Cosmic-ray Muon Physics with Water Cherenkov Detectors

19th, September 2025

II EU Workshop on Water Cherenkov Experiments for Precision Physics

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Contents

Introduction

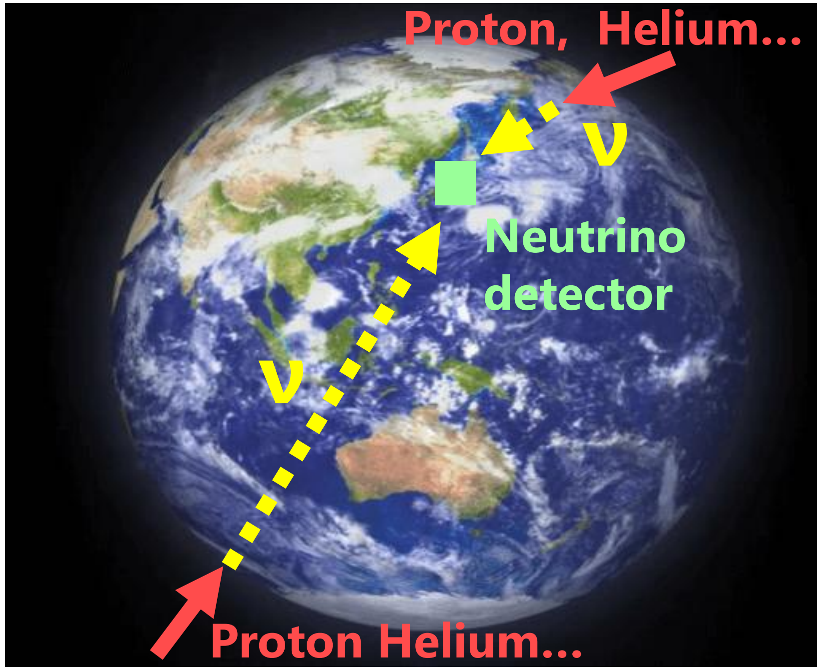
■ Atmospheric neutrinos

See Philipp's talk

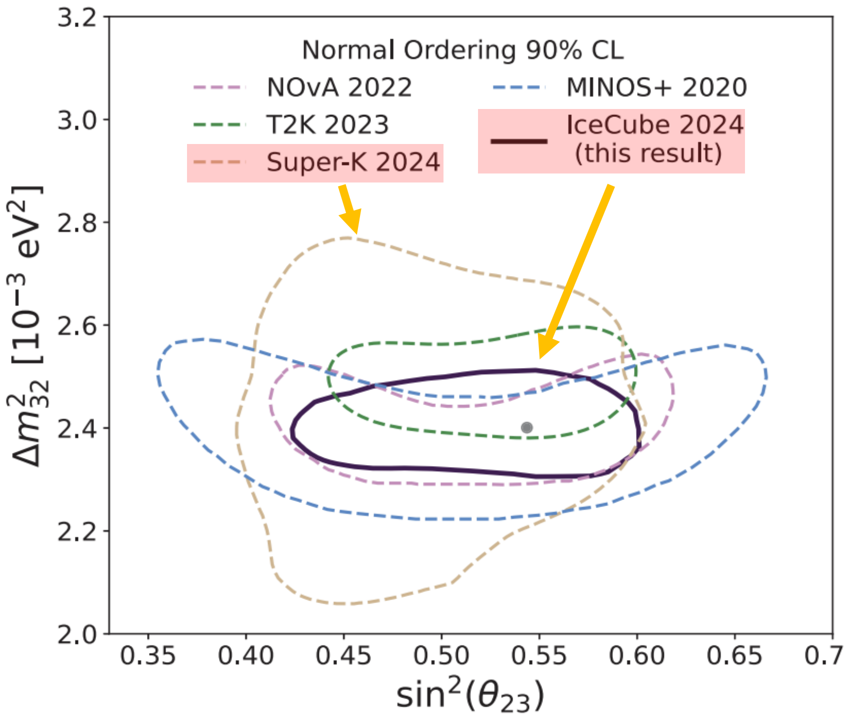
- Precise measurements have been conducted by several neutrino detectors.
- Wide range of energy, several neutrino flavors, different traversing length, etc.

  → **Current targets**: Mass ordering Δm^2_{32}, θ_{23} Octant, *CP* phase.
- **What items are really required for more precise measurements.**

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

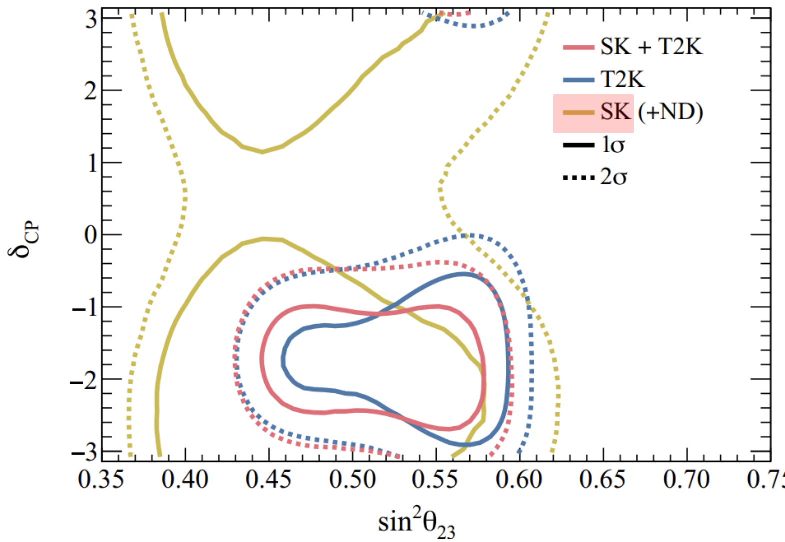


Anisotropic/isotropic



Phys. Rev. Lett. 134, 091801 (2025)

T2K+SK joint analysis



Phys. Rev. Lett. 134, 011801 (2025)

