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

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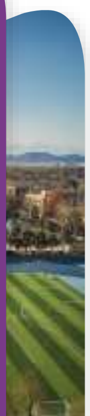


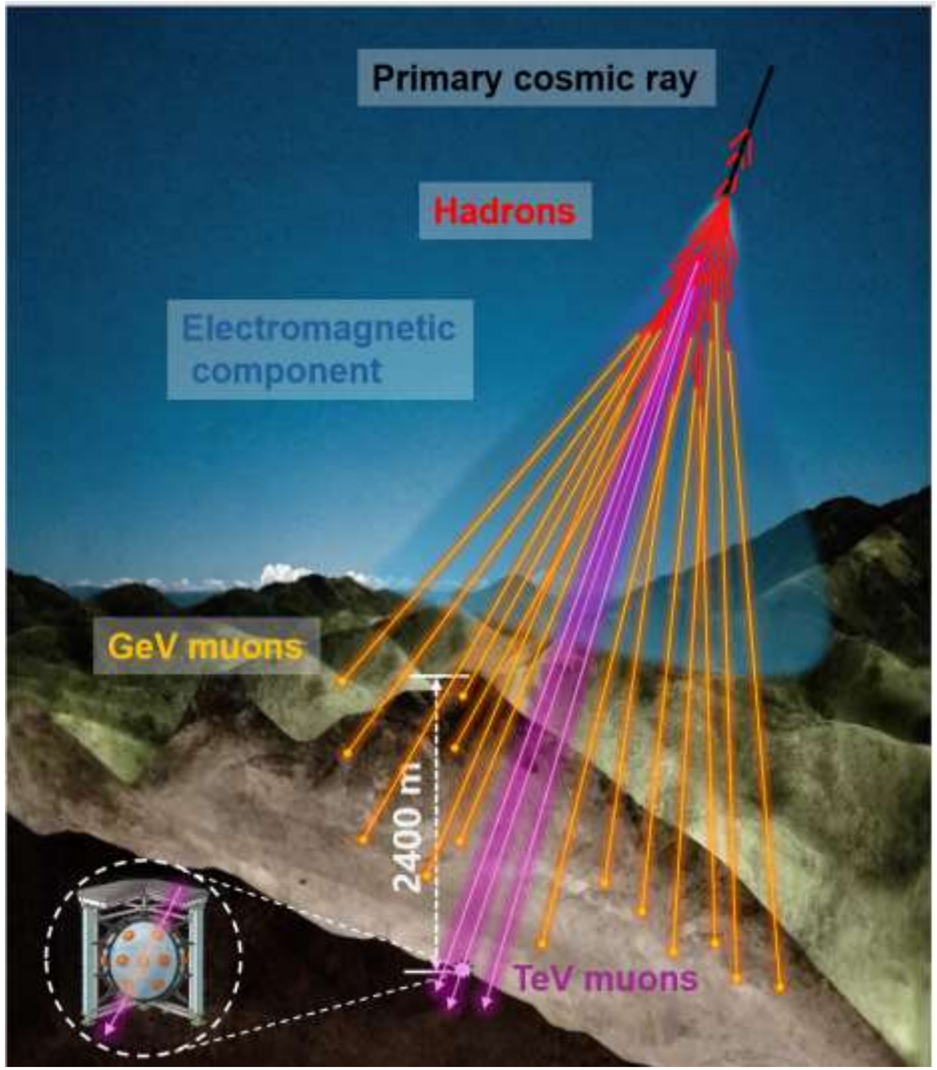
Muon Production in Air Shower

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

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

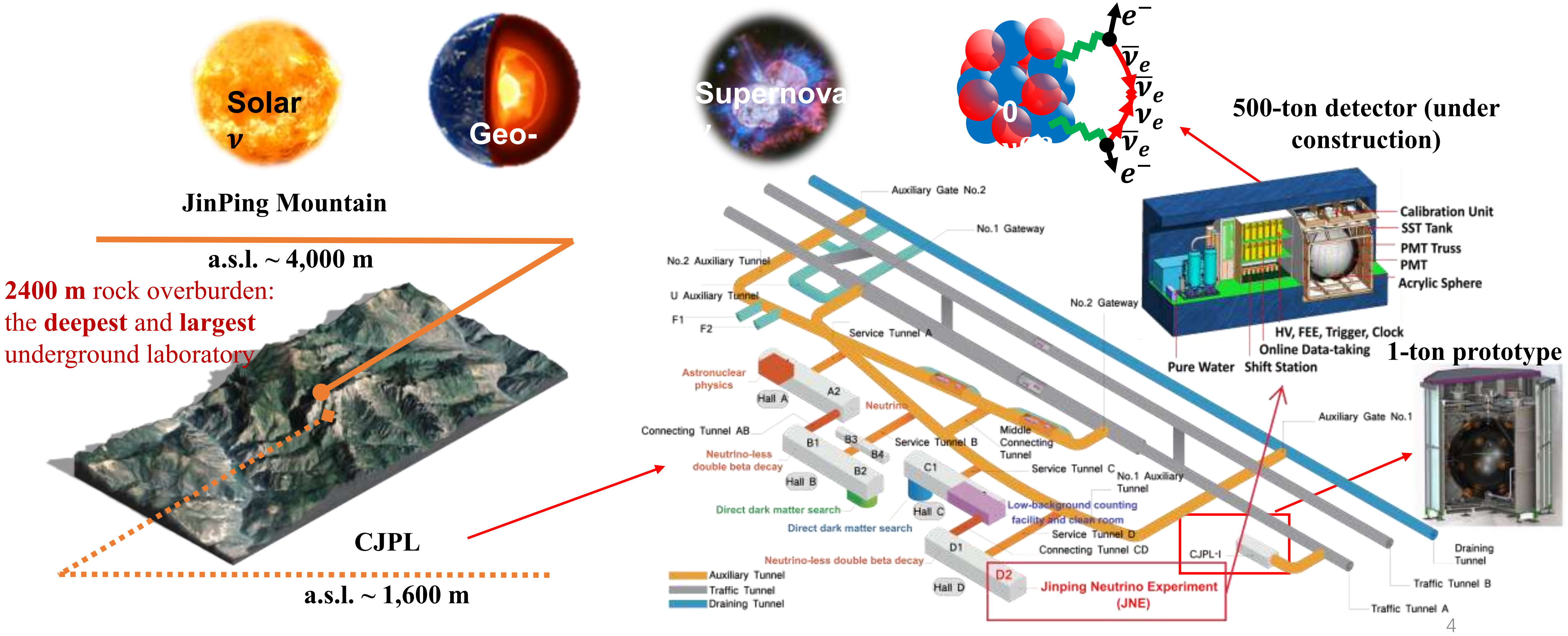
- Only TeV-muons can penetrate the rock overburden and arrive at underground laboratory.

- 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).

