清華大學 Tsinghua University

JINPING NEUTRINO EXPERIMENT

Simulation Study of Spallation Background for JNE-500ton Detector

Xinshun Zhang

Department of Engineering Physics, Tsinghua University, Beijing

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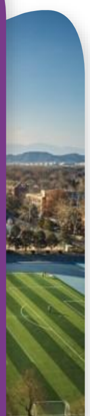
2025



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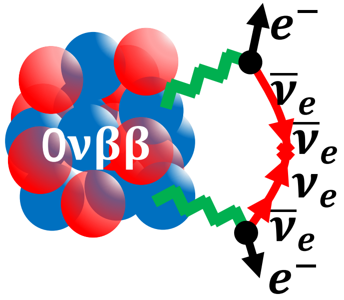
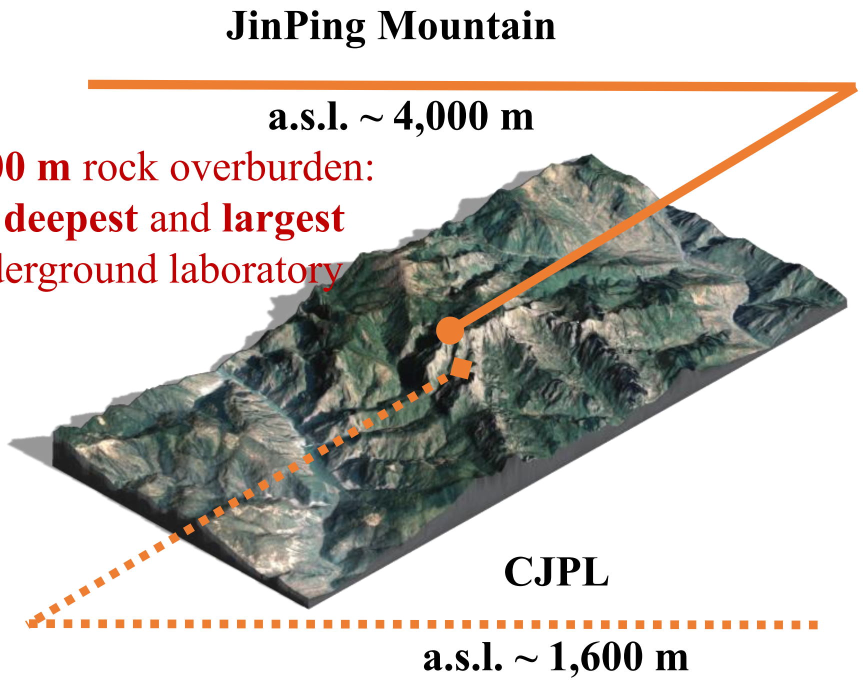
Introduction

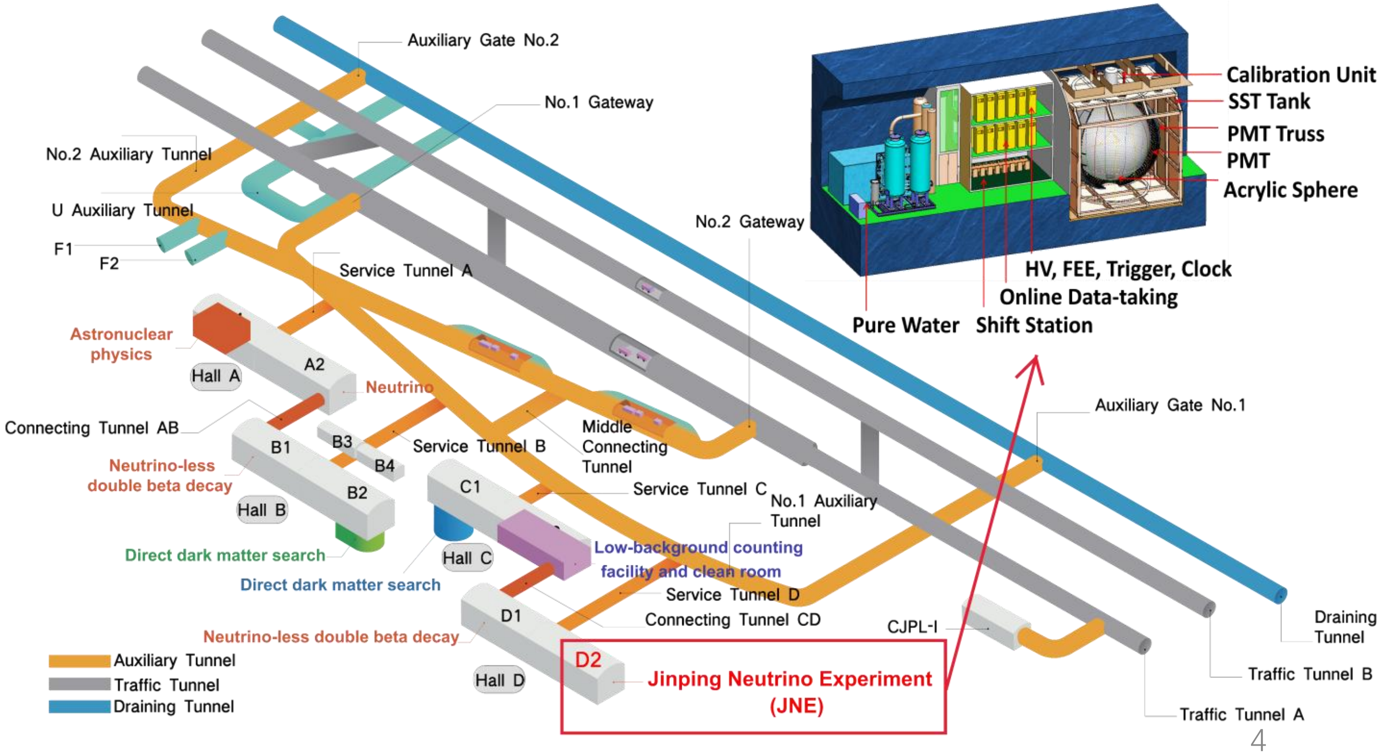
Jinping Neutrino Experiment (JNE)