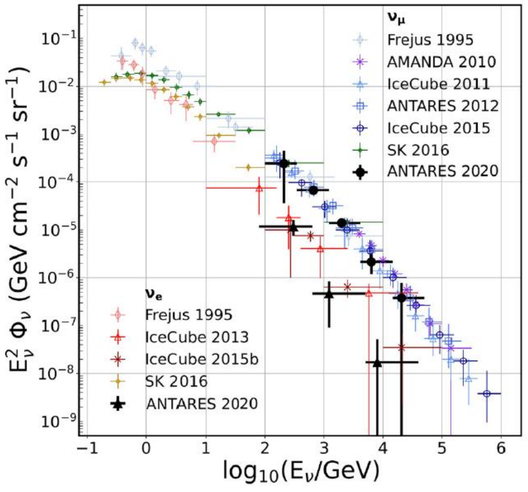
Uncertainties on atmospheric neutrinos

■ Current situation

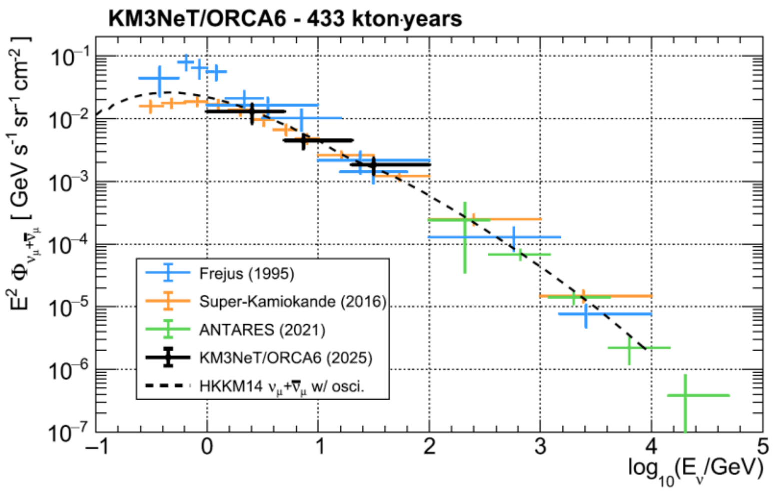
- Uncertainties in neutrino simulations:
  1) **Absolute flux** of atmospheric neutrinos
  2) **Flavor ratio** and **neutrino/anti-neutrino ratio**
  3) **Energy spectrum** of atmospheric neutrinos
  4) **Cross section** of neutrinos

- Cosmic-ray uncertainties
  a) Primary cosmic-ray **spectrum** and **chemical/mass composition**
  b) Atmospheric density, geo-magnetic field
  c) **QCD hadron models** (meson composition)
  → air-shower simulations

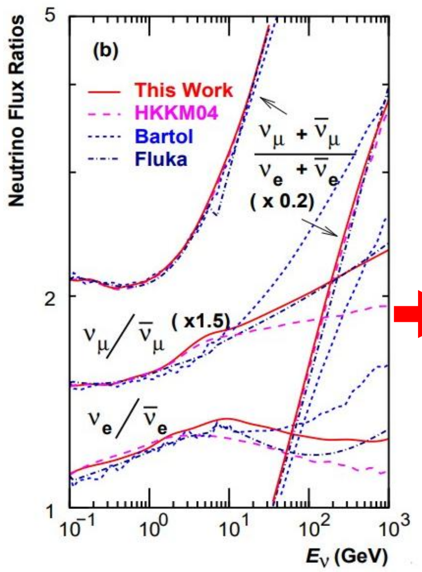
- How to reduce them?
  → **Cosmic-ray measurement** with neutrino detector !



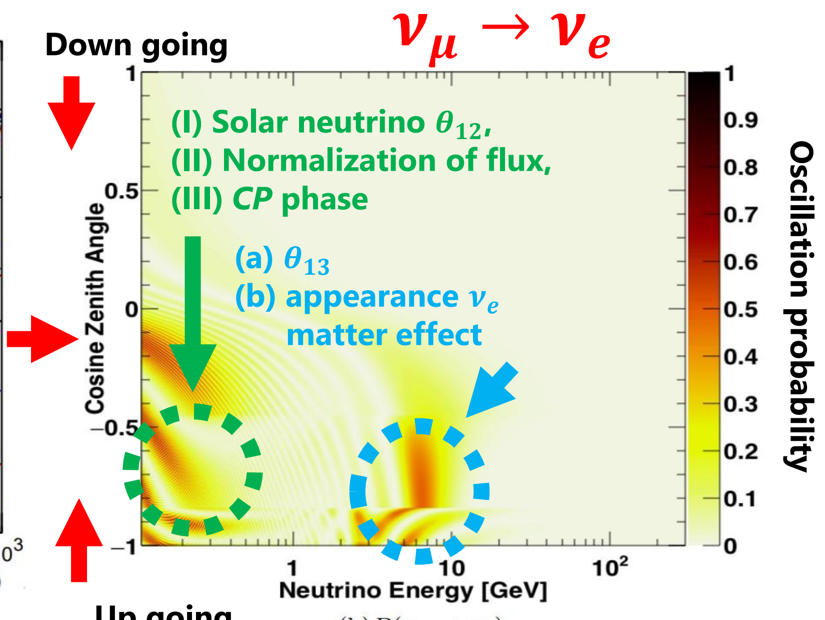
Phys. Lett. B 816, 136228 (2021)



Eur. Phys. J. C 85, 871 (2025)



Phys. Rev. D 75, 043006 (2007)