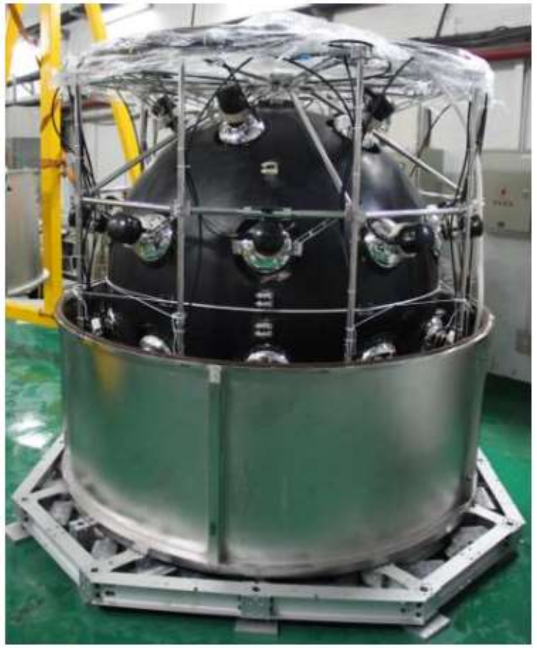


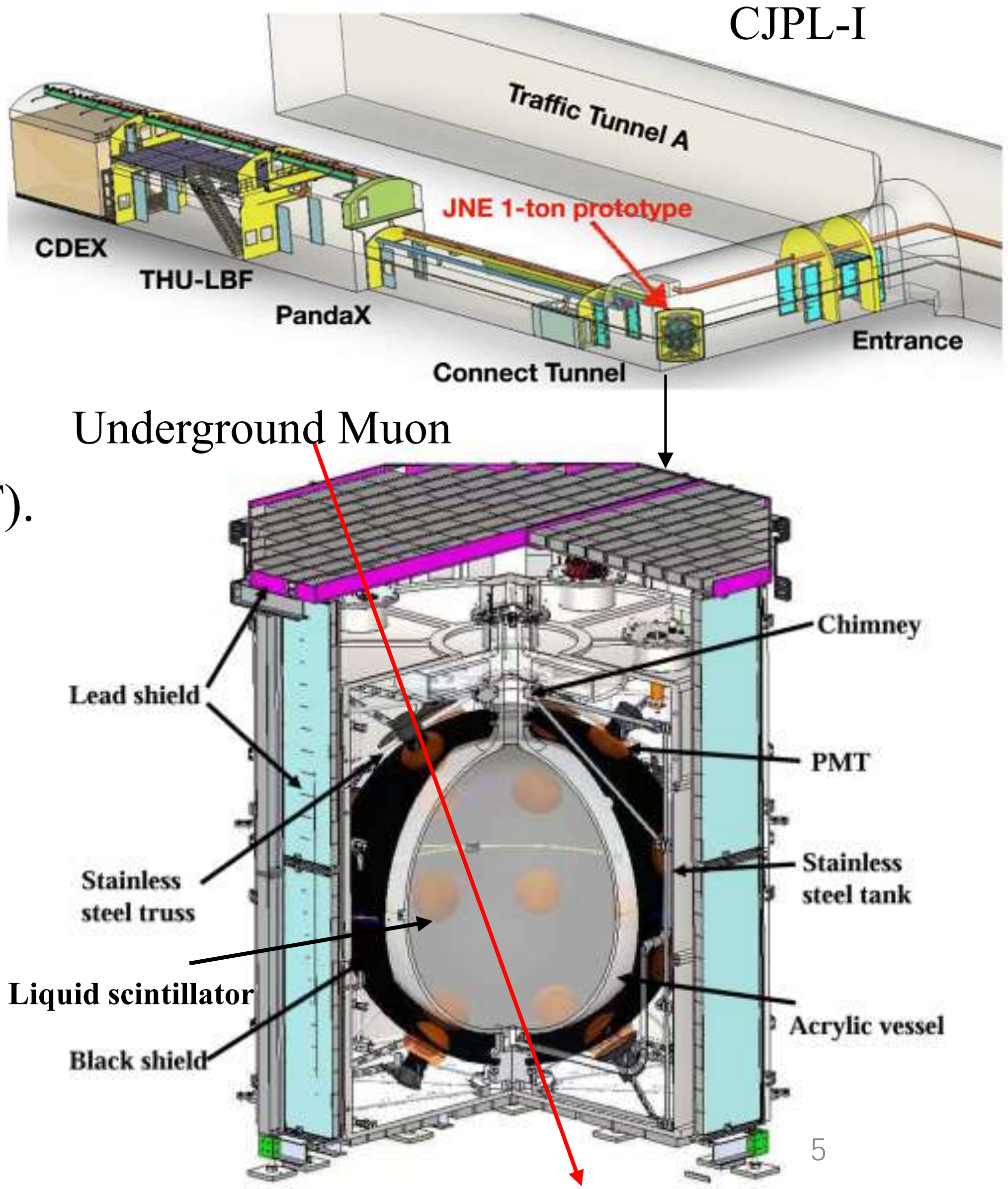
The One-ton Prototype Detector

- 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).



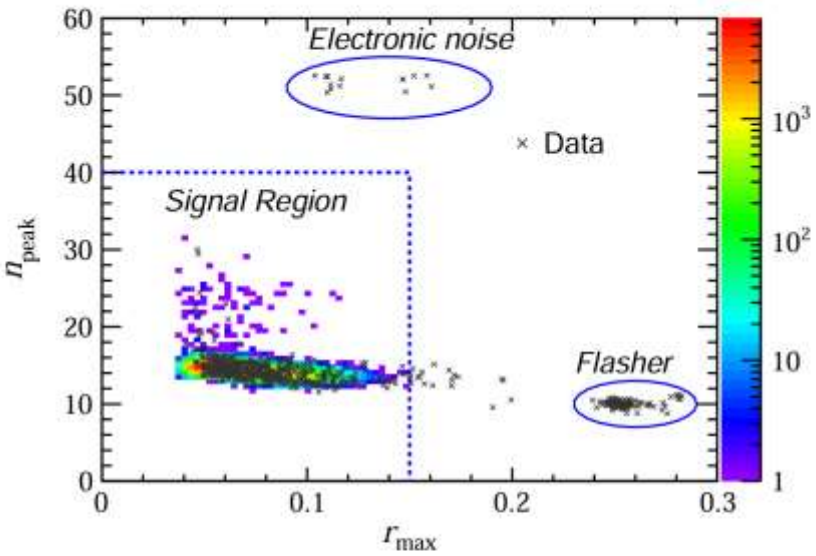


Muon Data and Flux Measurement

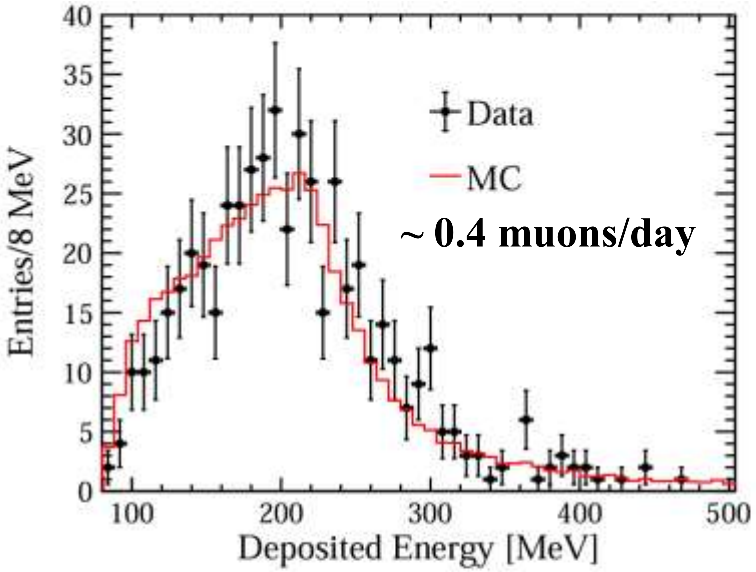
- The data were collected from July 31, 2017, to March 27, 2024, with 1338.6 days effective live time.
- A full-simulation is processed based on Geant4 for estimations of efficiencies and effective area.
- The underground muon flux at CJPL-I is measured as

