Flux and Threshold Estimation of Ultra High Energy Deep Underground Muons

Huiyou Chen and Zhe Wang

Tsinghua University

Outline

- Introduction
- Muon Simulation
  - H3A model for Cosmic Ray Energy Spectrum
  - Corsika Set
  - Surface High Energy Muon Spectrum
  - Muon Energy Threshold for Daya Bay Geographic Model
- Plan
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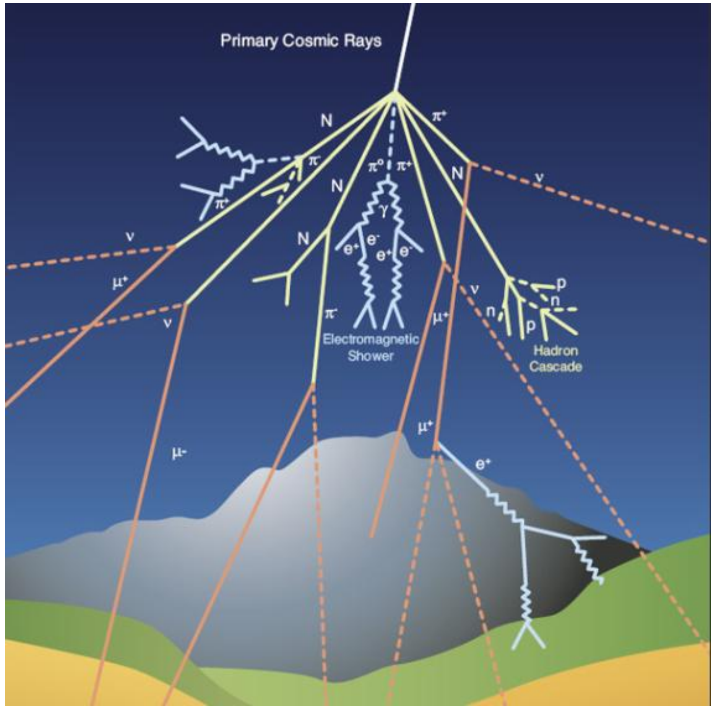
Introduction

Deep Underground Muons Sources

- Primary Cosmic rays interaction with atmosphere
- CC reaction of atmosphere muon neutrinos
- CC reaction of astrophysical muon neutrinos

- Some experiments
  - ICECUBE : ice
  - KM3NET : sea
  - Daya Bay, jinping : rock



Motivation

- Physics corresponding to deep underground muons
  - Validating the QCD model
  - Seasonal variations of the underground muon flux
  - Charged π/K ratio in atmosphere
  - Composition of primordial cosmic rays

Validating the QCD model

- High-energy hadronic interaction models
  - SIBYLL, QGSJET, EPOS, DPMJET
- Predictions of air-shower observables based on simulations show a strong dependence on the choice of the high-energy hadronic interaction model
- By reconstructing deep underground muon flux, one can provide strong tests of hadronic interaction models, as these measurements should be consistent with one another

