Tsinghua University

Investigating Muon Production in Air Shower at Depth of 2400 Meters Underground

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CONTENTS

2025

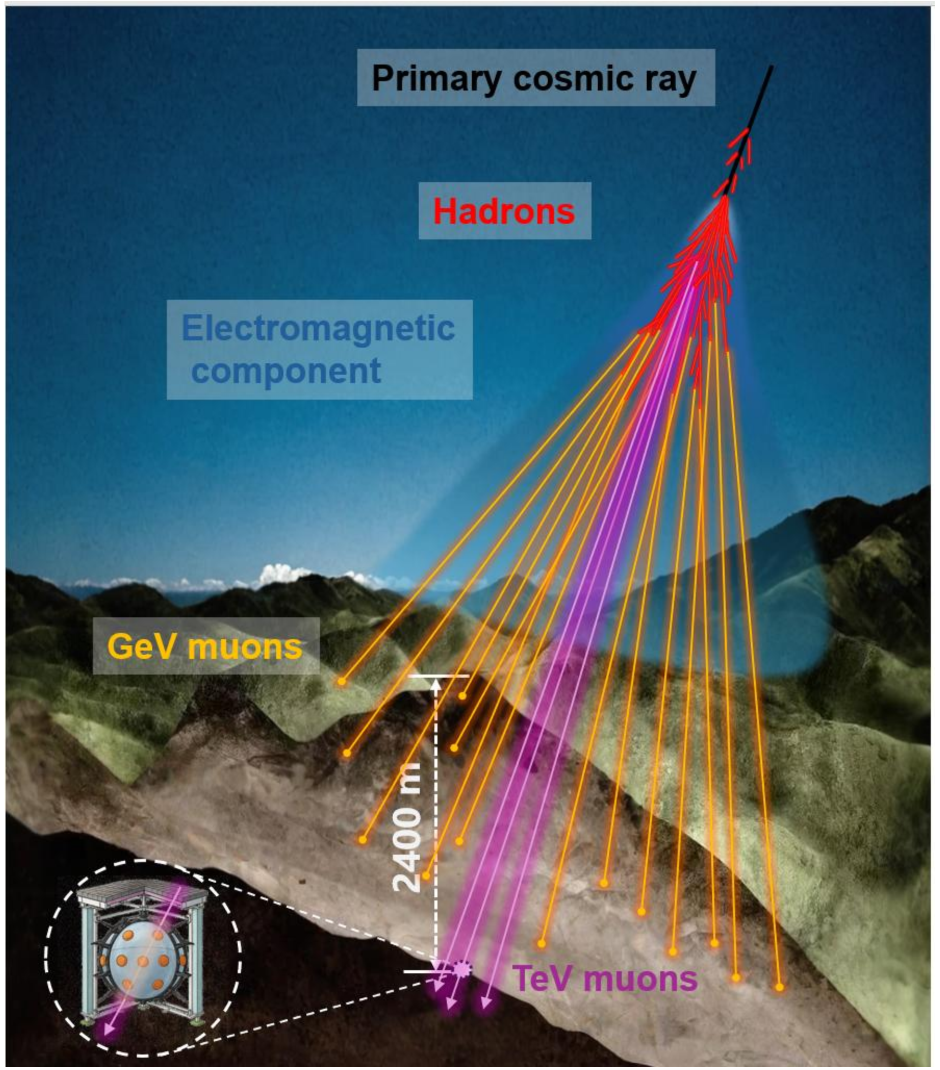
TeV-Muon Production in Air Shower

- Cosmic-rays strike the atmospheric nuclei, initiating extensive air shower and generate numerous hadrons.