Focus on **MeV-neutrino** related studies using water and LS as target



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





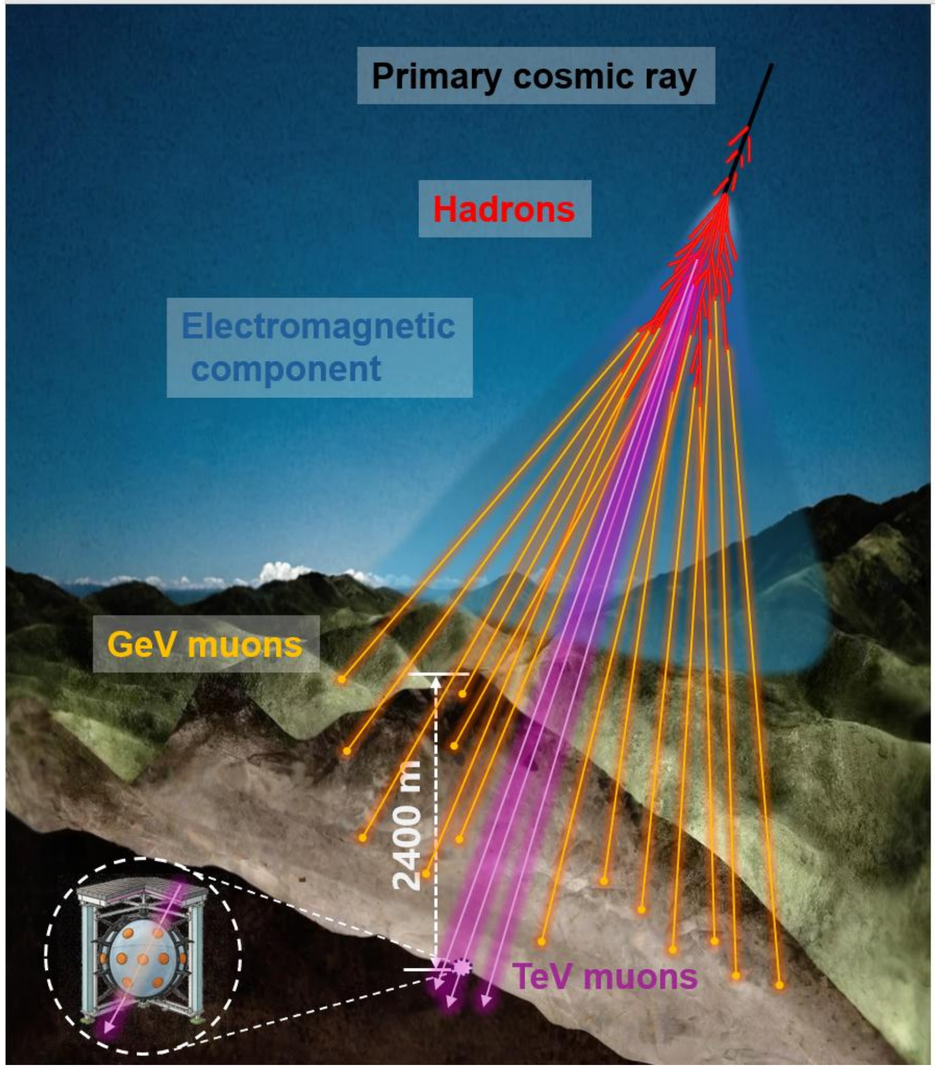
Underground Muons

- 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.

- After energy loss in the rock, muons with hundreds of GeV energies enter the underground laboratory and deposit energies in the detector



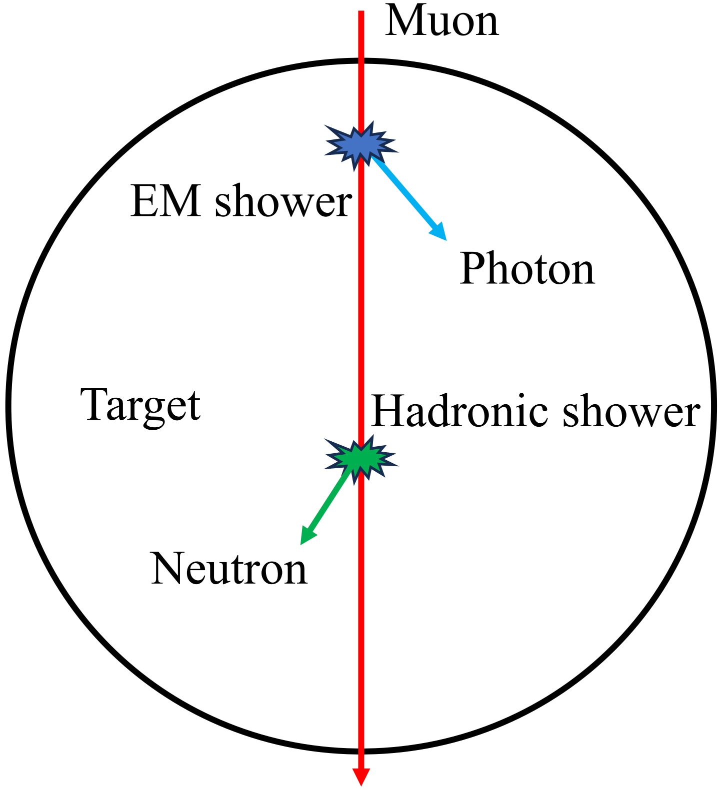
Muon Spallation Radioactivity

- High-energy muons generate showers in the detector, and produce high-energy secondary particles.
- These particles **interact inelastically** with target nuclei and produce spallation nuclei

