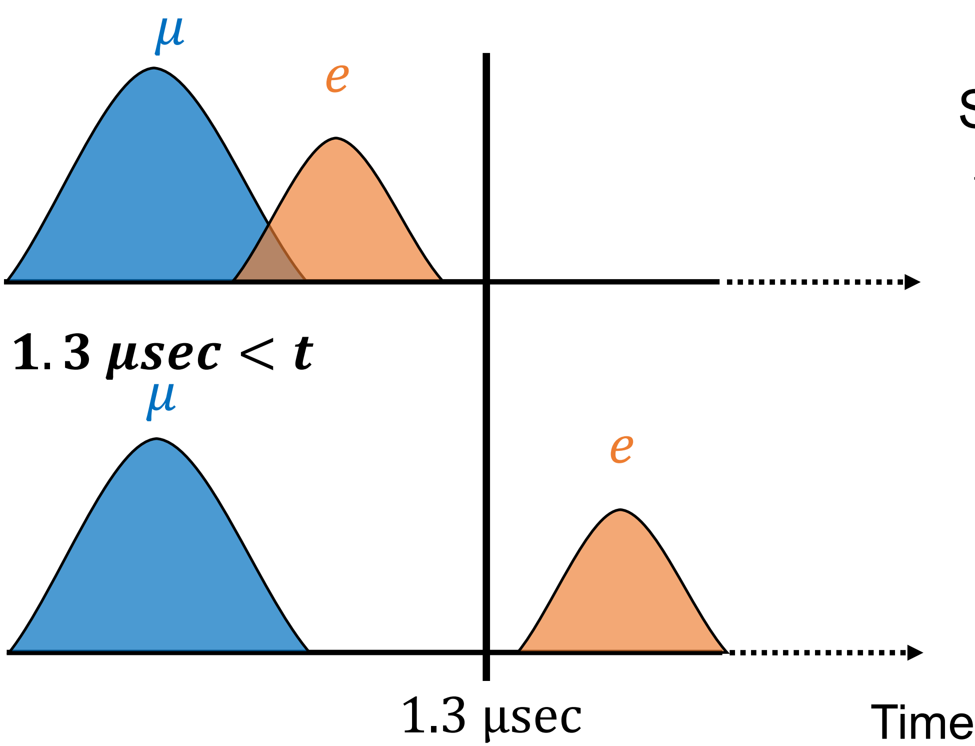
Time window of trigger

■ Time difference between μ-e decay events

① $t < 1.3$ μsec



② $1.3\ \mu sec < t$

Signals are overlapped
→ cannot distinguish μ, e signals

Apply longer time difference
→ avoid including mis-reconstruction events

(＊)Lifetime $\tau_{\mu} = 2.2$ μsec

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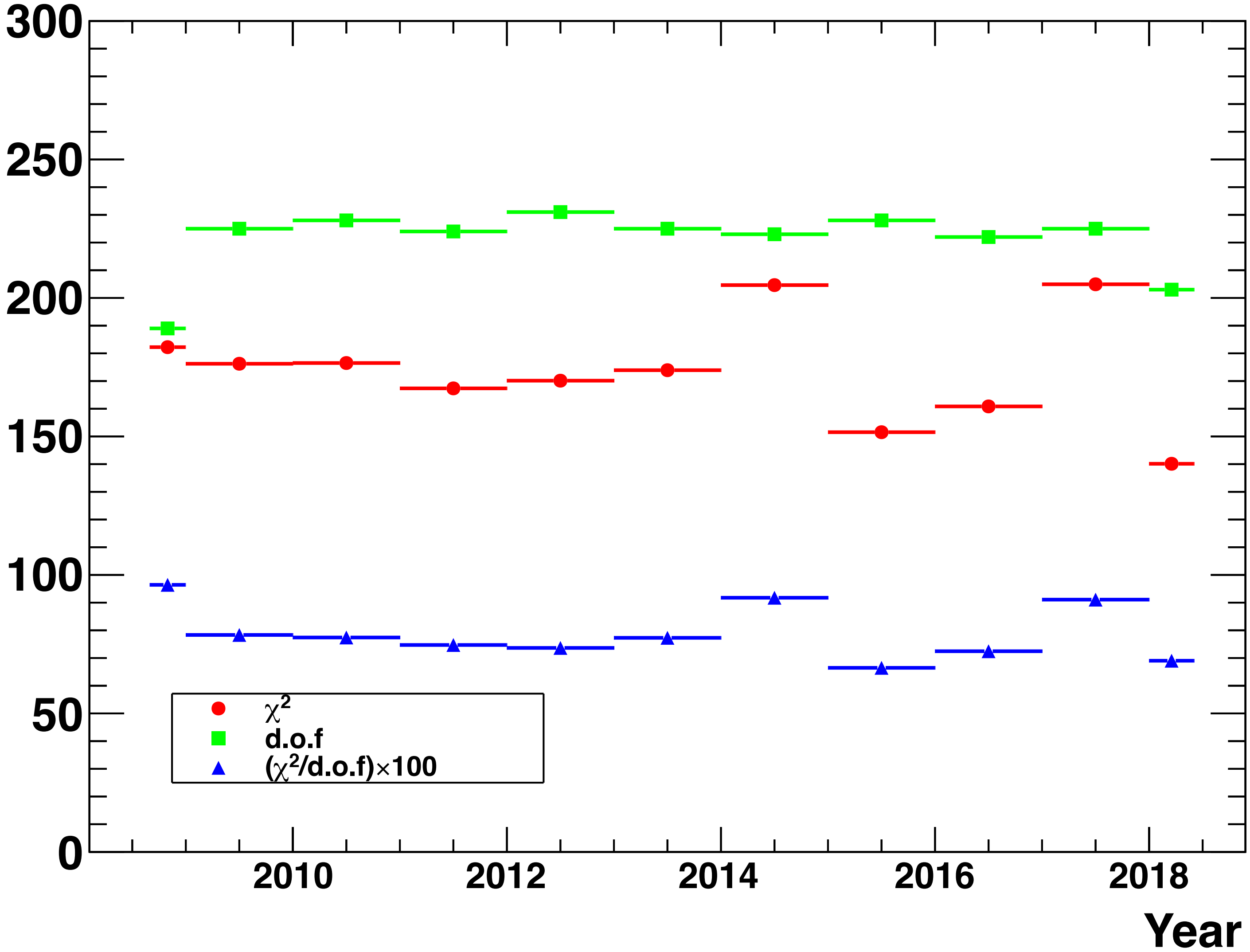
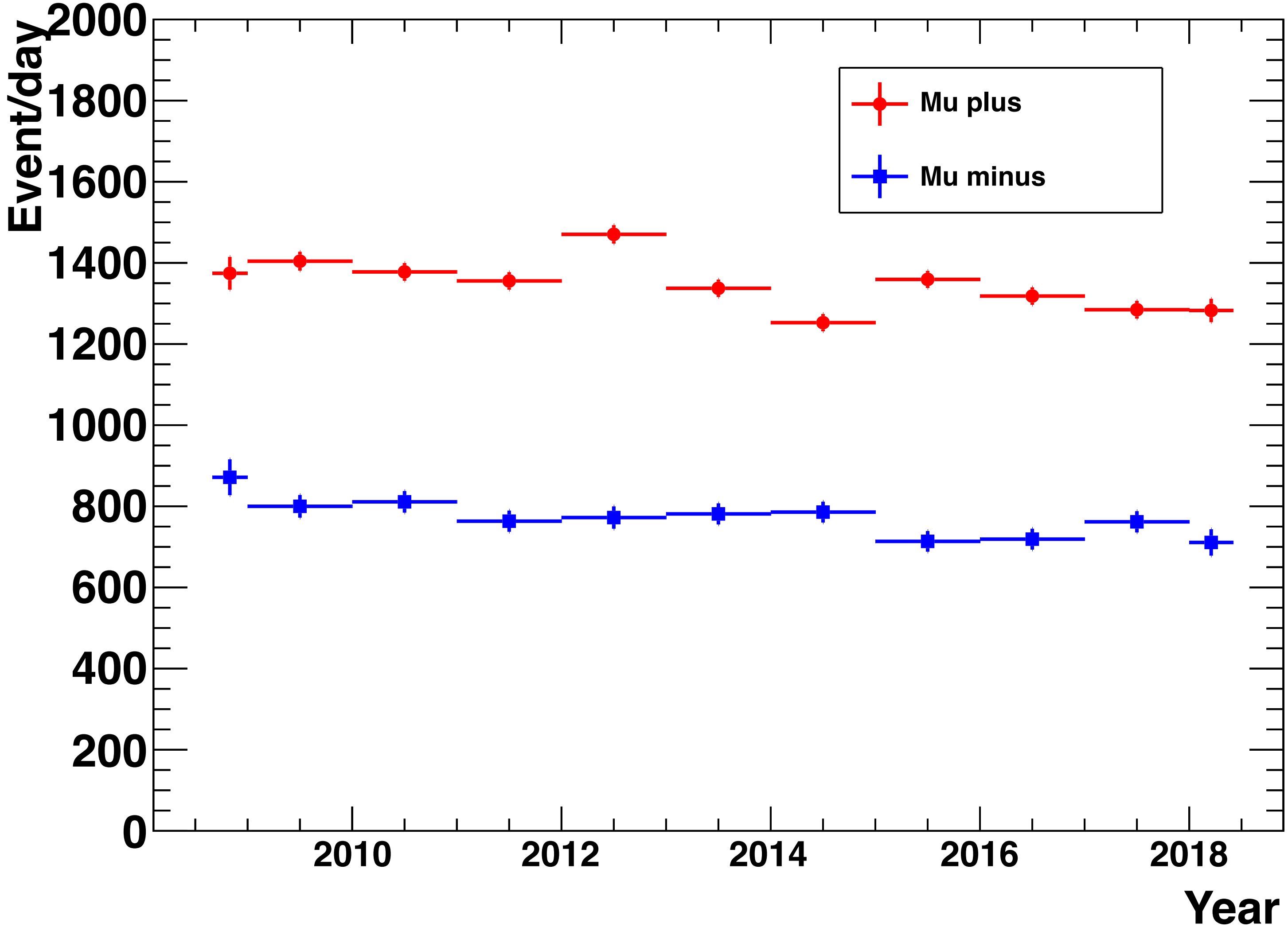
Fitting results of decay curve in SK-IV[19]