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

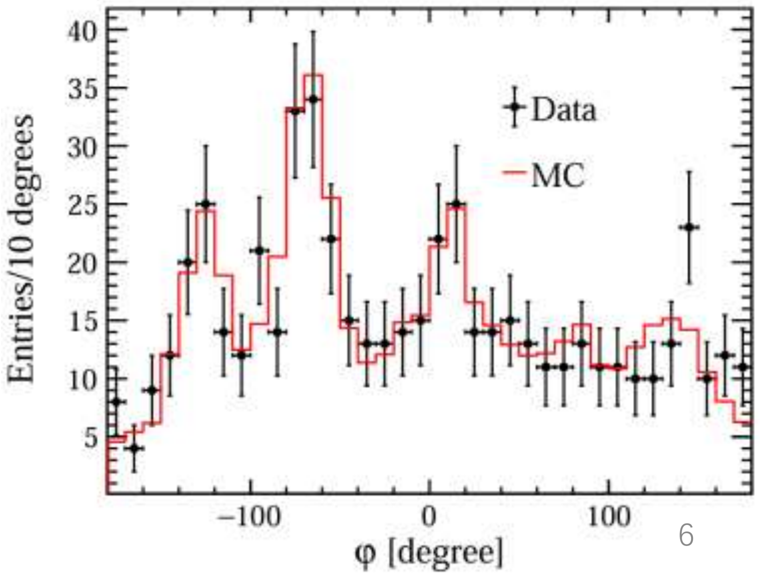
Muon signal selection



Reconstructed deposited energy

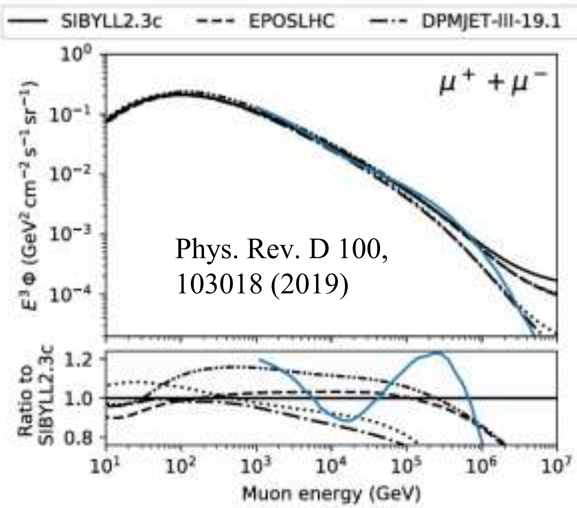


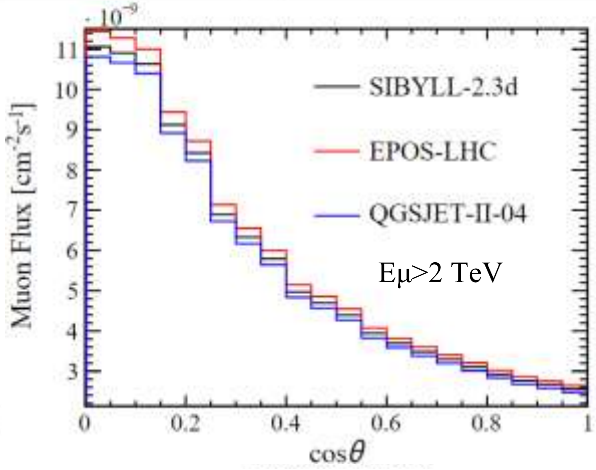
Reconstructed direction

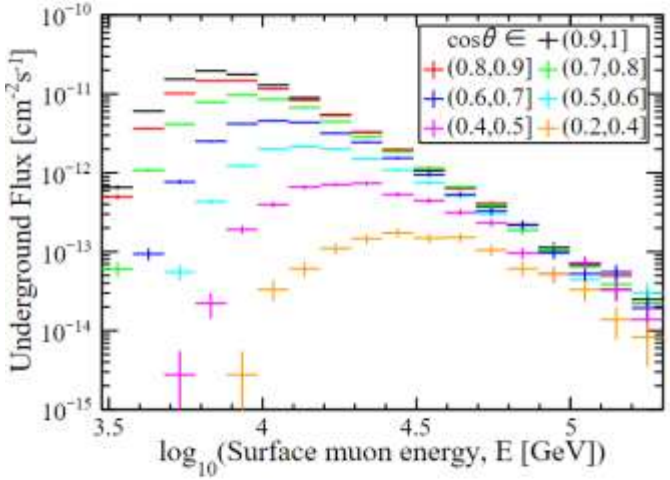


Underground Muon Flux Prediction

Cosmic ray+Hadronic model+MCEq package→Surface muon



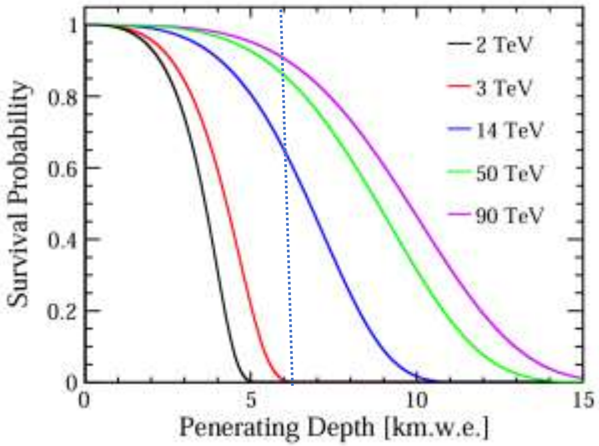


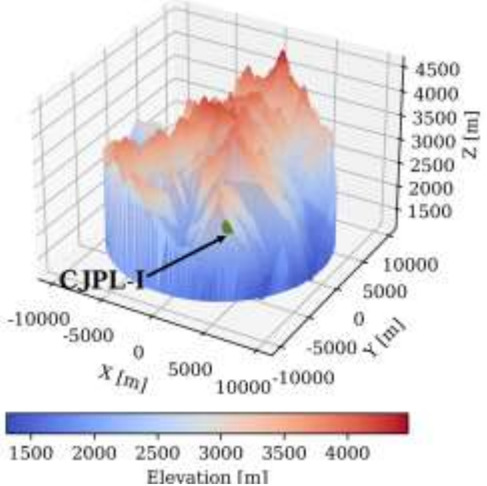