Low probability to produce hadronic shower

$$N_{EM} \gg N_H$$

Hadronic showers dominate the spallation background production



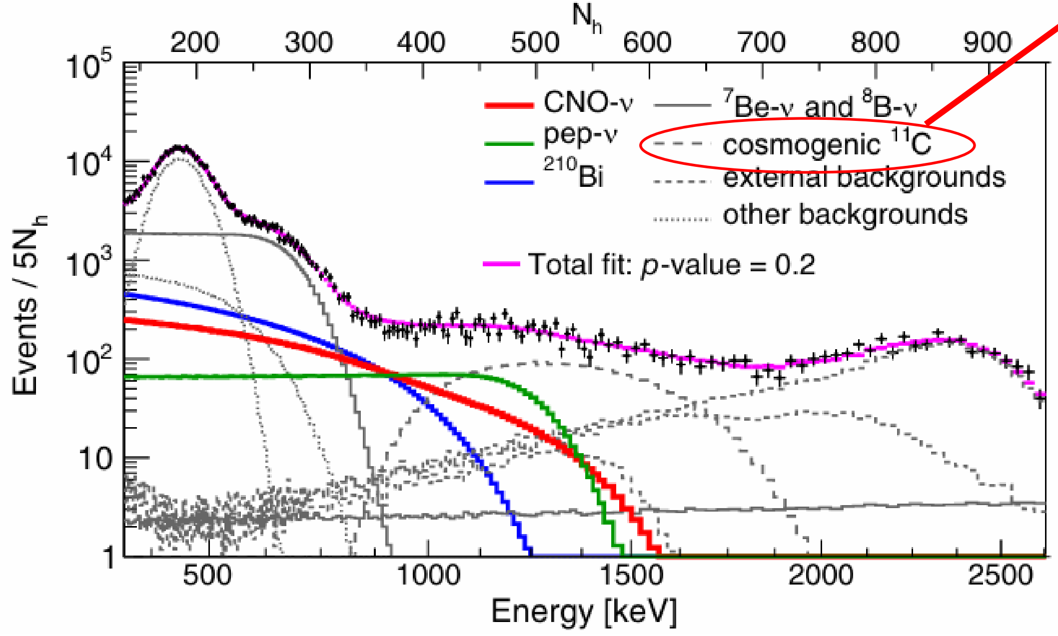
Isotope	Decay Mode	Q-value [MeV]	Half-life [s]
^{16}N	β^-	10.42	7.13
^{13}N	β^+	2.22	598
^{12}N	β^+	17.3	0.011
^{15}C	β^-	9.77	2.45
^{11}C	β^+	1.98	1222
^{10}C	$\beta^+\gamma$	3.65	19.3
^{9}C	β^+	16.5	0.127
^{13}B	β^-	13.4	0.0174
^{12}B	β^-	13.4	0.0202
^{8}B	$\beta^-\alpha$	18.0	0.77
^{11}Be	β^-	11.5	13.76
^{7}Be	EC	0.86	4.6×10^6
^{9}Li	β^-(49.5%)β^-n(50.5%)	13.6	0.178
^{8}Li	$\beta^-\alpha$	16.0	0.84
^{8}He	β^-(84.0%)β^-n(16.0%)	10.7	0.119
^{6}He	β^-	3.51	0.807

Important Background Source

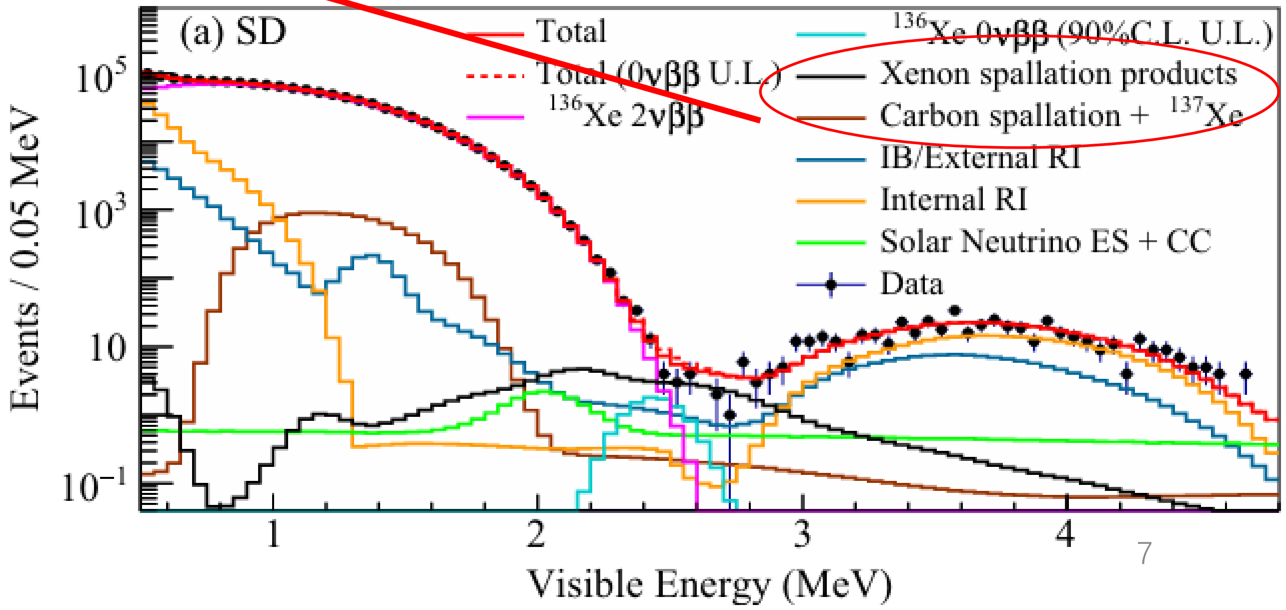
- Spallation radioactivity is important background source for MeV-scale neutrino-related studies:
  - β decays produce MeV-scale electron and positron: solar neutrino and 0νββ.
  - β/n decays produce cascade signals: geo-neutrino and diffused supernova neutrino background.