Model Test Result from ICECUBE

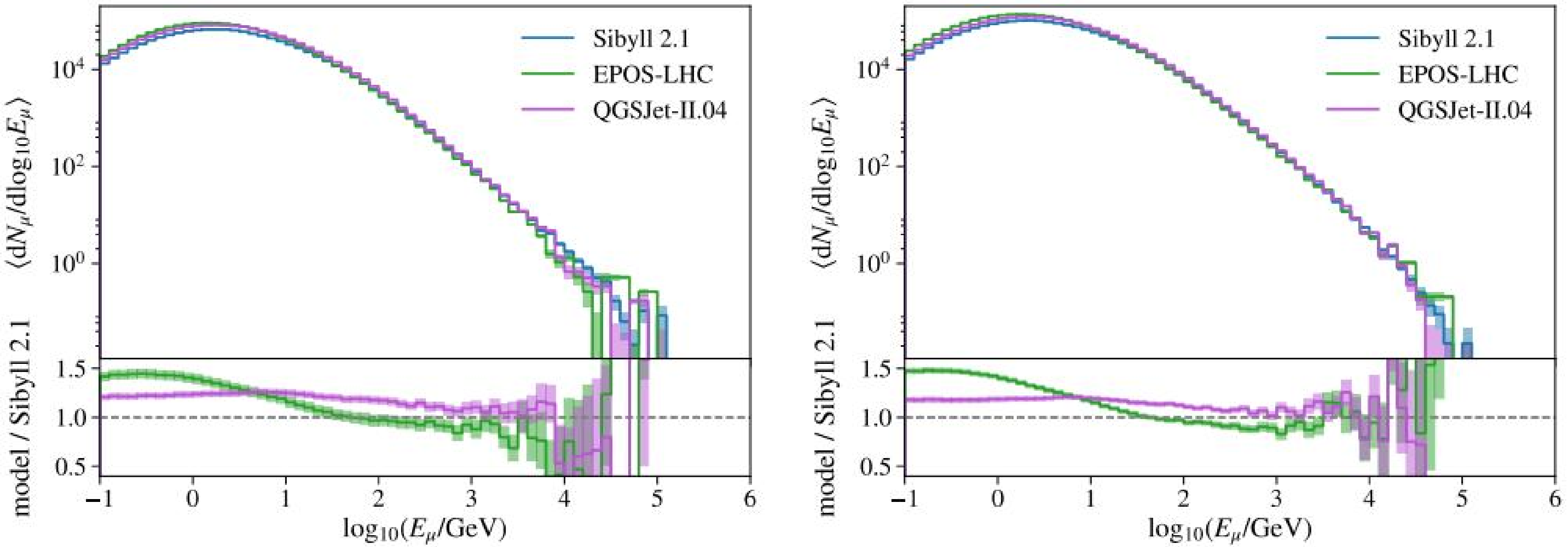


Figure 1: Muon spectrum in vertical proton (left) and iron (right) showers with primary energy around 10 PeV for Sibyll 2.1, QGSJet-II.04 and EPOS-LHC.

arXiv:2107.09387 [astro-ph.HE]

Seasonal variations of the underground muon flux

- The oscillatory movements of atmospheric air masses have been claimed to be the origin of the muon flux seasonal variation.
- We shall examine the periodic variation of the atmospheric density as an influence on the deep underground muon flux counting
- Comparison of experimental data and simulations can provide a deeper understanding of seasonal variations in atmospheric density

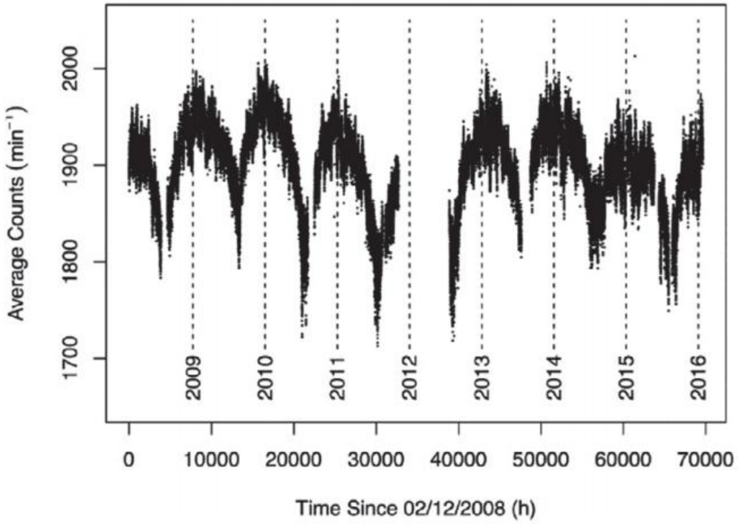


FIGURE 1 Measurement of muon counts over a period of 8 years from Takai et al. (2016)

DOI: 10.1002/asna.202113940

Charged π/K ratio in atmosphere

- The production of deep underground muons is dominated by pion and kaon decay
- Seasonal variations of the underground muon flux provide a method to measure the atmospheric π/K ratio
- Effective temperature coefficient, α_T correspond to seasonal variations muon flux