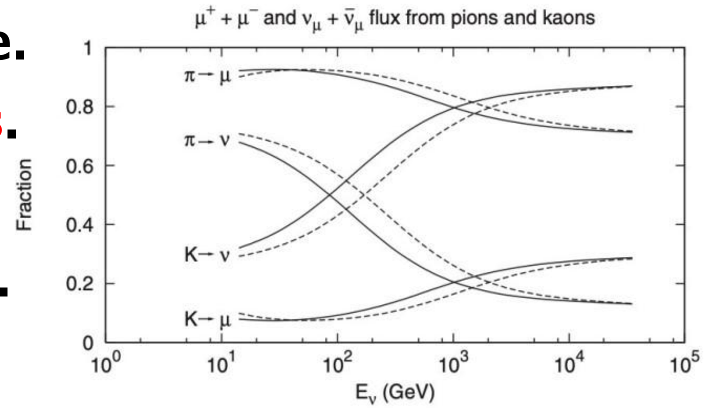


(b)$P(\nu_\mu \rightarrow \nu_e)$

Phys. Rev. D 97, 072001 (2018)

Muon flux modulation

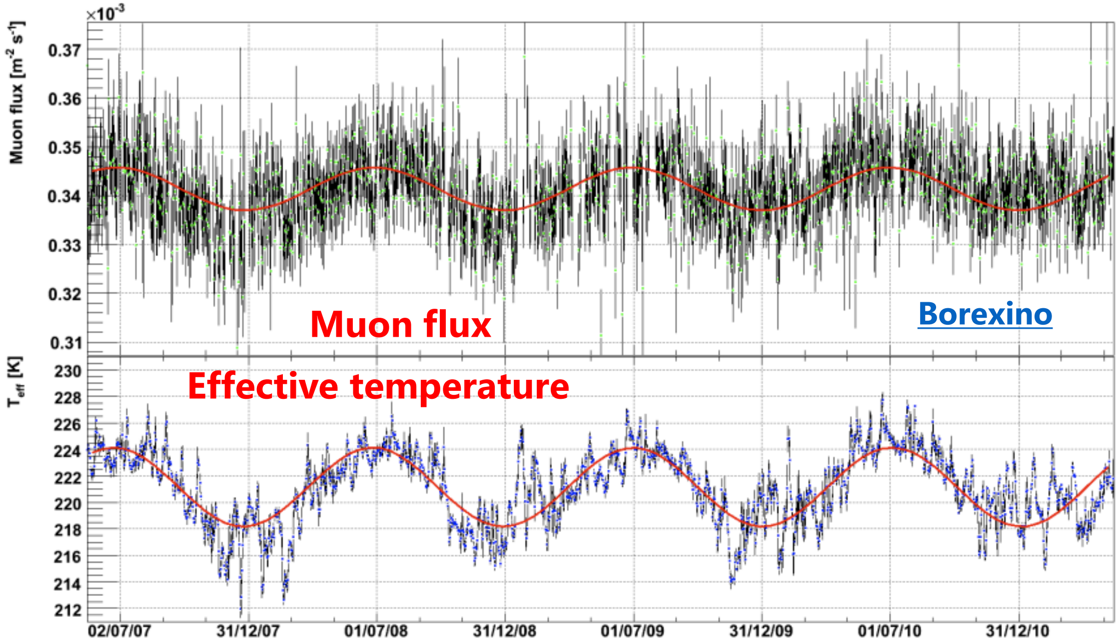
Solid: μ^+or ν
Dashed: μ^- or $\bar{\nu}$

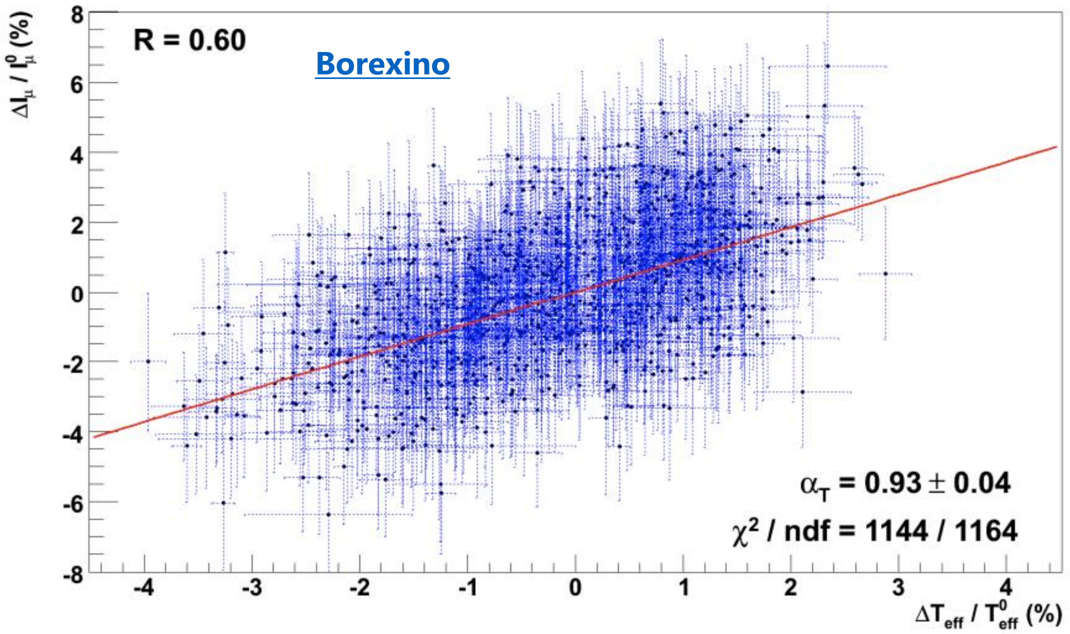


Earth Planet Sp 62, 195 (2010)

■ Seasonal variation of flux

- Primary cosmic-rays produces mesons (pion/kaon) in atmosphere.
- Cosmic-ray muons are produced by decays of their parent mesons.
  → Changing the fraction of mesons decaying before interacting,
  depending on the atmospheric density (effective temperature).
- Strong correlation between muon flux and effective temperature.



