清華大學
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JINPING NEUTRINO EXPERIMENT

Investigating TeV-scale muons in Air Shower at Depth of 2400 Meters Underground

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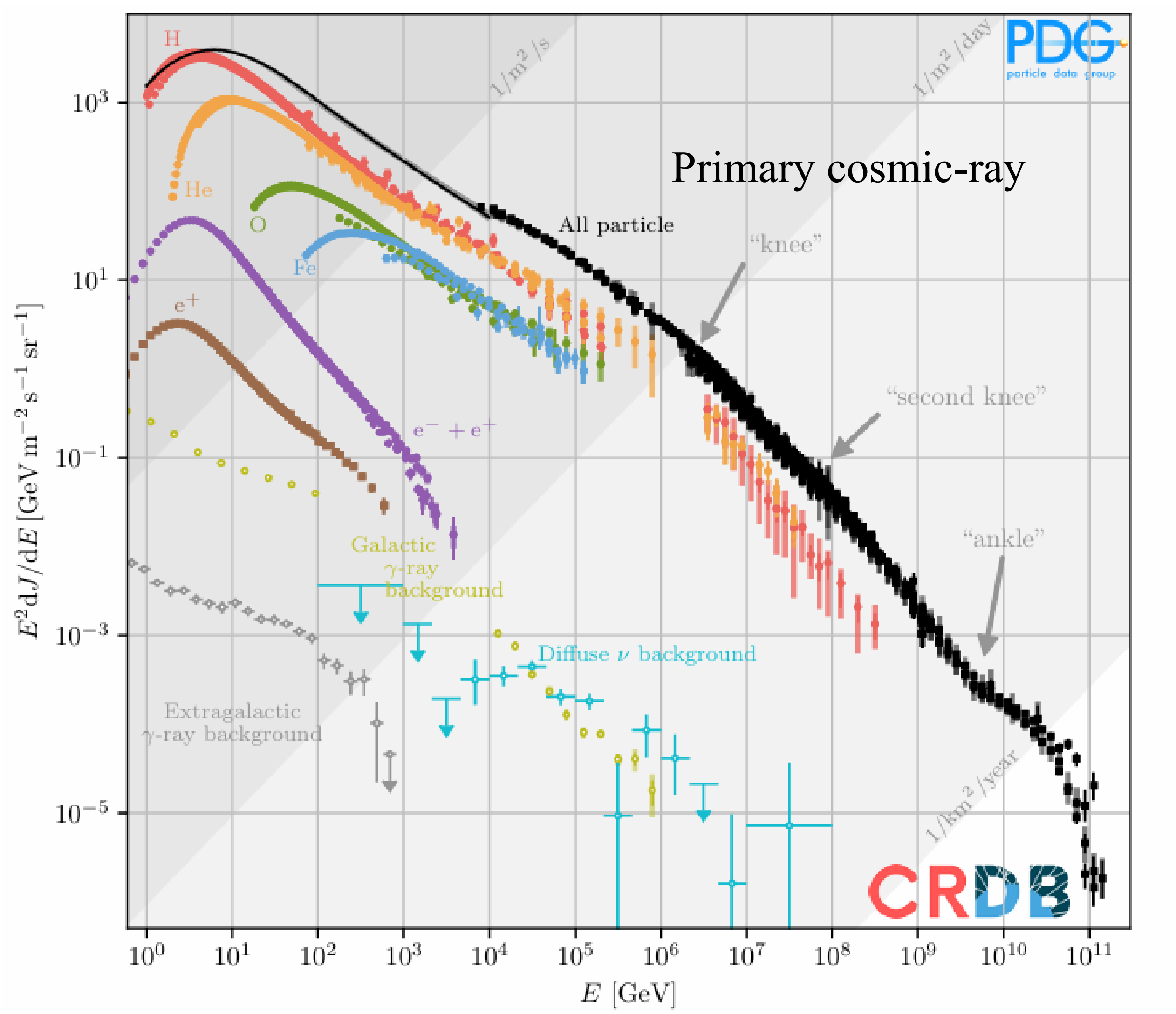
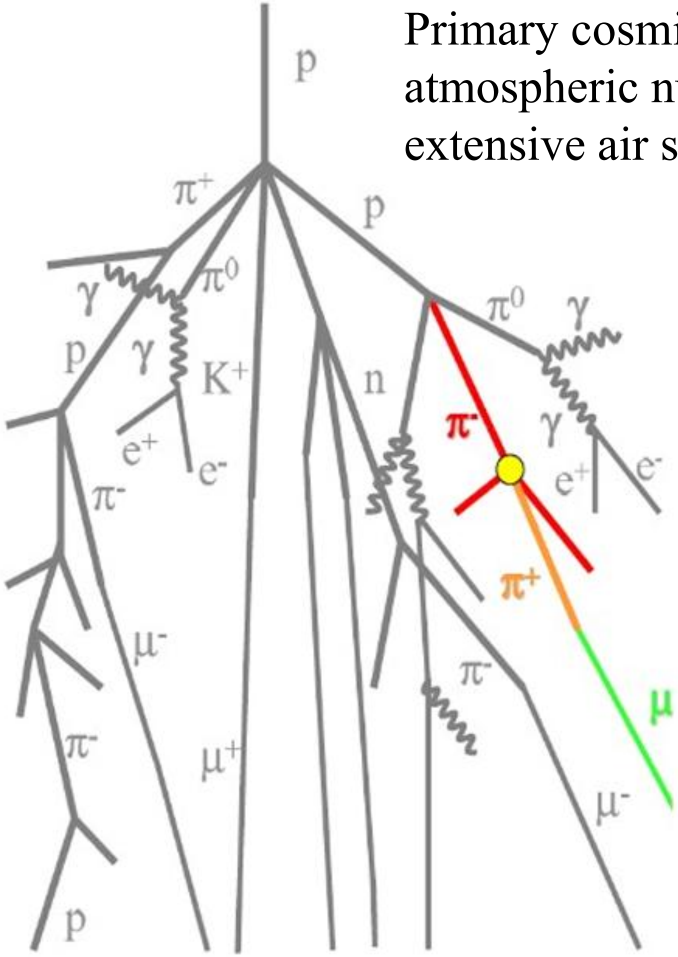
Introduction

Extensive Air Shower



Primary cosmic-rays interact with atmospheric nuclei, generating extensive air shower.



From R. Ulrich (KIT)

