



JINPING
NEUTRINO
EXPERIMENT



清华大学
Tsinghua University



湖南大学
HUNAN UNIVERSITY

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

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August 25, 2025

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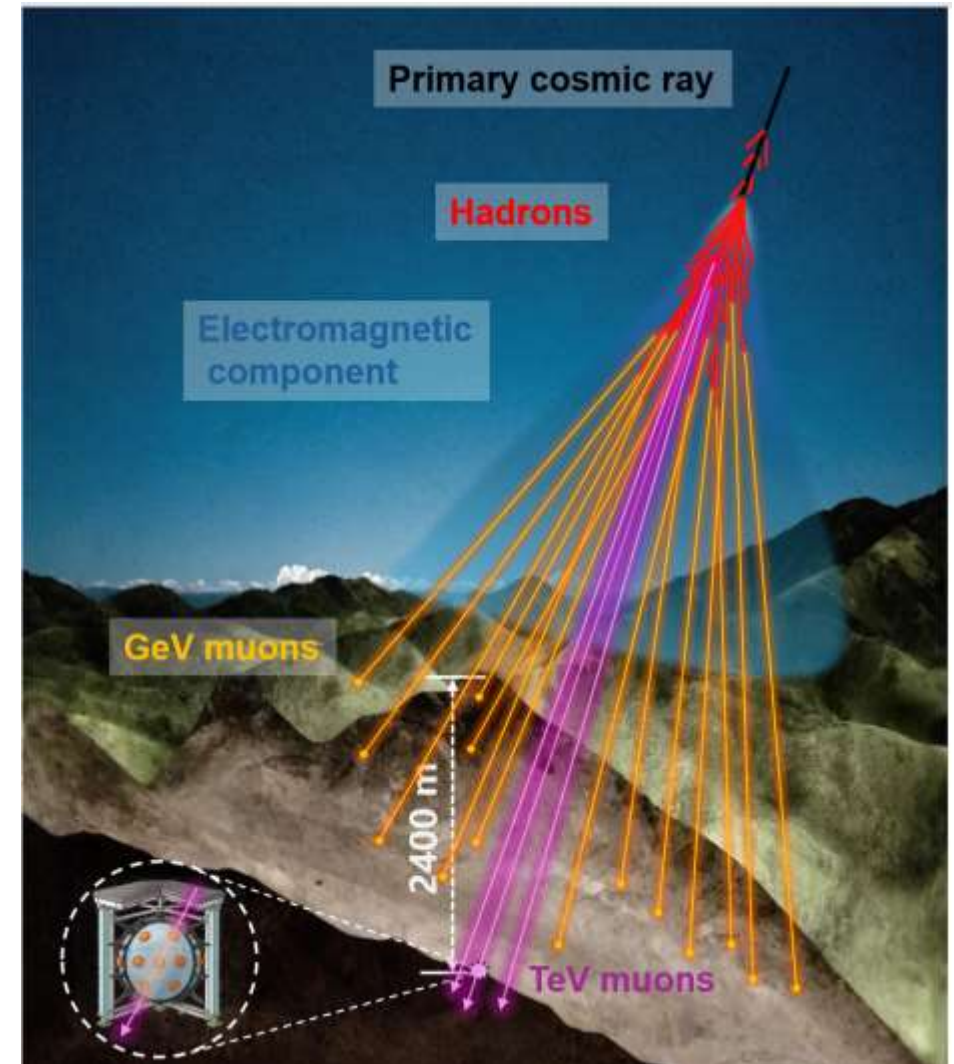
Muon Production in Air Shower

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

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

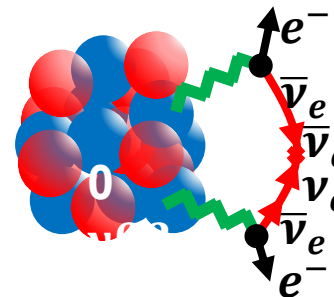
$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

- Only TeV-muons can penetrate the rock overburden and arrive at underground laboratory.
- These muons are produced in initial stages of air shower:
 - Carrying a significant fraction of cosmic-ray energy
 - Small transverse momenta
 - Providing information about hadronic interactions in the far-forward region



Jinping Neutrino Experiment

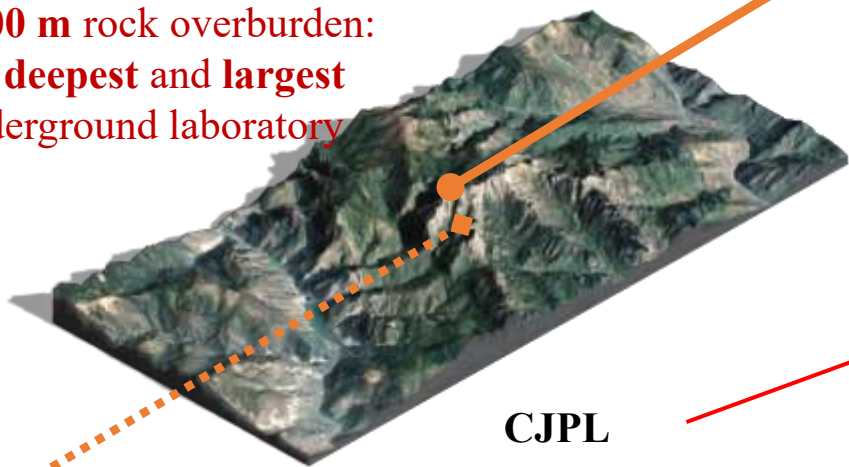
- Jinping Neutrino Experiment is a MeV-neutrino Observatory at China Jinping Underground Laboratory (CJPL).



