Study of coincident muon bundles at KamLAND and Super-Kamiokande

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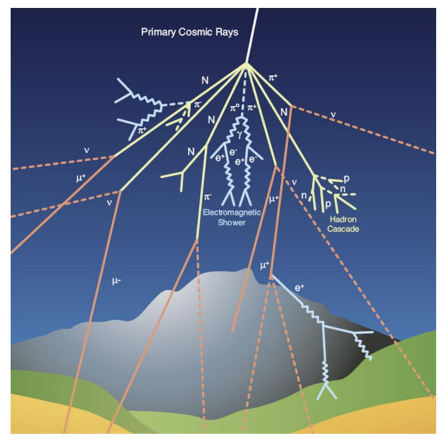
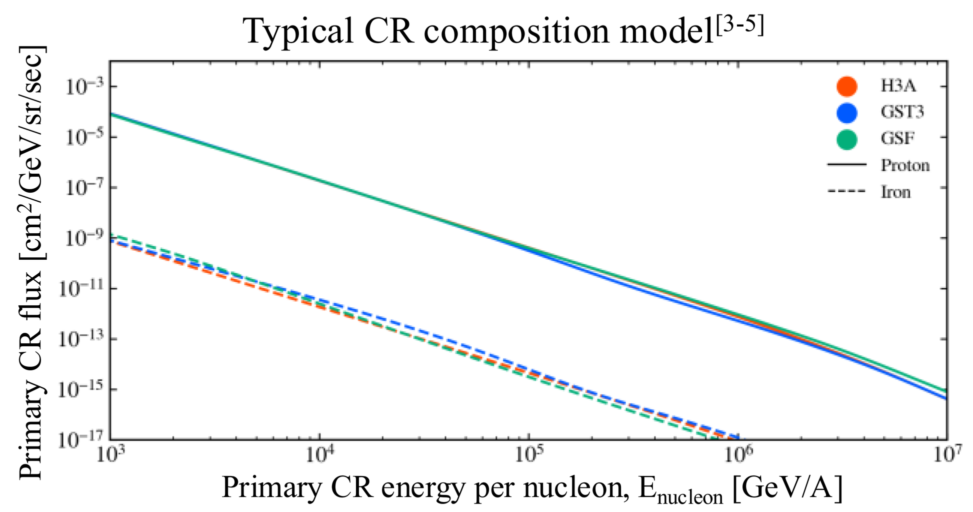
1. Introduction

- A cosmic ray (CR) generates multiple muons (muon bundle) via hadronic interaction with the air nuclei.
- The cross sections are tuned and extrapolated by QCD theory and accelerator data. (hadronic interaction model)

Muon Puzzle[1]

- **Observation data ≠ Theoretical predictions**
- Discrepancies in the muon number, lateral spread of muon bundles, and energy distribution
- Unexplained by any combination of primary mass composition and existing hadronic interaction models[2]
- Crucial for **high energy forward physics**