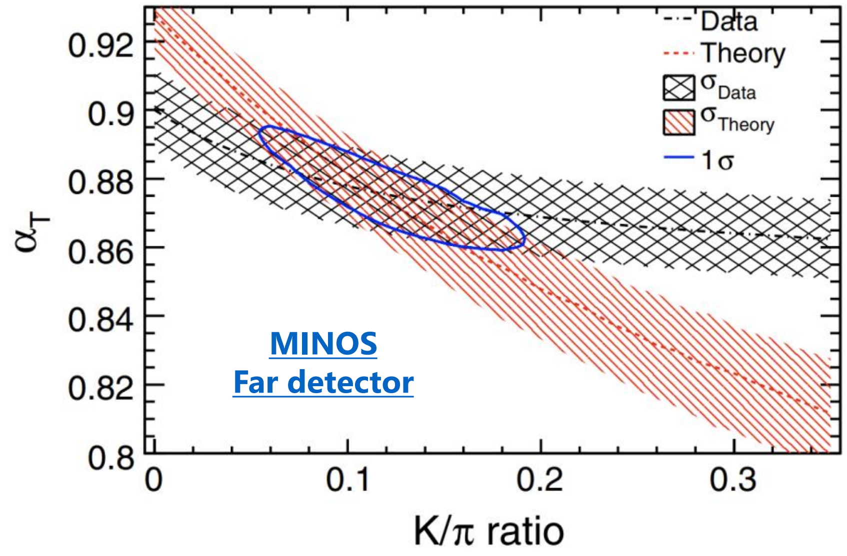


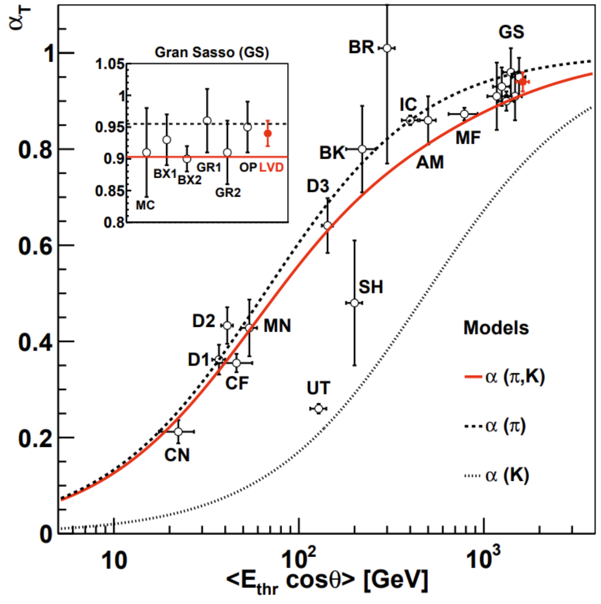
Kaon/Pion ratio

■ Meson fraction

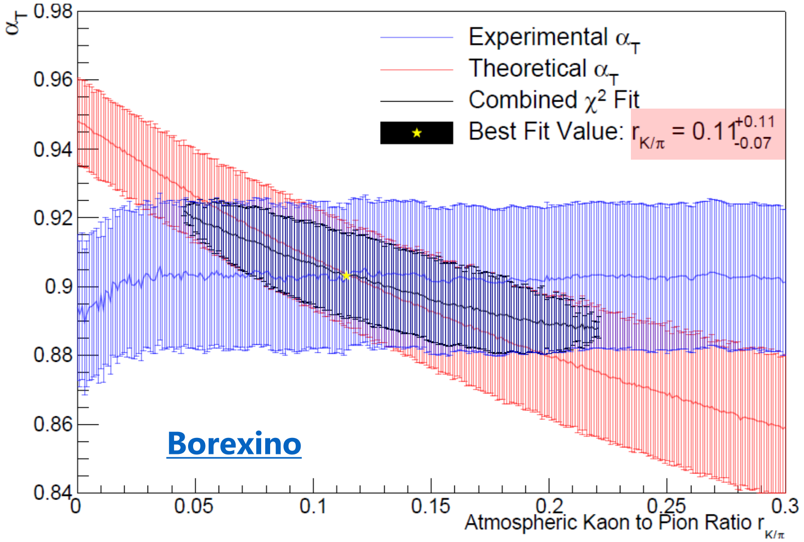
- Fraction of Kaon increases when muon energy is high.
  → Modulation measurement **constraints on Kaon/Pion ratio**.

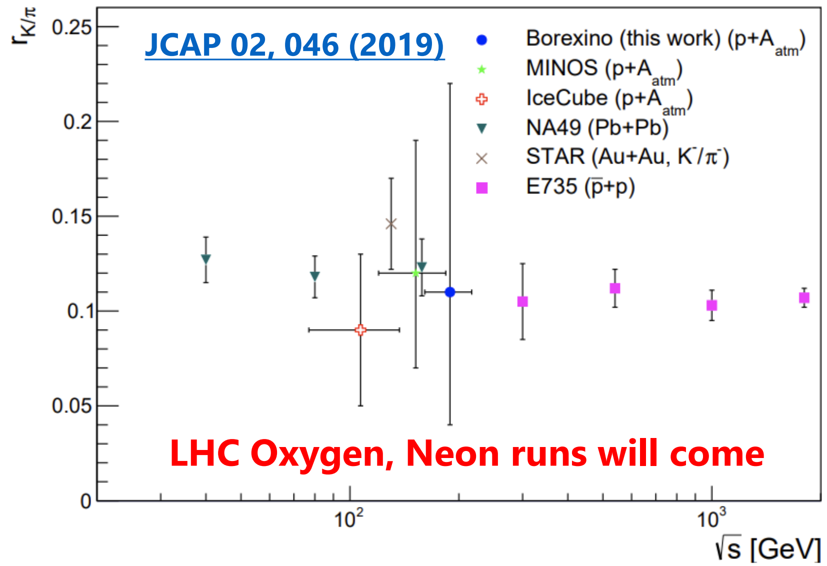
- With the different overburden of the detector locations,
  this parameter is well studied below 1 TeV/*c*.
- Also, tested **by accelerator experiments**.