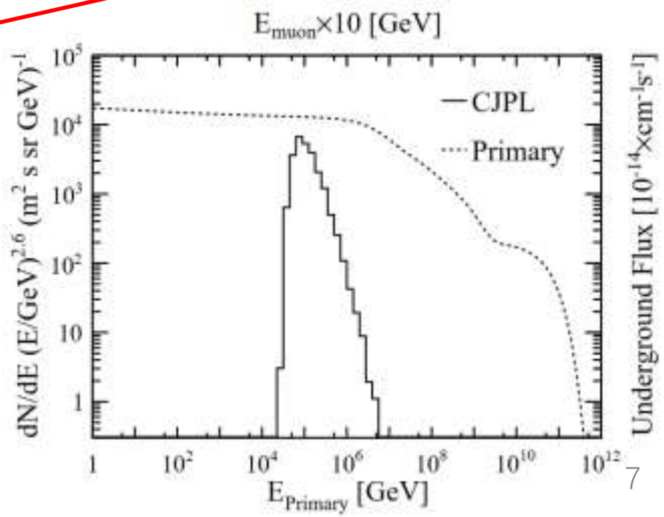
$$\text{Underground}: \phi_\mu = \int \phi_s(E,\theta,\varphi)P(E,X(\theta,\varphi))dEd\Omega$$

Mountain model+Geant4 simulation→Survival probability

Threshold: 3 TeV





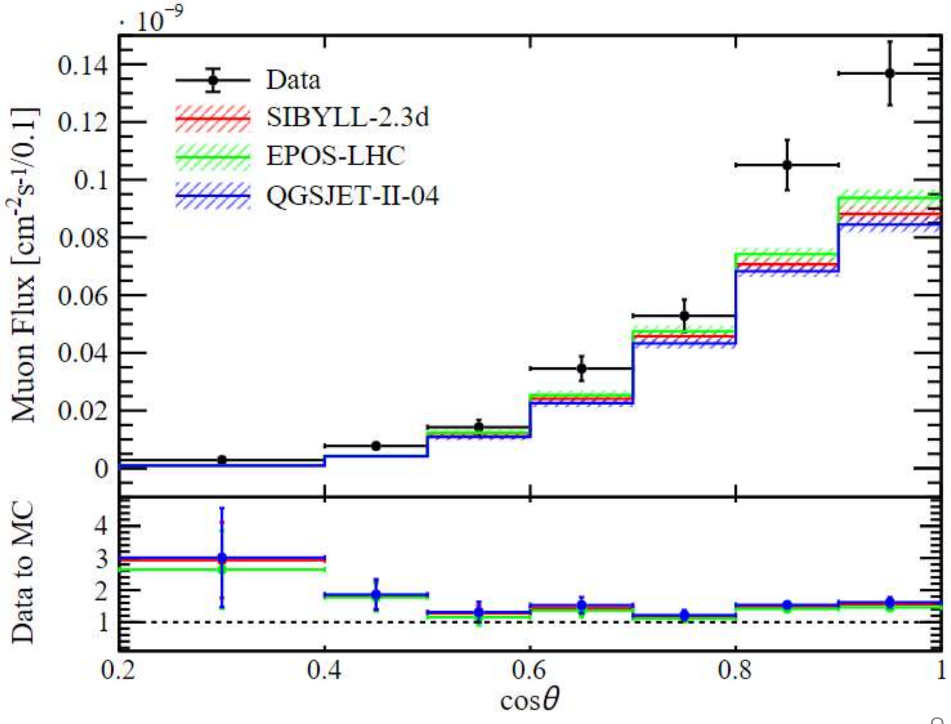


Comparisons

- 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

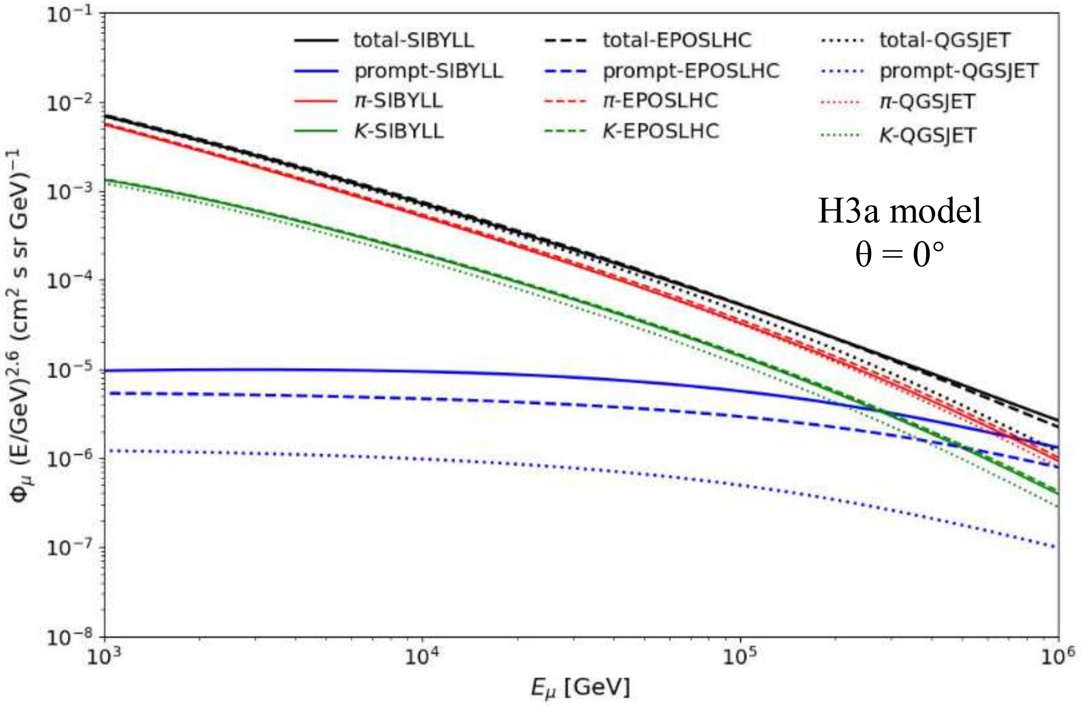
Model	Flux ratio	Excess significance
SIYBLL-2.3d	1.44±0.07	6.0σ
EPOS-LHC	1.38±0.07	5.5σ
QGSJET-II-04	1.51±0.08	6.7σ