Spallation Background

Borexino: solar neutrinos



KamLAND-ZEN: 0νββ



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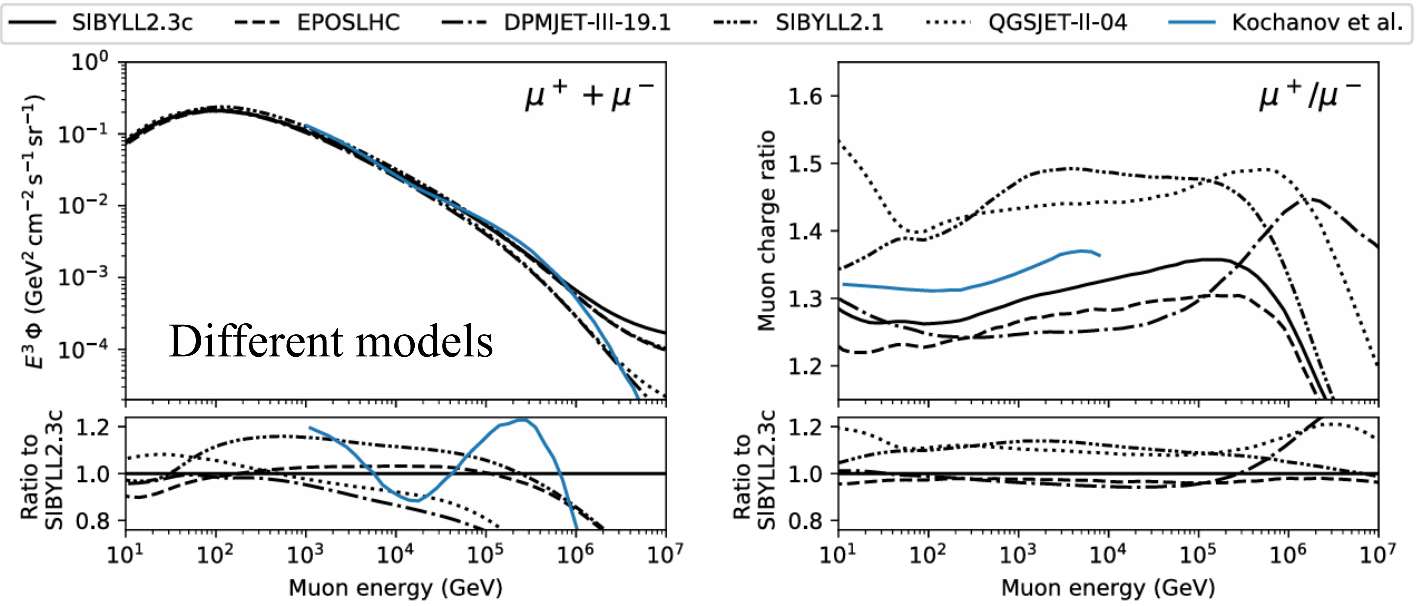
Method

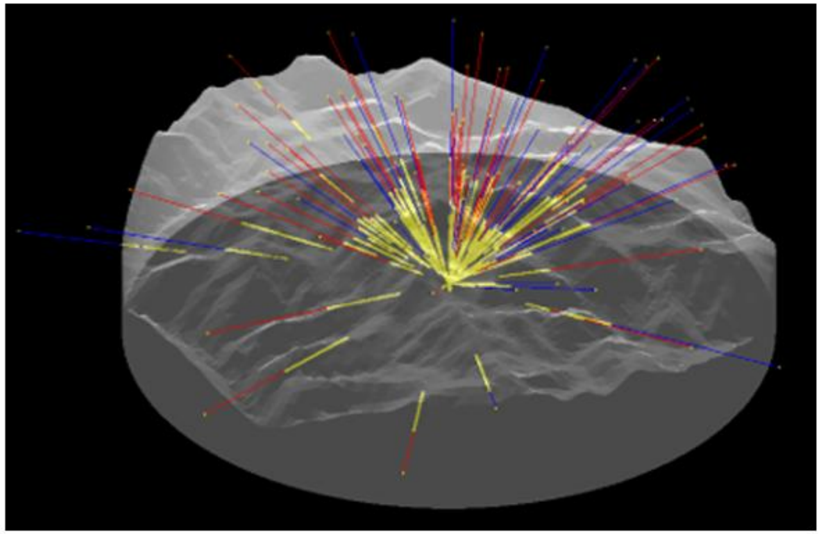
Muon Generation and Propagation

- Muons are produced in extensive air showers induced by primary cosmic rays (MCEq)
- Muons deposit energies in the rock overburden through ionization and radiative processes (Geant4)