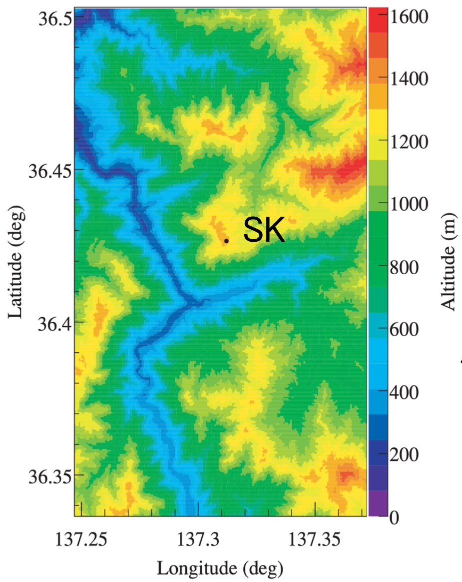
Stopping muon rate in SK-IV



Muon simulation with MUSIC

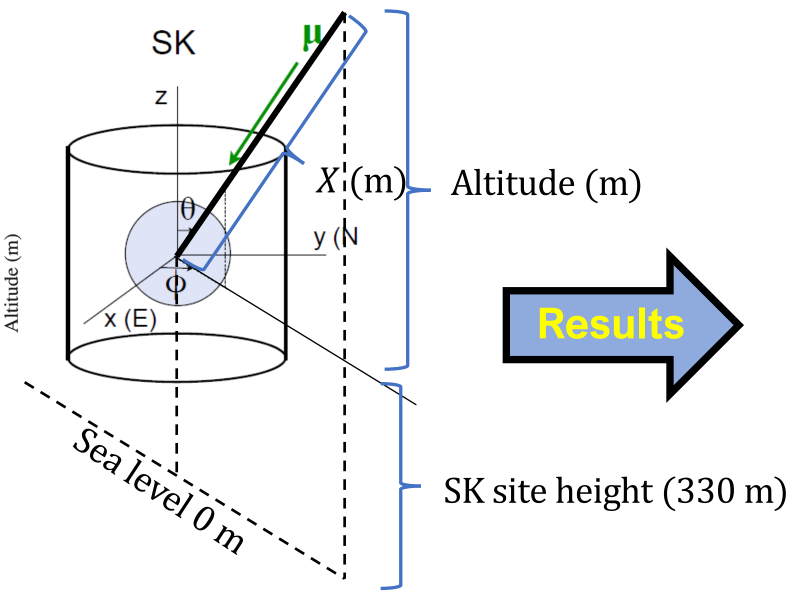
- Optimize the selection criteria for the data collection of muon decay events
  → consider muon flux at SK in MC
- **MUSIC**(Muon Simulation Code)[*]
  Three-dimensional simulation of the muon propagation
  → **calculate average muon energy, flux, and rate**

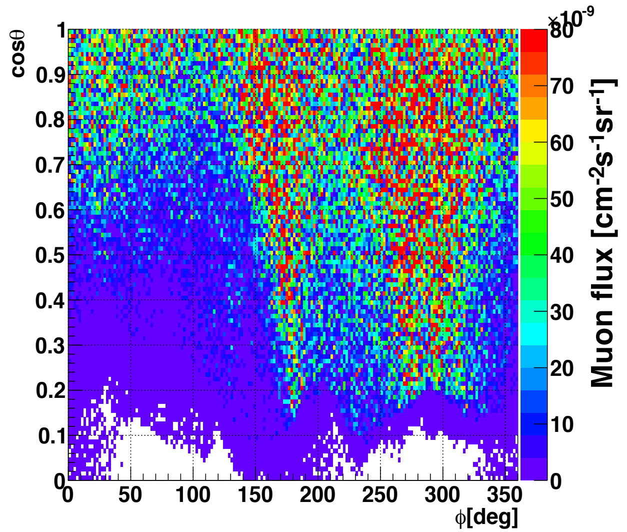
Digital Map 50 m Grid



Geographical Survey Institute of Japan(1997)