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

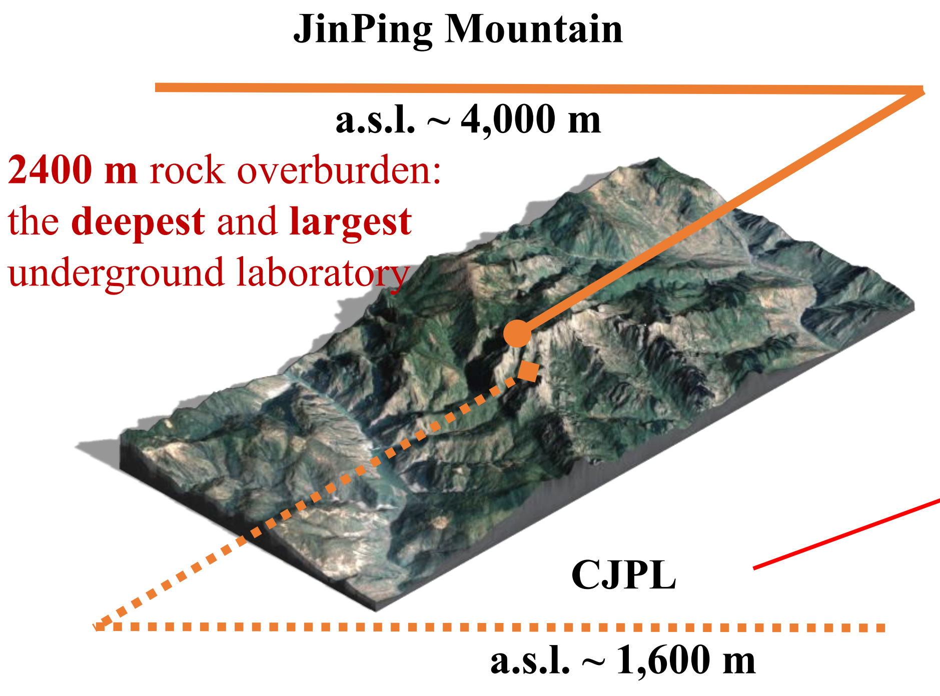
- Only TeV-muons can penetrate the rock overburden and arrive at underground laboratory.

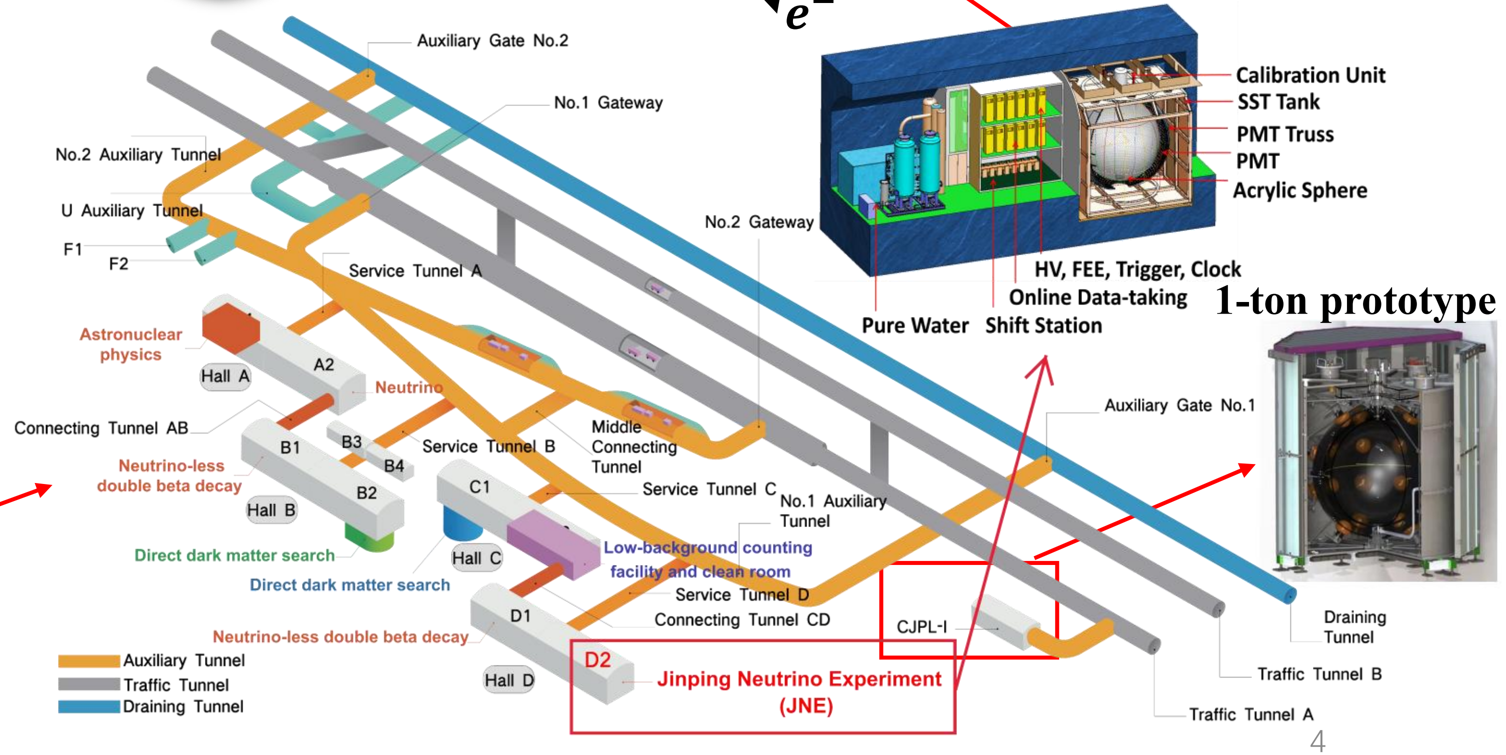
- Such muons are produced in initial stages of air shower:
  - Constrain hadronic interactions in the extreme-forward phase space
  - Infer cosmic-ray mass composition near the knee region