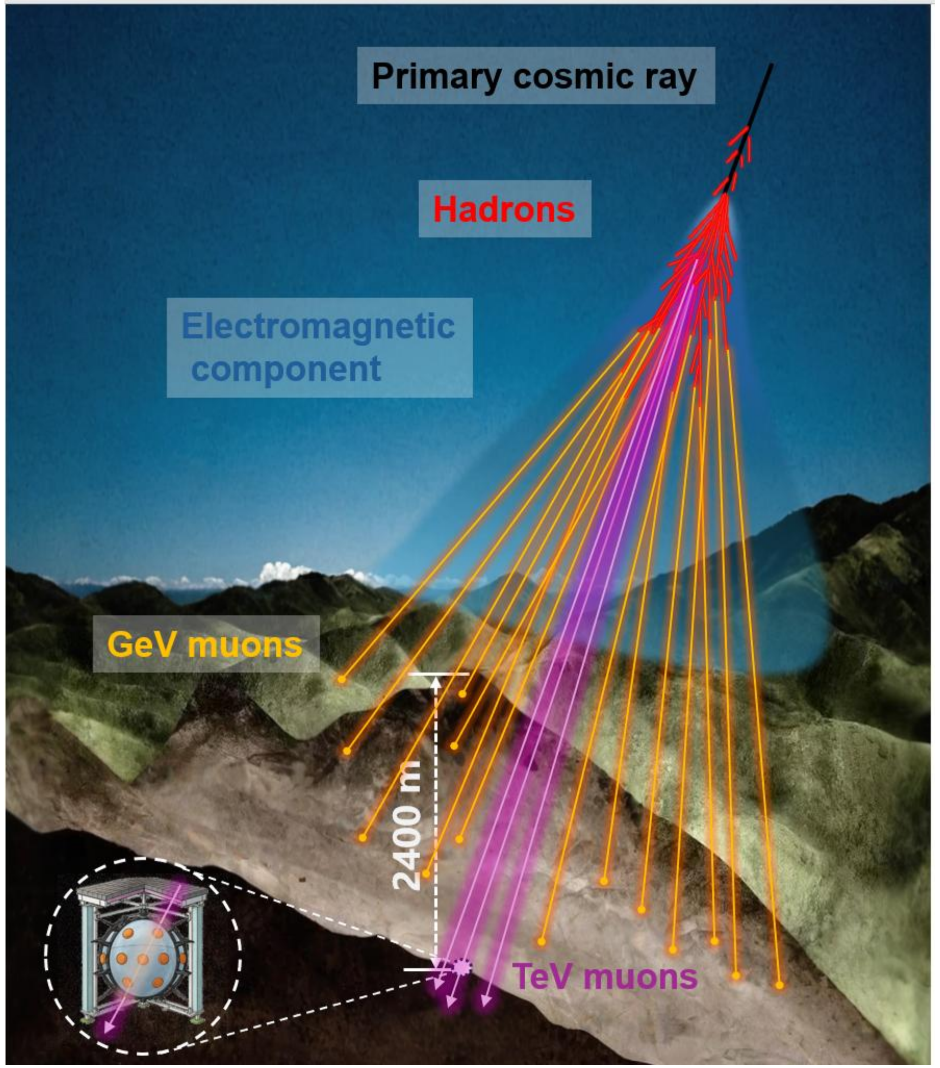
Underground Muons

- When shower stops at final stage, mesons with GeV energies decay and GeV-muons are produced, which can reach at the Earth surface.

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

- In contrast, only TeV-muons from rara decays of high-energy mesons can penetrate the rock overburden and arrive at underground laboratory.

- Such mesons 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



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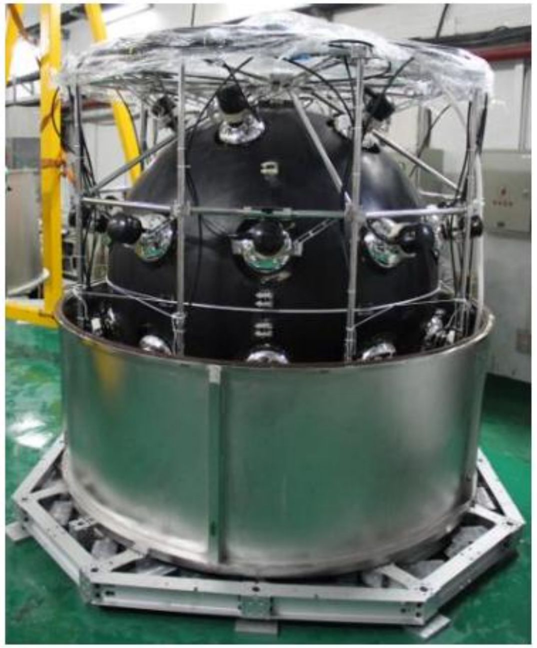
Method