Calculate energy loss of μ passing through a slant depth X of a matter

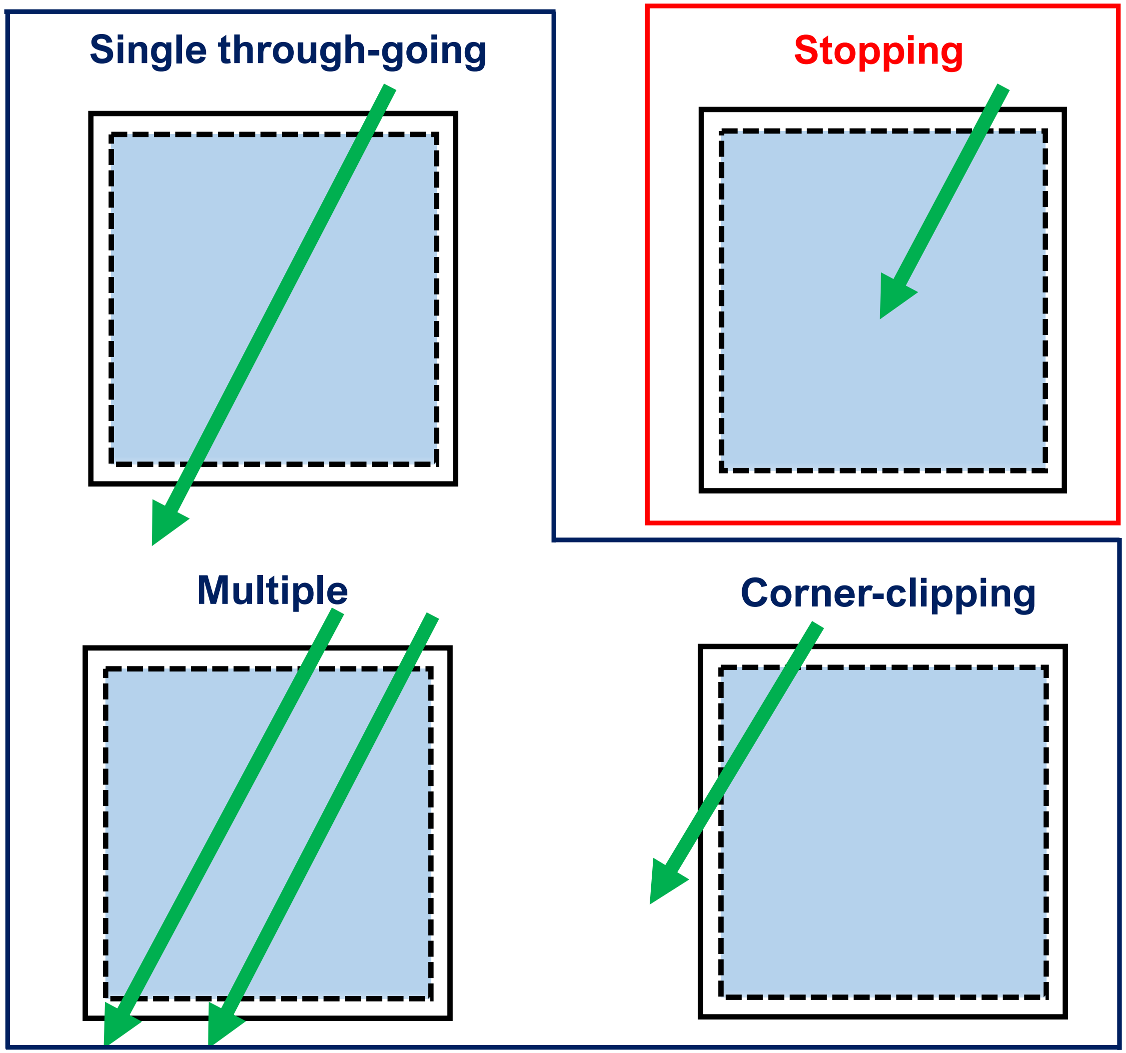




[*]Phys. Rev. D 74, 053007 (2006)

Classification of muon events

■ 4 types of cosmic-ray muon events



Signal events

- Stopping muon
  events stopping inside the ID

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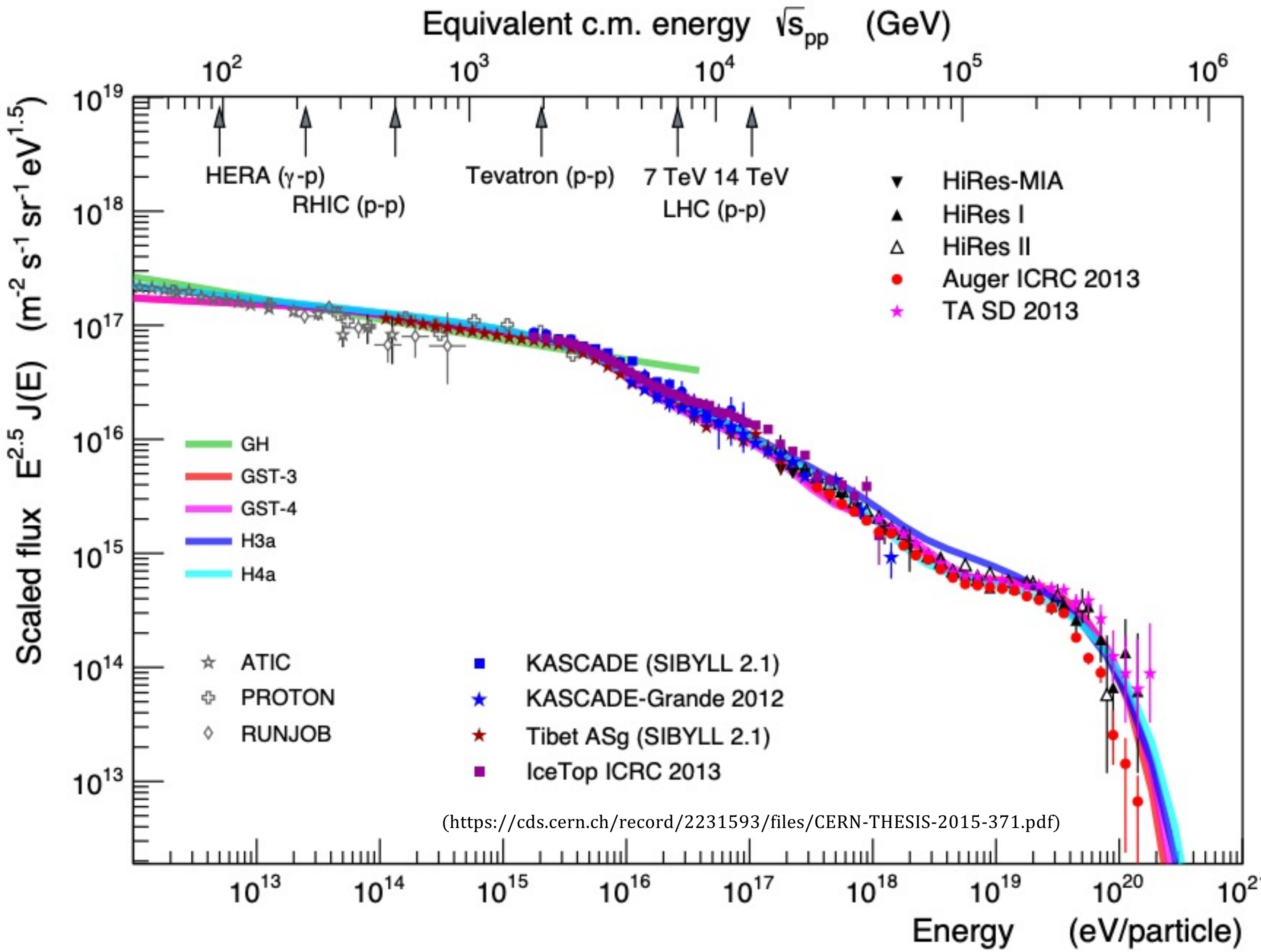
Cosmic-rays energy flux



(https://cds.cern.ch/record/2231593/files/CERN-THESIS-2015-371.pdf)

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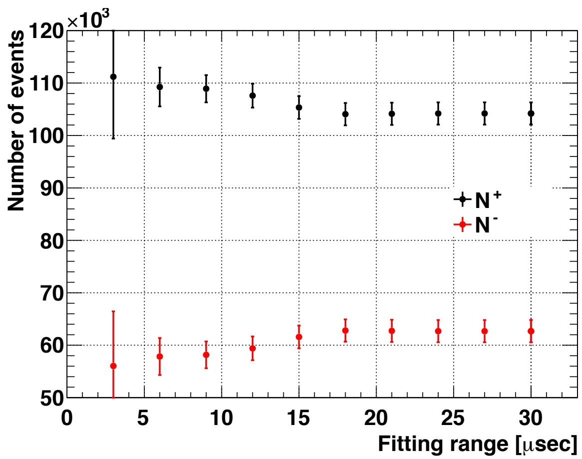
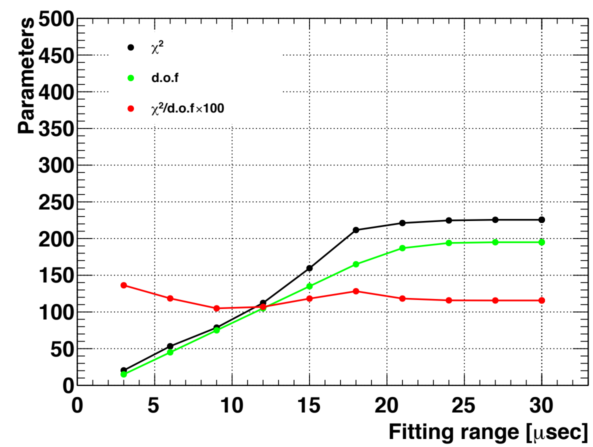
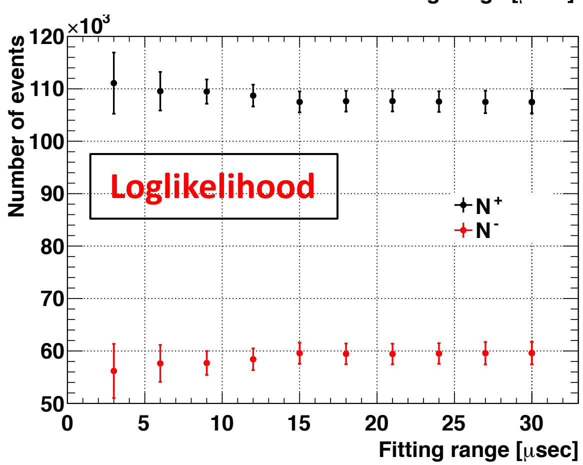
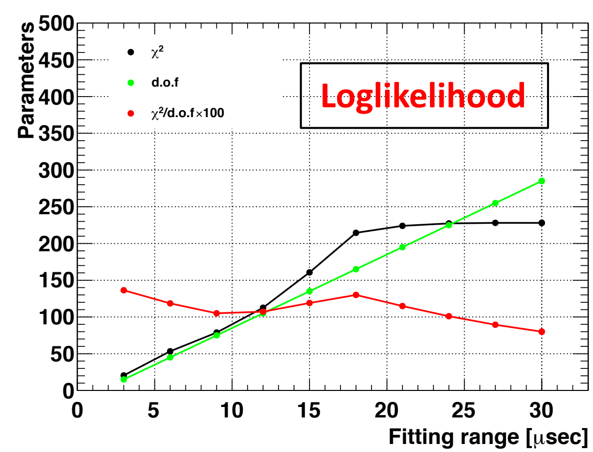
N_+, N_- dependency on fitting range