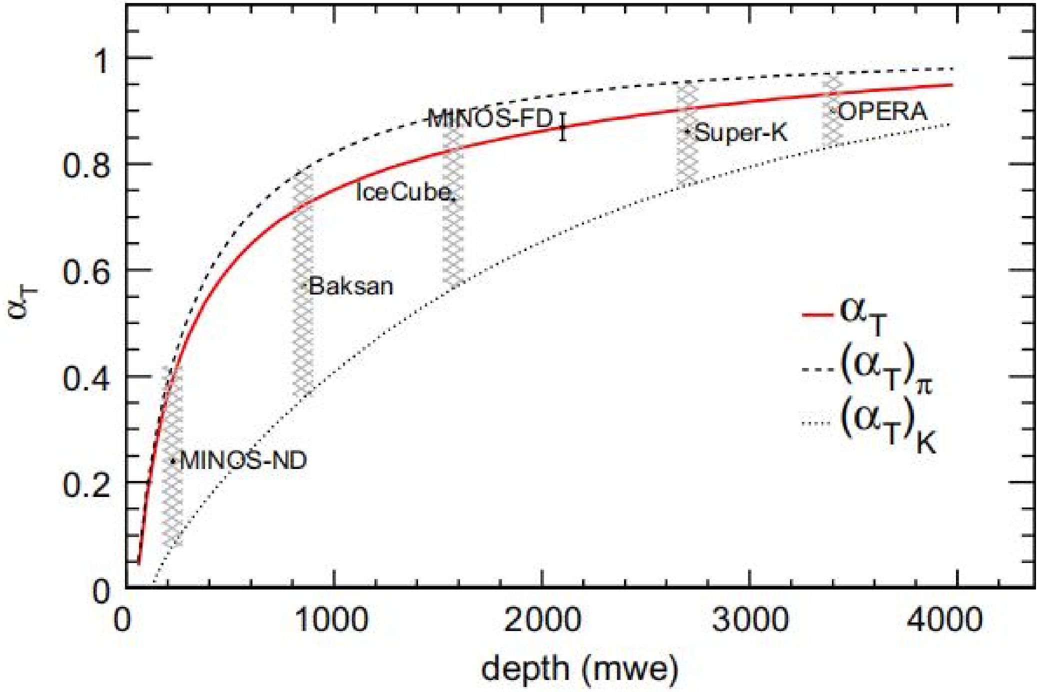


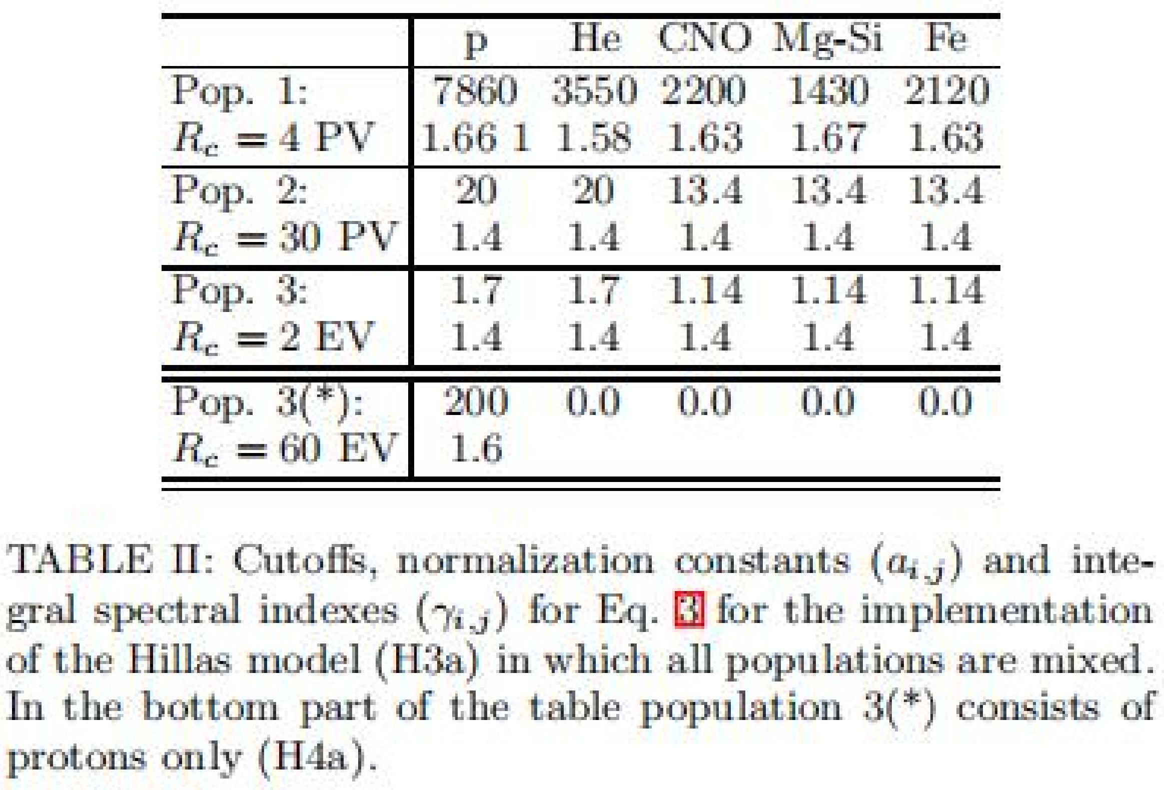
Fig. 3. The theoretical $\langle\alpha_T(X)\rangle$ (solid curve), the $\langle\alpha_T(X)\rangle_\pi$ (dashed curve), the $\langle\alpha_T(X)\rangle_K$ (dotted curve) for slant depths up to 4000 mwe. The MINOS data point is from [5]. The cross-hatched regions indicate the sensitivity (separation between the three models for a particular depth) that current underground detectors have to measurements of $\langle\alpha_T(X)\rangle$.