Muon production

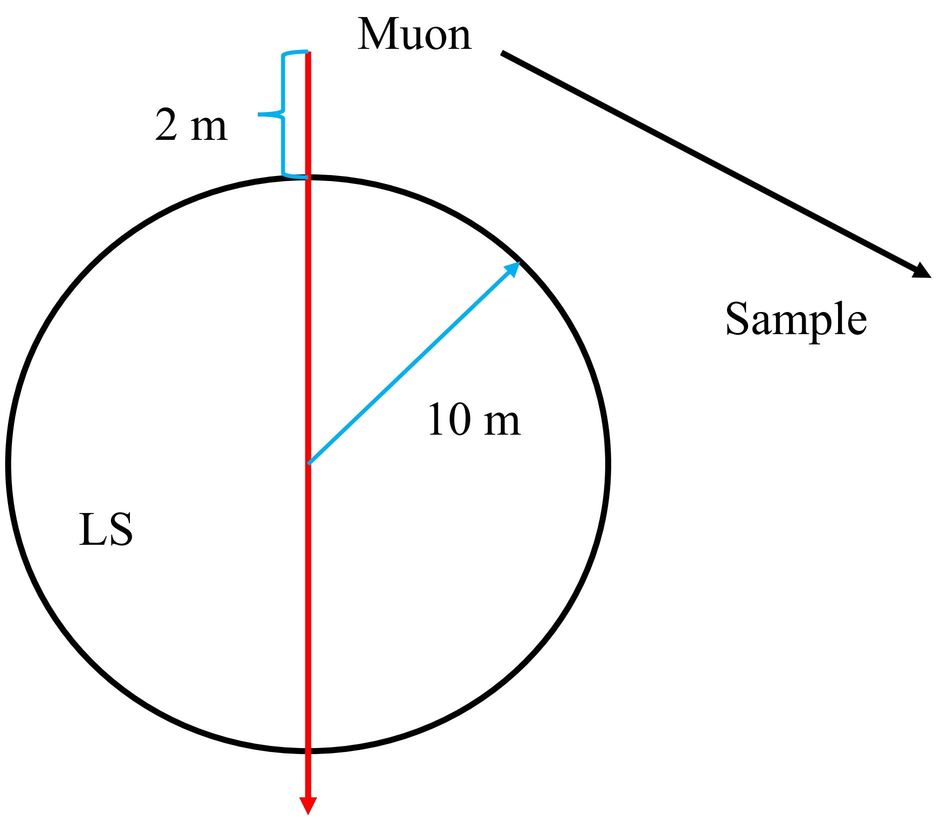


Muon propagation

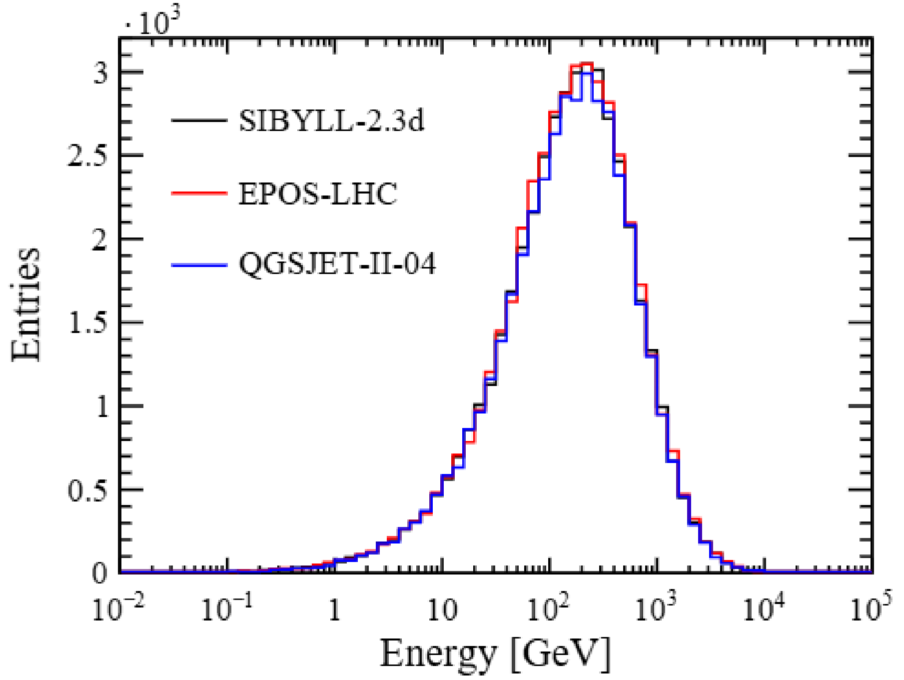


Spallation Simulation

- Muons are sampled from underground muon energy spectrum.
- Spallation processes are simulated with Geant4 and three physical lists are used:
    - QGSP-BERT-HP, QGSP-BIC-HP, FTFP-BIC-HP



Underground muon spectrum



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Result

Isotope Yield Calculation

- Spallation yield of isotope X can be calculated with simulation outputs.

$$Y_X = \frac{\overbrace{N_X}^{\text{Isotope X Number}}}{\underbrace{N_\mu}_{\text{Muon Number}} \times \underbrace{L_{avg}}_{\text{Muon Path Length}} \times \underbrace{\rho}_{\text{Target Density}}}$$

- Yield unit is $10^{-7}\mu^{-1}g^{-1}cm^2$ and three models are used:
  - Model1: QGSP-BERT-HP
  - Model2: QGSP-BIC-HP
  - Model3: FTFP-BERT-HP