JinPing Mountain

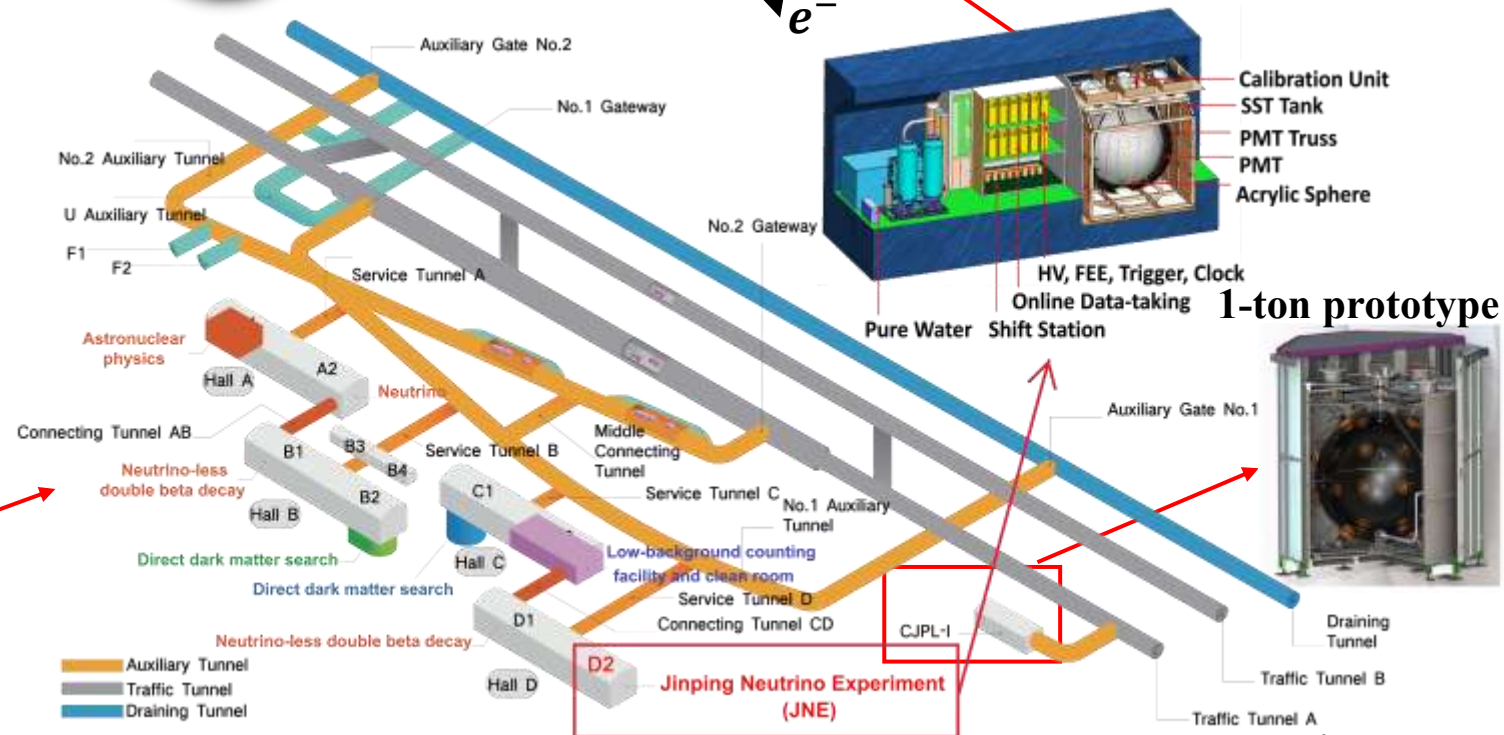
a.s.l. $\sim 4,000$ m

2400 m rock overburden:
the **deepest** and **largest**
underground laboratory



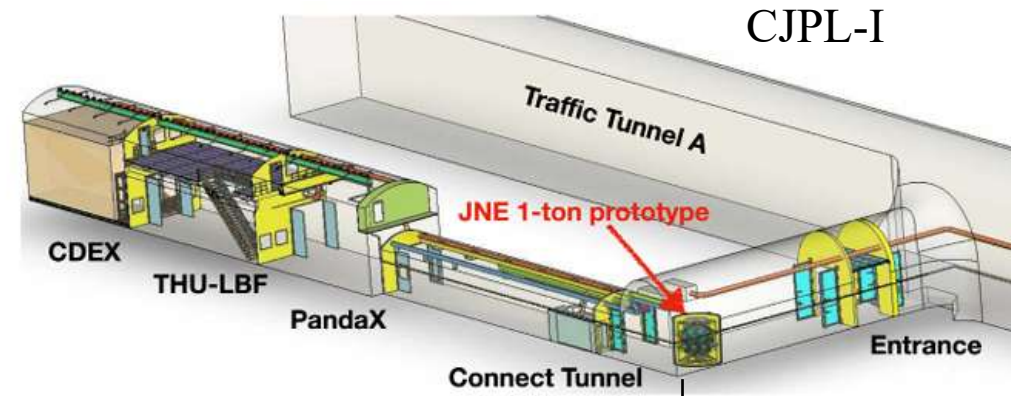
CJPL

a.s.l. $\sim 1,600$ m

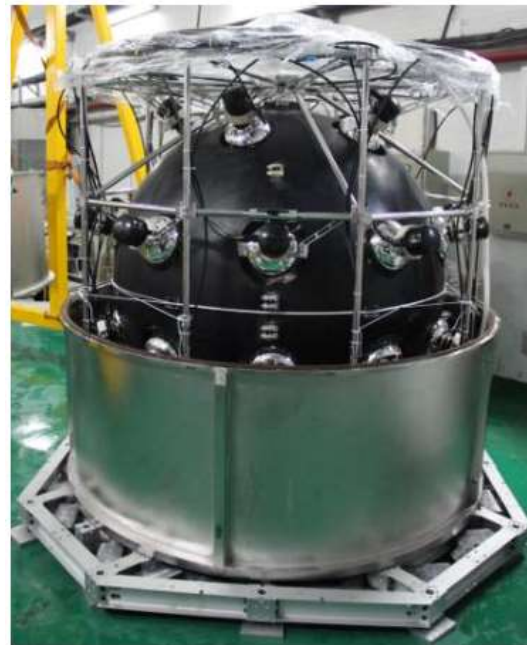
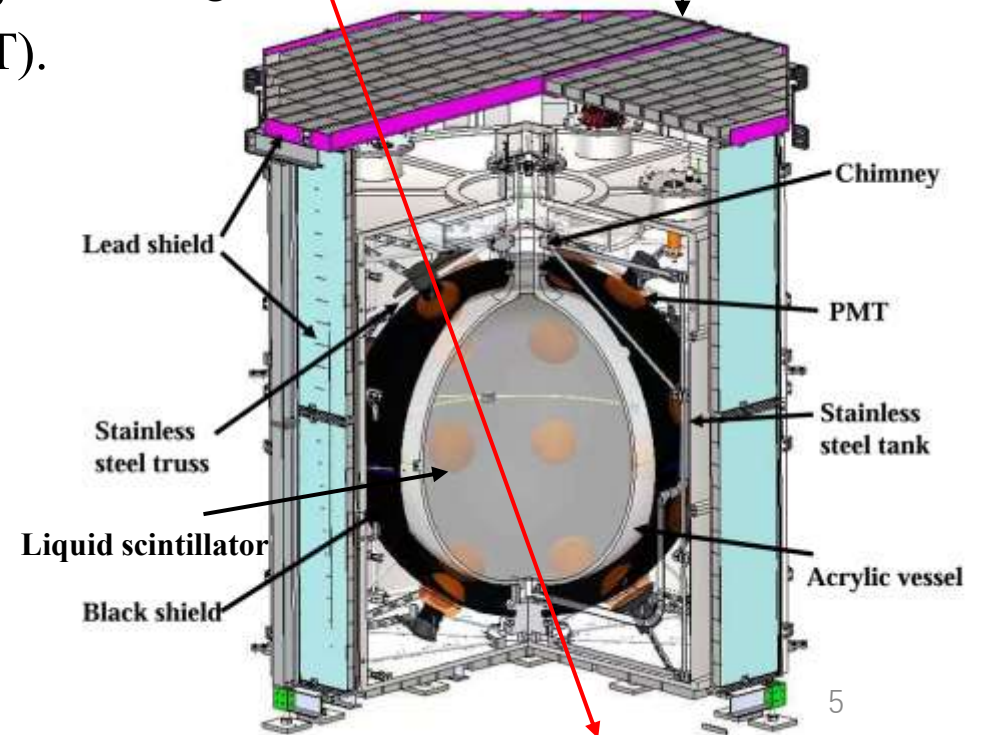


The One-ton Prototype Detector

- 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).