Jinping Neutrino Experiment

- Jinping Neutrino Experiment is a MeV-neutrino Observatory at China Jinping Underground Laboratory (CJPL).





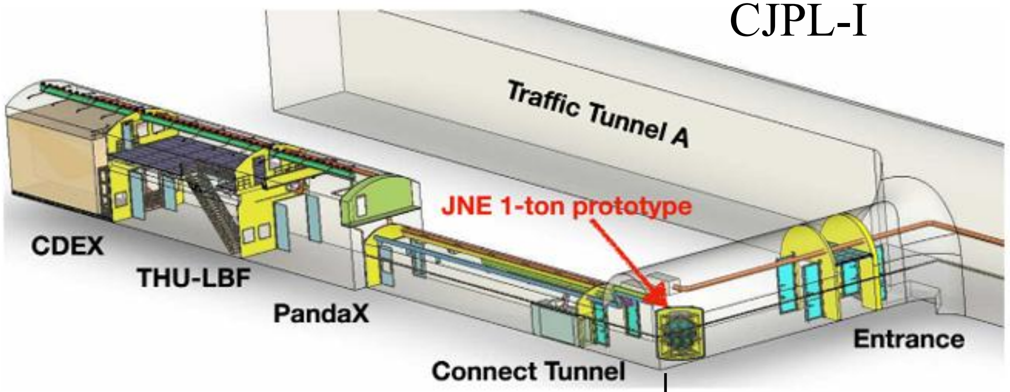
The One-ton Prototype Detector

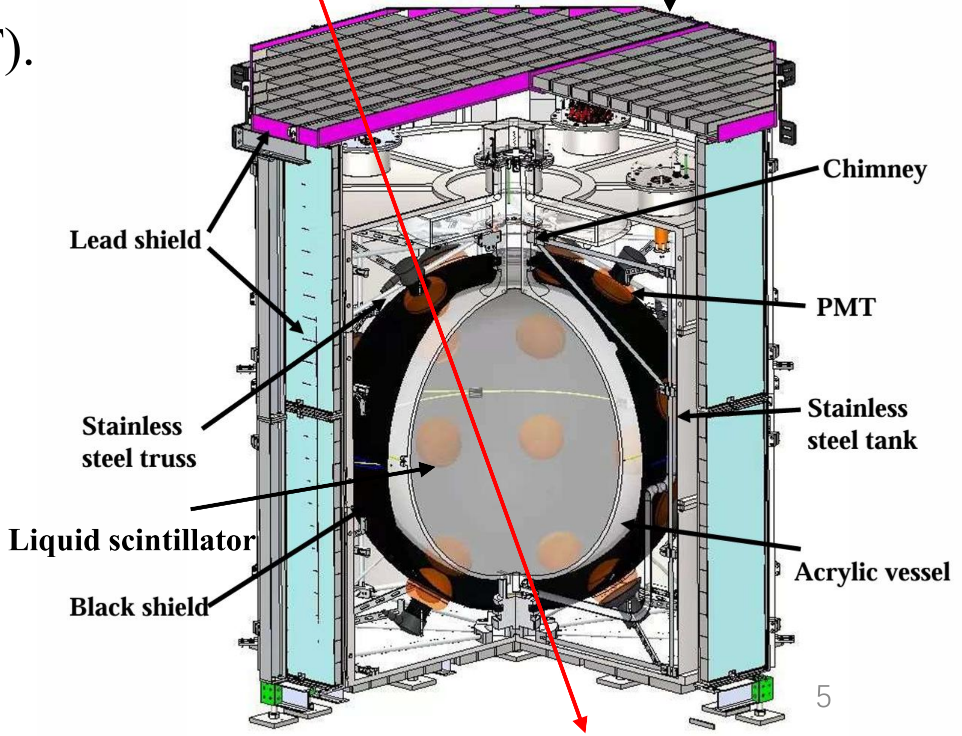
- The one-ton prototype detector is operational in CJPL-I as a **liquid scintillator detector** for technique test and radioactivity measurement in situ.