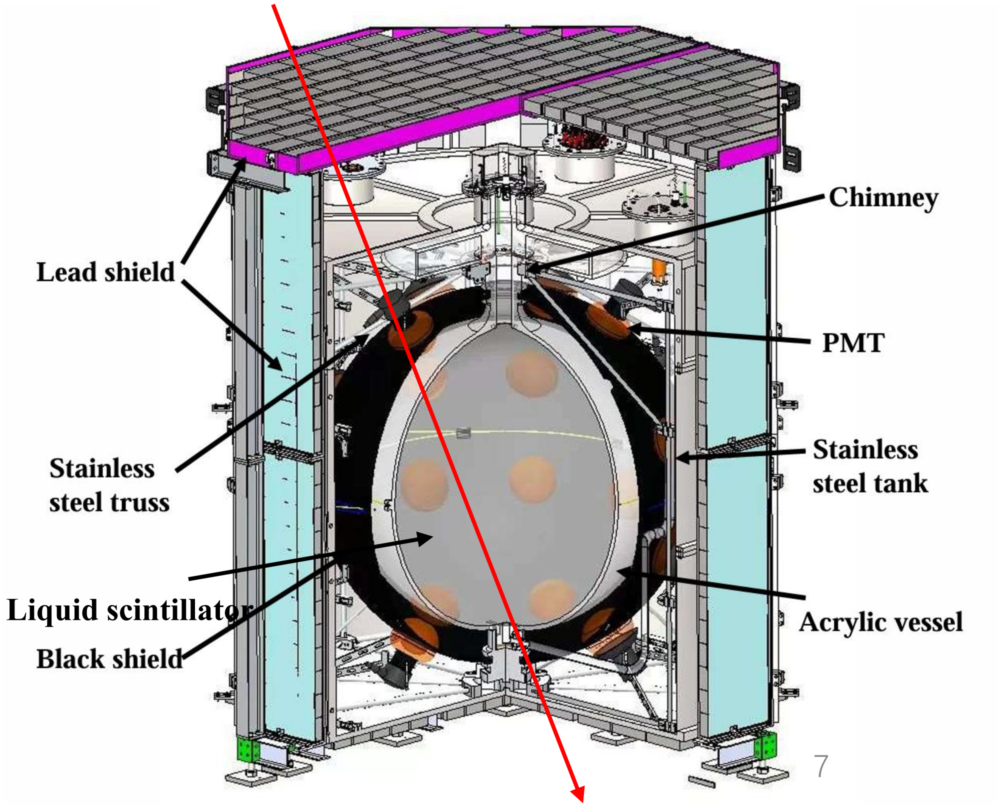
The One-ton Prototype Detector

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

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



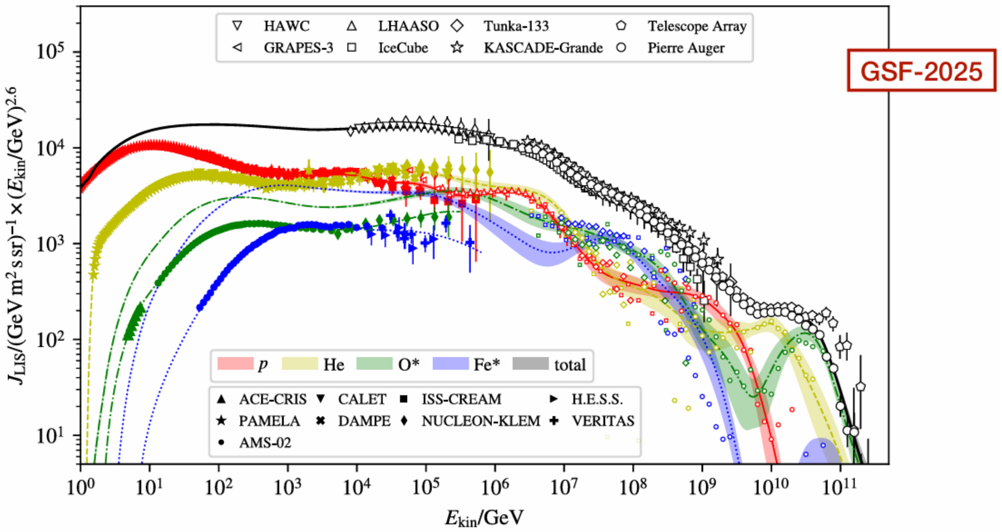
Underground Muon



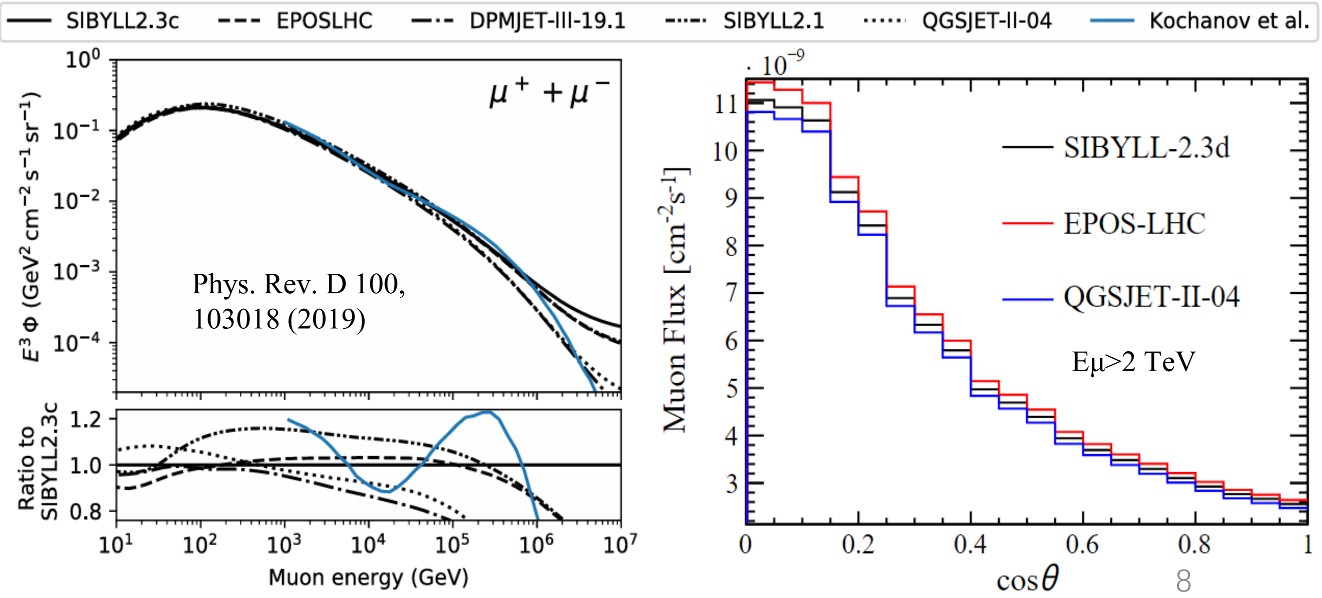
Simulation Framework: Surface

- MCEq: numerical solution of coupled cascade equations

- Inputs:
  - Cosmic ray: Global Spline Fit model
  - Hadron interaction: post-LHC models

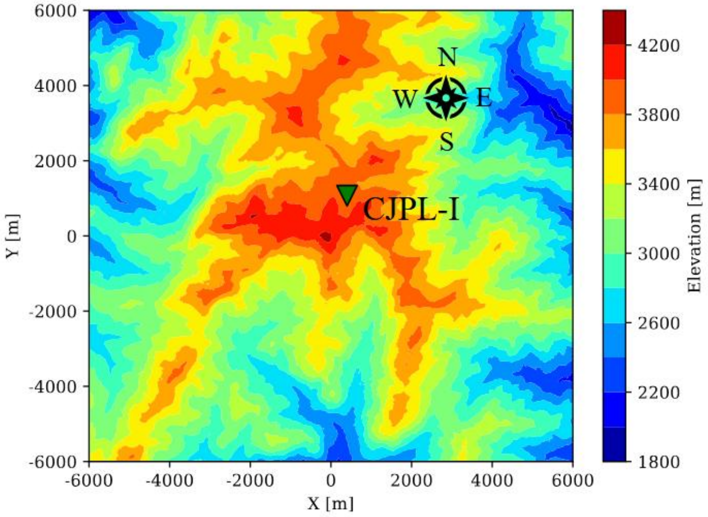


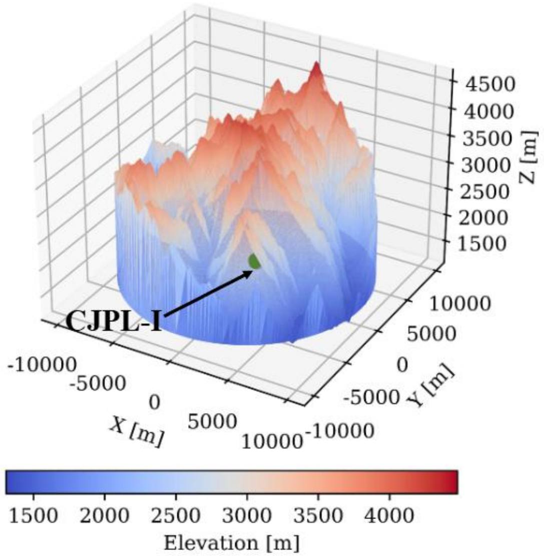
$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}\left(\mu(E)\Phi_h(E,X)\right) + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{int},l}(E_\ell)} + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N^{\mathrm{dec}}_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{dec},l}(E_\ell,X)}$$

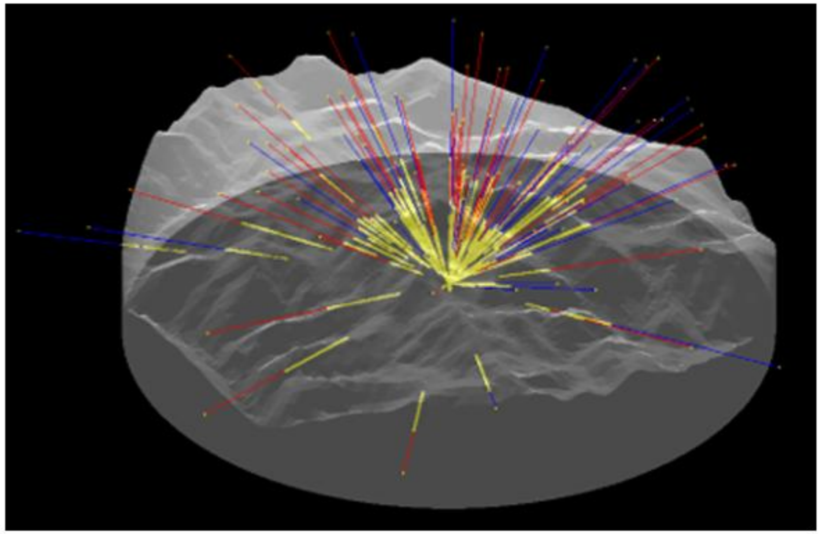


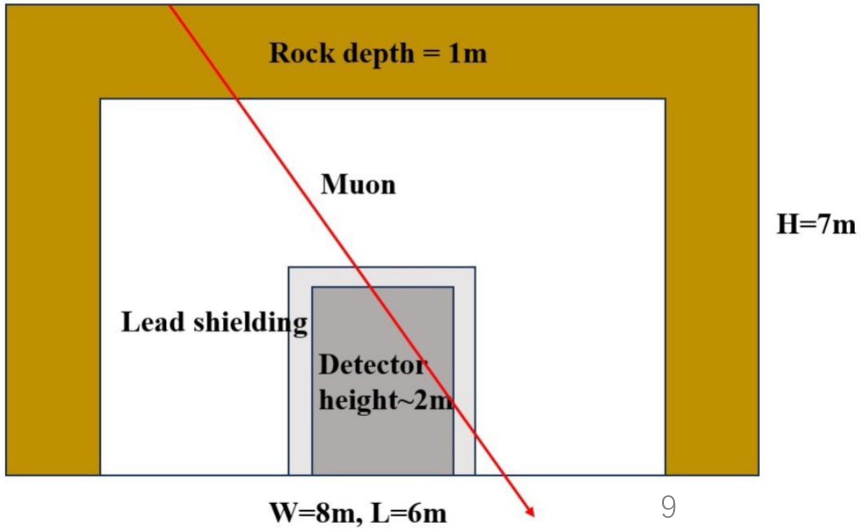
Simulation Framework: Underground

- A detailed model of mountain terrain
- Muon propagation: Geant4 simulation
- Detailed detector simulation:
  - Physical interaction
  - Optical photon propagation
  - PMT detection
  - Electronics