Underground Muon

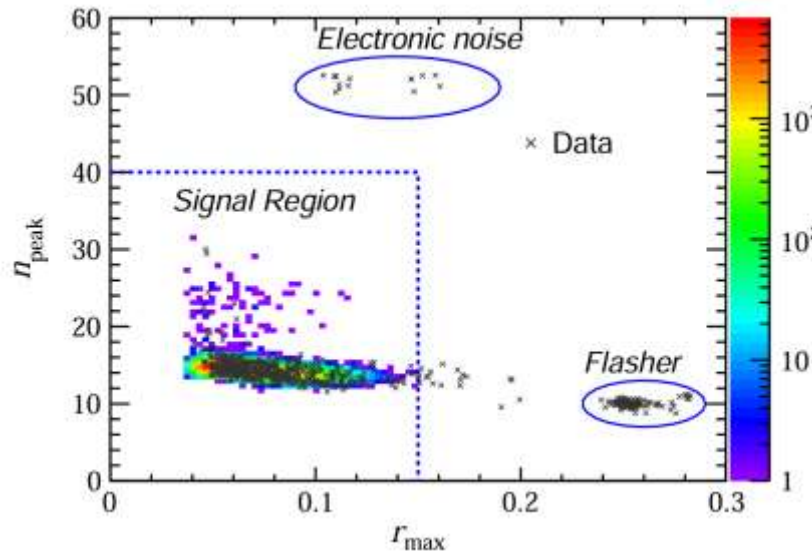


Muon Data and Flux Measurement

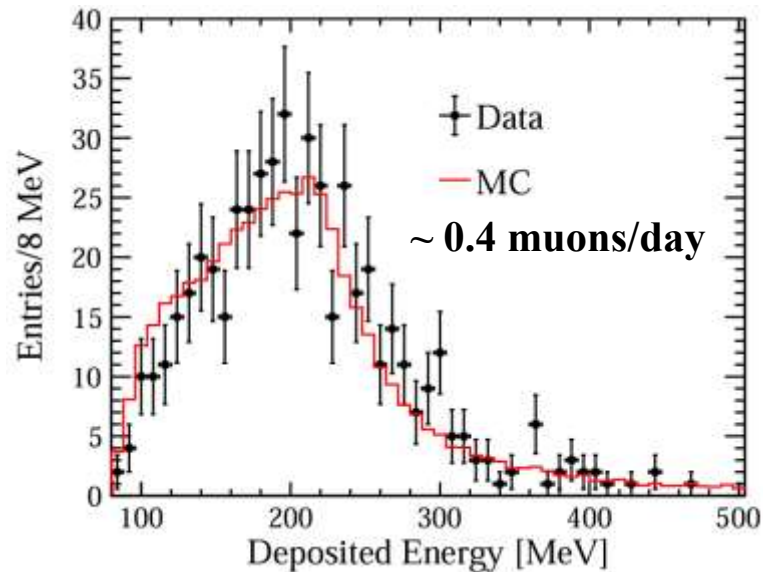
- The data were collected from July 31, 2017, to March 27, 2024, with 1338.6 days effective live time.
- A full-simulation is processed based on Geant4 for estimations of efficiencies and effective area.
- The underground muon flux at CJPL-I is measured as

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

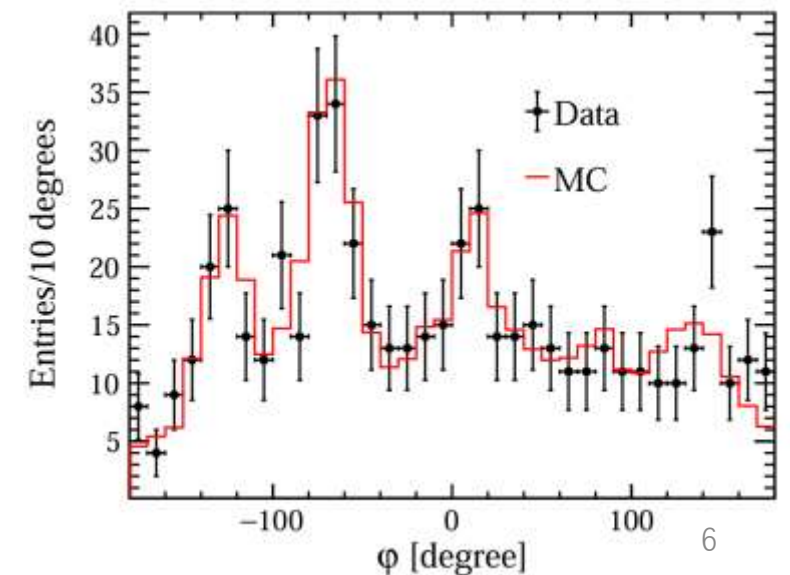
Muon signal selection



Reconstructed deposited energy

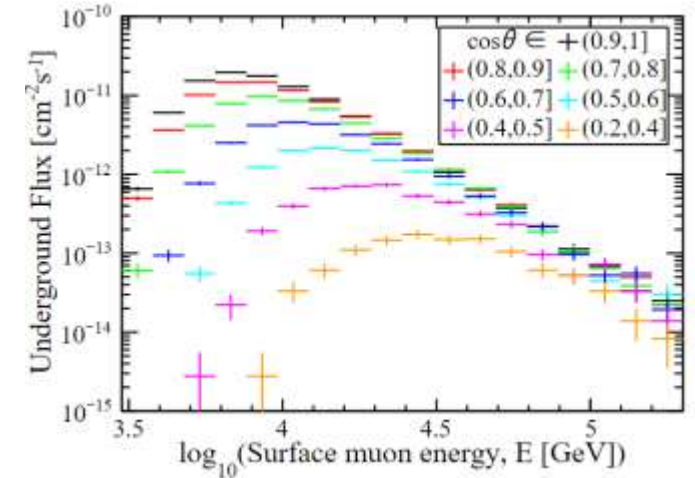
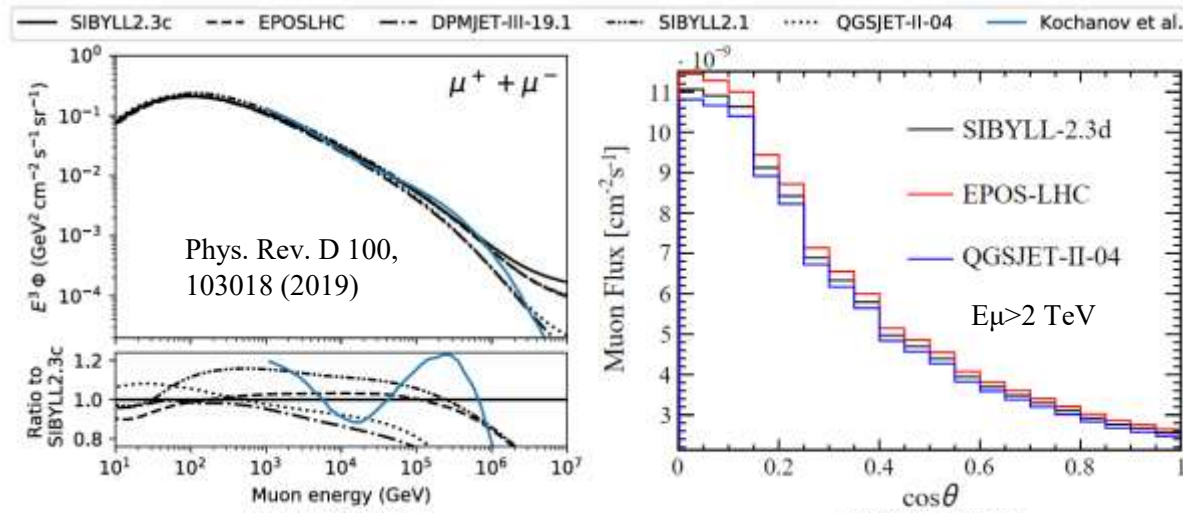