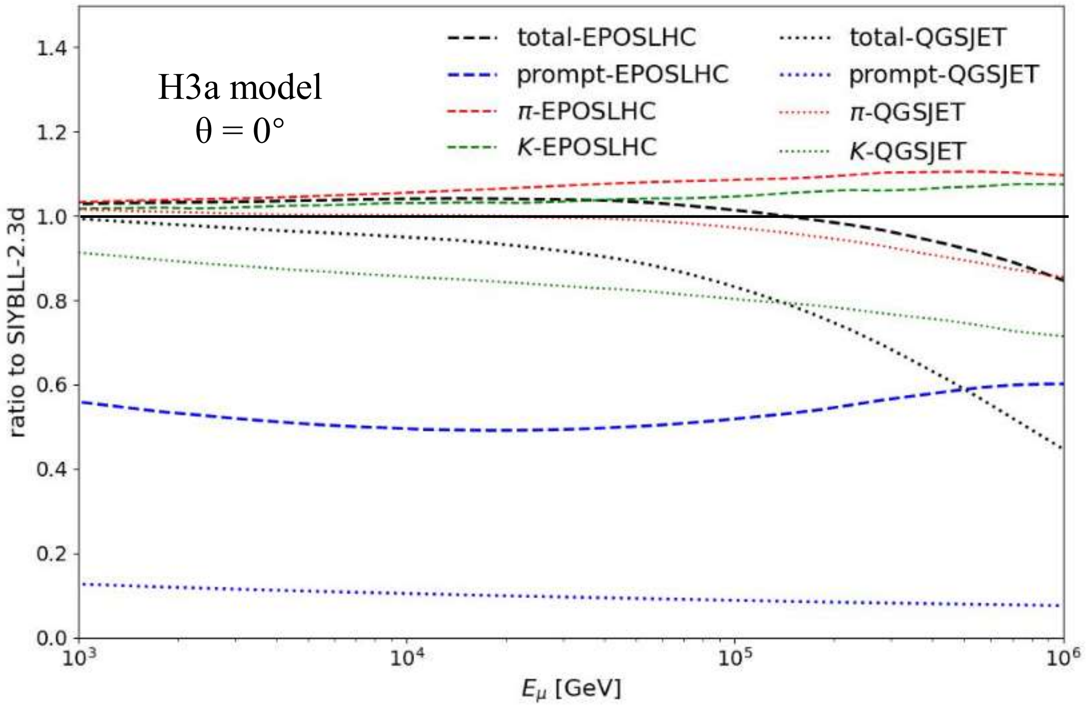


Similar excess observed by KM3NeT, Bess and L3+cosmic, but the intensity is different.

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 (enhanced multiplicity in hadronic interactions).

  - 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**.

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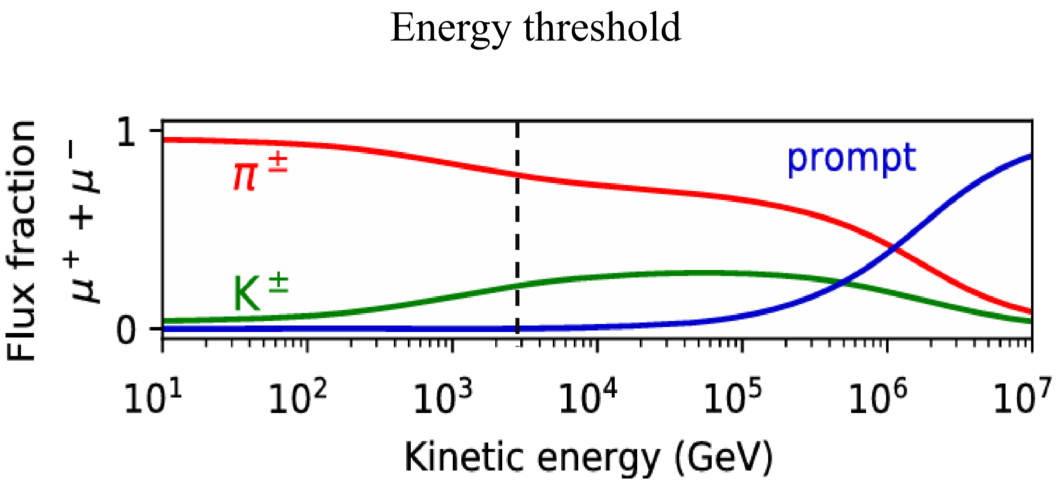


Probability to produce TeV-muon; Particle mass; Interaction length

$$R = \frac{P_{K^\pm}}{P_{\pi^\pm}} = \frac{b_{K^\pm}}{b_{\pi^\pm}} \cdot \frac{m_{K^\pm}}{m_{\pi^\pm}} \cdot \frac{\tau_{\pi^\pm}}{\tau_{K^\pm}} \times \frac{\lambda_{int,K^\pm}}{\lambda_{int,\pi^\pm}} =$$

~5 for $K^\pm$

~60000 for D^+

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 leading hadronic interactions models. **About 40% discrepancies** are observed. Some potential origins are discussed.

- The latest hadronic models 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 understand these discrepancies, including flux seasonal variation, muon charge ratio and polarization, direction anisotropy, and etc.