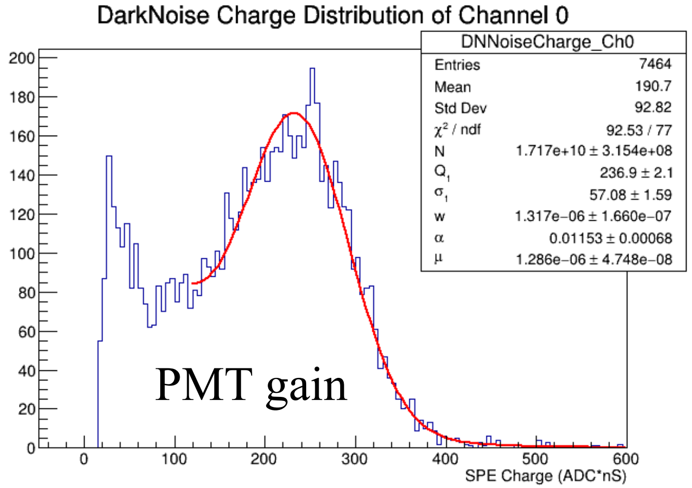


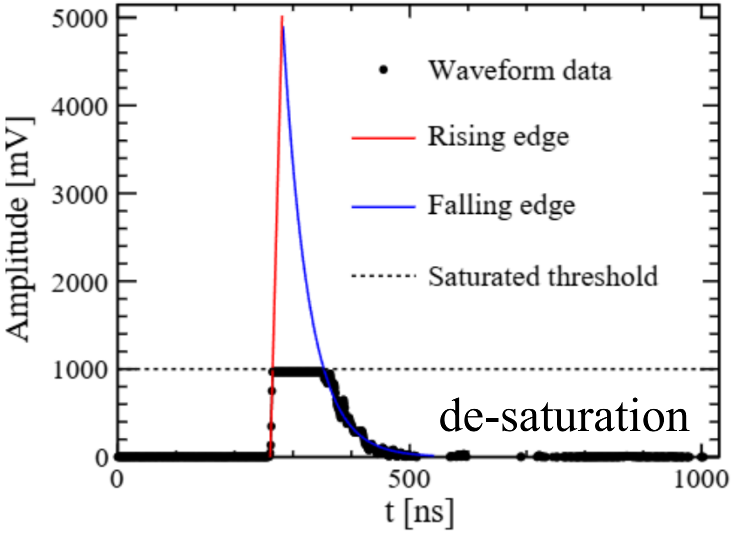




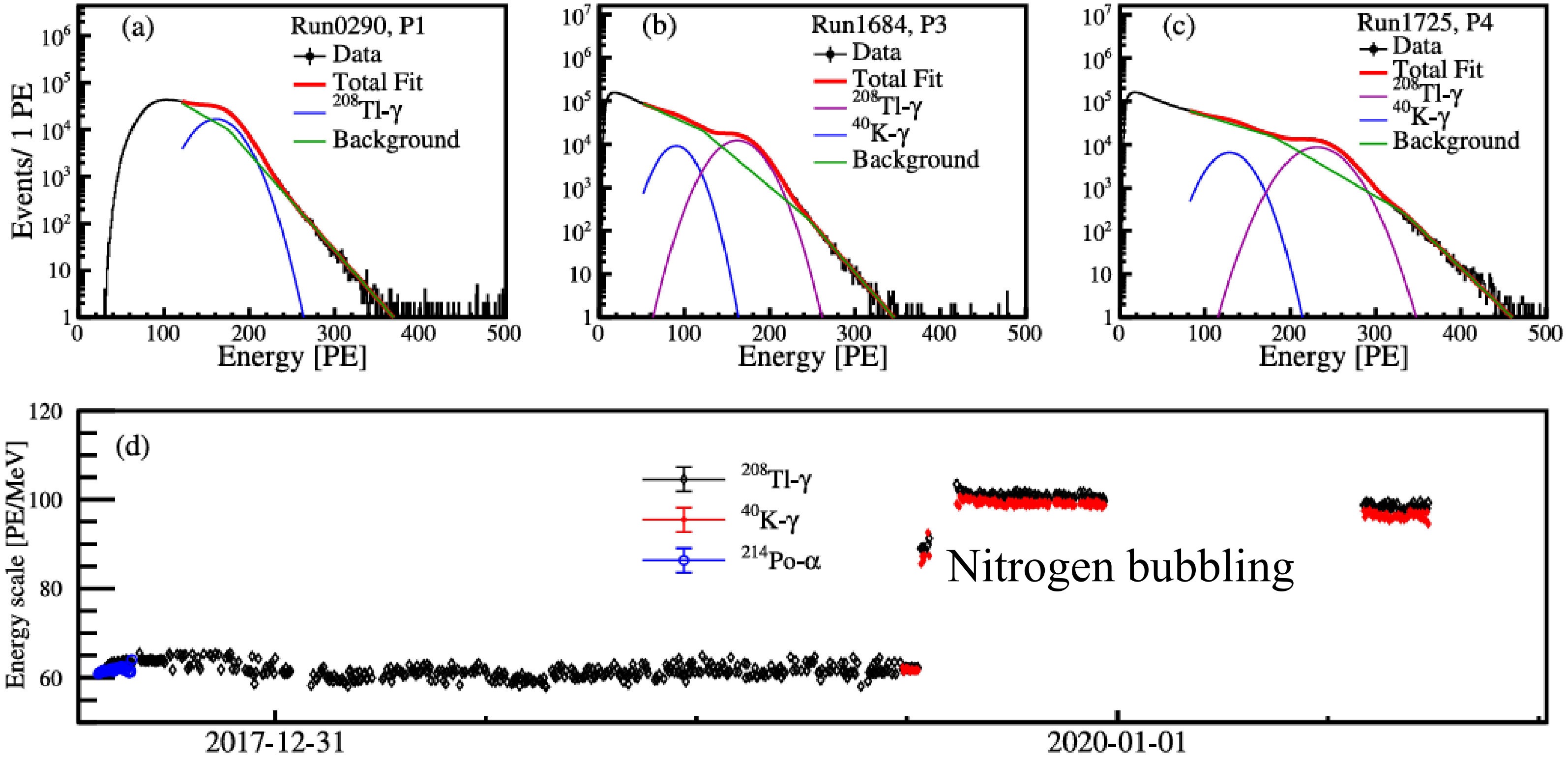
Energy Reconstruction

- The total number of photonelectrons on PMTs is considered as the reconstructed energy.





- The energy scale is calibrated with the natural radioactivity.

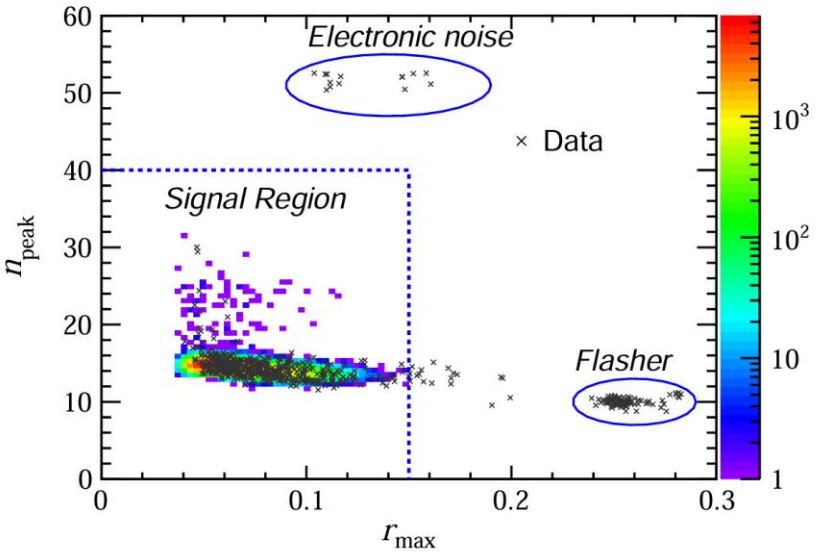


Muon Flux Measurement

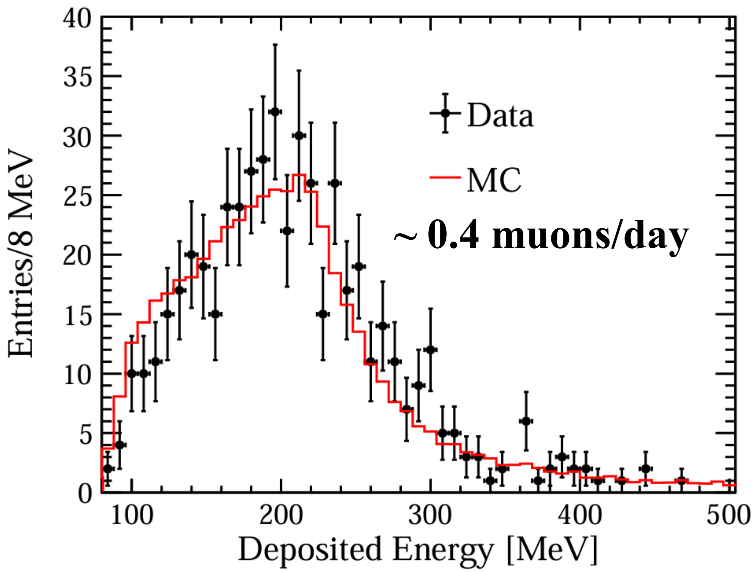
- The data were collected from July 31, 2017, to March 27, 2024, with 1338.6 days effective live time.
- A full-simulation is processed based on Geant4 for estimations of efficiencies and effective area.
- The underground muon flux at CJPL-I is measured as