Reconstructed direction



Underground Muon Flux Prediction

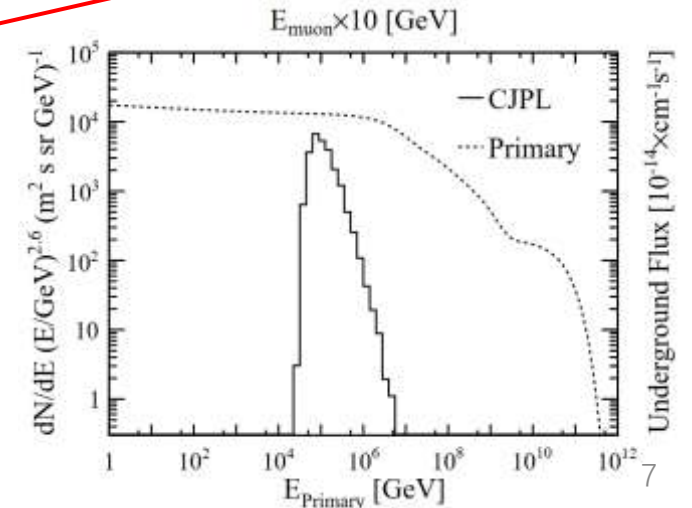
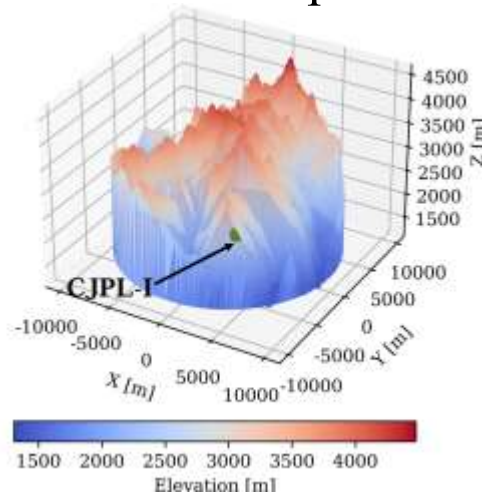
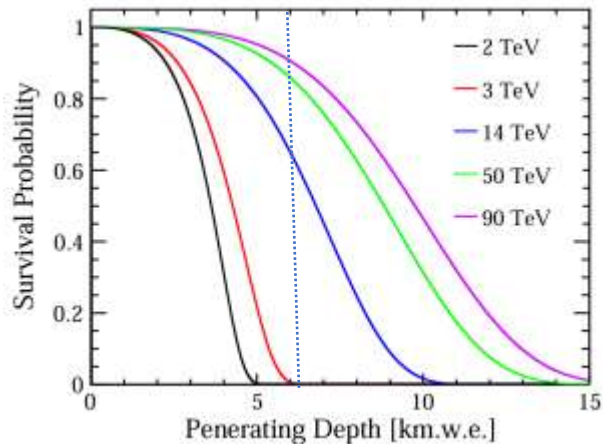
Cosmic ray+Hadronic model+MCEq package→Surface muon



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

Mountain model+Geant4 simulation→Survival probability

Threshold: 3 TeV



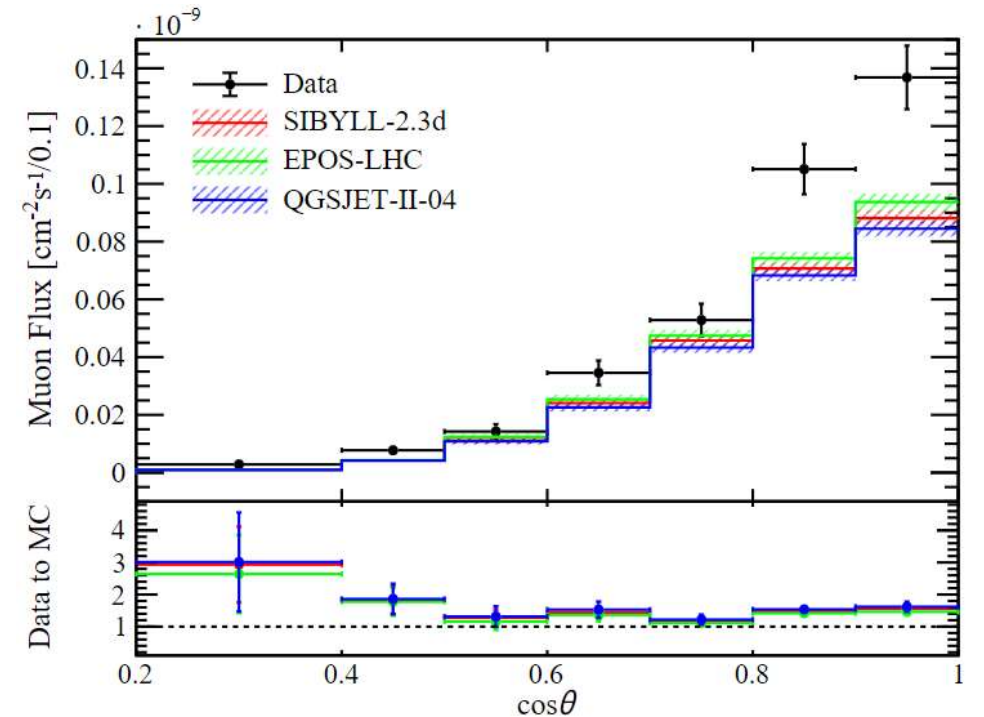
Comparisons

- Global Spline Fit model (GSF2017), is used as the cosmic-ray model.
- Model-related uncertainties are not included here.
- **About 40% discrepancies** are observed across all leading hadronic models.
- No significant angular dependence is observed.

		Uncertainty [%]
Measurement	Statistics	4.2
	Systematics	2.2
Prediction	Seasonal variation	0.5
	Detector position	1.6

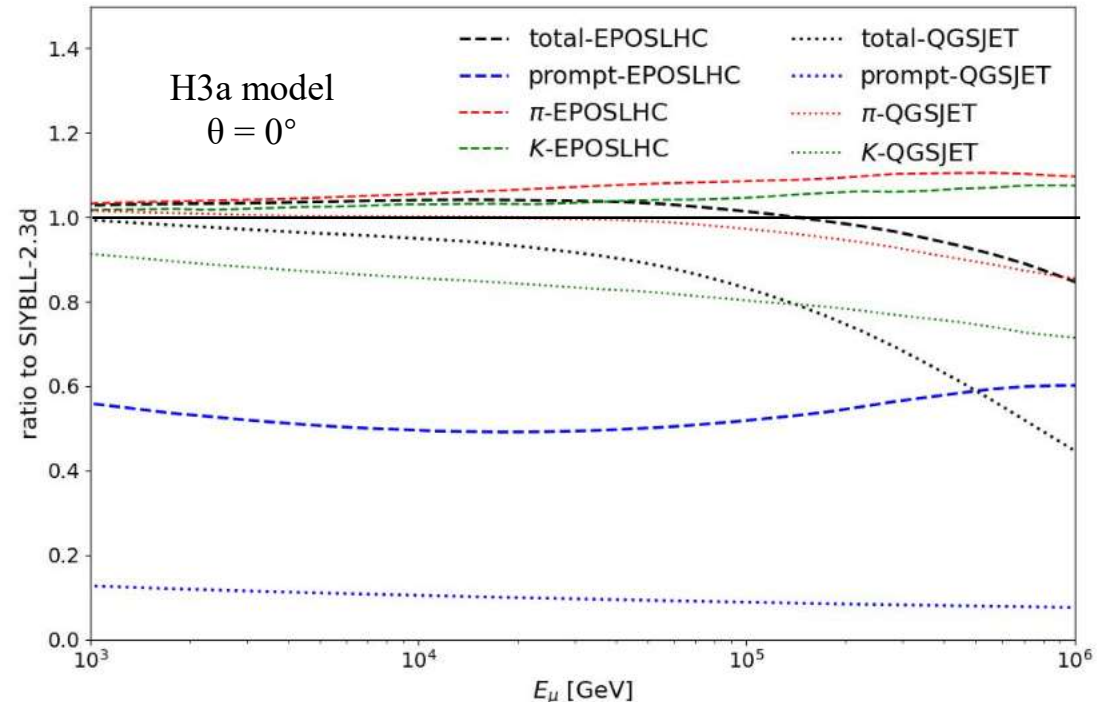
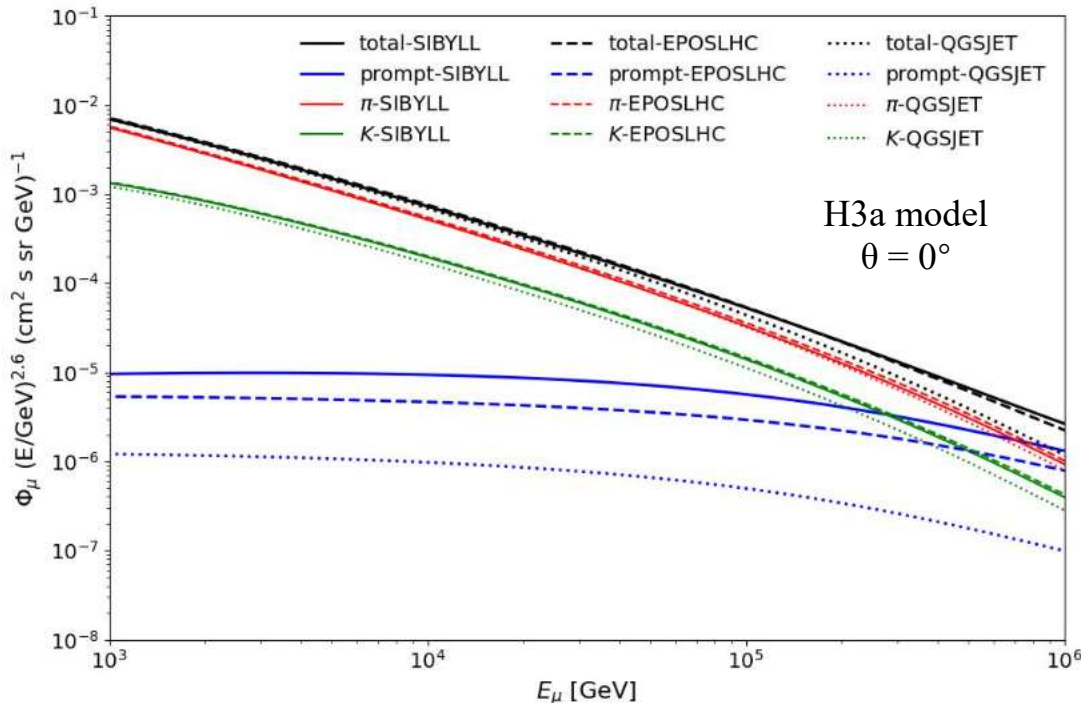
Model	Flux ratio	Excess significance
SIYBLL-2.3d	1.44 ± 0.07	6.0σ
EPOS-LHC	1.38 ± 0.07	5.5σ
QGSJET-II-04	1.51 ± 0.08	6.7σ