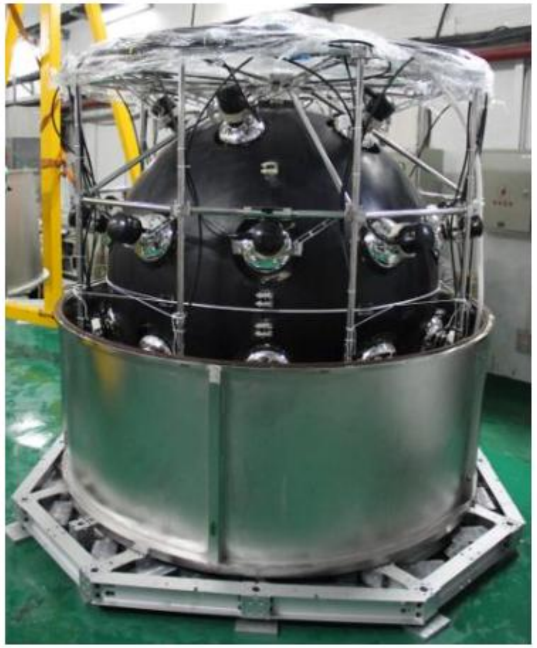
- In this work, this detector is used for muon detection.

- Underground muons deposit energy inside and **produce numerous scintillation photons** to be detected by photomultiplier tubes (PMT).

CJPL-I





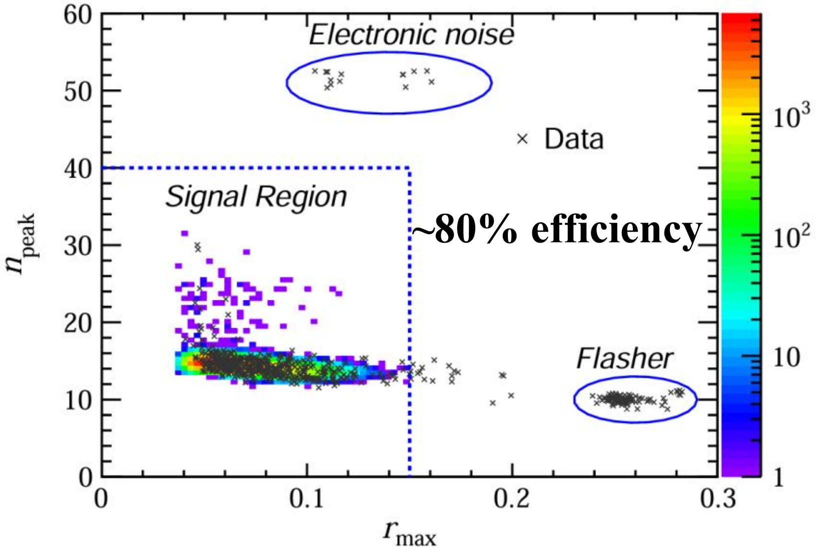


Muon Data and Flux Measurement

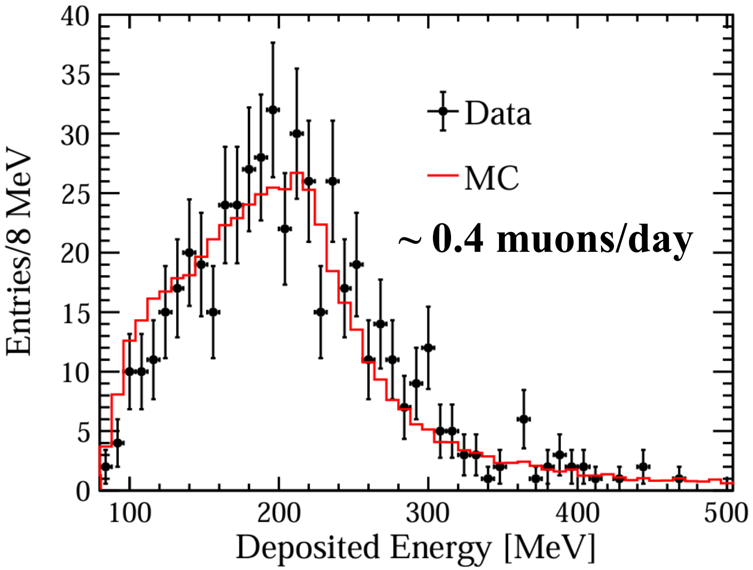
- The data were collected from July 31, 2017, to March 27, 2024, with 1338.6 days effective live time.
- A full-simulation is processed based on Geant4 for estimations of efficiencies and effective area.
- The underground muon flux at CJPL-I is measured as