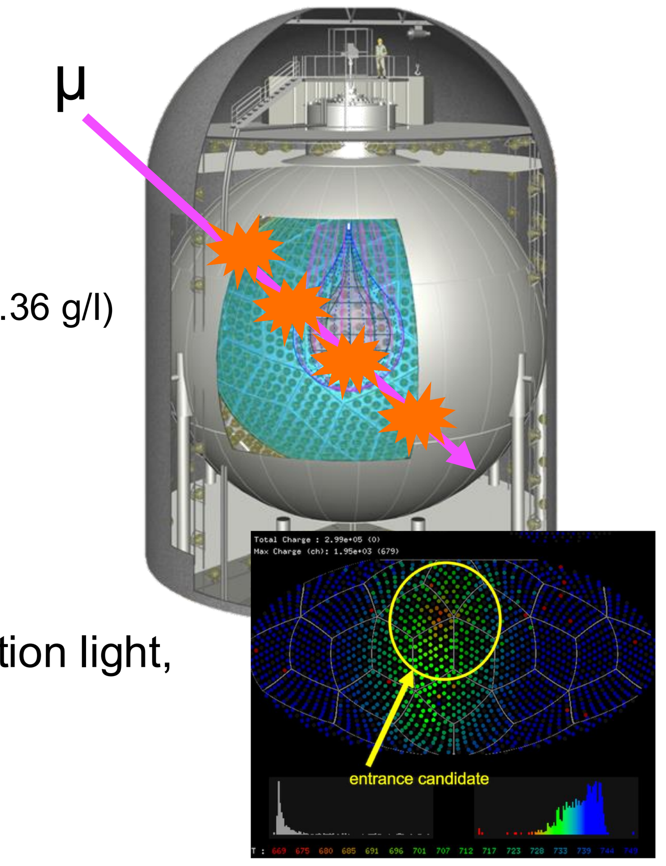




2. Detector

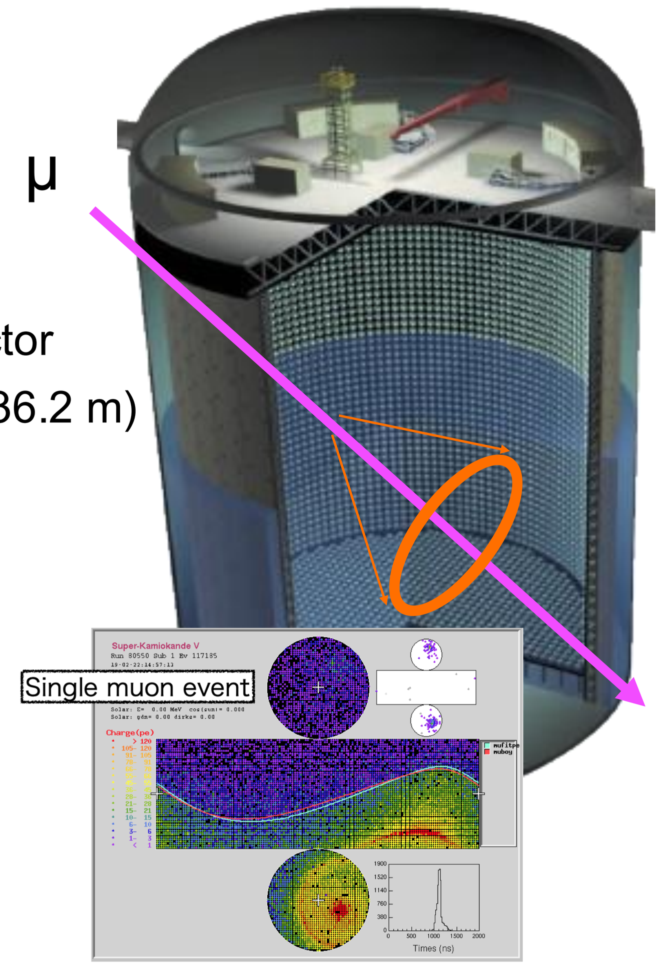
Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND)

- Data taking period: 2002 - 2024
- Inner detector
  - 1 kt liquid scintillator detector (r=6.5 m) Dodecane (80%),Pseudocumene(20%), PPO (1.36 g/l)
  - 1325 17-inch + 554 20-inch PMTs
- Outer detector
  - 3 kt water Cherenkov detector
  - 20-inch PMTs
- From time and charge information of scintillation light, we reconstruct the muon direction.
- Muon rate: 0.34 /sec[6]



Super-Kamiokande (Super-K)

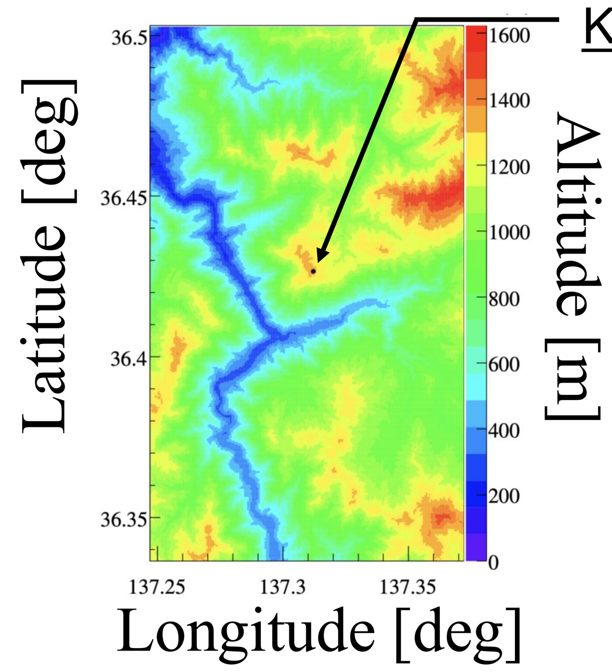
- Data taking period: 1996-
- Inner detector
  - 32.5 kt Water Cherenkov detector Cylinder volume (r=16.9 m, h=36.2 m)
  - ~10000 20-inch PMTs
- Outer detector
  - Water Cherenkov detector (~2 m pure water layer)
  - 1,885 20-inch PMTs
- Muon rate: 2.2 /sec[7]