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



Comparison of Hadronic Interaction models

- With MCEq, the muon flux contributions can be decomposed and compared among different models.
- EPOS-LHC model exhibits more meson production than SIYBLL
- QGSJET-II-04 model has less Kaon production than SIYBLL while similar number of pion is produced.
- SIYBLL-2.3d model generates more prompt contributions than others.



Discussion of Observed Discrepancies

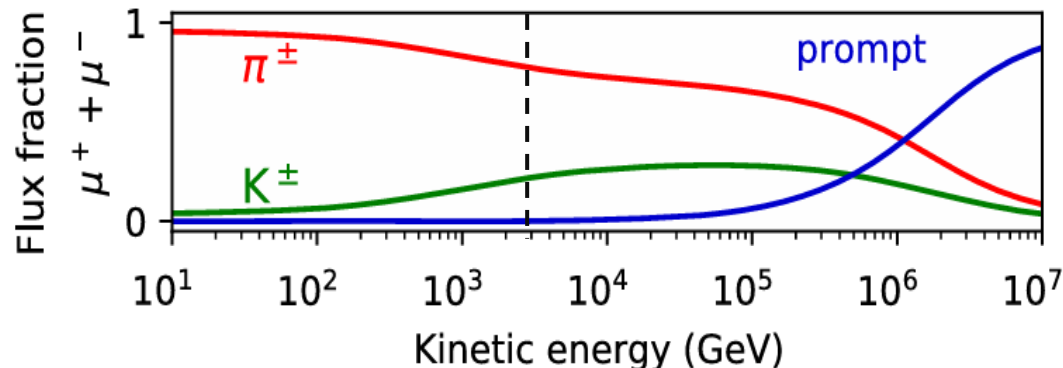
■ Based the differences of models, some explanations are available accounting for the observed discrepancies:

- An enhancement of **total hadron production** in the initial interactions of air showers.
- A modest enhancement of **strange and charmed meson production** in the initial processes of air showers.
- Other origins: limited experimental knowledge about cosmic ray, especially **mass composition**.

➤ Constrains on $\ln A$? Indicating heavier component? (ongoing)

Astrophys. Space Sci. 367, 27 (2022)

Energy threshold



Probability to produce
TeV-muon

Particle mass

Interaction length

$$R = \frac{P_{K^\pm}}{P_{\pi^\pm}} = \frac{b_{K^\pm}}{b_{\pi^\pm}} \cdot \frac{m_{K^\pm}}{m_{\pi^\pm}} \cdot \frac{\tau_{\pi^\pm}}{\tau_{K^\pm}} \times \frac{\lambda_{int,K^\pm}}{\lambda_{int,\pi^\pm}} = \begin{matrix} \sim 5 \text{ for } K^\pm \\ \sim 60000 \text{ for } D^+ \end{matrix}$$

Branch ratio of
decaying to muon

Particle lifetime

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.
- The latest hadronic interaction and cosmic ray models proposed recently on ICRC can potentially resolve the discrepancy in this study.
- 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.



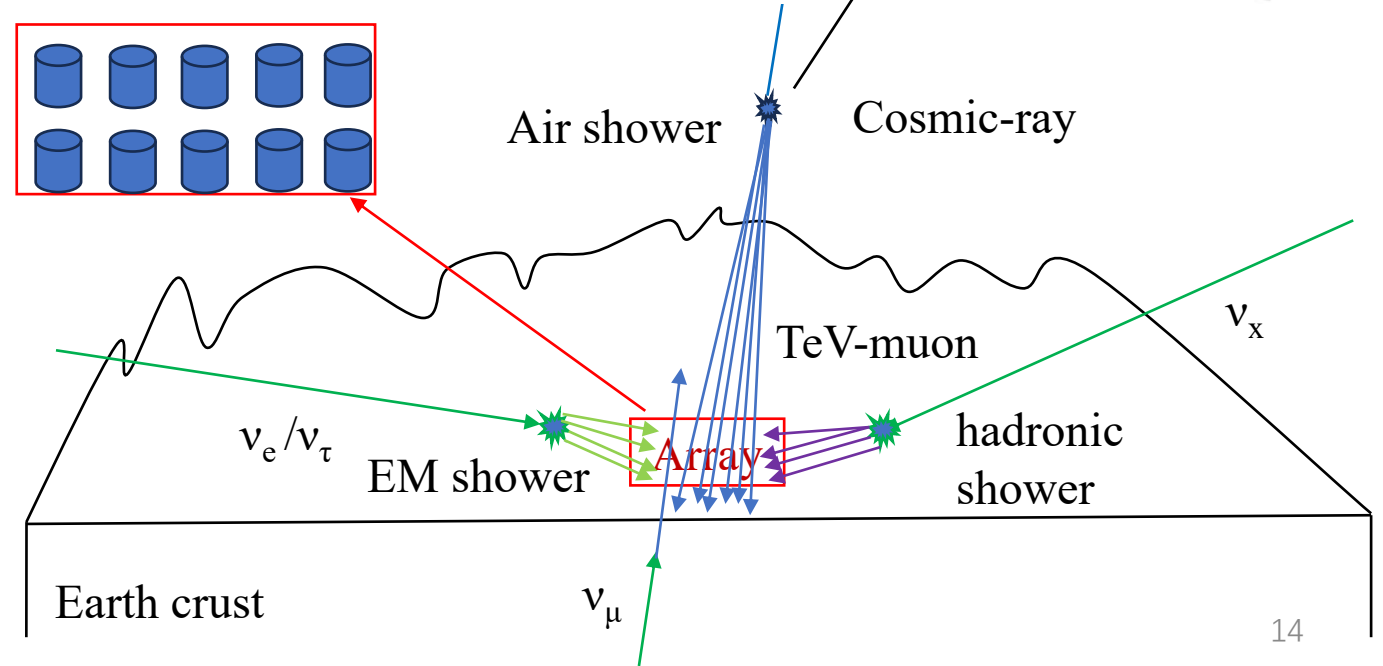
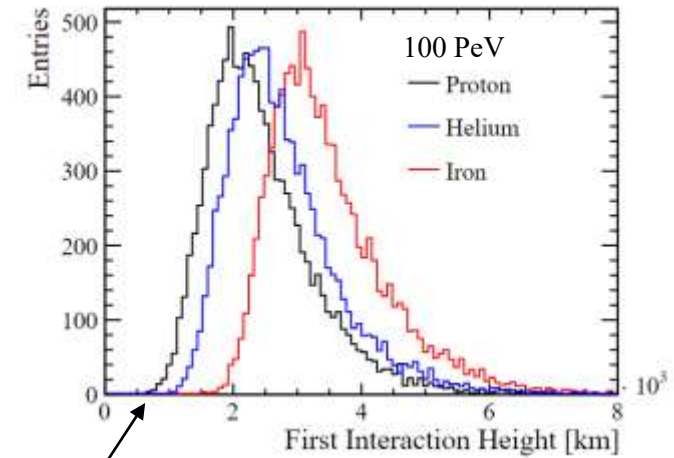
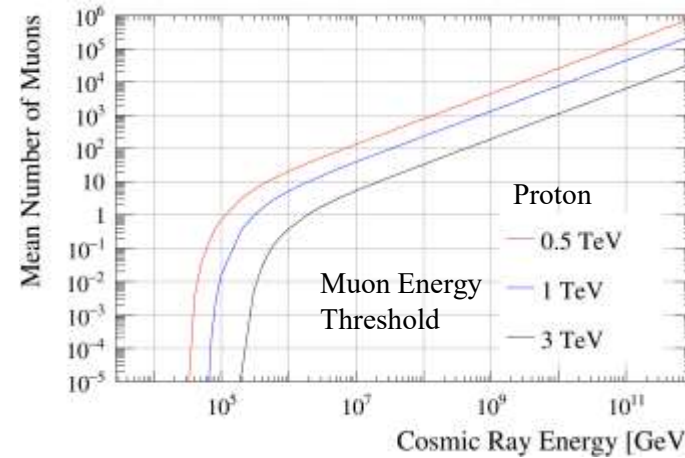
Thanks for Listening