- Change the upper fitting range 3 μsec～30 μsec (3μsec step) and check the validity: $N_\pm$, χ^2/dof
- Fitting method w/ and w/o loglikelihood





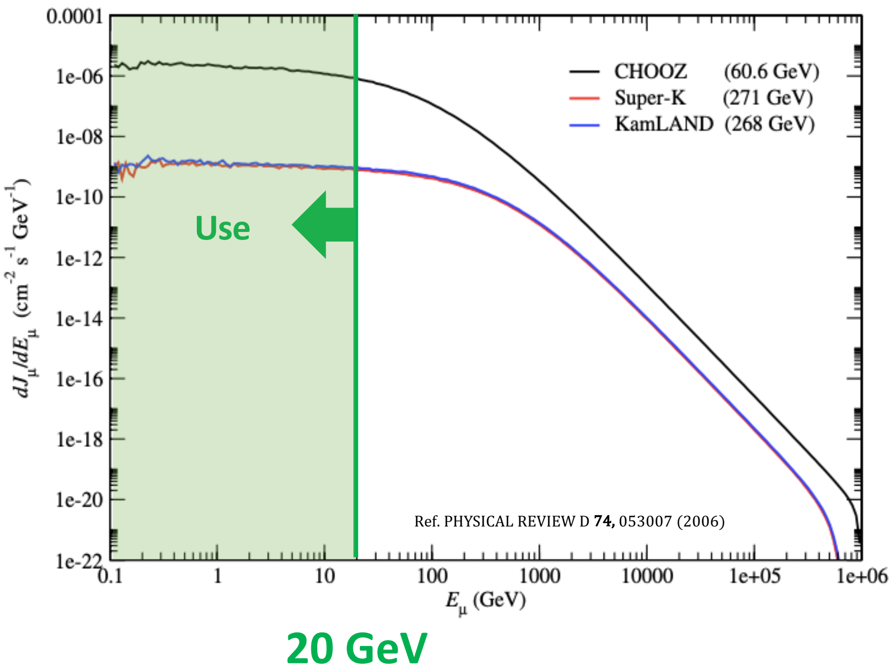




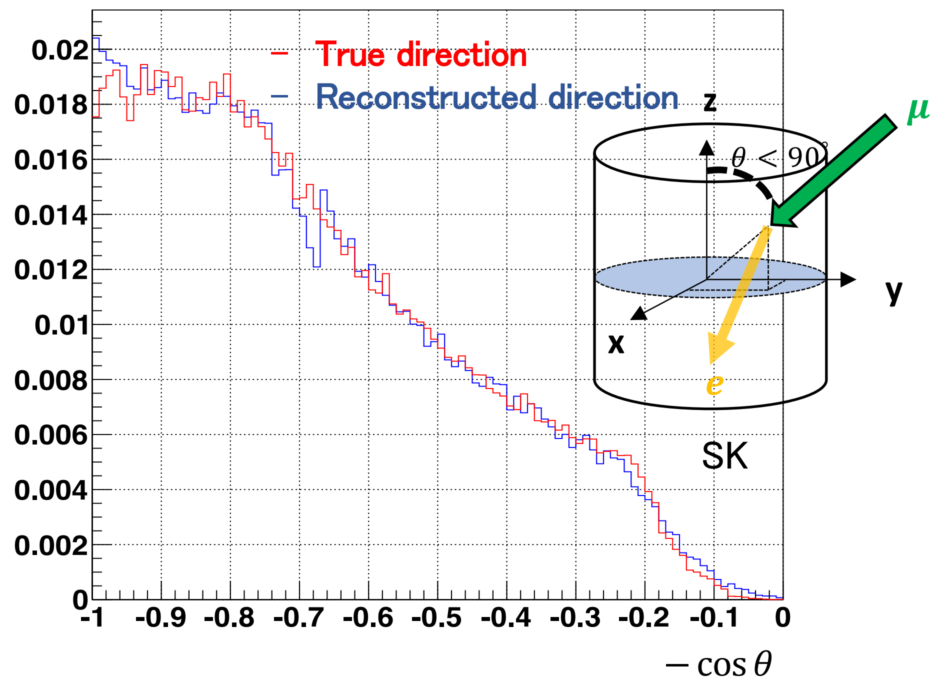
Muon simulation

Generate $E \leq 20$ GeV stopping muons according to the MUSIC flux at SK

Muon energy flux @ SK



Zenith angle distribution in MC



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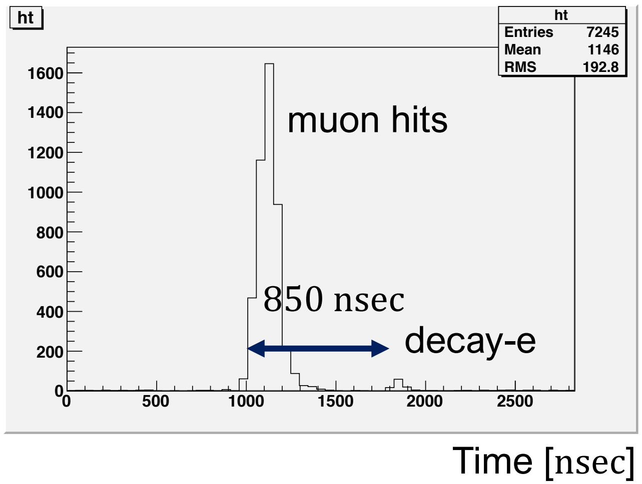
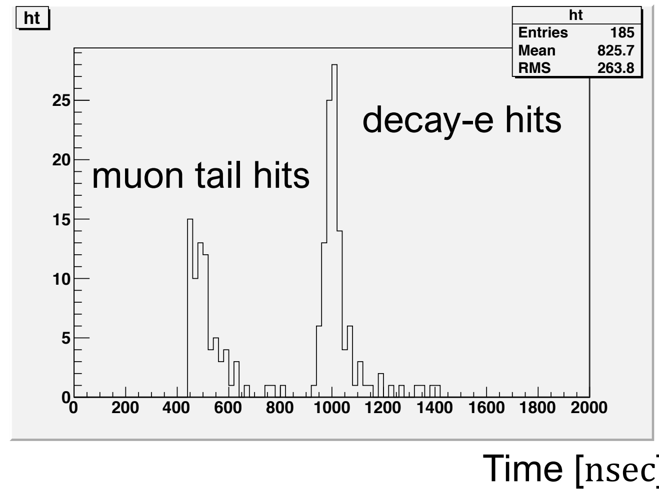
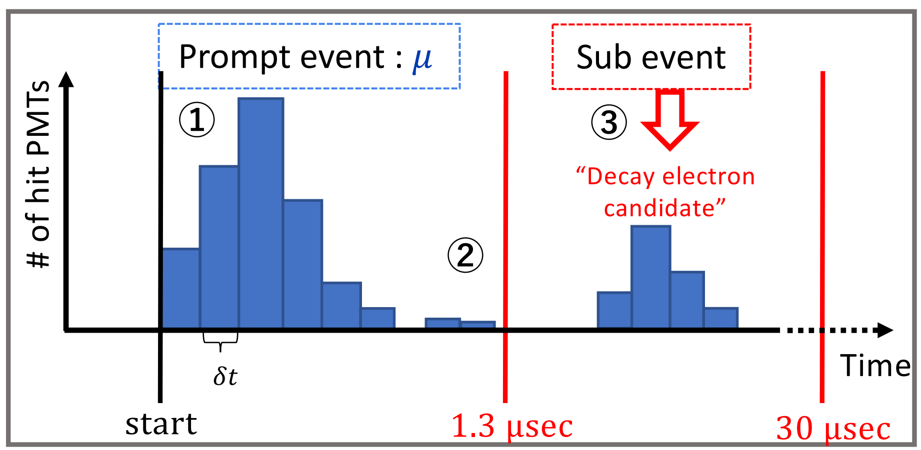
Time window of trigger