3. Location

- Both detectors are located 1000 m underground (~2700 m w.e., Kamioka, Japan).
- The rock filters out GeV-range muons.
  - **It allows for the selective detection of higher energy muons at surface (E_μ>~600 GeV).**

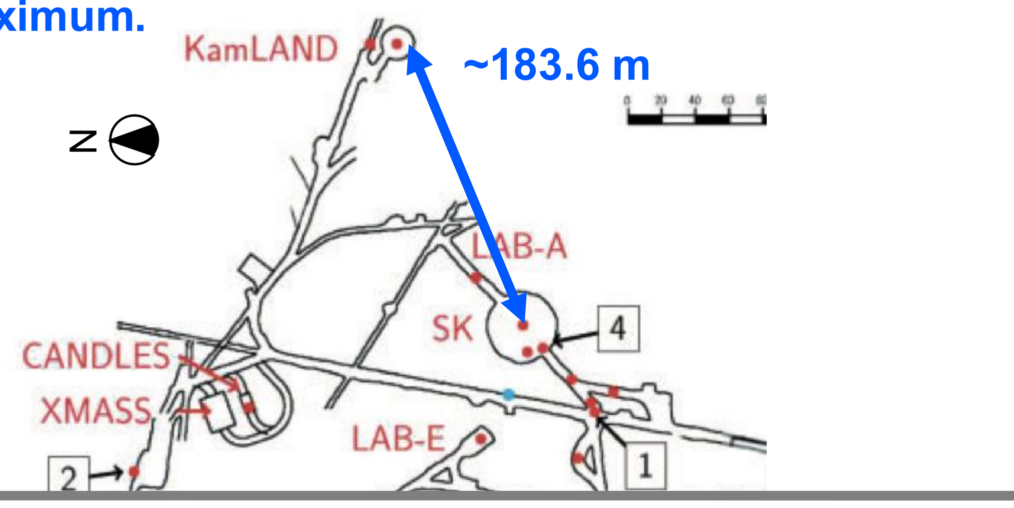
Focuses on muons produced in the primary stages of the shower cascade.[1]



Kamioka laboratory[8]

Distance between KamLAND & Super-K ~183.6 m

Measurement of muon bundles spreading over ~200 m at maximum.