Backup

Physical Potential of an Underground Array

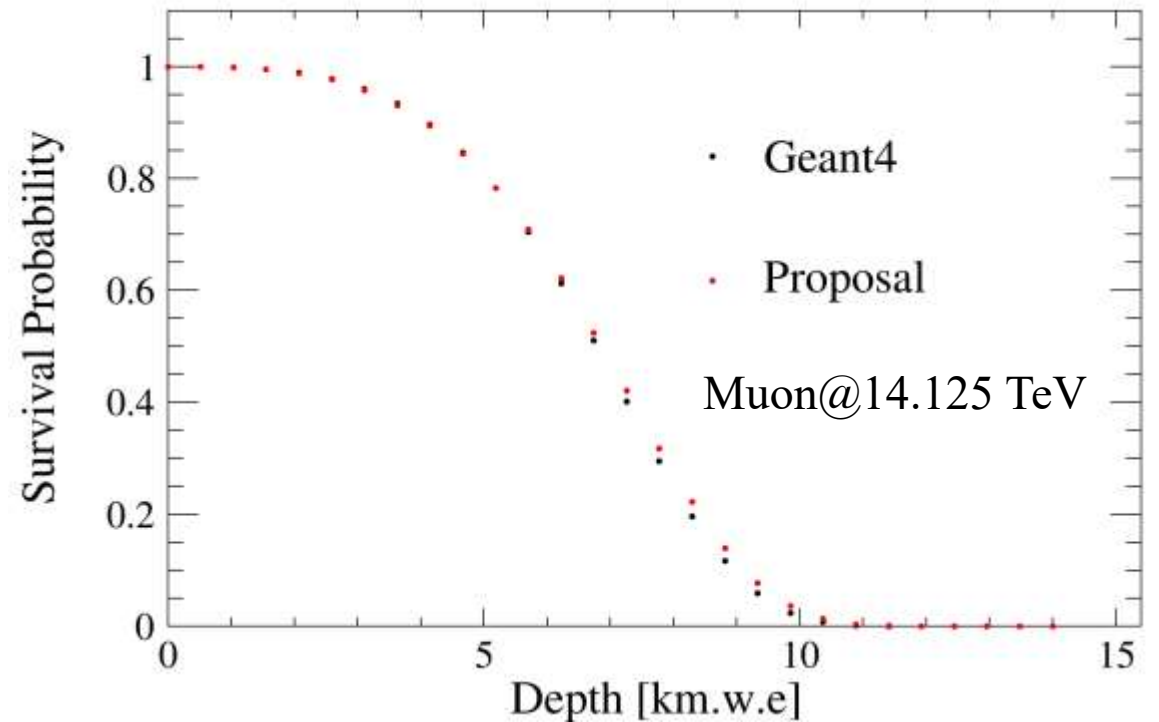
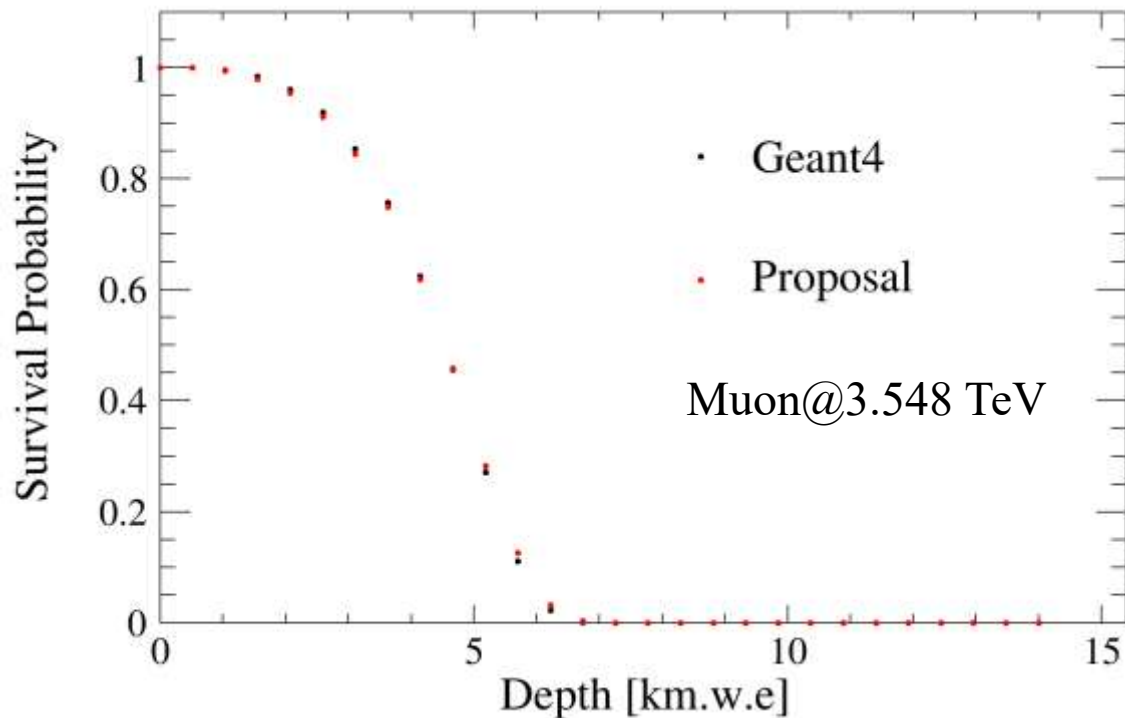
Corsika7.7550

- An underground array of similar detectors:
 - Interaction vertex reconstruction
 - Particle identification
- Cosmic-rays:
 - Particle: TeV-muons in shower
 - Energy: 10 PeV to EeV and above
 - More information about shower
- Atmospheric and astrophysical neutrinos:
 - Interact with **local rock and crust**
 - Up-muon from ν_μ charge current
 - EM shower from ν_e/ν_τ charge current
 - Hadronic shower from ν_x neutral current
- Further detailed studies are ongoing.