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

Muon signal selection



Reconstructed deposited energy



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

Muon Direction Reconstruction

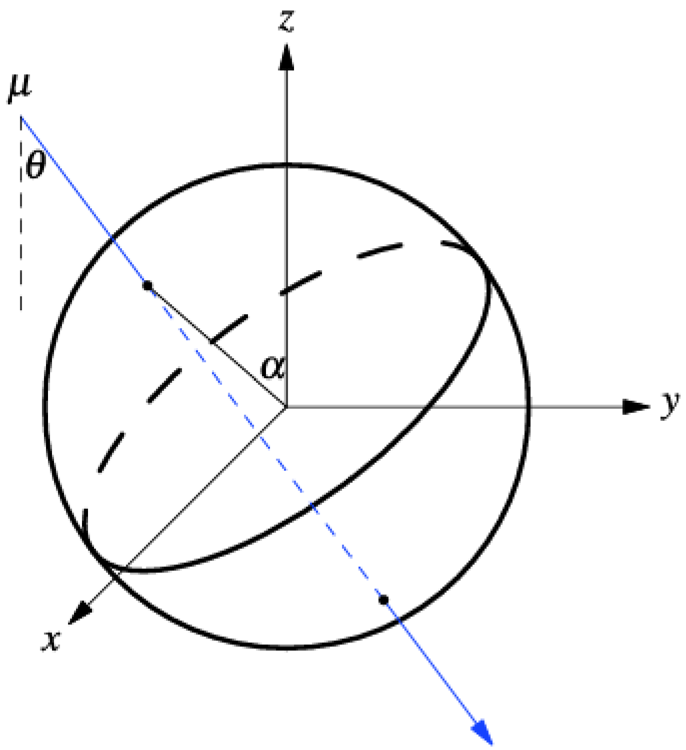
- A template-based reconstruction method is used for muon direction.
- The templates are generated in the simulation.
- The most similar templates compared with data are selected for reconstruction.

$$\tilde{\boldsymbol{T}} = ((t_0 - \mu_t)/\sigma_t, (t_1 - \mu_t)/\sigma_t, \cdots, (t_{29} - \mu_t)/\sigma_t),$$

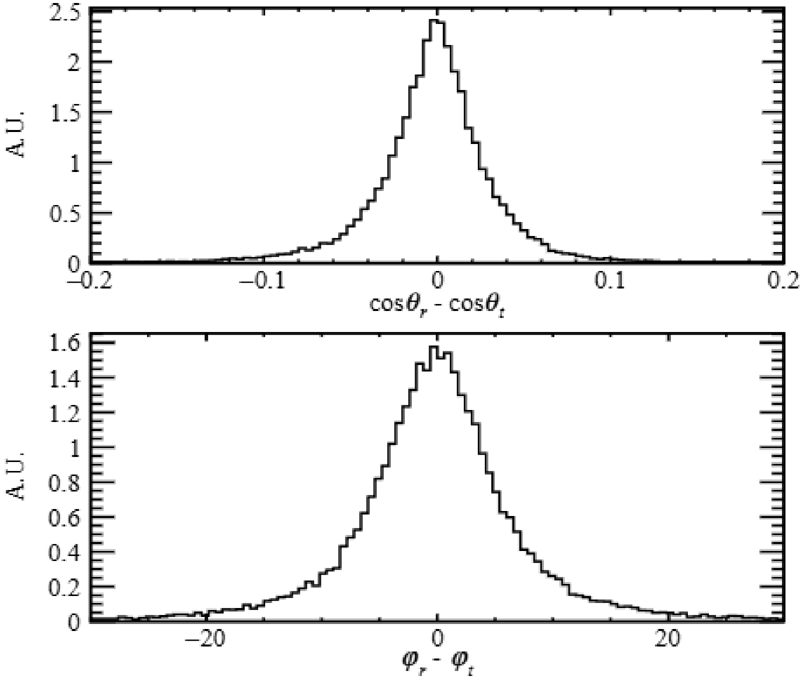
$$\tilde{\boldsymbol{C}} = ((c_0 - \mu_c)/\sigma_c, (c_1 - \mu_c)/\sigma_c, \cdots, (c_{29} - \mu_c)/\sigma_c),$$

$$\boldsymbol{R} = (\tilde{\boldsymbol{T}}, \tilde{\boldsymbol{C}}). \qquad d = |\boldsymbol{R_d} - \boldsymbol{R_t}|.$$

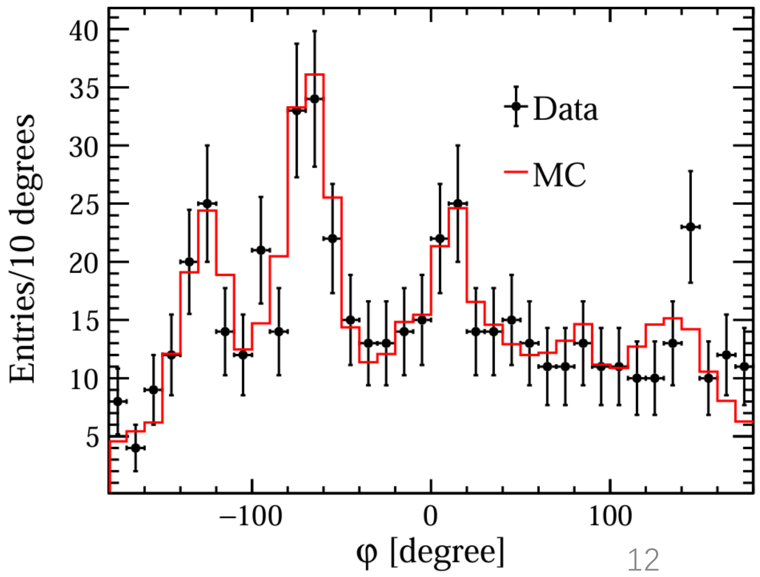
$$\boldsymbol{P} = \frac{\sum_{i=1}^{k} \frac{1}{d_i} \boldsymbol{P_i}}{\sum_{i=1}^{k} \frac{1}{d_i}},$$