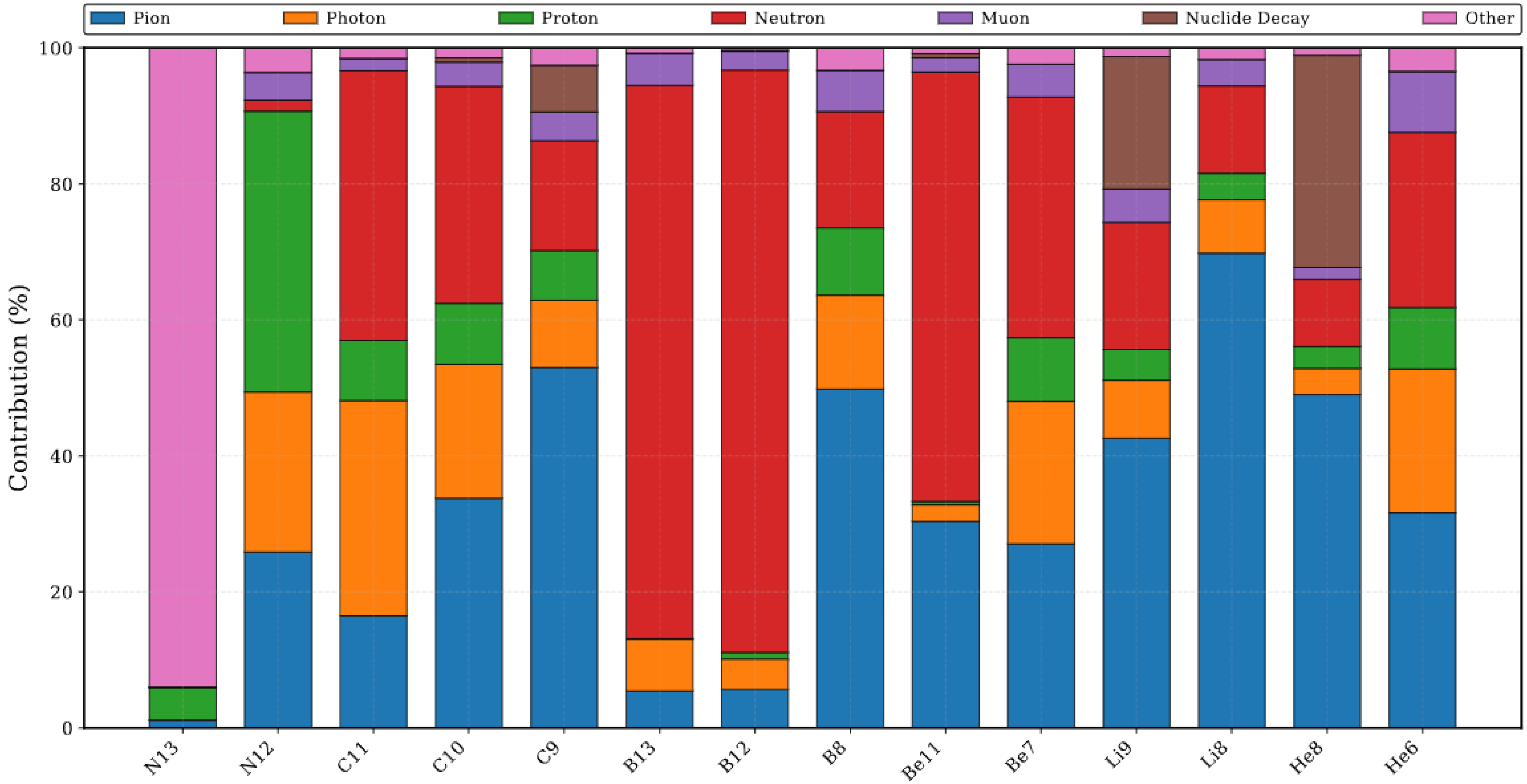
LS target

Isotope	Model1	Model2	Model3	Variation [%]
^{13}N	0.65	0.76	0.65	16.9
^{12}N	1.57	2.18	1.60	38.8
^{11}C	386.60	305.72	392.39	20.9
^{10}C	28.18	25.36	28.68	10.0
^{9}C	0.42	0.57	0.44	35.7
^{13}B	0.18	0.17	0.19	5.6
^{12}B	21.58	13.93	21.96	35.4
^{8}B	1.12	1.59	1.14	41.9
^{11}Be	0.40	0.43	0.40	7.5
^{7}Be	35.73	47.22	36.45	32.2
^{9}Li	1.84	1.86	1.87	1.6
^{8}Li	5.12	11.49	5.23	124.4
^{8}He	0.22	0.31	0.24	40.9
^{6}He	4.57	15.06	4.67	229.5

Hadron Source

- Inelastic interactions of neutron and pion from hadronic showers dominate the spallation radioactivity in LS

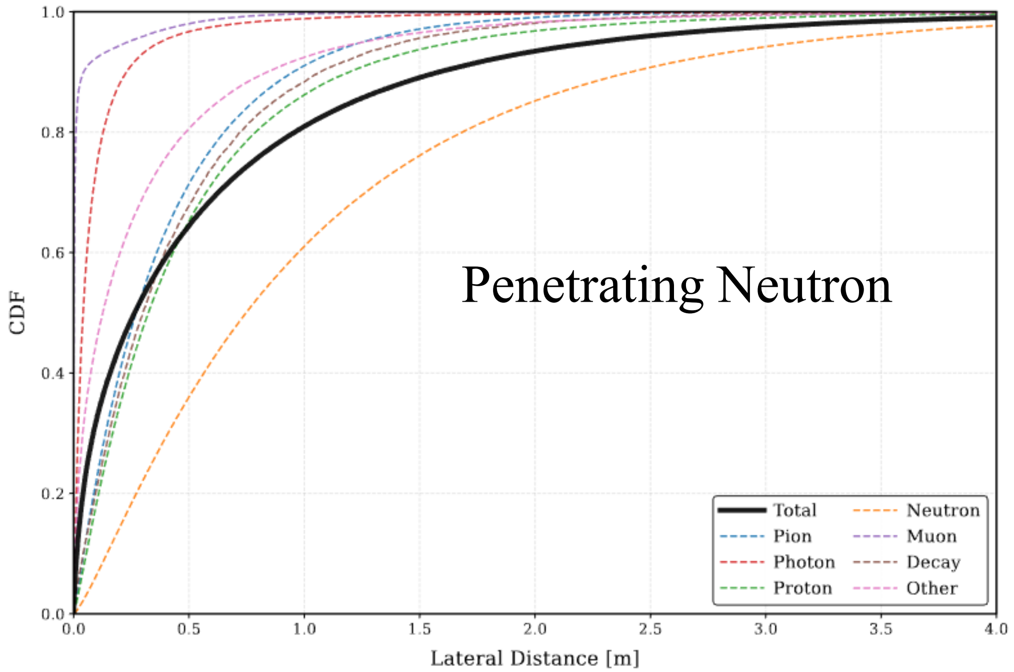
QGSP-BERT-HP



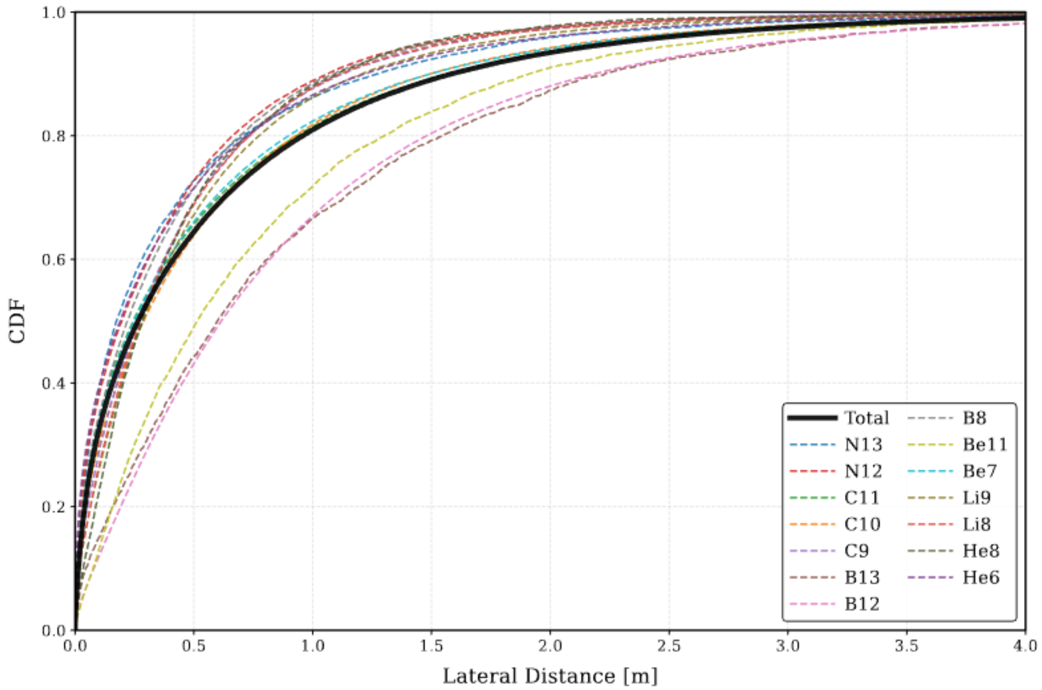
Lateral Distribution

- Spallation nuclei are produced near the muon track with about 4 m radius
- Secondary neutrons are more penetrating than other particles.

Hadron source



Isotope type



Uncertainty Estimation

Muon charge ratio is uncertain and spallation yield varies between positive and negative.

Variations of total yield are taken as uncertainty.