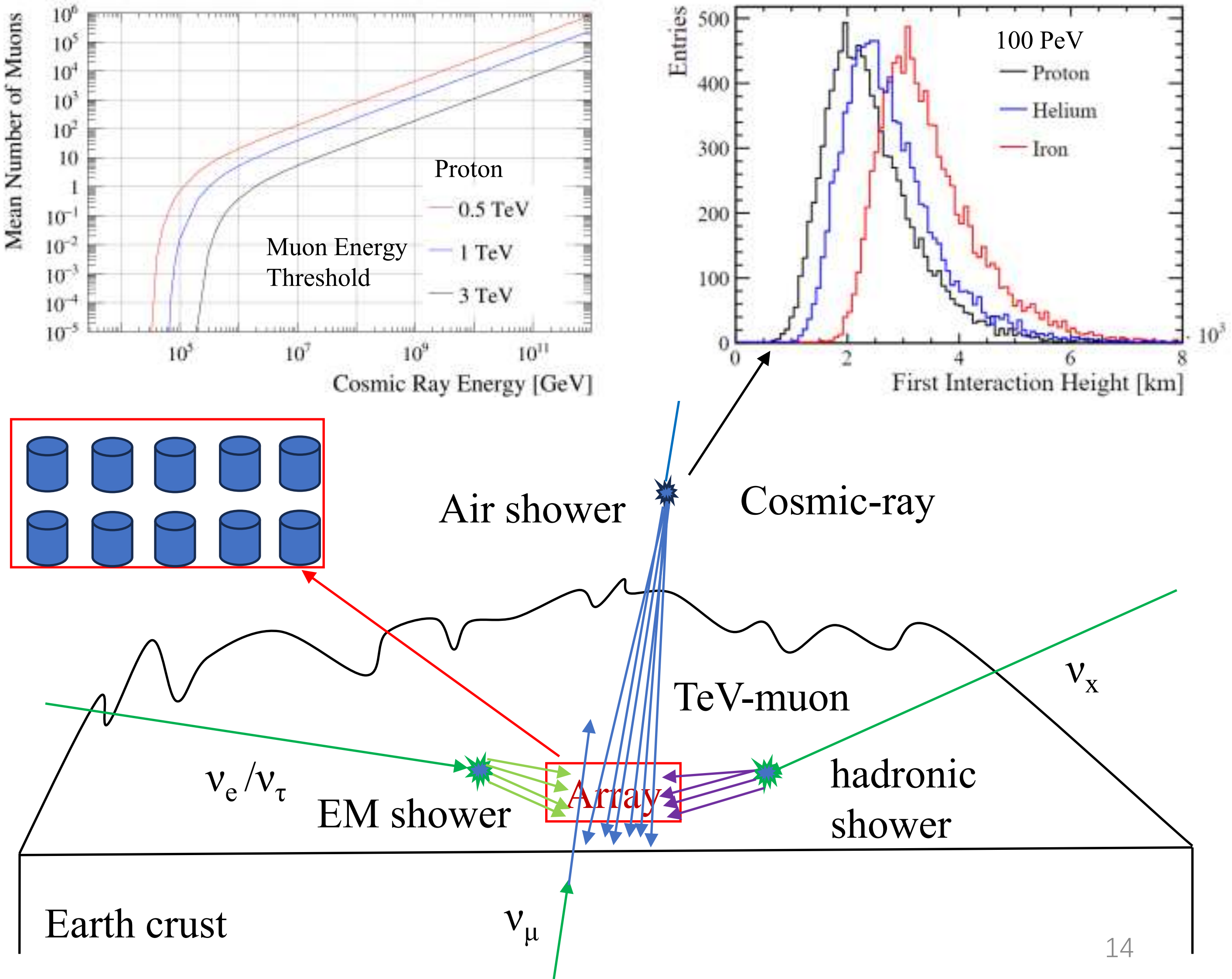

Thanks for Listening

Backup

Physical Potential of an Underground Array

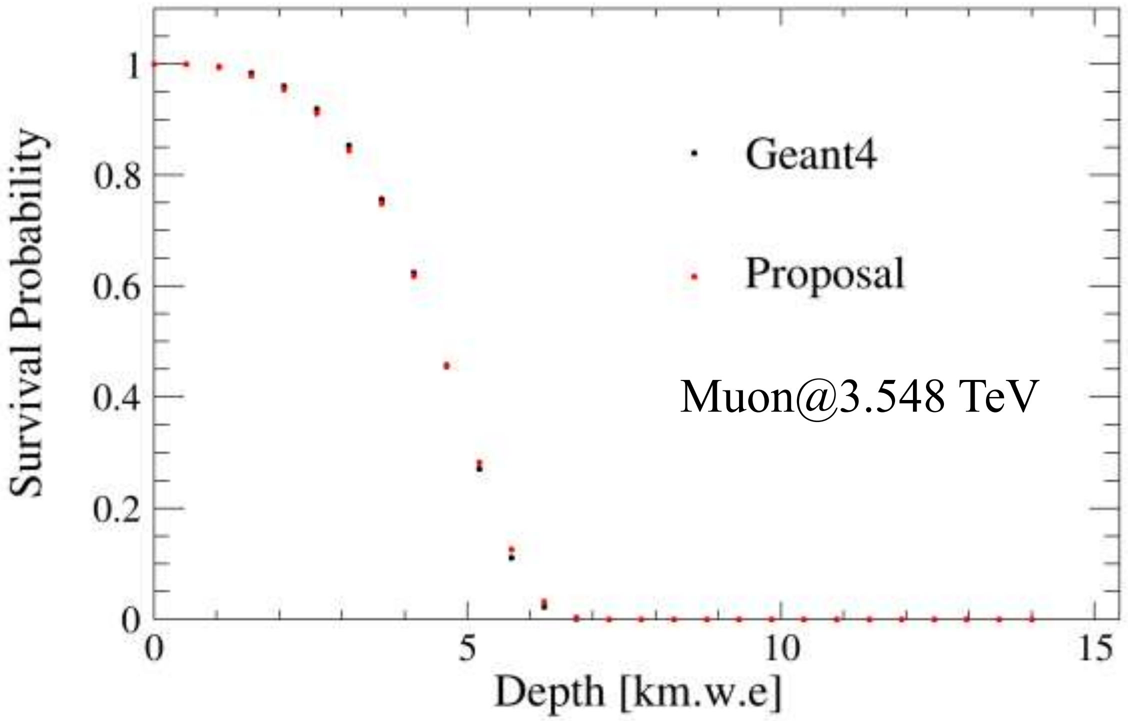
Corsika7.7550

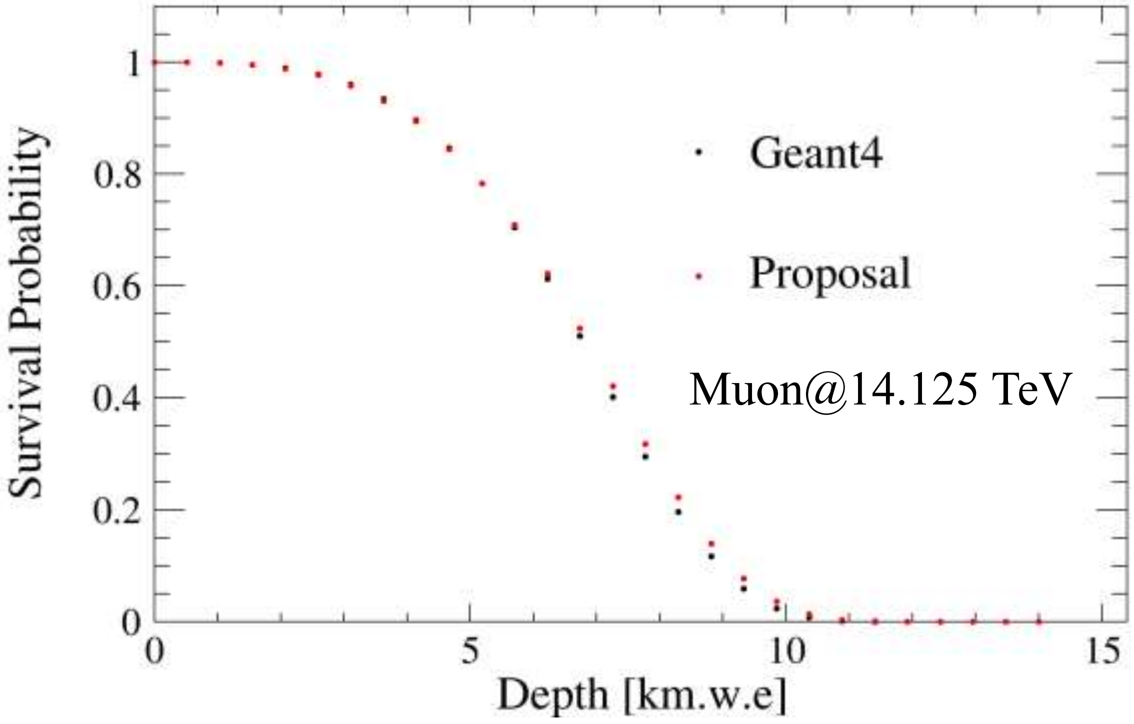
- An underground array of similar detectors:
  - Interaction vertex reconstruction
  - Particle identification
- Cosmic-rays:
  - Particle: TeV-muons in shower
  - Energy: 10 PeV to EeV and above
  - More information about shower
- Atmospheric and astrophysical neutrinos:
  - Interact with **local rock 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 blow ~6 km.w.e
- Show differences at large penetrating depths