Intrinsic Resolution: 4.5°



Azimuth angle reconstruction

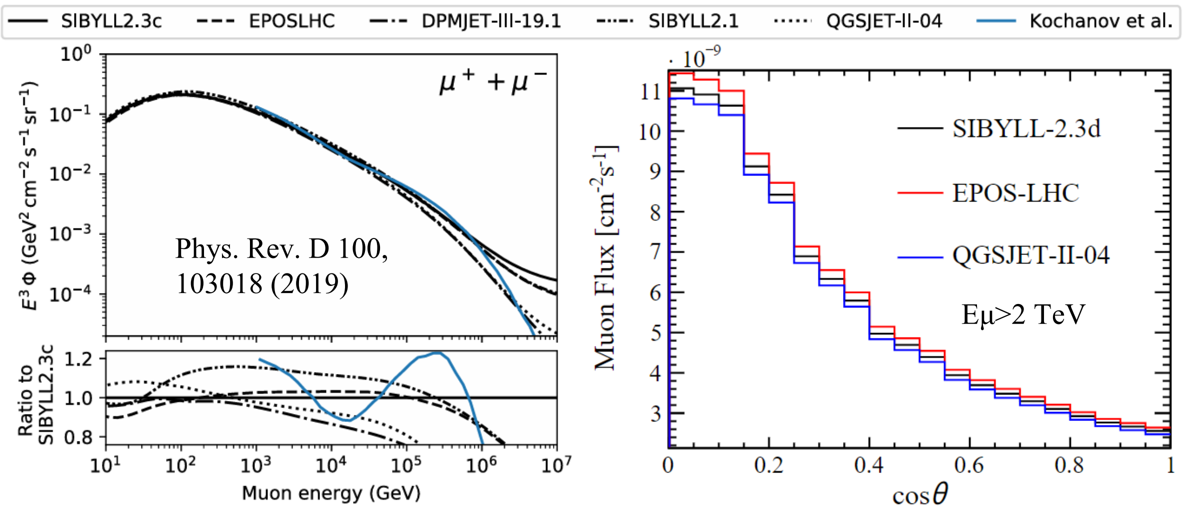


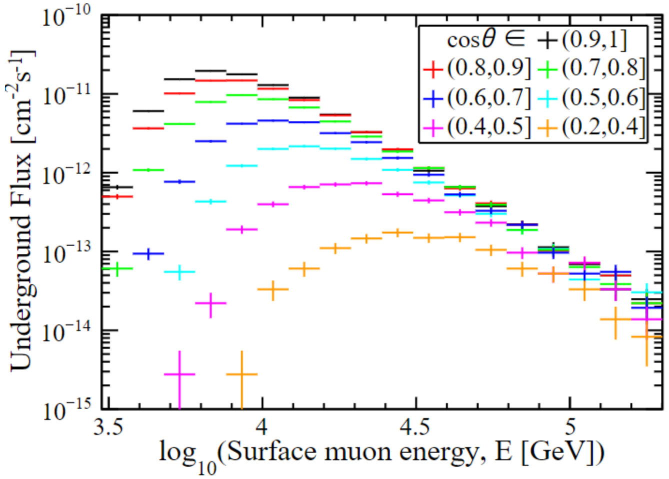
03

Result

Underground Muon Flux Prediction

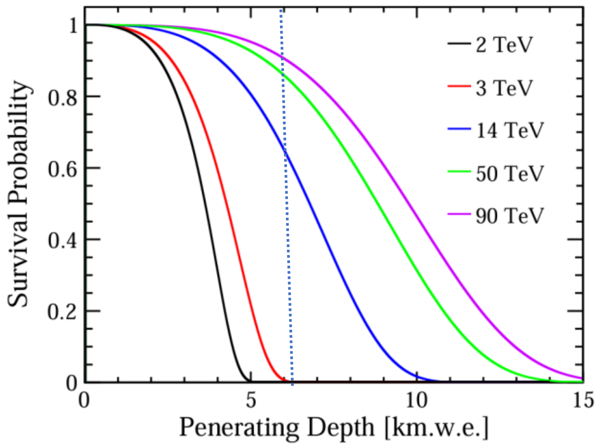
Cosmic ray+Hadronic model+MCEq package→Surface muon

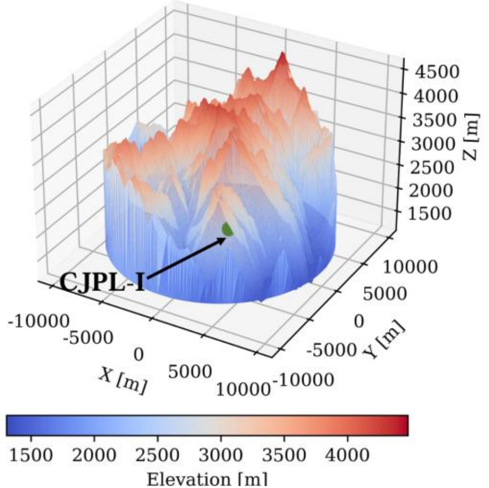


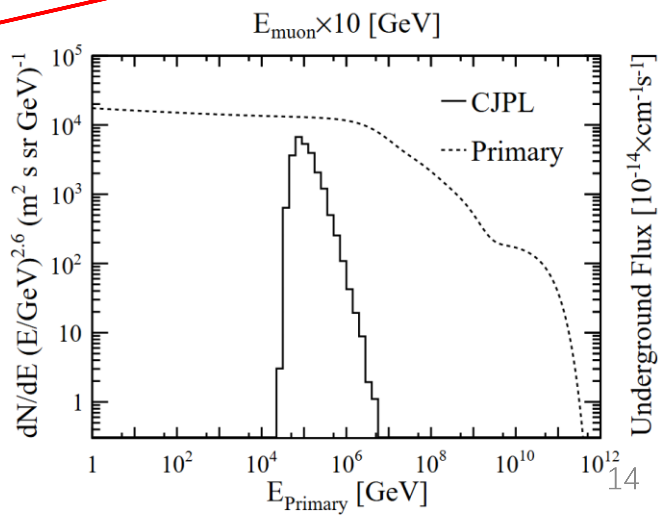


$$\text{Underground}: \phi_\mu = \int \phi_s(E,\theta,\varphi)P(E,X(\theta,\varphi))dEd\Omega$$