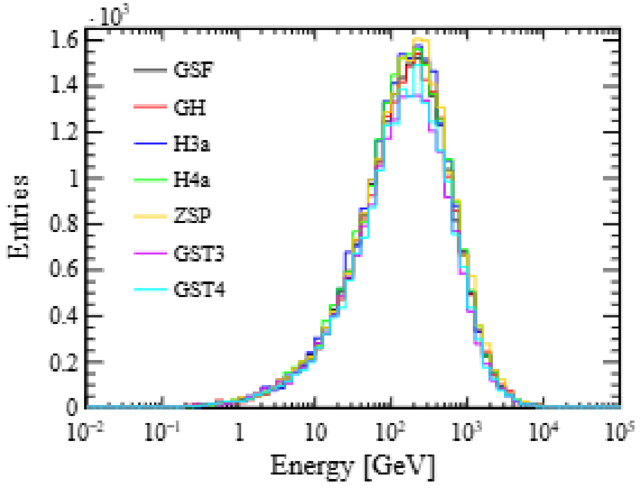
Variations among models originate from neutrons.

Different inputs generate various underground muon spectrum.

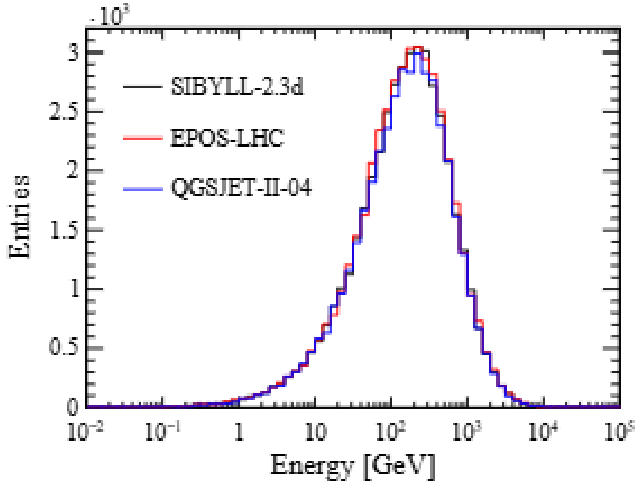
Source	Uncertainty
Muon spectrum	4.1%
Muon charge ratio	2.8%
Hadronic Model	12.6%

Isotope	Model1	Model2	Model3
Li8(n)	0.66	6.56	0.67
Li8	5.12	11.49	5.23
He6(n)	1.18	11.94	1.20
He6	4.57	15.06	4.67
C11(n)	153.11	68.73	156.11
C11	386.60	305.72	392.39
B12(n)	18.48	10.69	18.79
B12	21.58	13.93	21.96

Primary cosmic-ray



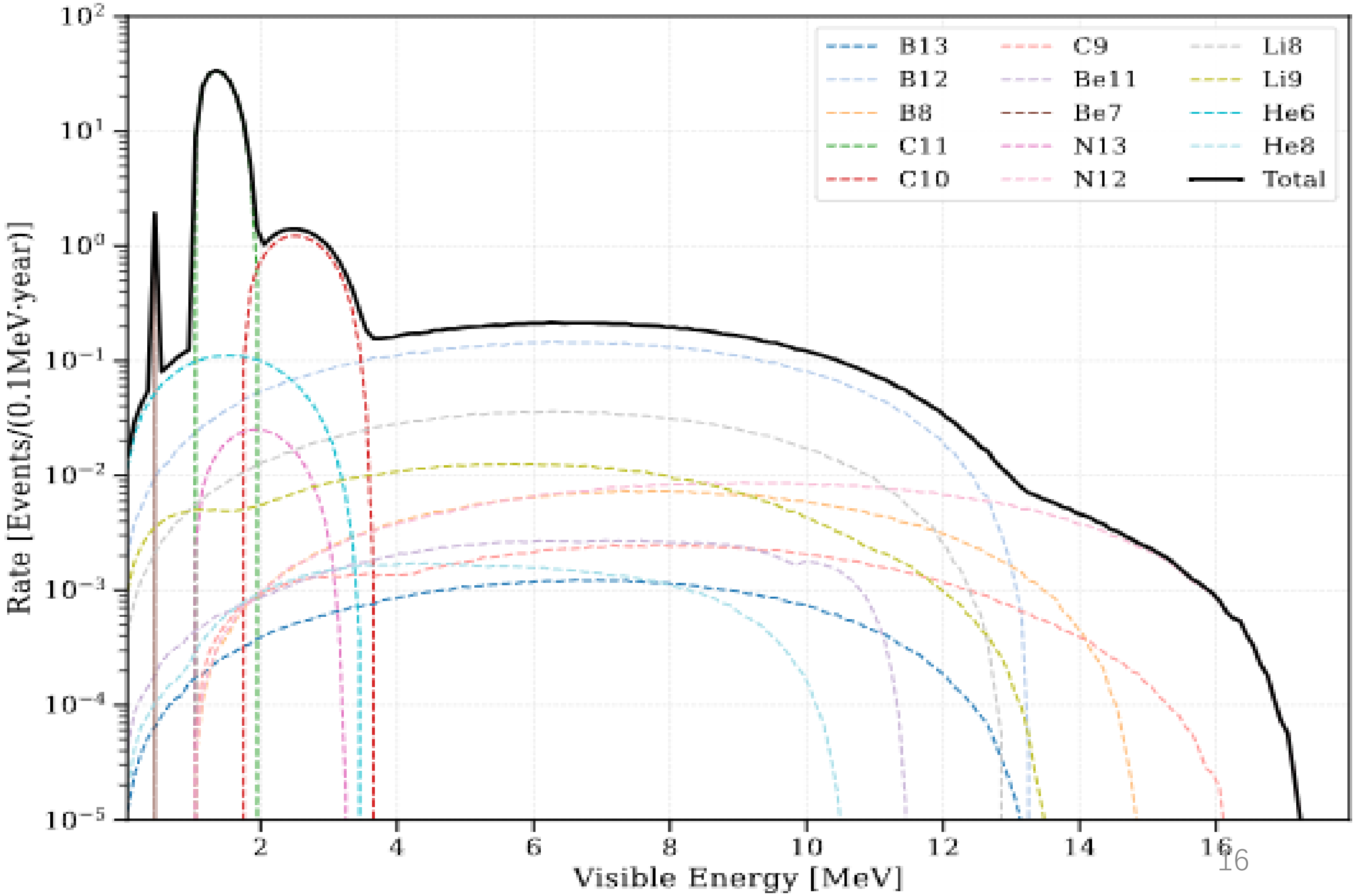
Hadronic interaction in atmosphere



Background Spectrum

- Using Geant4 decay database, the decays of spallation nuclei are simulated.
- The visible energy is calculated by summing the energies of:
  - electron/positron
  - de-excitation gammas
  - Annihilation gammas for positron