DOI: 10.1016/j.astropartphys.2009.12.006

Muon Simulation

H3A model for Cosmic Rays

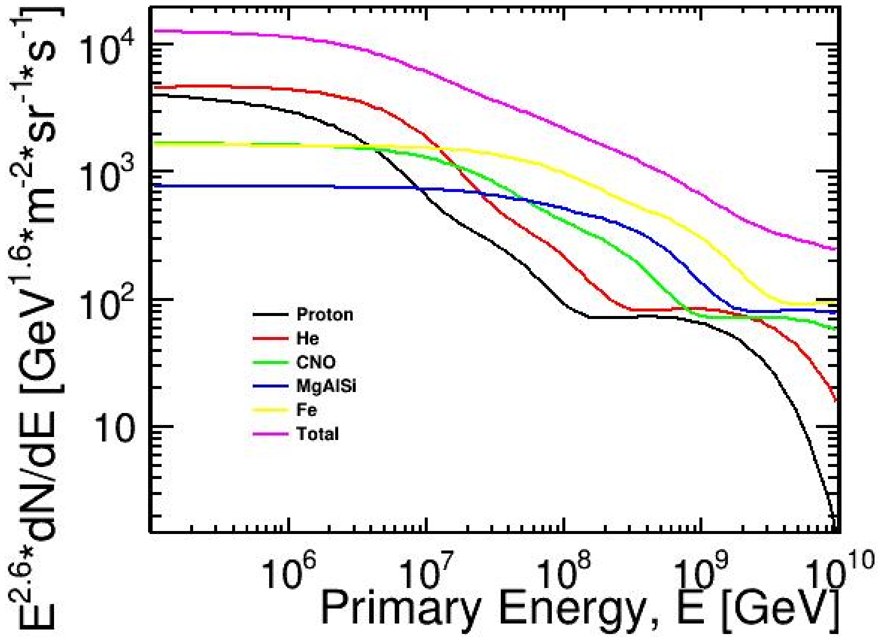
- Muon simulation start with the cosmic rays
- H3A model divides cosmic ray energy spectrum into five mainly parts



	p	He	CNO	Mg-Si	Fe
Pop. 1:	7860	3550	2200	1430	2120
$R_c = 4$ PV	1.66 1	1.58	1.63	1.67	1.63
Pop. 2:	20	20	13.4	13.4	13.4
$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Pop. 3:	1.7	1.7	1.14	1.14	1.14
$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4
Pop. 3(*):	200	0.0	0.0	0.0	0.0
$R_c = 60$ EV	1.6				