Mountain model+Geant4 simulation→Survival probability

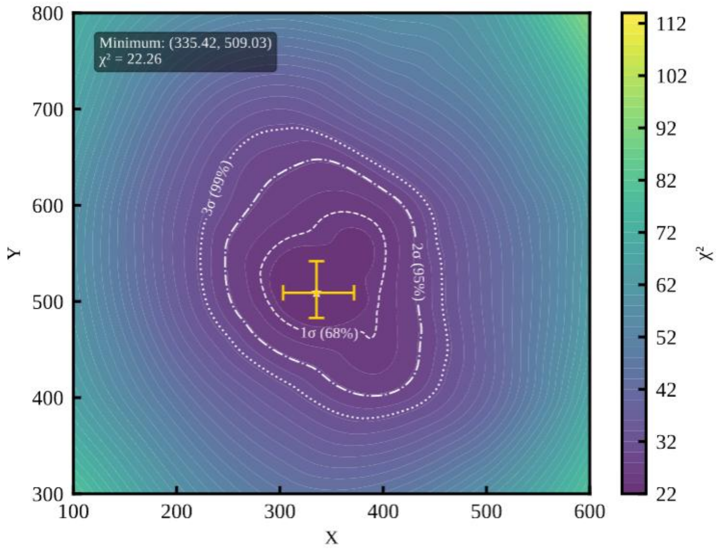


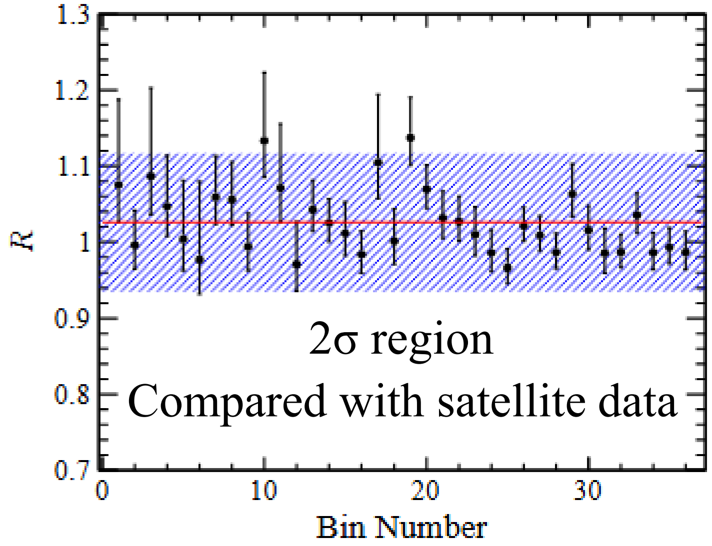




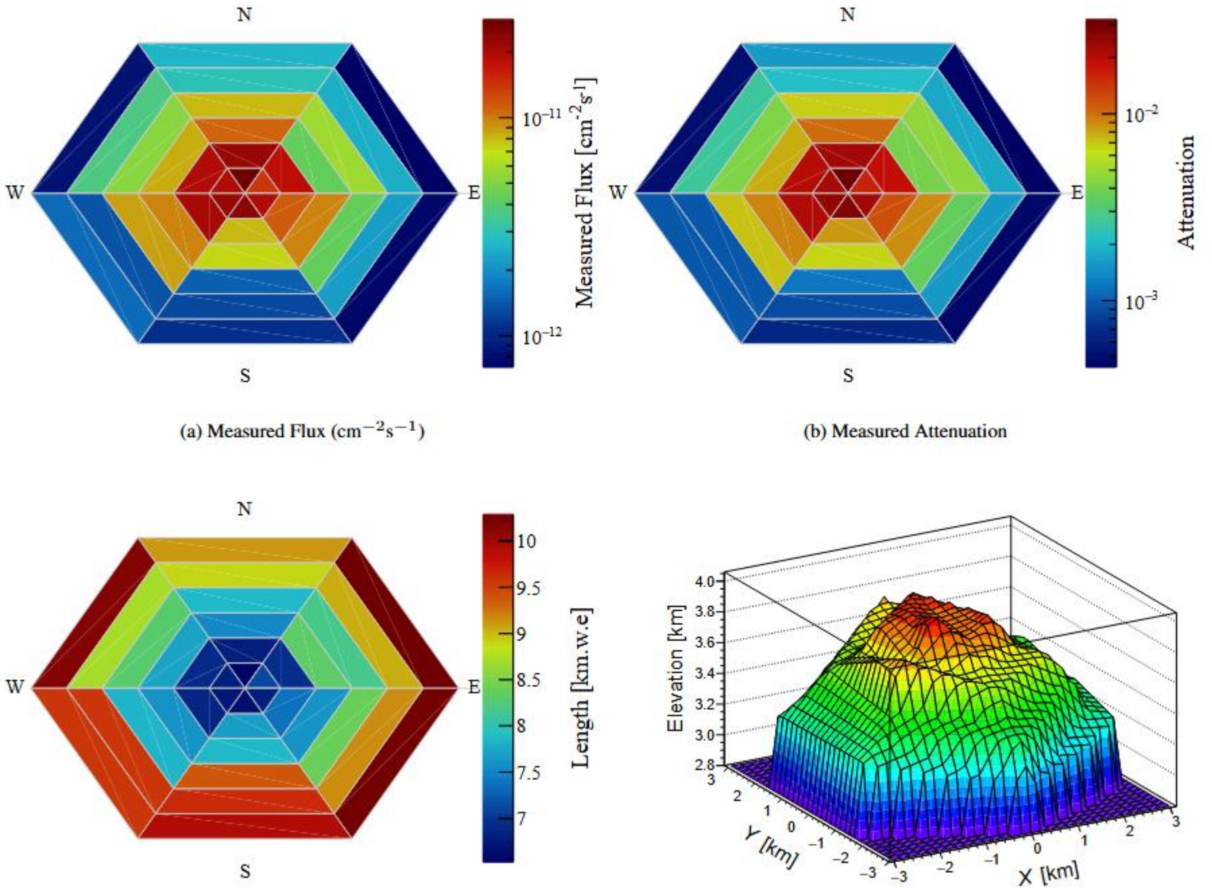
Mountain Muography

Detector position scan





$$\chi^2 = \sum_i \frac{(n^i_{\mathrm{data}} - n^i_{\mathrm{sim}}(\eta))^2}{n^i_{\mathrm{data}}},\qquad \phi(\theta,\varphi) = \frac{N(\theta,\varphi)}{\epsilon(\theta,\varphi)S(\theta,\varphi)T},\qquad P(\theta,\varphi) = \frac{\phi(\theta,\varphi)}{\phi_s(\theta,\varphi)},$$



(a) Measured Flux ($\mathrm{cm^{-2}s^{-1}}$)

(b) Measured Attenuation

(c) Measured Slant Depth (km.w.e.)

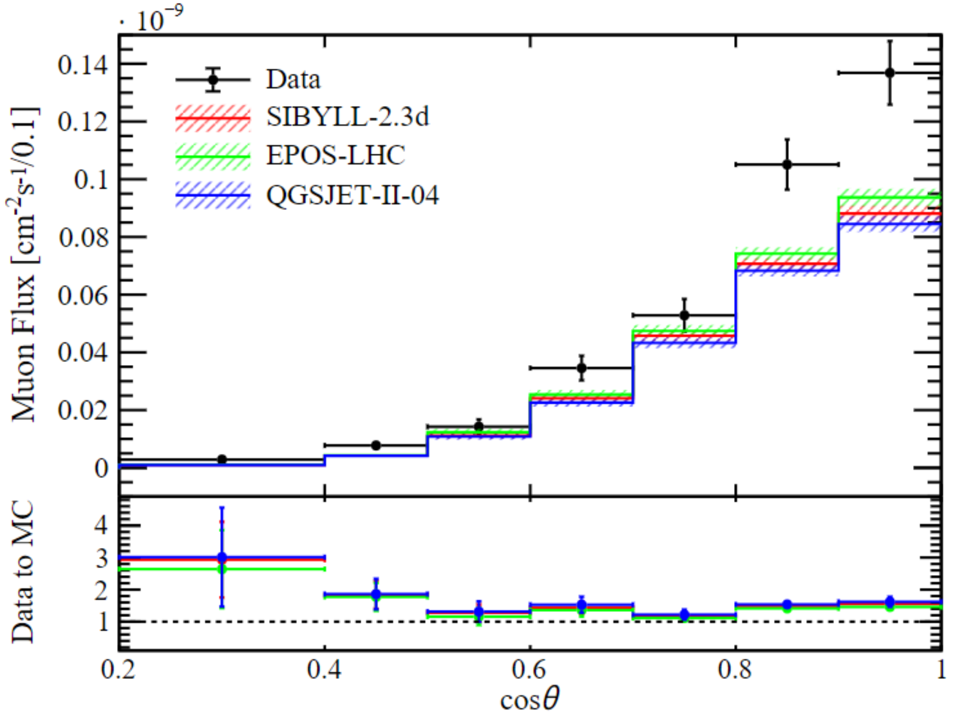
(d) Reconstructed Terrain

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

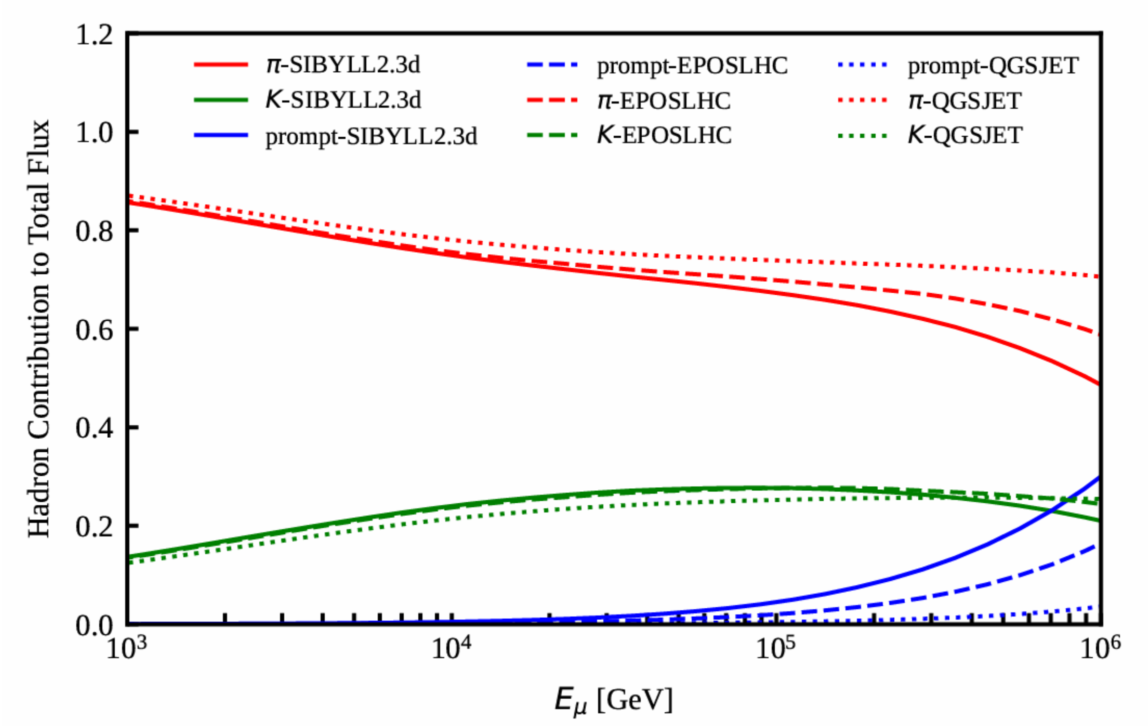
Model	Flux ratio
SIBYLL-2.3d	1.44±0.07
EPOS-LHC	1.38±0.07
QGSJET-II-04	1.51±0.08