Prompt event



Sub event





→ **Time interval between $\mu - e$ should be $1.3\ \mu\text{sec} \le t$**

Muon lifetime in medium

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{capture}} + \frac{1}{\tau_{decay}}$$

τ_{total} : Lifetime of μ^- in medium (observed)
τ_{decay} : Free decay time of μ^-(in vacuum)
$\tau_{capture}$: Captured time of μ^- in medium (depends on the charge of the nucleus)

$$\Lambda_{total}\,[s^{-1}] = \frac{1}{\tau_{capture}} = \frac{1}{\tau_{total}} - \frac{1}{\tau_{decay}} = \frac{1}{\tau_{\mu^-}} - \frac{1}{\tau_+}$$

Particle	τ_{decay}	τ_{total}	$\tau_{capture}$	Λ_C
μ^-	$2.197\ \mu sec$	$1.795\ \mu sec$	$9.809\ \mu sec$	0.184

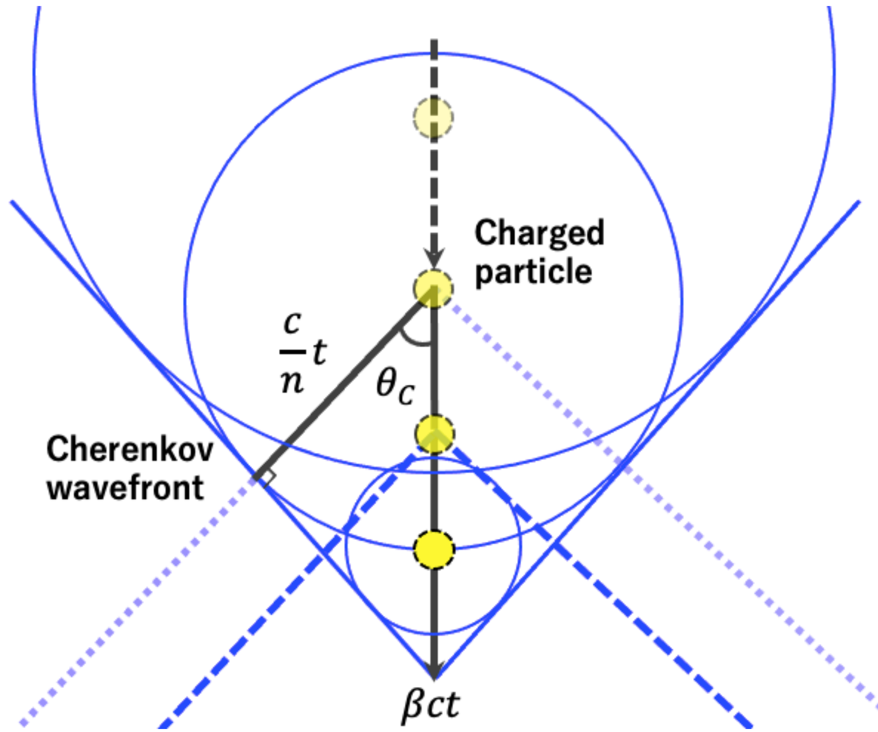
(Phys.Rev.C.35, 2212(1987))

Cherenkov radiation

Cherenkov light is emitted by the charged particles moving faster than the speed of light in a medium

$$v > \frac{c}{n}$$

c: speed of light in vacuum
n: refractive index of the medium
c/n: speed of light in medium



Cherenkov light is emitted in a conical shape at an angle θ_C:

$$\cos\theta_C = \frac{1}{n\beta}$$

$n \cong 1.33$ (in pure water) and particle velocity close to c ($\beta \sim 1$)
→ Cherenkov angle $\theta_C \cong 42°$

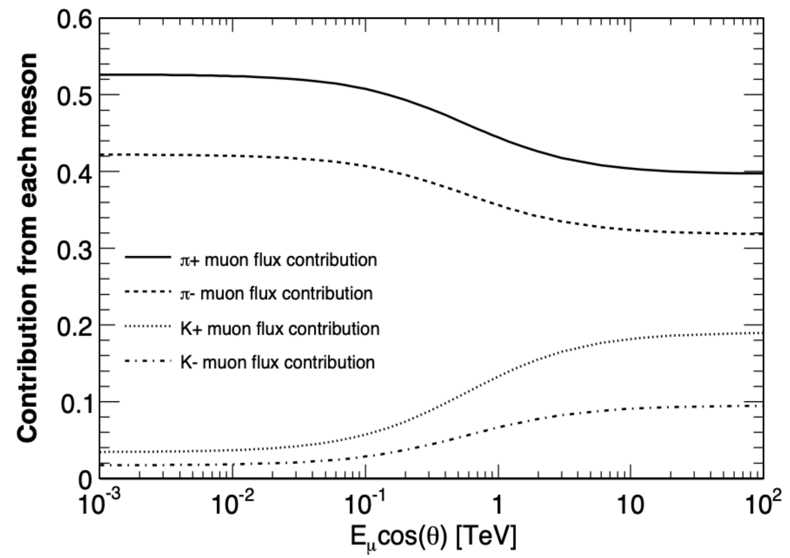
Muon charge ratio: π/K model

1. Consider only π/K meson production

2. Postulates energy independent ratio:

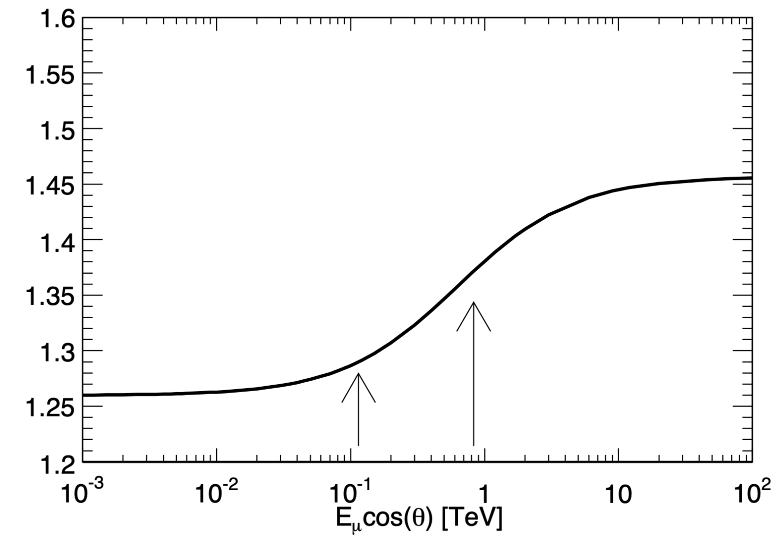
$$r_\pi = \frac{\pi^+}{\pi^-}\left(= \frac{f_\pi}{1-f_\pi}\right),\ r_K = \frac{K^+}{K^-}\left(= \frac{f_K}{1-f_K}\right)$$

3. Contributions from charm particle are ignored (below 10 TeV)



$$r_\mu = \frac{\left\{\frac{f_\pi}{1\,+\,1.1E_\mu\cos\theta/115\ \mathrm{GeV}} + \frac{\eta\times f_K}{1\,+\,1.1E_\mu\cos\theta/850\ \mathrm{GeV}}\right\}}{\left\{\frac{1-f_\pi}{1\,+\,1.1E_\mu\cos\theta/115\ \mathrm{GeV}} + \frac{\eta\times(1-f_K)}{1\,+\,1.1E_\mu\cos\theta/850\ \mathrm{GeV}}\right\}}$$

(η: Gaisser constant 0.054)



P.A. Schreiner, J. Reichenbacher, M.C. Goodman, Astropart. Phys. 32 (1) (2009) 61