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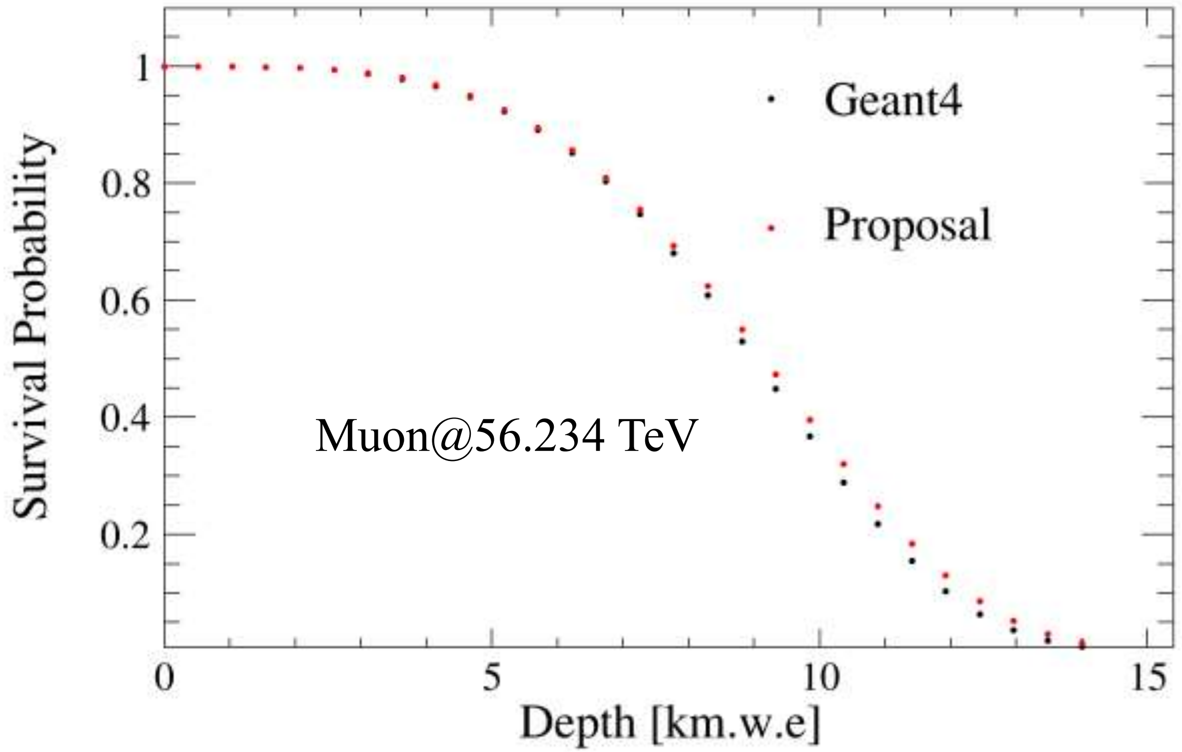
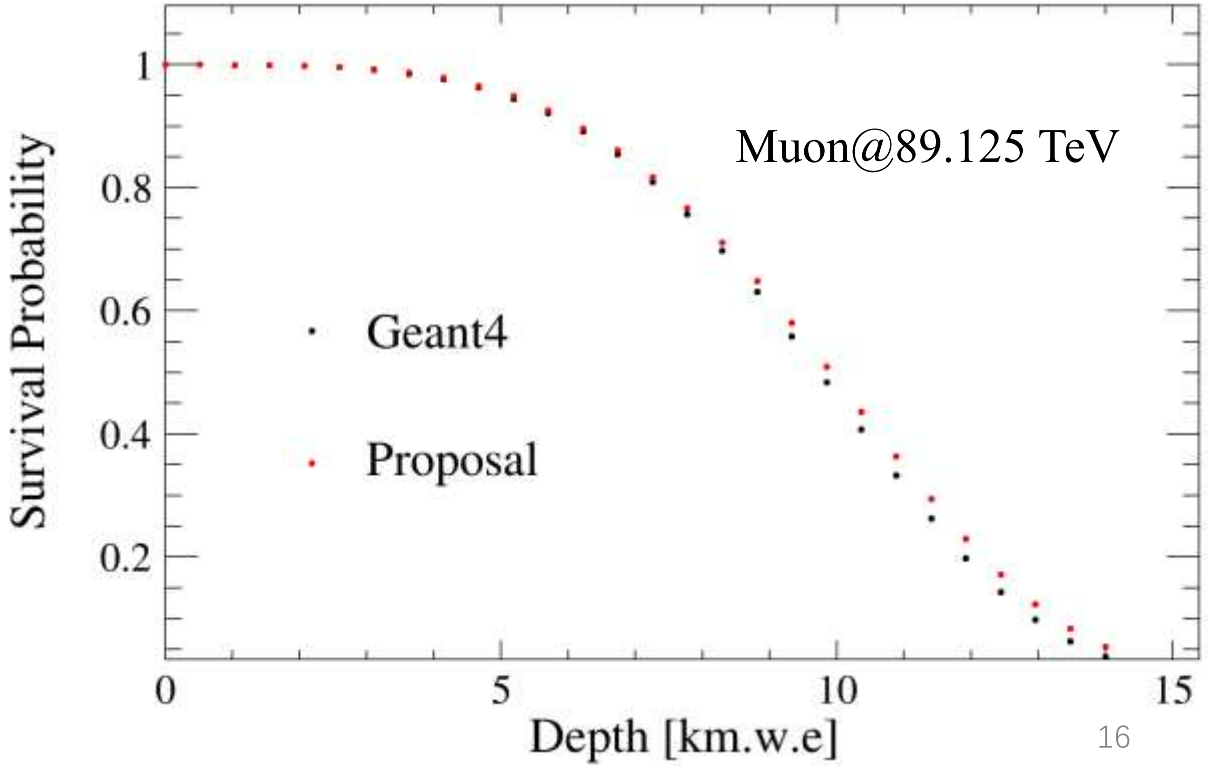