Phys. Rev. D 100, 062002 (2019)

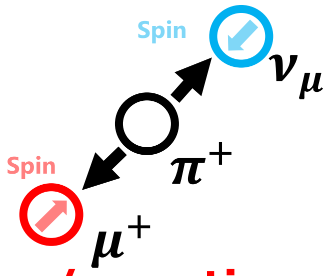


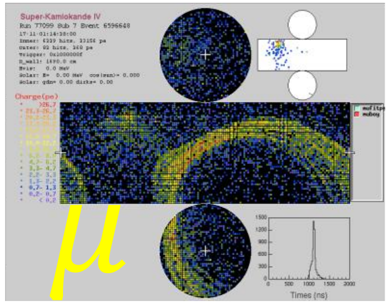


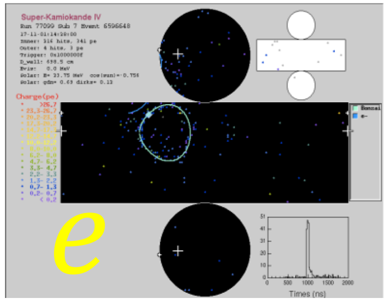
Charge ratio and polarization

■ Information of parent particles

- Secondary particles have an excess of positive charge due to primary cosmic-ray.
- Cosmic-ray muon is **fully polarized** with parallel direction to muon momentum because of two body decay of parent mesons.



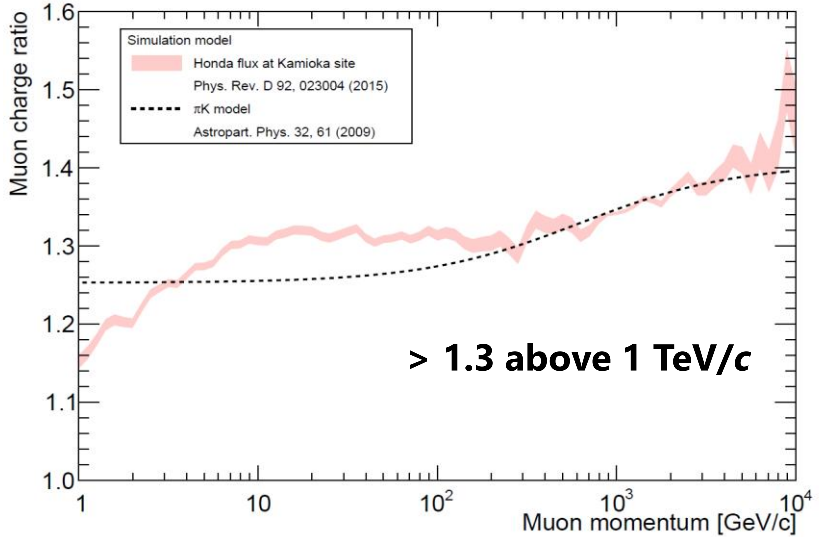


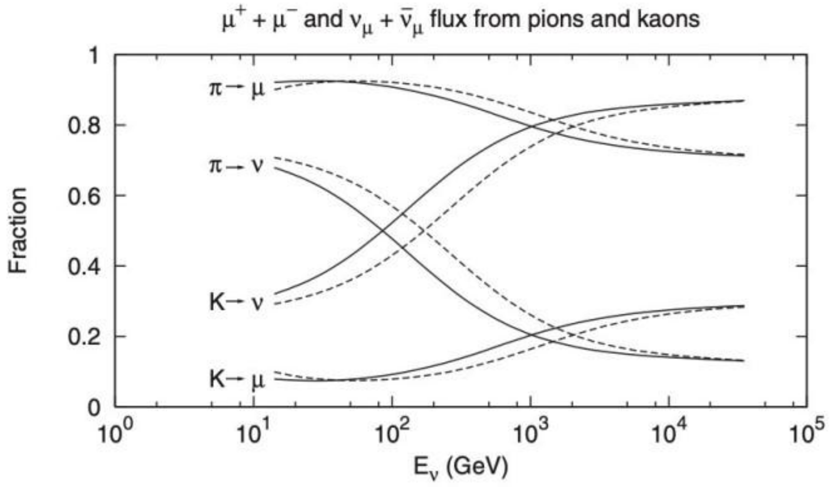


■ Stopping muon decay

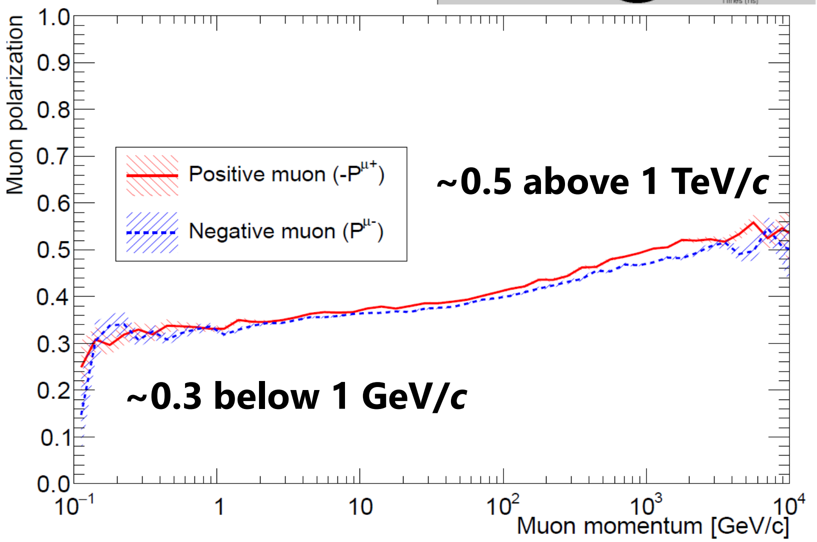
- **Decay time** and **energy spectrum** reflect the **fraction of positive/negative muon**.

→ **Opening angle** between muon and decay-electron reflects its polarization.