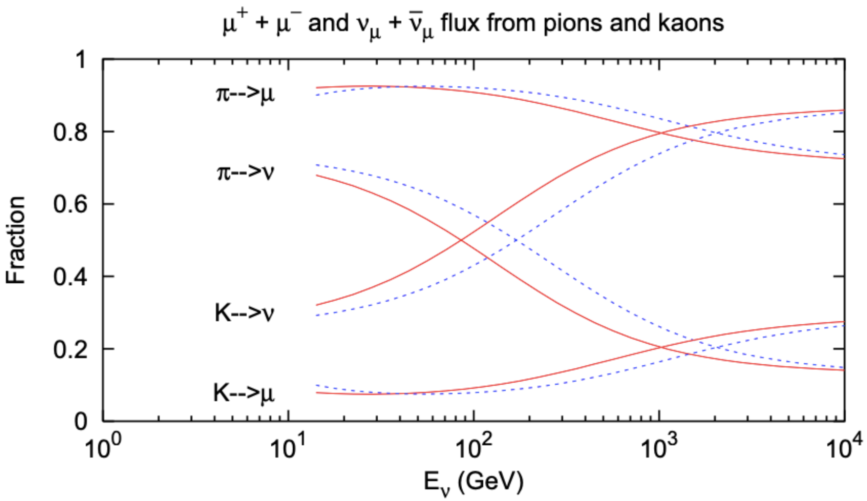
Compare the r_π, r_K in data with that in atmospheric neutrino fluxes simulation

Atmospheric neutrino flux

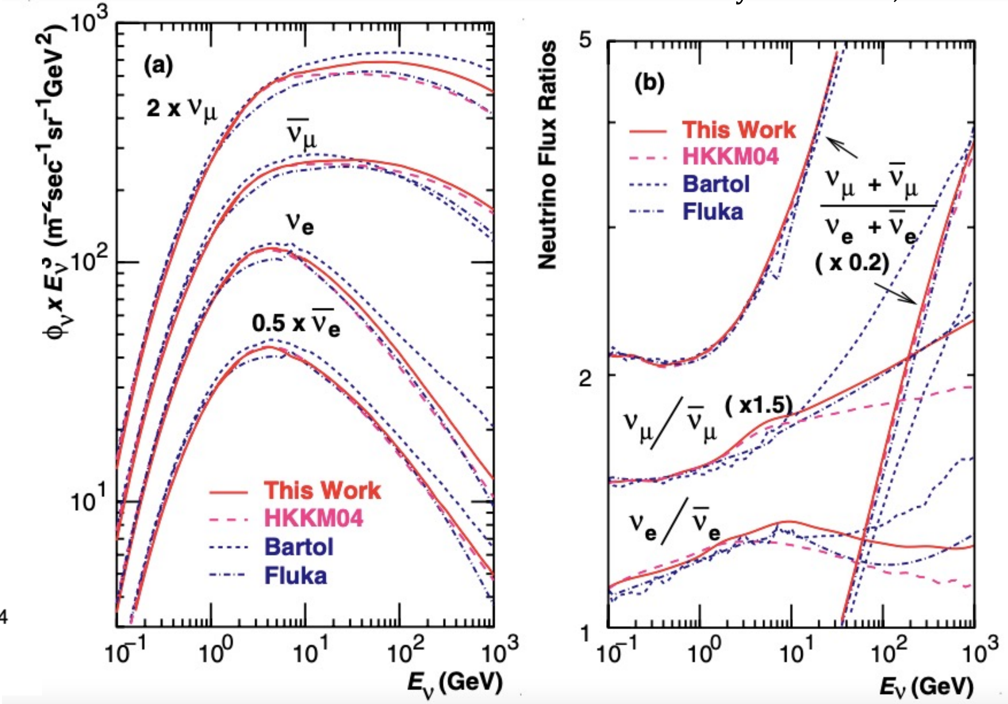
Physics motivation

The precise estimation of the absolute atmospheric flux is highly required
→ uncertainty of its flux above 10 GeV is limited due to small statistics and the uncertainties of μ, π, K fluxes and their charge ratio

→ Directly reflects the neutrino/anti-neutrino ratio



M. Honda et al. Phys. Rev. D 75, 043006



Systematic uncertainties

■ Muon charge ratio in SK-IV data (2971.1 days)

N_+	N_-	$R(\mu^+/\mu^-)$
$1{,}411{,}442.5 \pm 12475.2$	$789{,}185.5 \pm 17934.3$	$1.459 \pm 0.036(\mathrm{stat.})$

→ **Statistical and fitting errors** on number of events, N_+: 0.9%, N_-: 2.2%

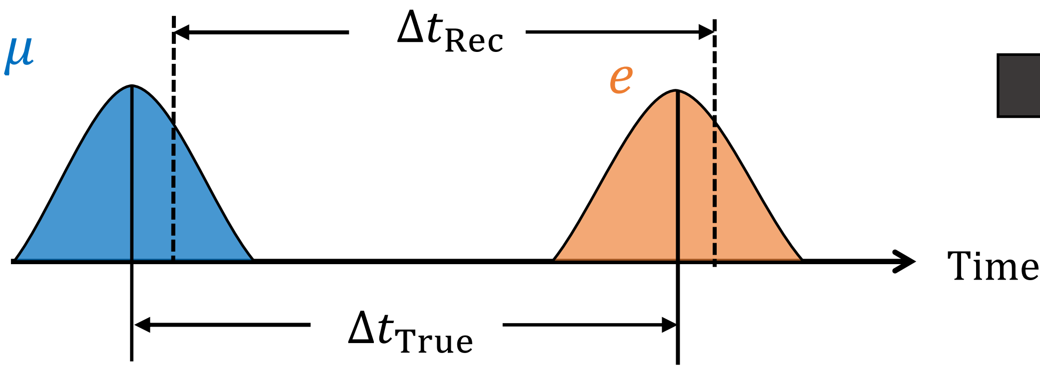
Systematic uncertainty is not considered

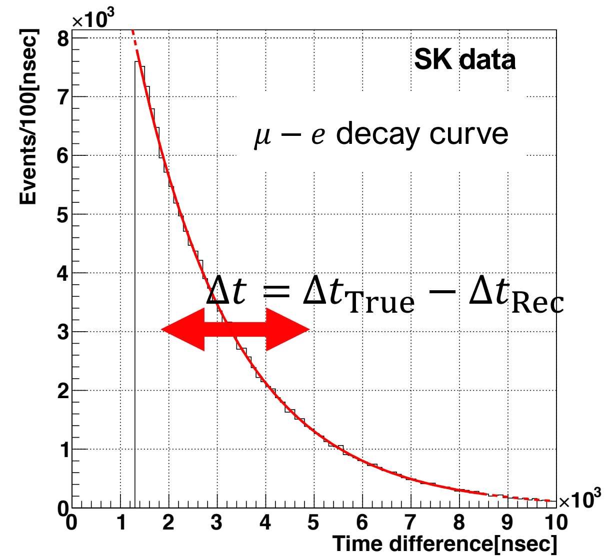
■ Systematic uncertainties on (N_+, N_-)

	Candidates of systematic uncertainties
(1)	Timing resolution
(2)	Contamination of de-excitation γ-rays from exited $^{16}\mathrm{N}^*$