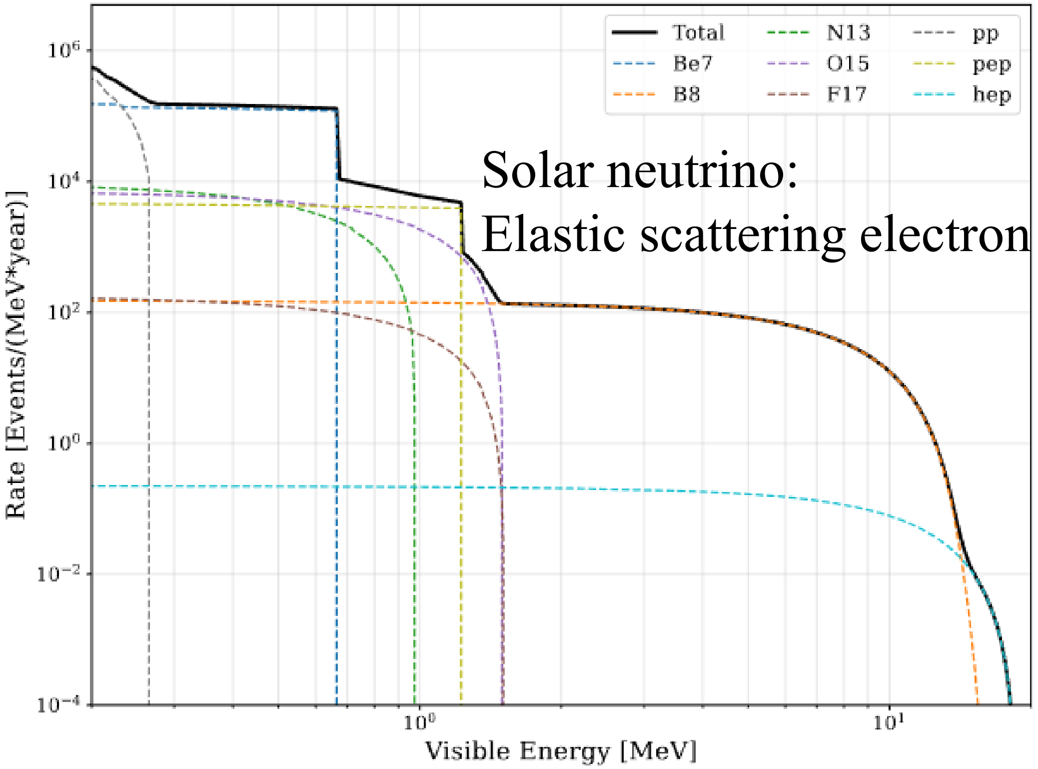
Spallation background spectrum: 0-17 MeV

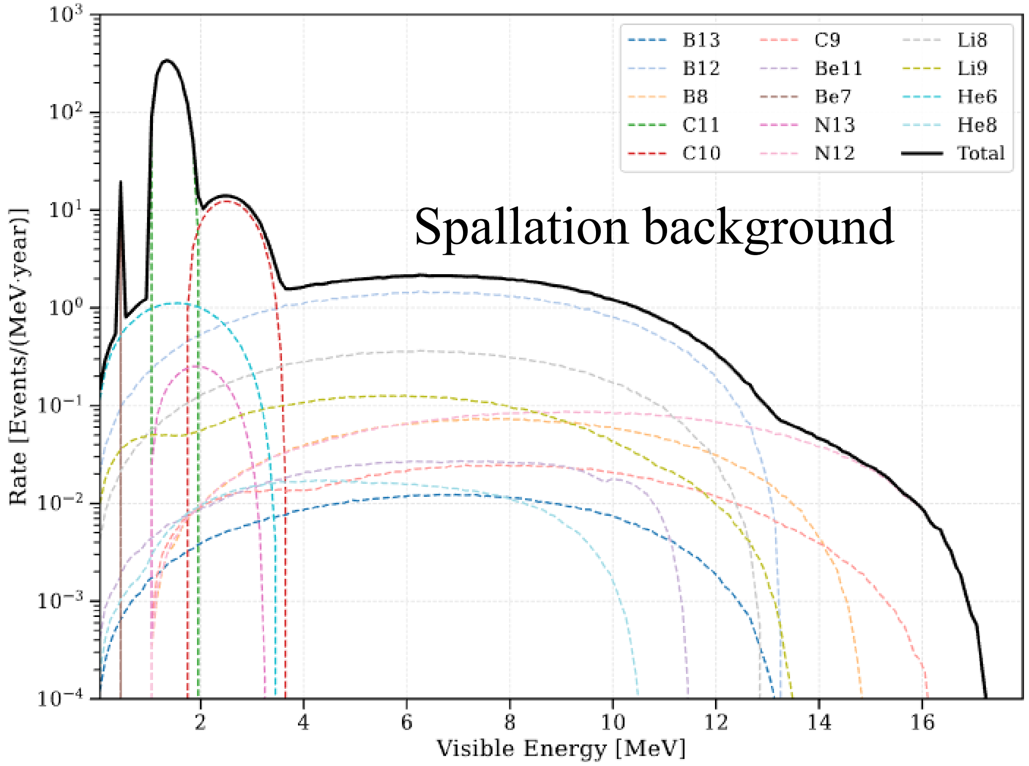


Spallation Background Rate

- The expected neutrino and spallation rates for JNE 500-ton detector are calculated in units of events per year

Source	Spallation	Be7	CNO	pep	B8 (>3MeV)	Spallation (>3MeV)
Events/year	244.6	88147	12227.5	4435	405	16.8





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Summary

Summary

- In this study, we show a detailed simulation study of muon-induced spallation backgrounds in the JNE 500-ton detector. Several features of spallation are investigated. Consequently, the results show that the muon spallation radioactivity at CJPL is **a sub-dominant background** for solar neutrino studies.

Thanks for Listening