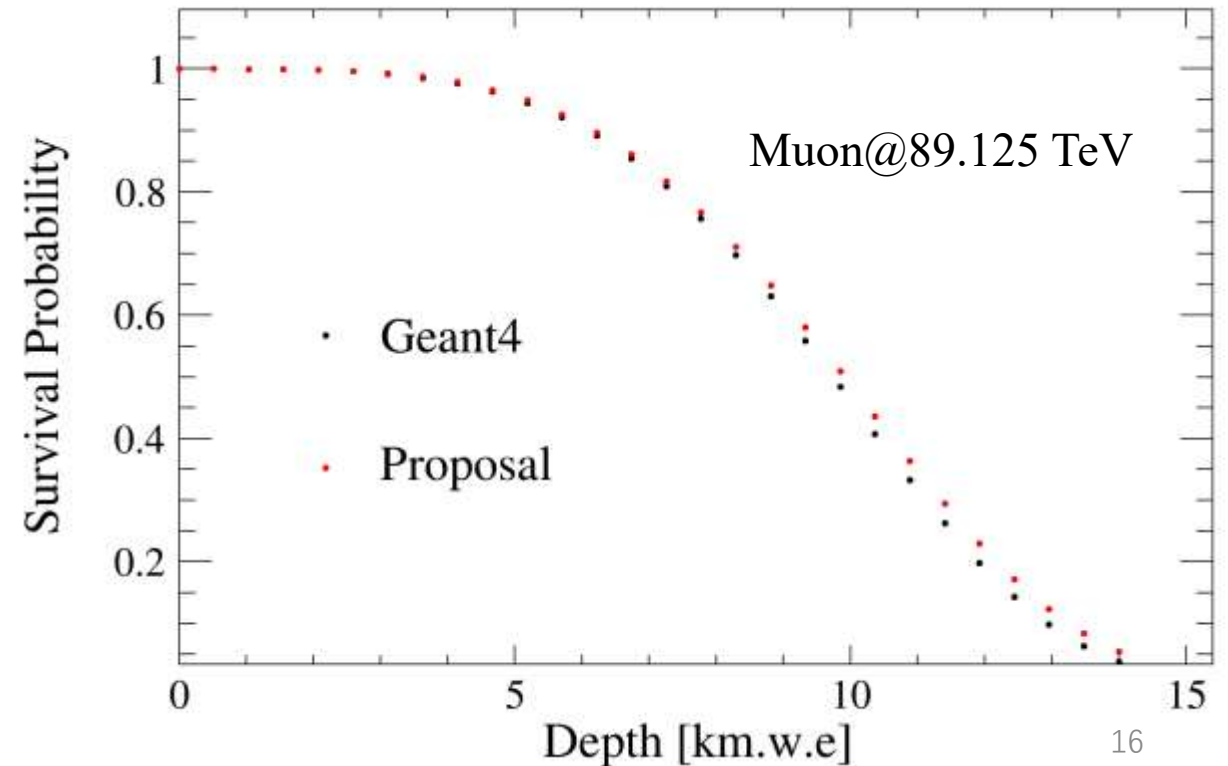
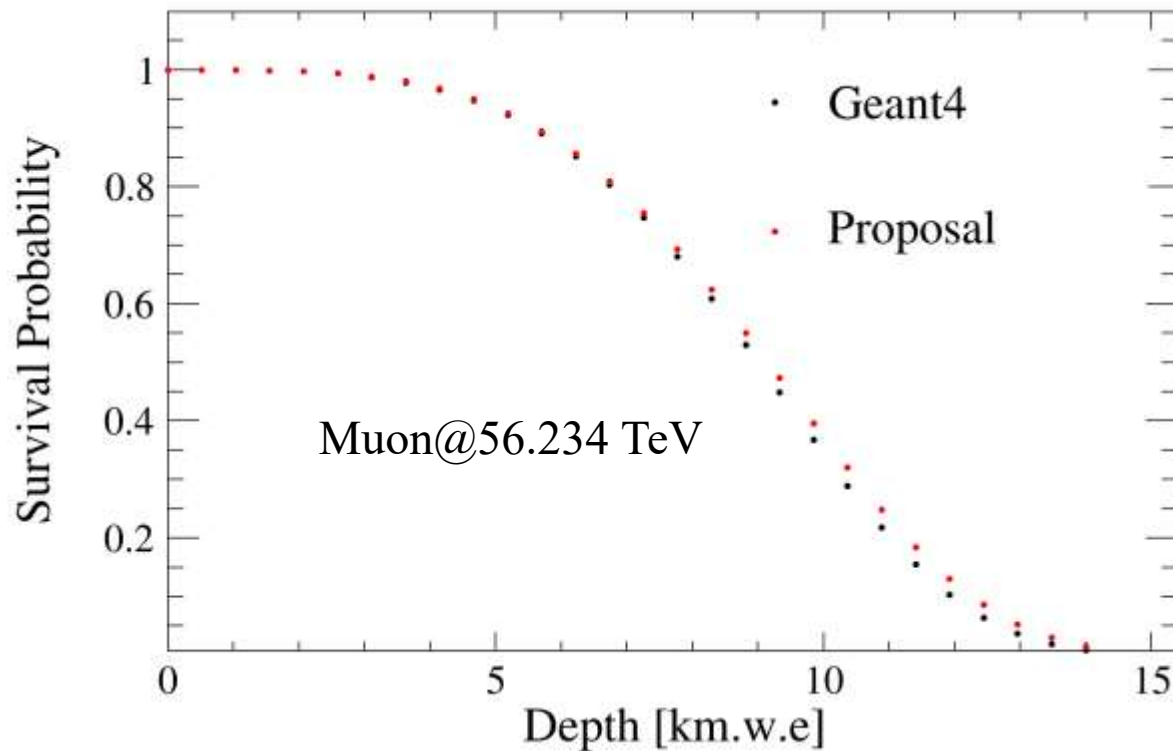
Muon Propagation Comparison

- Consistent for penetrating depth below ~ 6 km.w.e
- Show differences at large penetrating depths



Muon Propagation Comparison

- Consistent for penetrating depth below ~ 6 km.w.e
- Show differences at large penetrating depths



Systematic Uncertainties

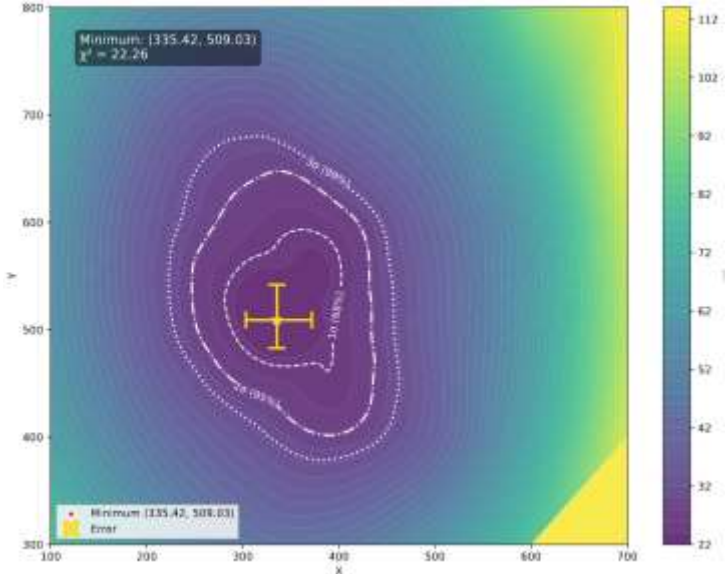
Measurement

Source	Uncertainty	Flux Uncertainty
Energy scale	$\pm 5\%$	$\pm 1.6\%$
	$\pm 1.1\%$	$\pm 0.4\%$
Acrylic vessel radius	± 0.5 cm	$\pm 1.5\%$
Lead shielding thickness	± 5 cm	$\pm 0.2\%$
Rock thickness	± 50 cm	$\pm 0.7\%$
Physical model	$\pm 50\%$	$\pm 0.5\%$
Muon generator		$\pm 0.2\%$
Latitude and longitude	± 100 m	$\pm 1.1\%$
Elevation	± 100 m	$\pm 0.6\%$
Total		$\pm 2.2\%$