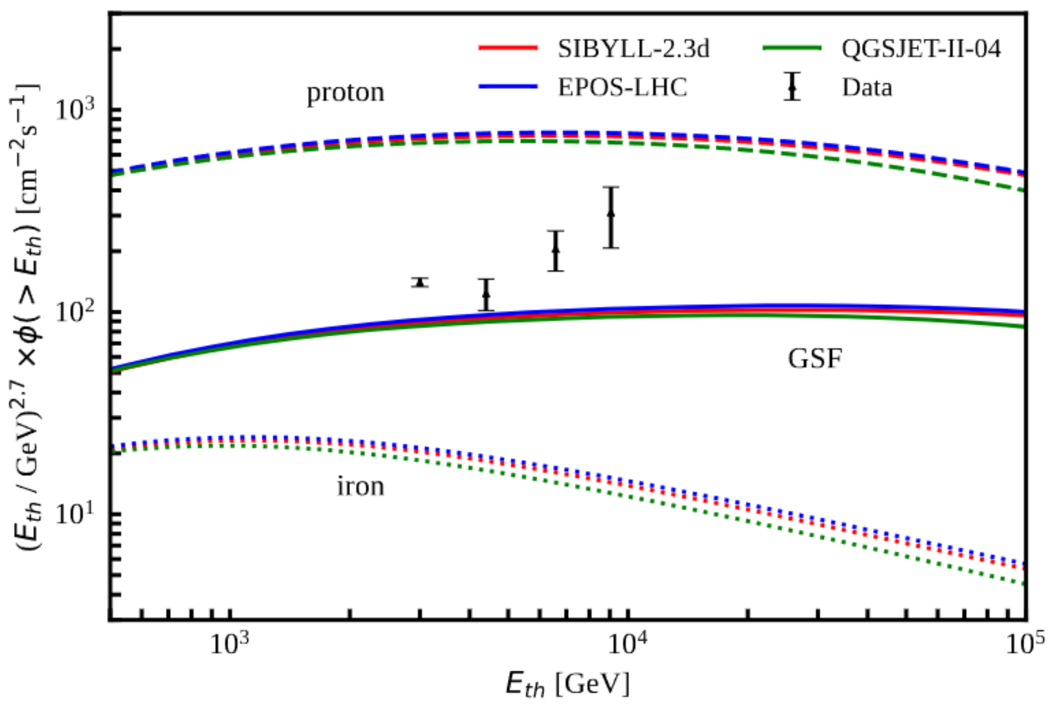


Similar excess observed by KM3NeT, Bess and L3+cosmic, but the intensity is different.

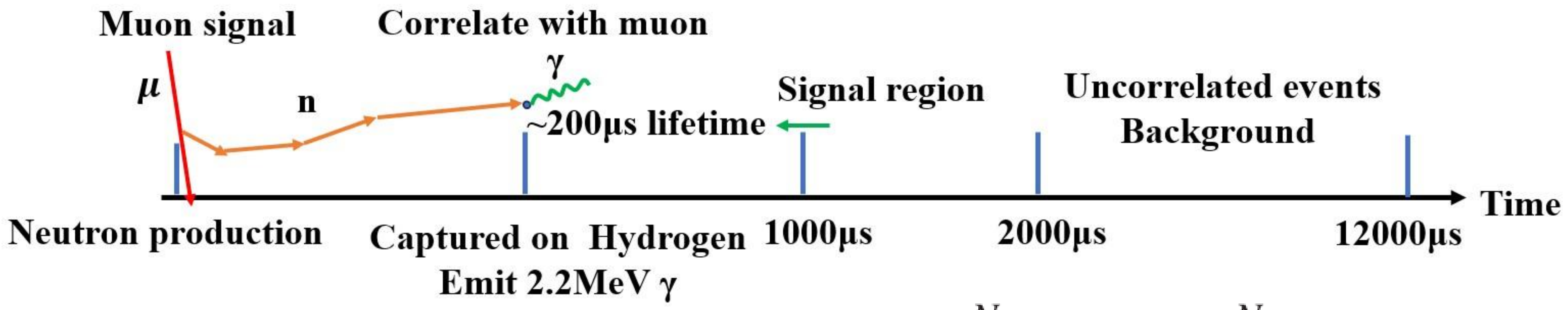
Interpretation of the excess

- 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



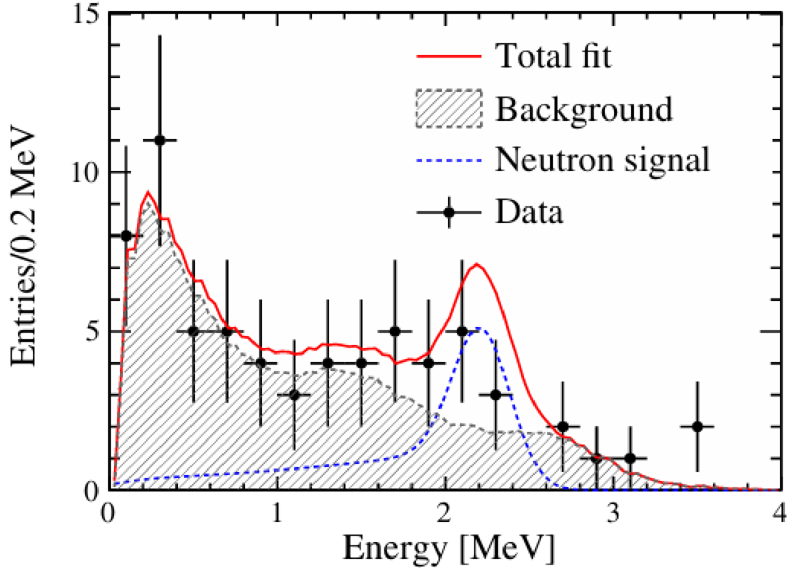


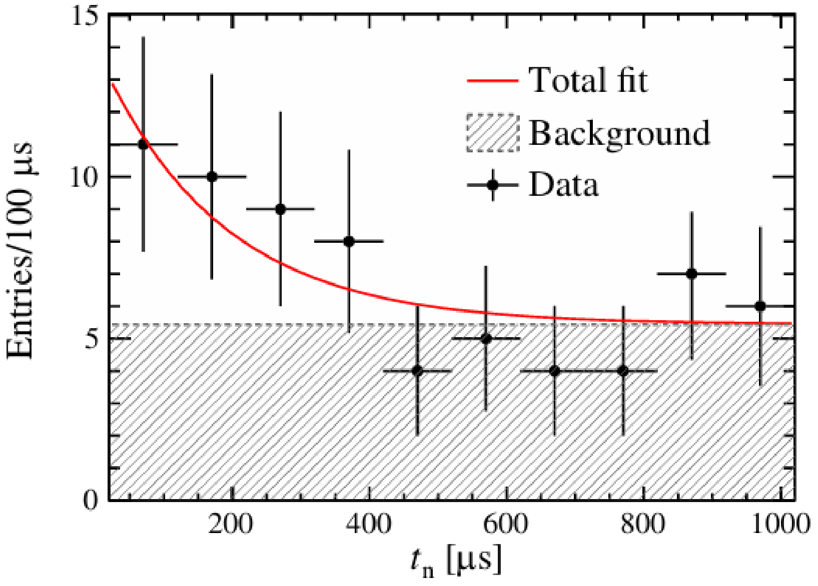
Muon-induced Neutron Yield

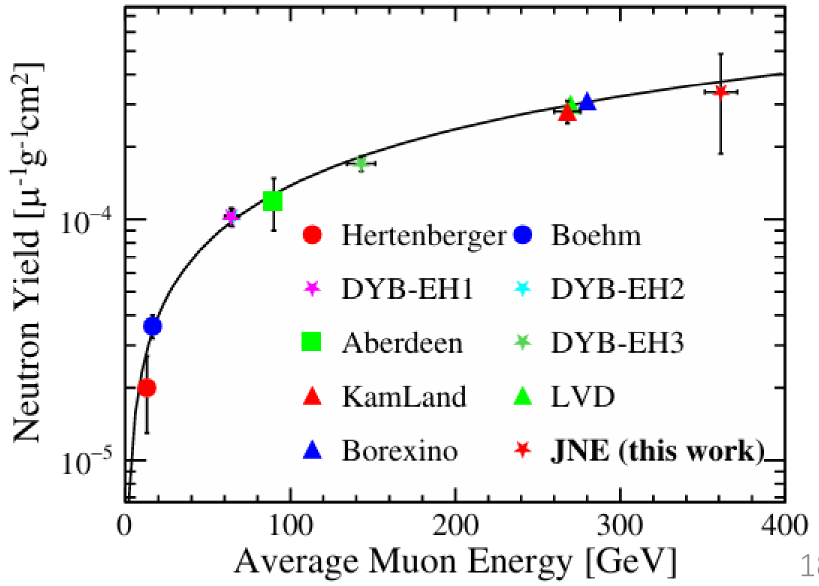


$$\mathcal{L} = \frac{\nu^m}{m!} e^{-\nu} \prod_{i=1}^{m} [f_1(E_i, \kappa) f_2(t_i)] N(\kappa)$$

$$Y_n = \frac{N_n}{(\sum L_\mu) \times \rho} = \frac{N_n}{N_\mu \times L_{avg} \times \rho}$$







04

Summary & Outlook

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 of the discrepancies 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