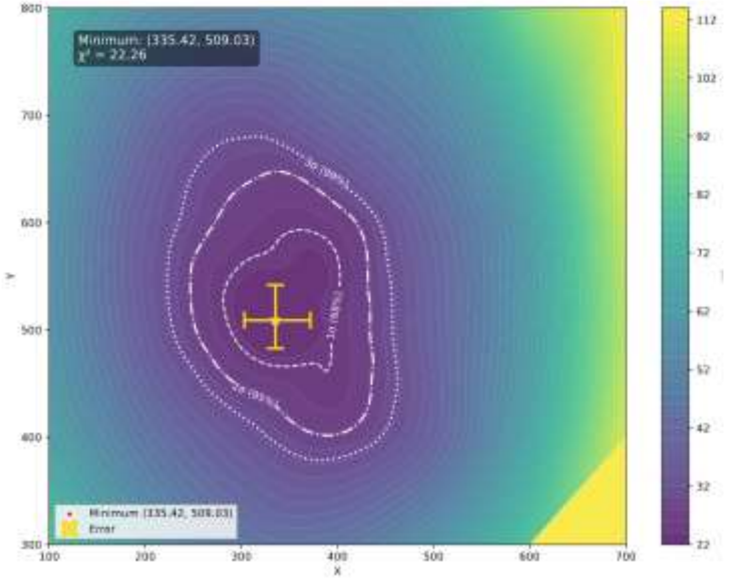


Systematic Uncertainties

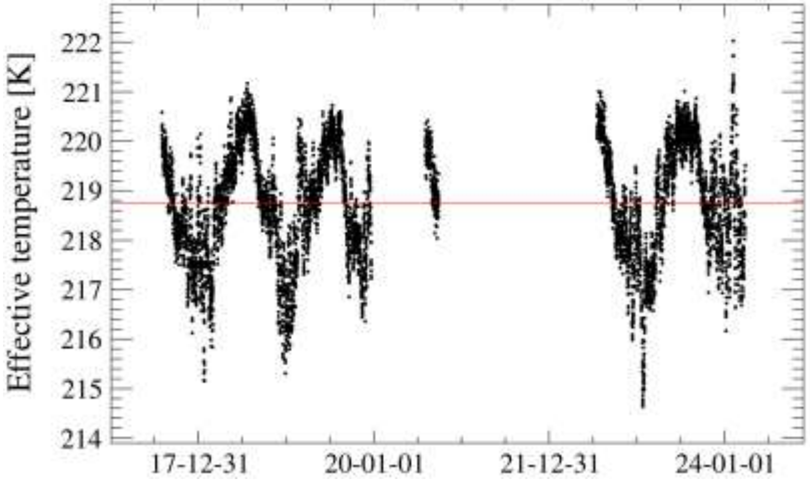
Measurement

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

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

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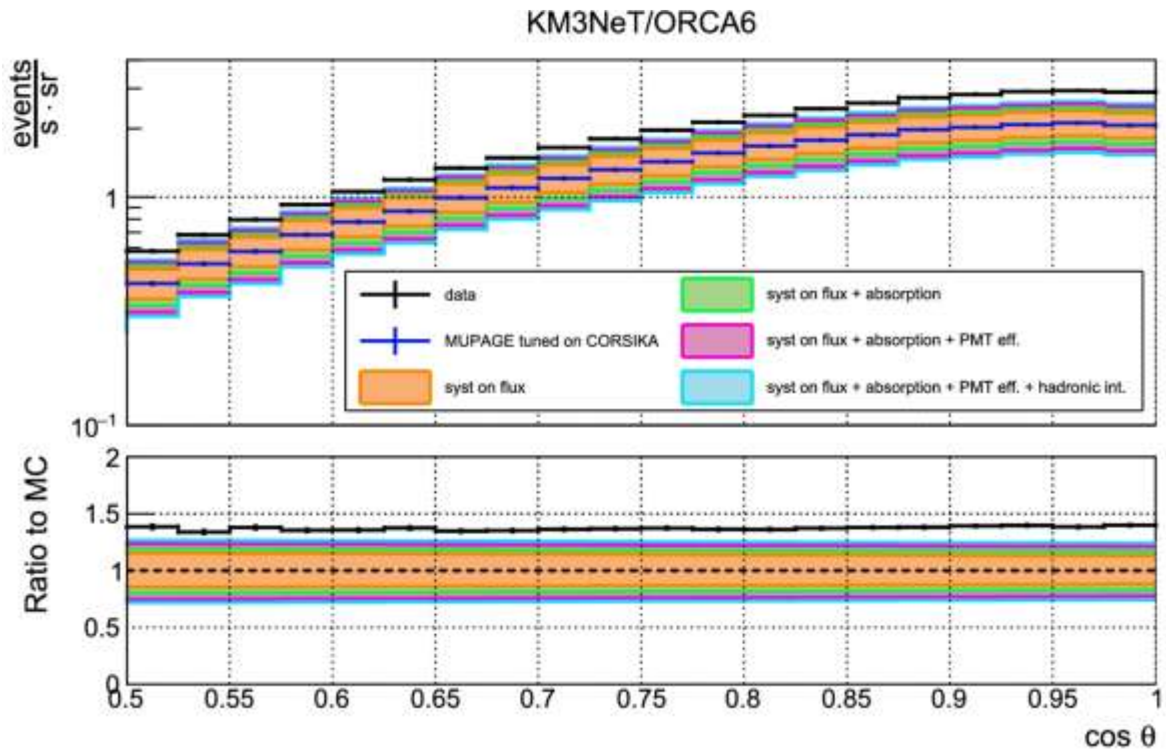

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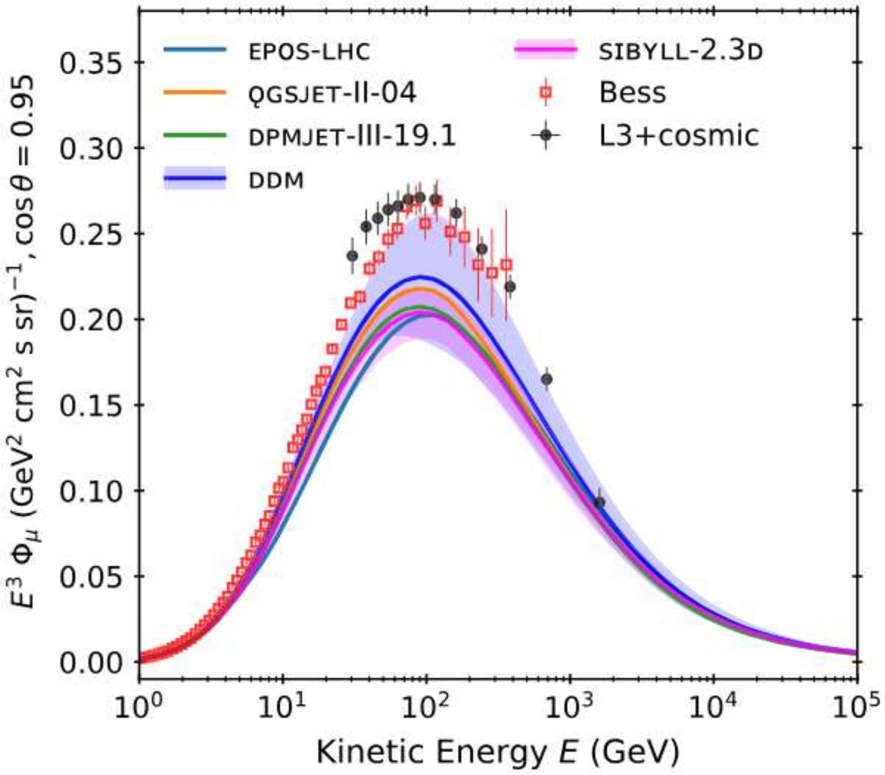

Interaction Height

- 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.