$$\phi_\mu = \frac{N_{\text{total}}}{T \times S} = \frac{N_\mu}{\varepsilon \times S \times T} = \mathbf{(3.54 \pm 0.15(stat.) \pm 0.08(sys.)) \times 10^{-10}\ cm^{-2}s^{-1}}$$

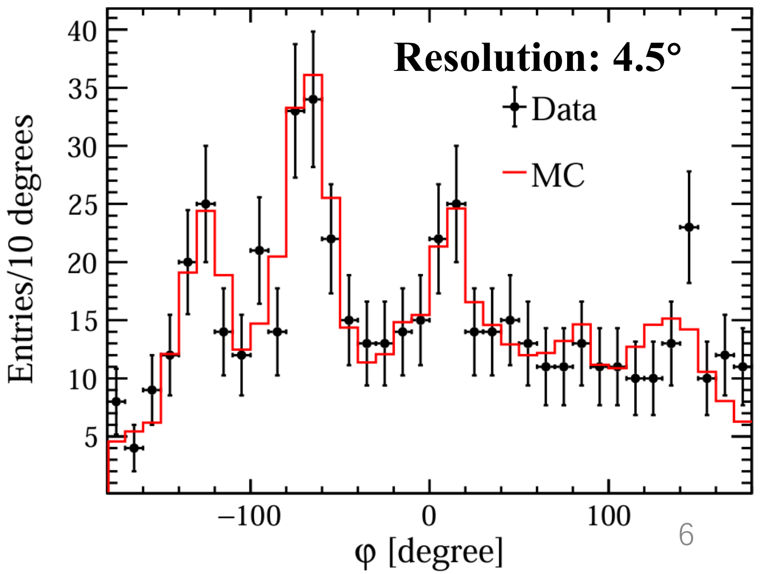
Muon signal selection



Reconstructed deposited energy

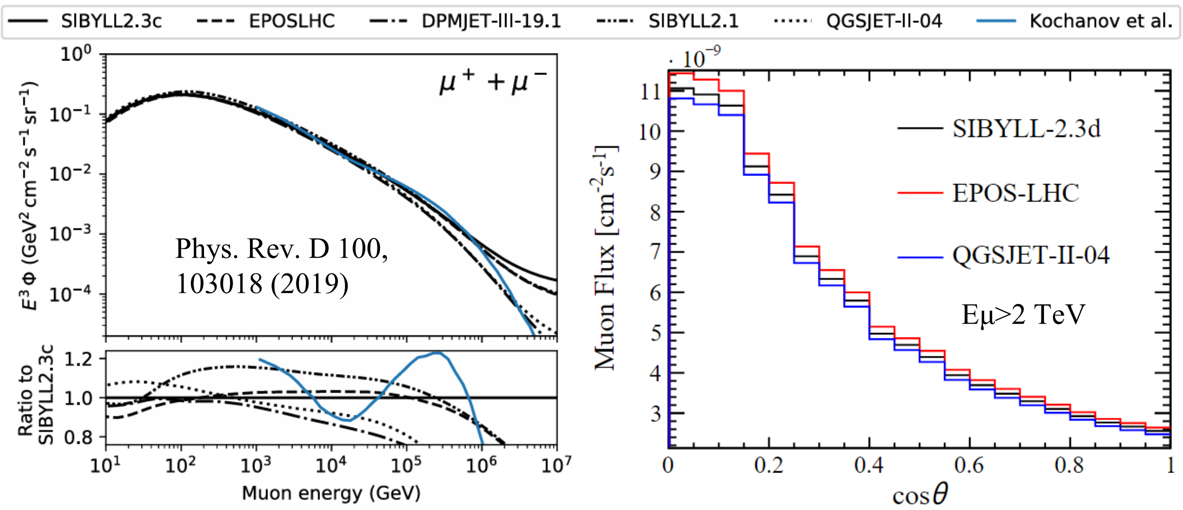


Reconstructed direction



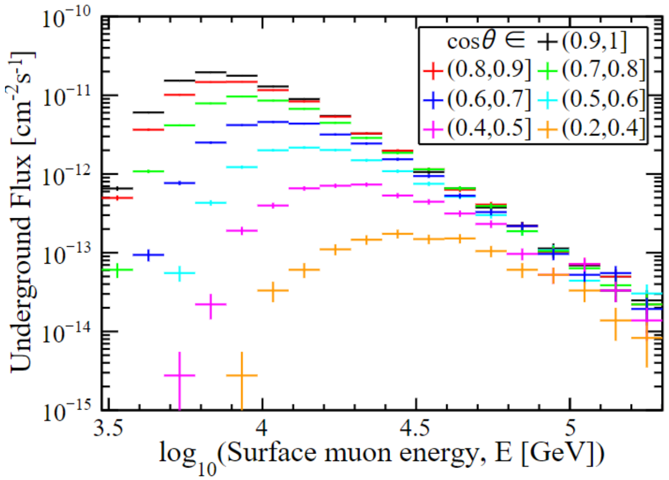