Estimation of systematic uncertainties

1. Uncertainties on timing resolution
   → Time difference between Δt_{True}, Δt_{Rec}



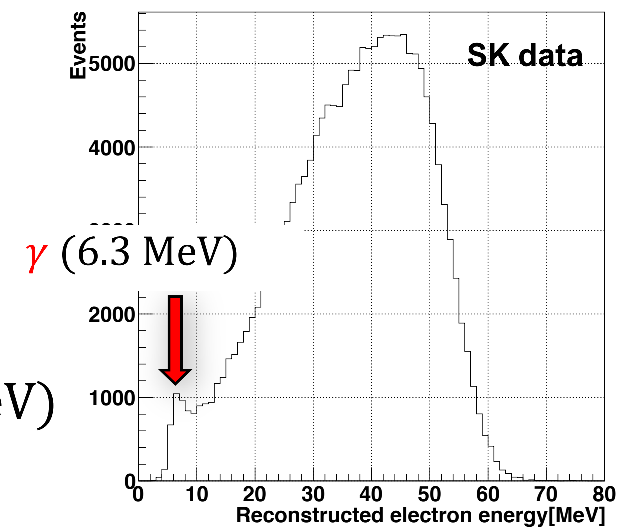


2. De-excitation γ-rays from μ^- capture by $^{16}\mathrm{O}$

$$\mu^- + {}^{16}\mathrm{O} \rightarrow \nu_\mu + {}^{16}\mathrm{N}^*$$

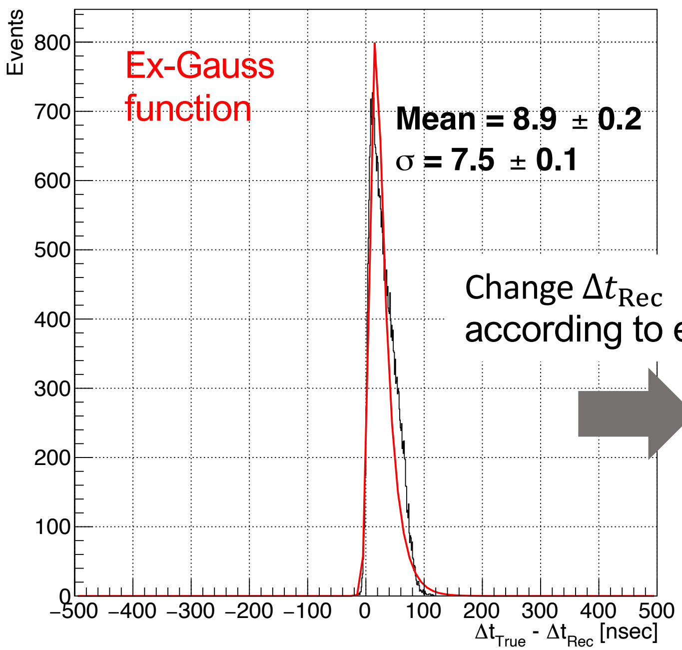
$$\downarrow$$

$$^{15}\mathrm{N} + \gamma \text{ (max 10.8 MeV)}$$

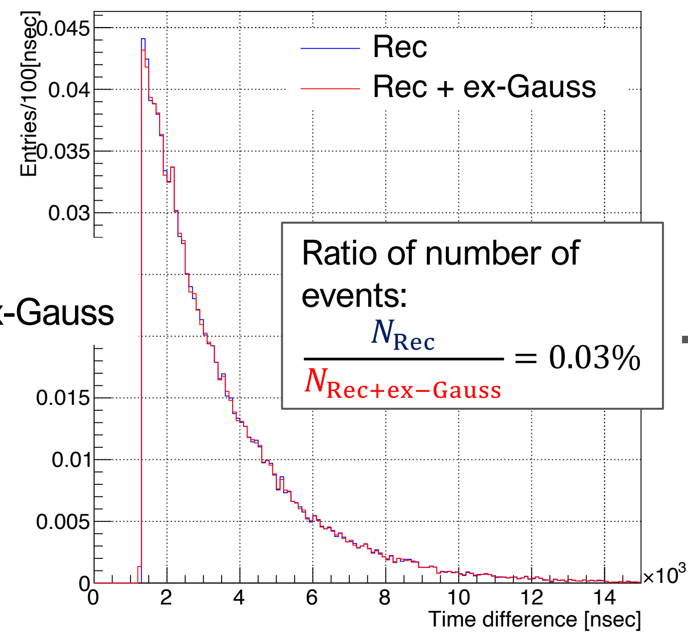


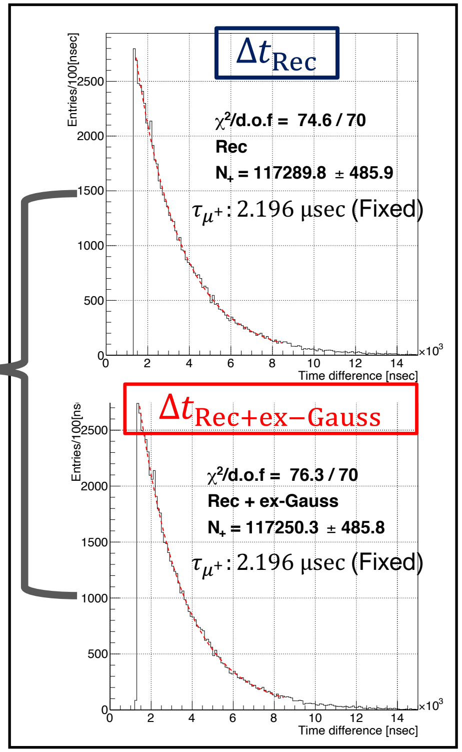
Uncertainties on timing resolution

Compare the time difference between Δt_{True} and Δt_{Rec} in simulation
→ consider the uncertainties around Δt_{Rec} and count the variation of N



Change Δt_{Rec} according to ex-Gauss





Uncertainties on number of events 0.03%
→ total uncertainties on muon charge ratio 0.04%

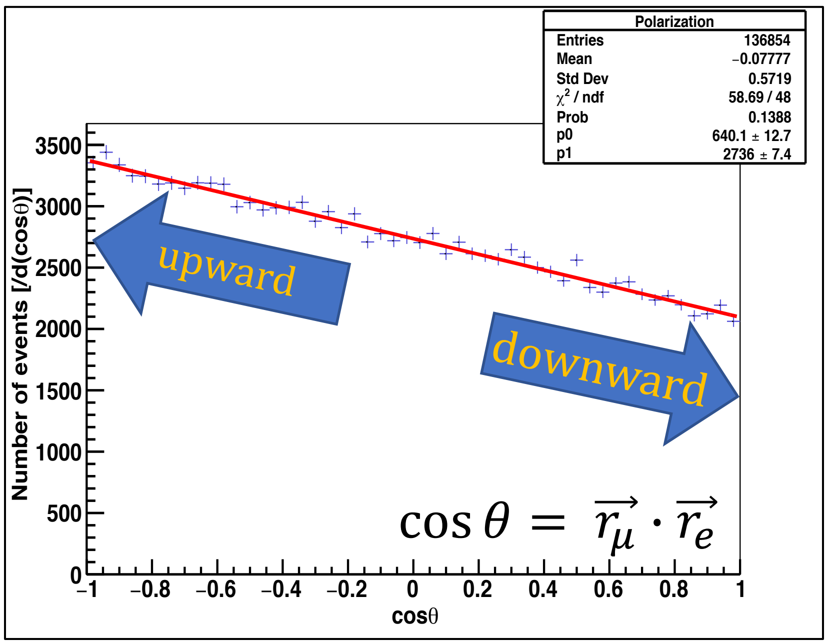
Measurement of the polarization

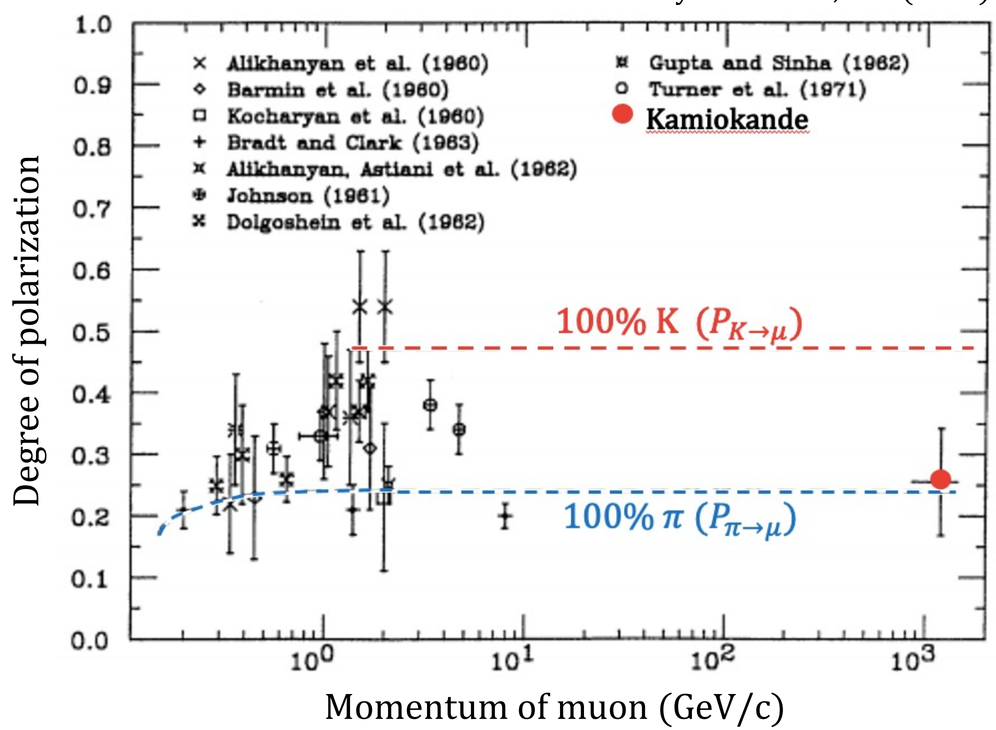
■ Method

Measure the angular correlation between the direction of the stopped muons and the decay electrons

$$\frac{dN}{d(\cos\theta)} \propto (1 - 2{x_0}^2 + {x_0}^4) - \left(\frac{1}{3} + \frac{2{x_0}^3}{3} - {x_0}^4\right) P_{ob} cos\theta \qquad (* \, x_0 \approx E/52.8)$$