TABLE II: Cutoffs, normalization constants ($a_{i,j}$) and integral spectral indexes ($\gamma_{i,j}$) for Eq. 3 for the implementation of the Hillas model (H3a) in which all populations are mixed. In the bottom part of the table population 3(*) consists of protons only (H4a).

$$\phi_i(E) = \sum_{j=1}^{3} a_{i,j} E^{-\gamma_{i,i}} \times exp[-\frac{E}{Z_i R_{c,j}}]$$

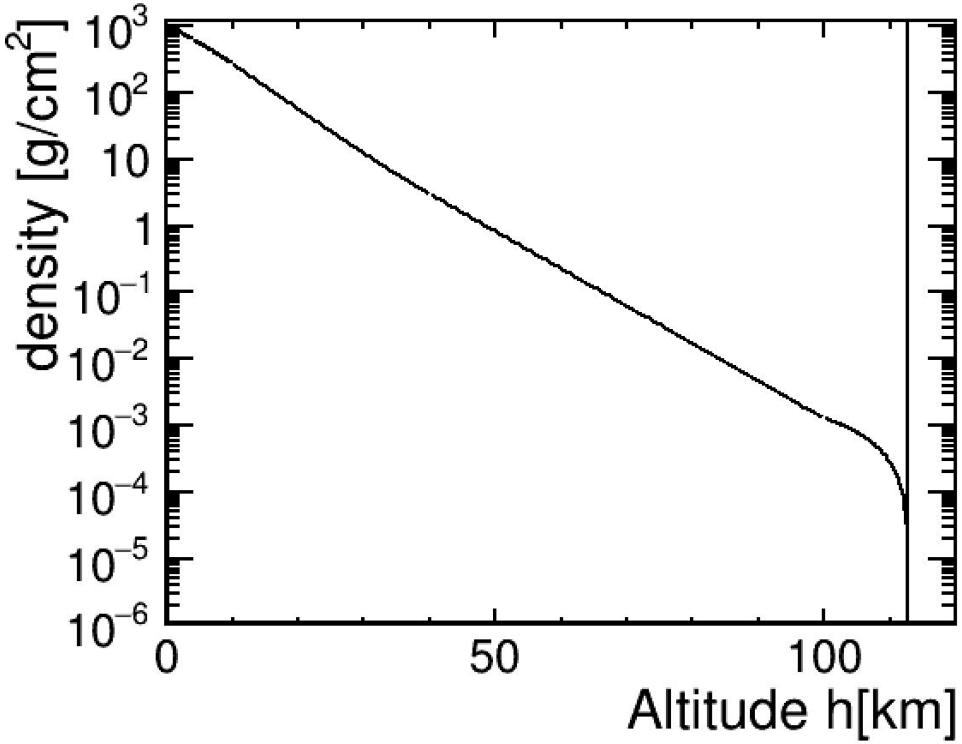


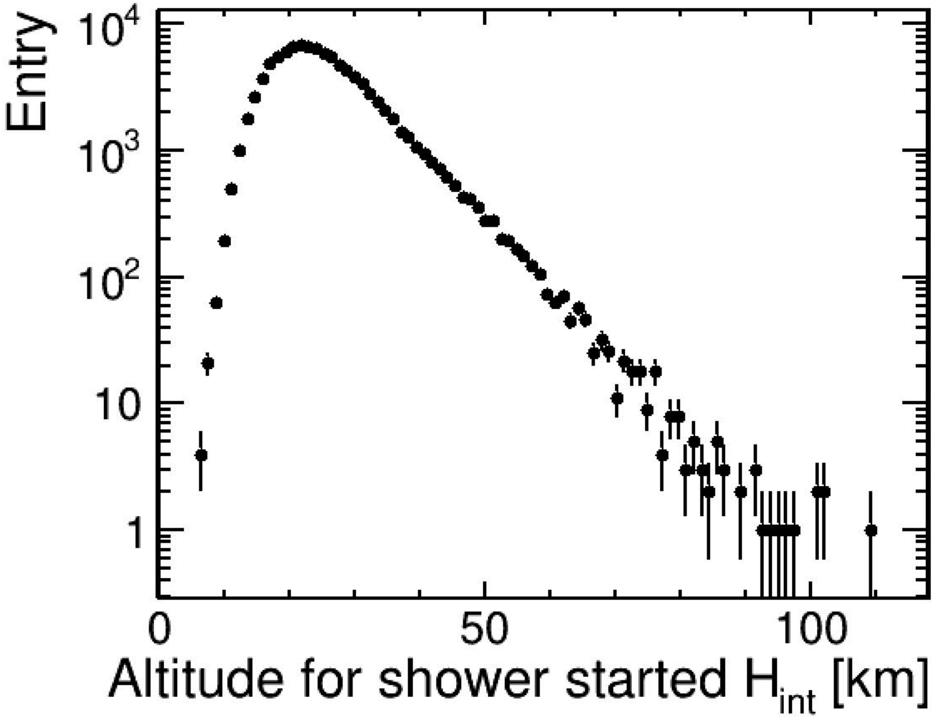
DOI: https://doi.org/10.48550/arXiv.1303.3565

Corsika Set

- According to the H3A model, the atmospheric clustering of the five initial components is simulated with Corsika separately
- Corsika make option
  - High-Energy Hadronic Interaction Models: SIBYLL
  - Low-Energy Hadronic Interaction Models: URQMD