Underground Muon Flux Prediction

Cosmic ray+Hadronic model+MCEq package→Surface muon



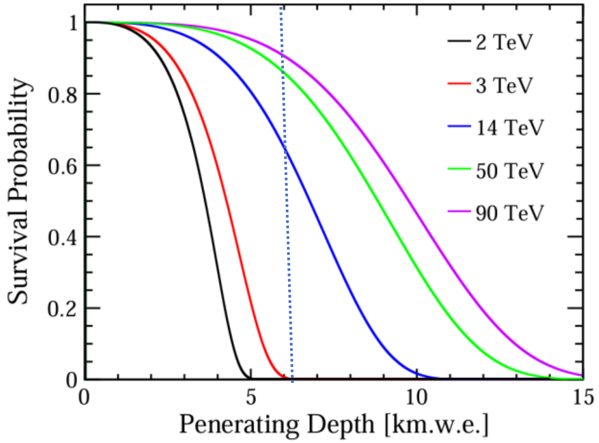
Muon threshold: 3 TeV

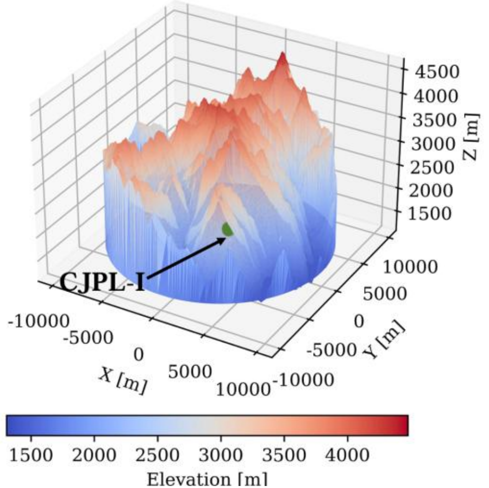
Single muon dominant



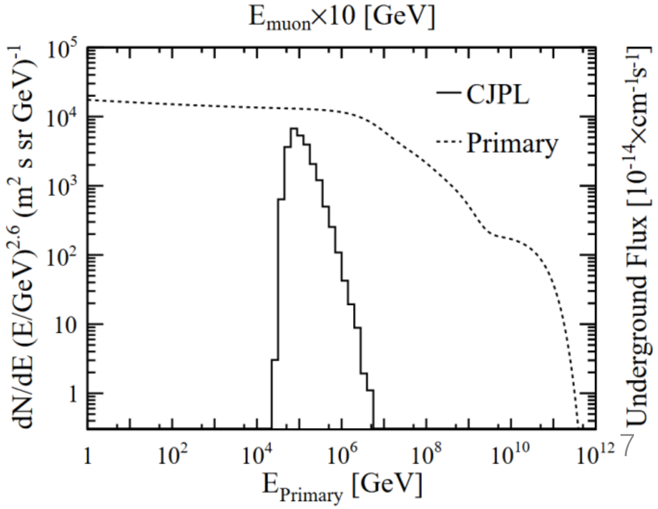
$$\text{Underground}: \phi_\mu = \int \phi_s(E,\theta,\varphi) P(E, X(\theta,\varphi)) dE d\Omega$$