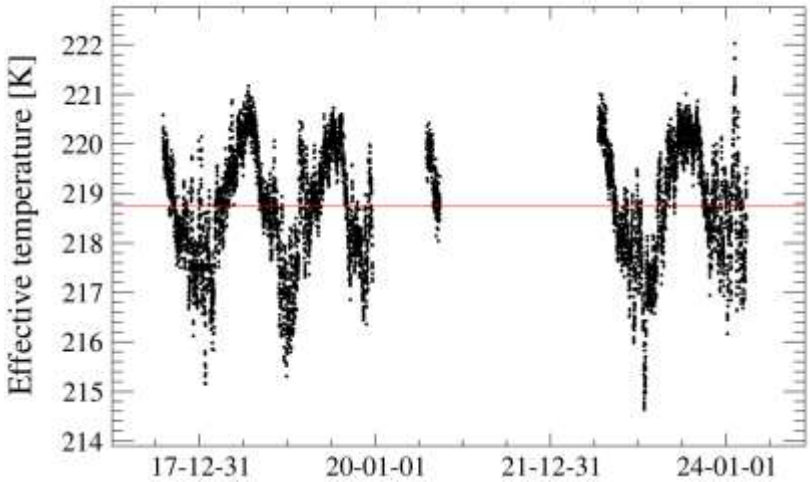
Efficiency

Effective area

Prediction



Position-induced

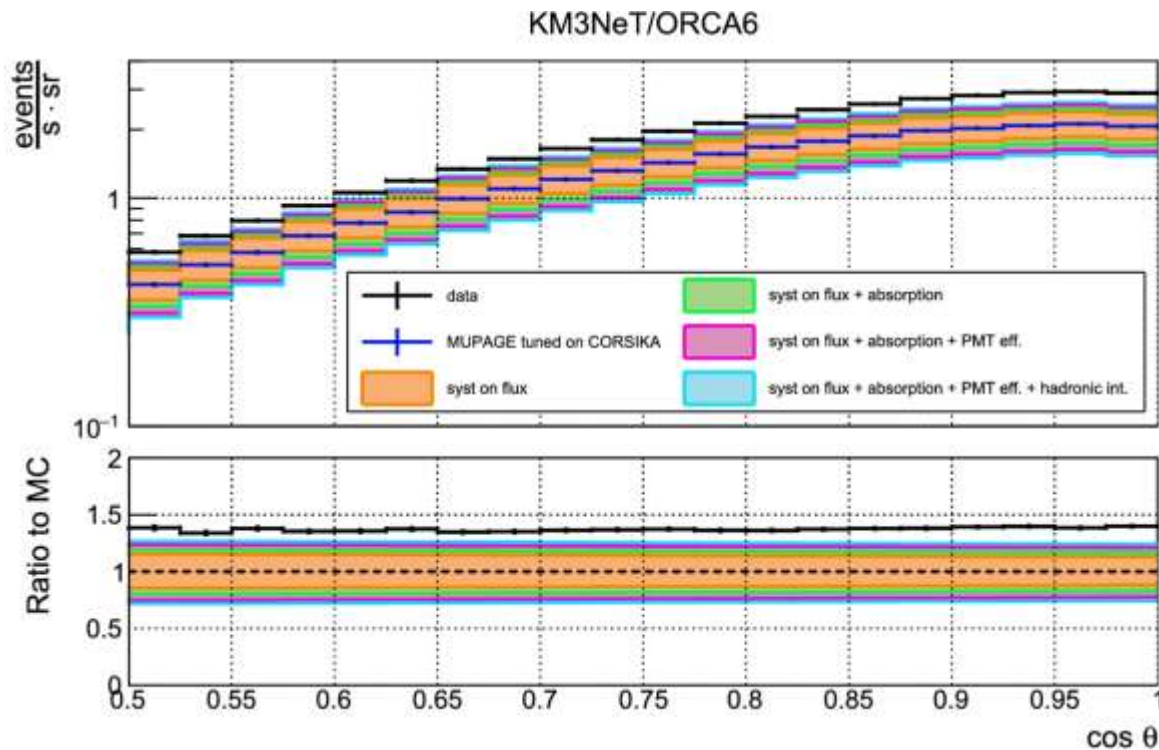


Seasonal variation

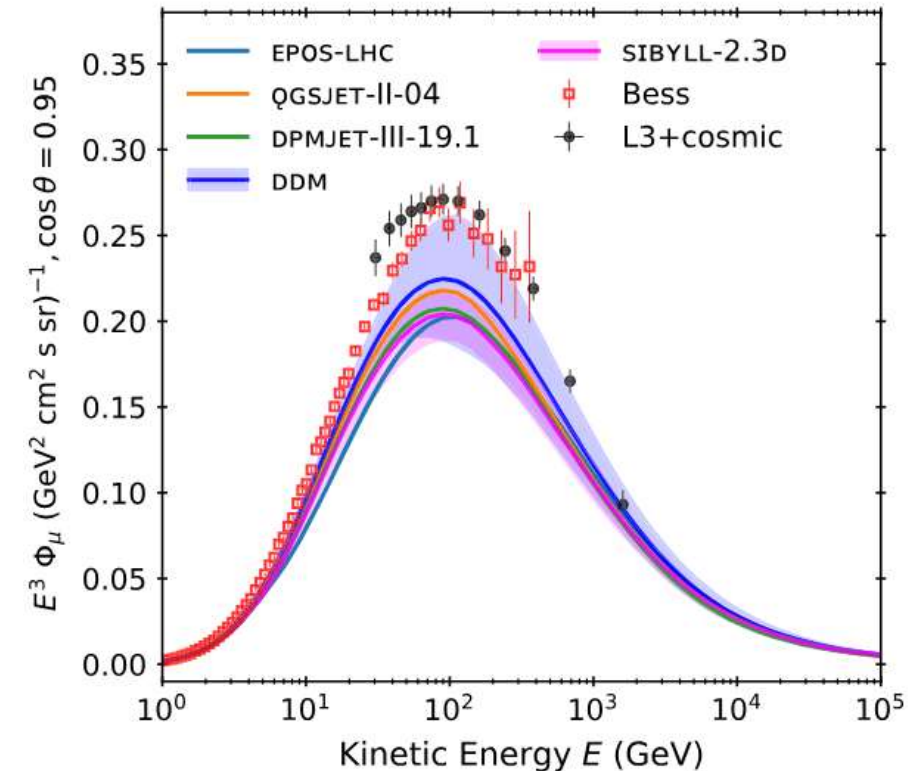
Other Experiments

- The similar discrepancy for **sub-TeV** muons is also reported in other experiments:
 - Underwater telescope: KM3NeT
 - Ground-based spectrometer: Bess and L3+cosmic

Eur. Phys. J. C 84, 696 (2024)



Astrophys. J. 928,27 (2022)



Interaction Height

- The interaction height is sensitive to the mass composition and nearly independent on the energy of cosmic-ray.
- Based on the direction of TeV-muons, this parameter can be reconstructed to infer the mass composition.