M. Yamada et al. Phys. Rev. D 44, 617 (1991)

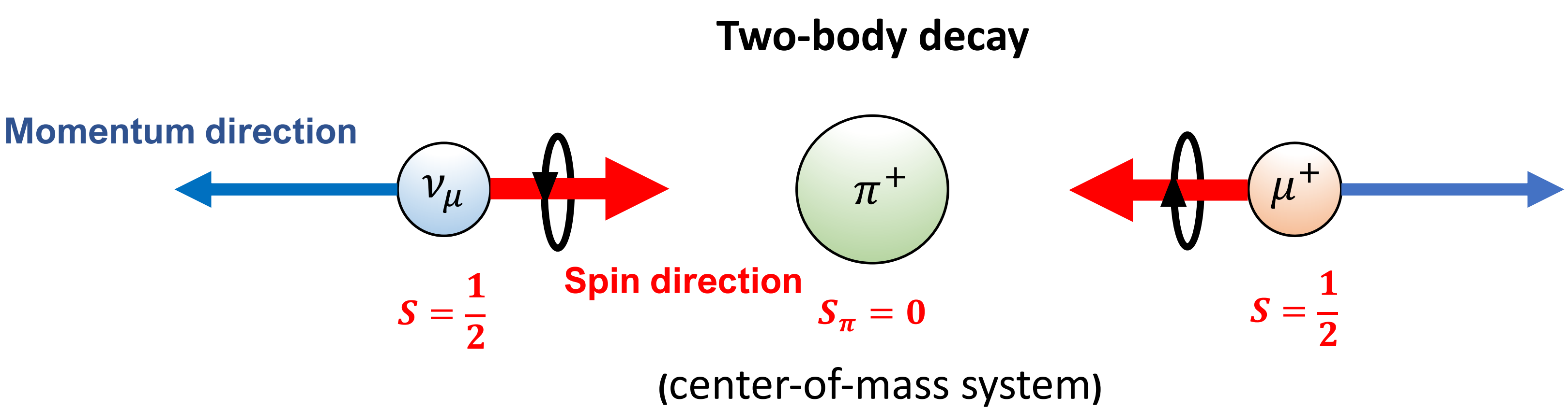




Muon spin polarization

Tow-body decay

$\pi^{\pm}$ (spin 0) satisfy the spin conservation law before and after tow-body decay
ν_{μ} spin is fixed to the opposite direction of the traveling direction

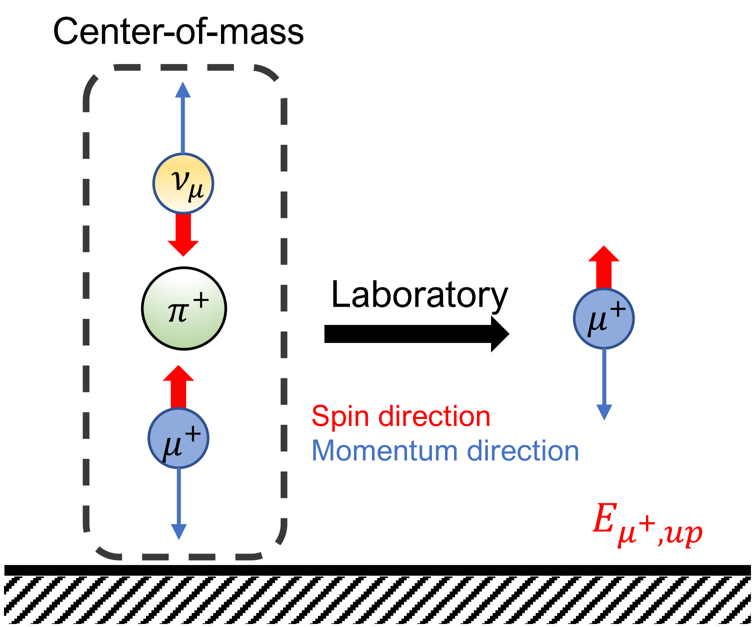


μ^+ spin direction is opposite to the momentum direction due to the law of angular momentum (center-of-mass system)
→ Fully polarized $P_\mu = 1$

Muon spin polarization

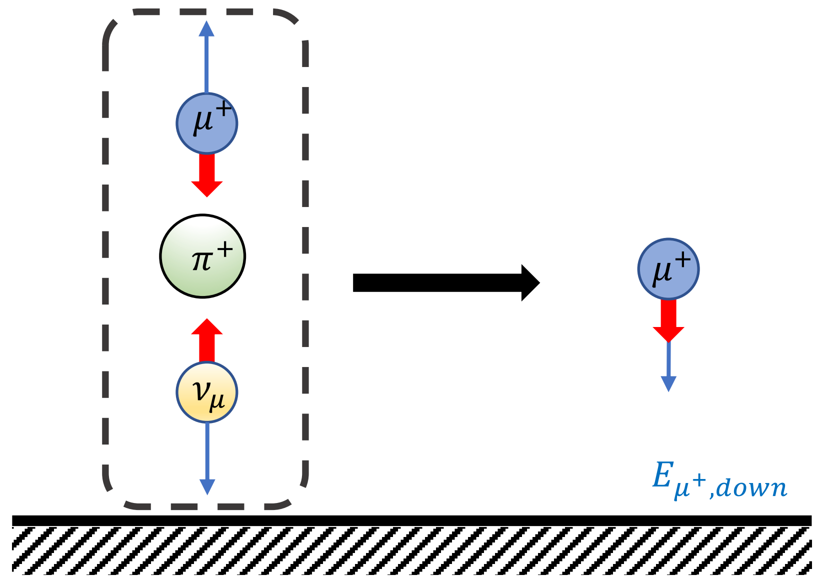
Spin direction upward

Produced by low/high energy π



Spin direction downward

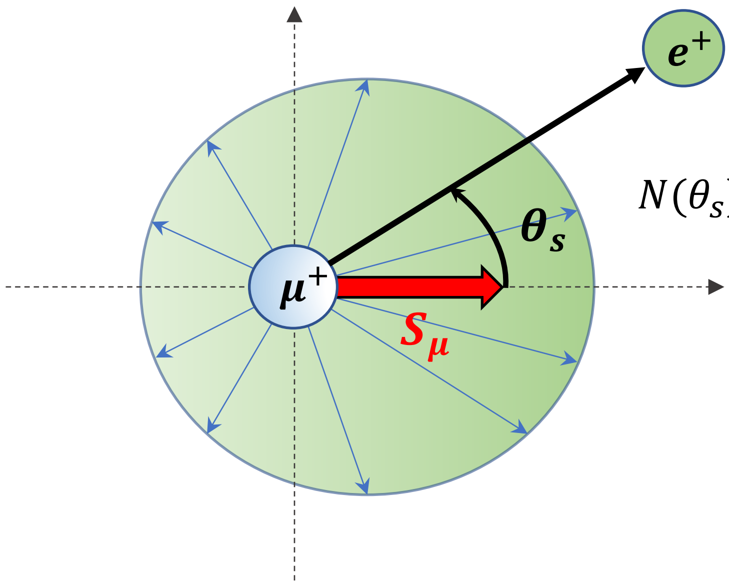
Produced by high energy π
($E_{\mu^+,up} = E_{\mu^+,down}$)



Cosmic-ray energy spectrum (power law)
$\rightarrow \mu^+$ with upward spin are more likely to be observed

Angular distribution of decay electrons

Angular distribution of decay electrons correspond to the spin direction of muons $\boldsymbol{S_\mu}$



$$N(\theta_s) \propto 1 + \frac{1}{3} P_\mu \cos\theta_s$$

→ Electrons are more likely to be distributed around the muon spin $\boldsymbol{S_\mu}$ direction