Mountain model+Geant4 simulation→Survival probability





Primary CR: 10TeV-PeV

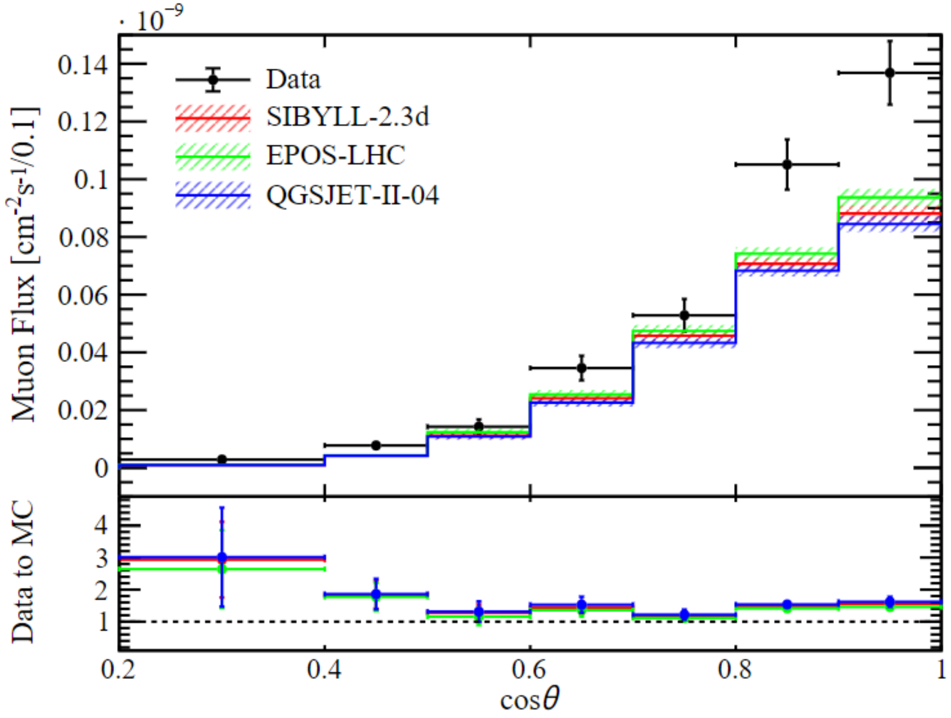


Comparisons

- **About 40% discrepancies** are observed between data and all leading hadronic models.
- The discrepancy significance is about 2σ.
- No significant angular dependence is observed.

		Uncertainty [%]
Measurement	Statistics	4.2
	Systematics	2.2
Prediction	Seasonal variation	0.5
	Detector position	1.6
	CR model	11.8
	Hadronic model	4.8

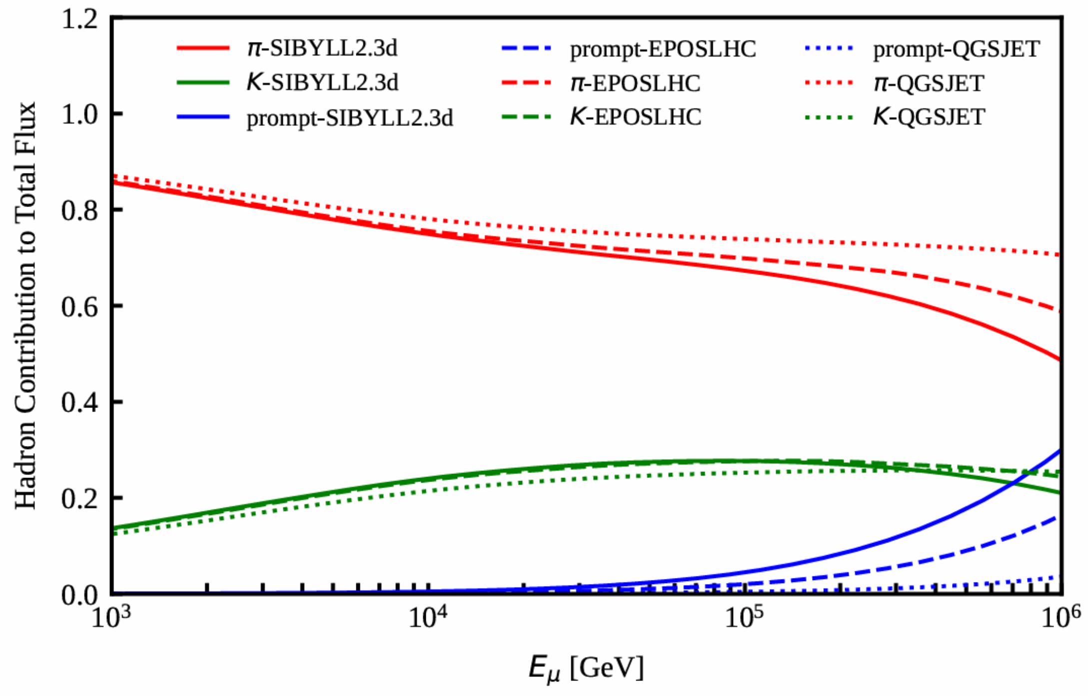
Model	Flux ratio
SIBYLL-2.3d	1.44±0.07
EPOS-LHC	1.38±0.07
QGSJET-II-04	1.51±0.08