[Earth Planet Sp 62, 195 (2010)]



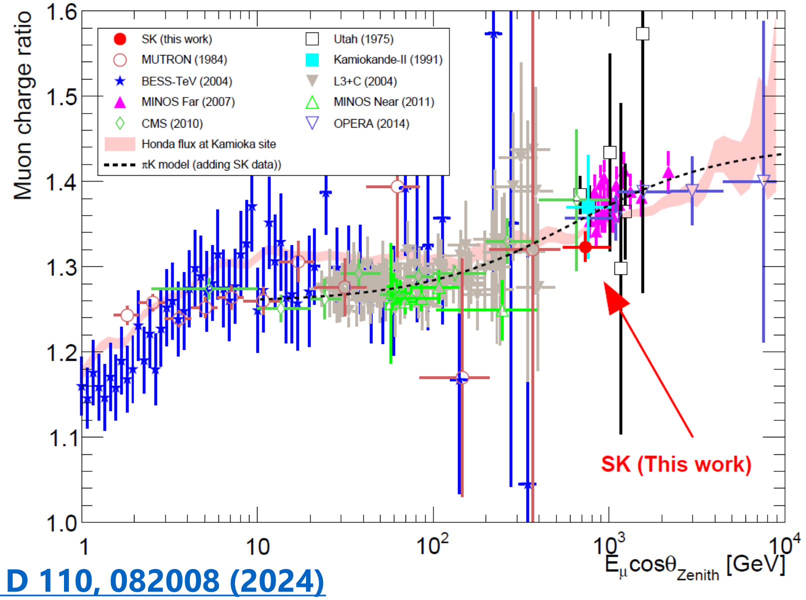
Measurement results

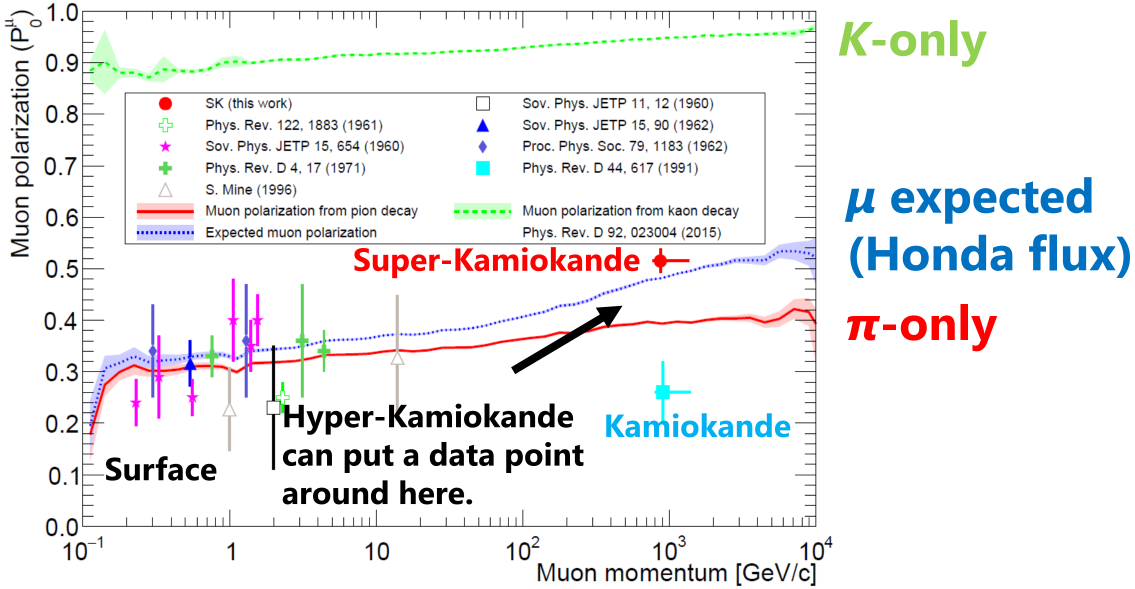
■ Comparison with other experiments and simulations

- Charge ratio: **1.32±0.02**, which is **consistent with other experimental data**.
  → Also, **consistent** with Honda flux model while **1.9σ tension** with πK model.

- Polarization: **the most precise measurement** (**0.52±0.02** at the production site).
  → **1.5σ tension** with Honda flux model and **excludes π-only scenario** by more than 5σ.

- Those measurement can **constraint on neutrino/anti-neutrino ratio and flavor ratio**.





[Phys. Rev. D 110, 082008 (2024)]