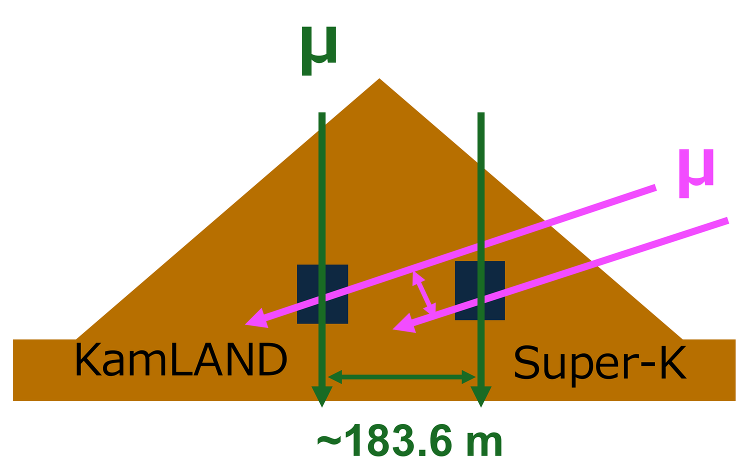


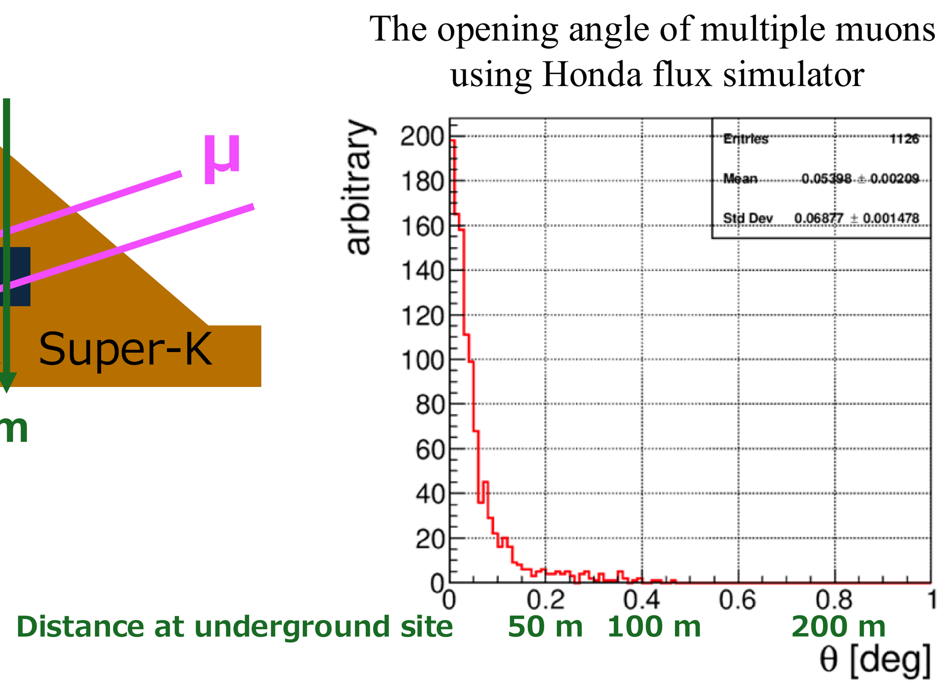
4. Motivation & Objective

Compare predicted vs. observed muon spread and the number **at the primary collision.** It probes the QCD interaction opening angle[9].

Coincidence muon search using KamLAND & Super-K

The zenith angle distribution of coincidence events can be translated into a spatial spread of up to ~200 m.





This poster evaluates expected coincidence muon rate systematically as a 1st step.

5. Expected muon rate from Monte Carlo simulation

We perform comprehensive Monte Carlo simulations and estimate the coincidence muon rate from current hadronic interaction model.

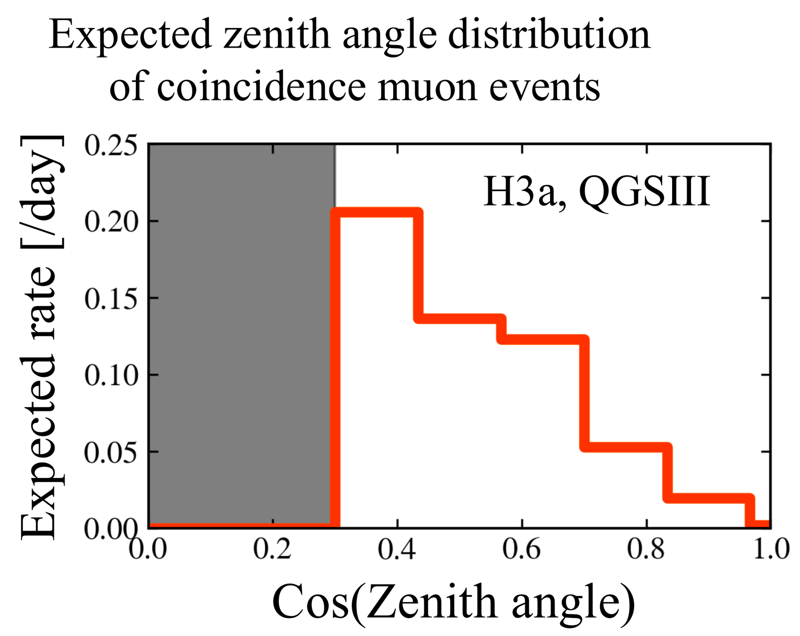
Simulation flow

Primary cosmic ray
Energy per nucleus: 10^3-10^7 GeV
Zenith angle: 0–70°

Air shower simulation
CORSIKA[10] (COsmic Ray SImulations for Kascade, version 77550)
Assuming hadronic interaction model
Local atmospheric condition
Local magnetic field
Using FLUKA[11] for low-E_μ hadronic interactions

Rock Propagation simulation
MUon SImulation Code[12] (MUSIC)
Rock density: 2.70±0.05 g/cm³
Typical rock in Kamioka

Expected muon rate



Coincidence muon rate (zenith angle: 0–70°, rock density: 2.70 g/cm³)

Primary CR composition	Hadronic interaction model	Muon rate [/day] (+statistic error)
H3a[3]	QGSIII[13]	0.54±0.24
	SIBYLL[14]	0.28±0.04
GST3[4]	QGSIII	0.42±0.22
	SIBYLL	0.18±0.03
GSF[5]	QGSIII	0.56±0.23
	SIBYLL	0.30±0.05

- Air shower simulations are time-consuming, resulting in large statistical errors.

6. Summary

✓ Test the **muon spatial distribution discrepancy** between theory and observation.
→ **Coincidence muon measurement between KamLAND and Super-K**

✓ We developed simulation framework of coincidence muon events and estimate the expected rate systematically.

7. Prospect

- Simulation of zenith angle>70° (Deeper understanding of the effects of atmospheric conditions and geomagnetic field)
- Joint real data analysis between KamLAND and Super-K (**MOU concluded**)
- Extend up-going muon search from TeV astrophysical neutrinos

Reference

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