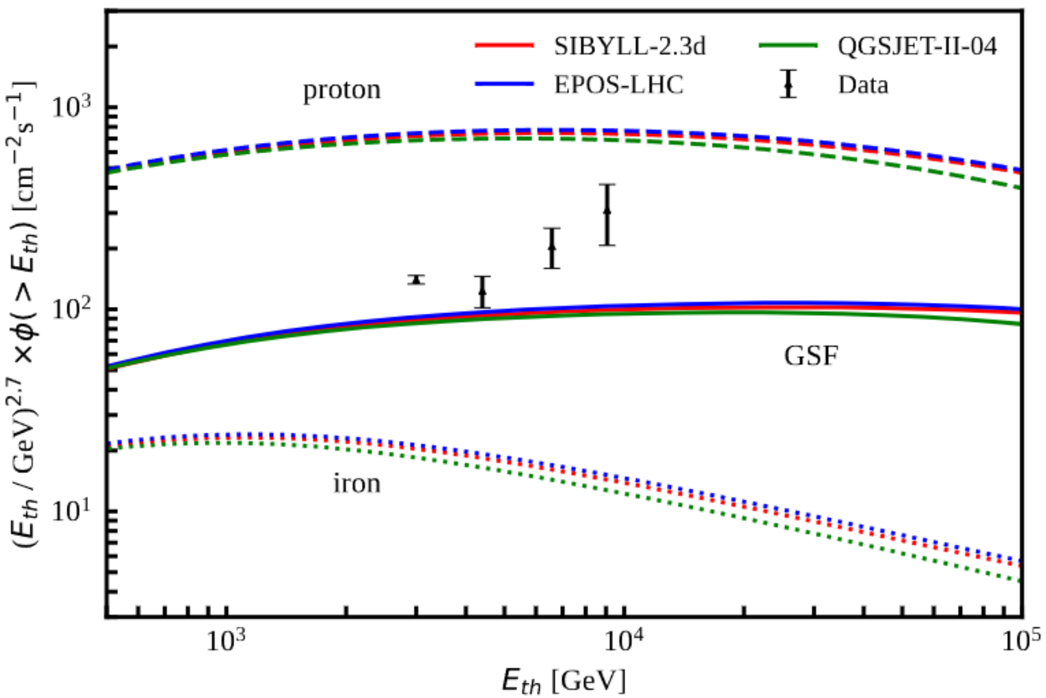


Similar excess observed by KM3NeT, Bess and L3+cosmic, but the intensity is different.

Interpretation of the excess

- We interpret the observed excess in two ways:
  - Hadronic interactions in the initial interactions of air showers:
    - An enhancement of **total hadron production above TeV (dominantly pion).**
    - An enhancement of **strange and charmed meson production.**
  - Primary cosmic rays:
    - **A lighter component** for cosmic rays





Summary and Outlook

- In this study, we have conducted the first investigation of the muon production with **energies exceeding 3 TeV** in air shower at CJPL with the one-ton prototype detector of the Jinping Neutrino Experiment.

- The measured muon flux is compared with those predicted based on various hadronic interactions models. **About 40% discrepancies** are observed. Some potential origins are discussed.

- In the future, the ongoing 500-ton detector of Jinping Neutrino Experiment will collect numerous high-energy muon data, and more related studies can be performed to help us to figure out the muon production, including flux seasonal variation, muon charge ratio and polarization, direction anisotropy, and etc.


Thanks for Listening