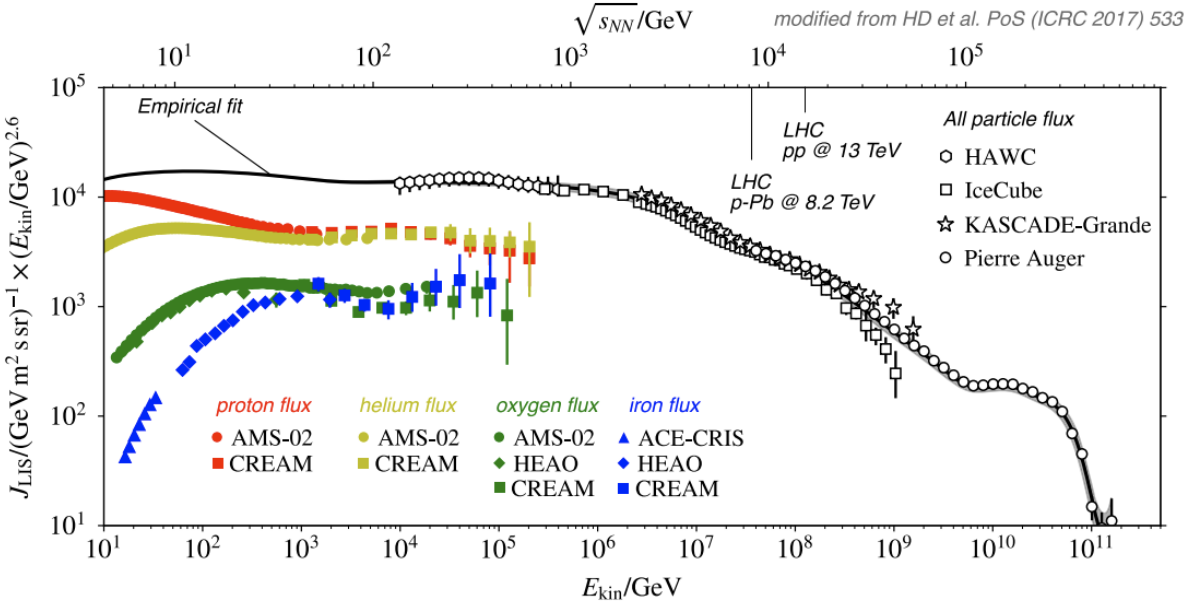
Multiple muon tracks

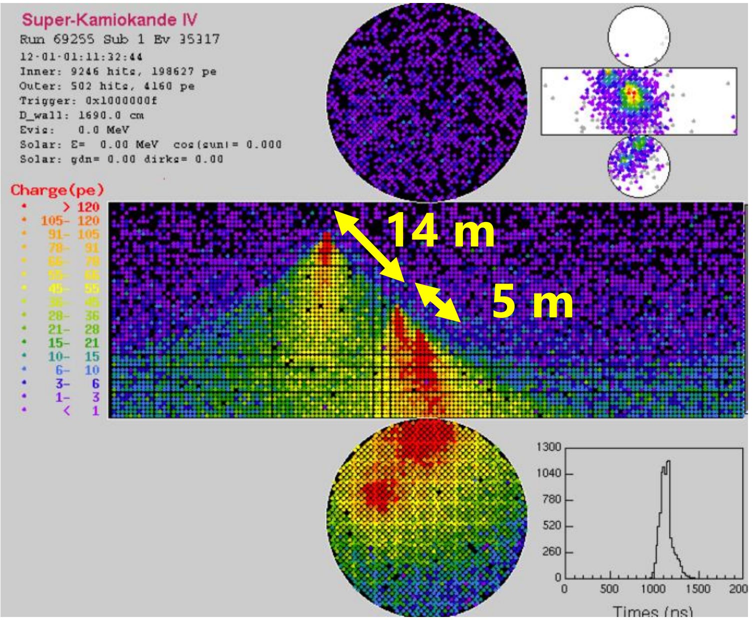
■ Muon puzzle

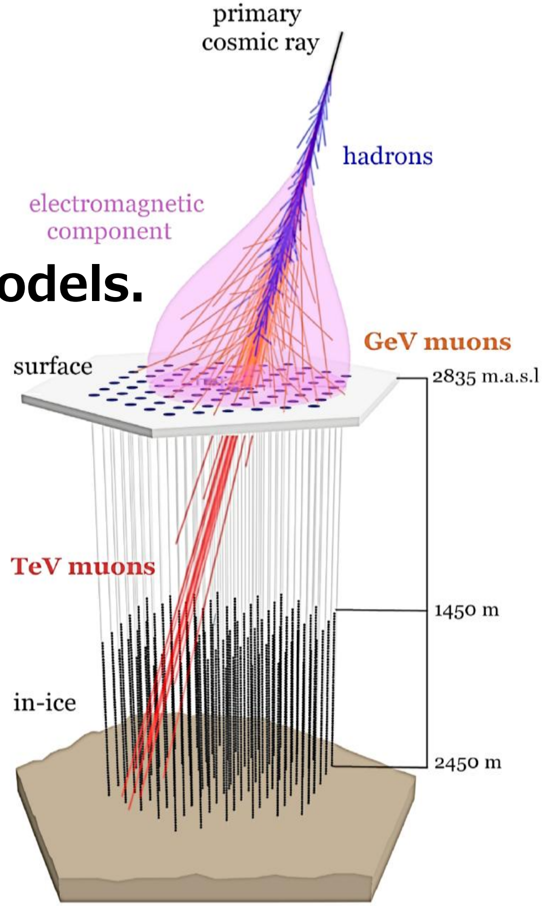
- Muon puzzle: **About 10% discrepancy** between air shower simulations and measurements.
  → Mass composition of primary cosmic-ray is key (high multiplicity ~ heavy component).

■ Muon bundle

- Multiple muon track (muon bundle) attracts attention.
  → **Multiplicity** and **spatial distribution** are important to understand QCD models.







arXiv: 2506.19241

Measurement results

■ Muon multiplicity

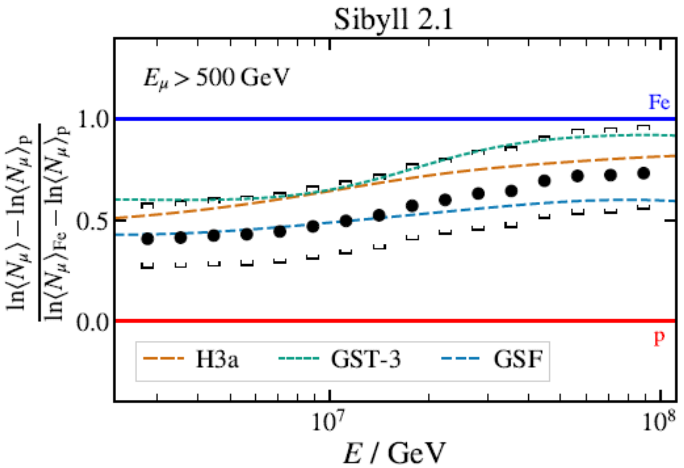
- IceCube experiment measured the **average number of muon tracks**.
  → Test the QCD hadron model and cosmic-ray flux models.

$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_{\mathrm{p}}}{\ln\langle N_\mu\rangle_{\mathrm{Fe}} - \ln\langle N_\mu\rangle_{\mathrm{p}}}$$

Measured number of muons

Expected by proton

Expected by iron

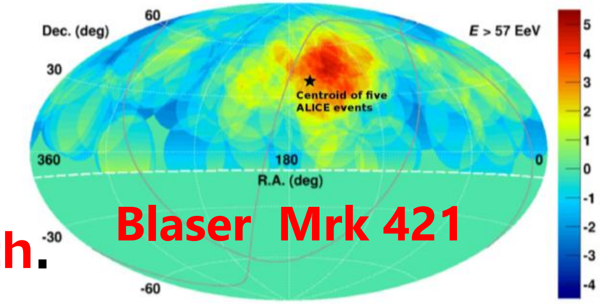


- Measured number of muons is **consistent with** air-shower simulations.

arXiv: 2506.19241

■ Future prospect

- Super-Kamiokande and Hyper-Kamiokande can measure **spatially dense muon multiplicities**.
  - We are developing new muon fitter algorithm based on transformer to determine multiplicity and spatial distribution.



- Muon bundle may useful for anisotropy of muon and **point source search**.
  → Example: Direction of cosmic-ray muons more than 100 by ALICE experiment

Astrophys. J. 839, 31 (2017)   Astrophys. J. Lett. 790, L21 (2014)

Summary

- Precise measurement of atmospheric neutrino oscillation parameters are important to determine mass ordering Δm^2_{32}, θ_{23} Octant, and *CP* phase.
  → the uncertainties of atmospheric neutrinos should be reduced.

- Cosmic-ray muon is key to reduce such uncertainties.
  → Flavor ratio, neutrino/anti-neutrino ratio, and absolute flux of atmospheric neutrinos.

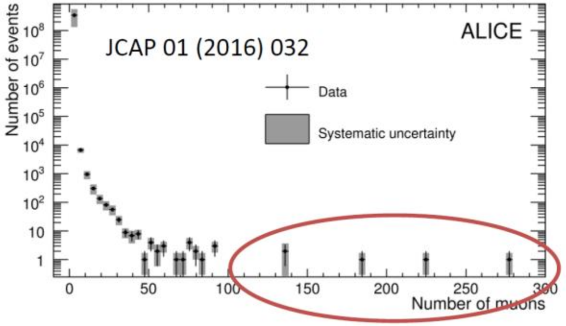
- Neutrino detectors also observe cosmic-ray muons.
- Briefly overview the latest measurement results of cosmic-ray muons:
  1) Seasonal modulation (Kaon/Pion ratio)
  2) Charge ratio and polarization by Super-Kamiokande
  3) Muon bundles by IceCube

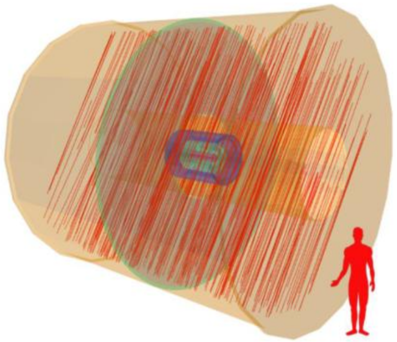
- Further precise measurement is necessary with Water Cherenkov detectors.

Back up slides

Detection of CR by the LHC ALICE experiment

Recently the ALICE experiment has been used to perform studies that are of relevance to astro-particle physics.

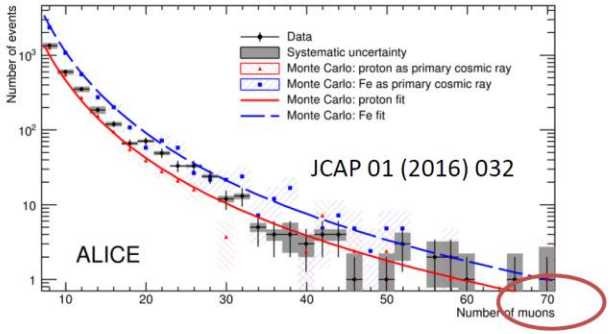




$0^\circ < \Theta < 50^\circ$

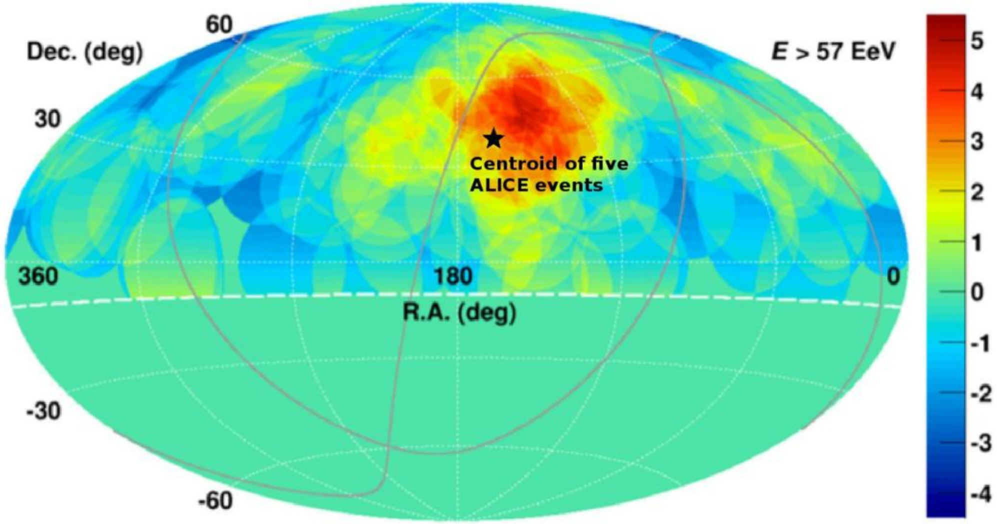
$E_\mu > 16\ \mathrm{GeV}/\cos\Theta$

Total time of data taking: 30.8 days



ALICE experiment registered the presence of large groups of muons produced in EAS by cosmic ray interactions in the upper atmosphere.

Anisotropy of arrival directions



Aitoff projection of the UHECR map in equatorial coordinates taken from Telescope Array Collaboration data **[The Astrophysical Journal Letters 790 (2014) L21]**

See the following slide