  - Electromagnetic Interactions: NKG/EGS4
  - Cherenkov Options: No
  - Other Non-standard Options: 4+6+7a
    - NEUTRINO version
    - CHARMed particle/tau lepton version with PYTHIA
    - CURVED atmosphere version

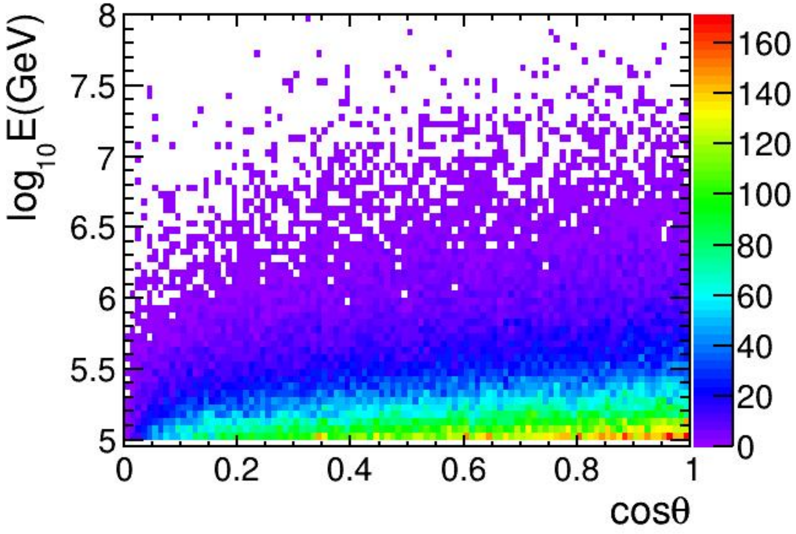
Atmospheric density profile and initial reaction height sampling





Corsika Input and Output

- Input
  - Particle type: Proton, He, CNO, MgAlSi, Fe
  - Energy: energy range $[10^7, 10^9]$ GeV, divide into 10 bins according to logE.
  - Events:10000
  - These settings mainly take into account the time required for simulation, it will be optimized later
- Output
  - Particle type: muon, neutrino, π, K etc.
  - Energy and zenith angle for different particle at earth surface
  - The histogram is an output example



Muon energy Vs. cosθ

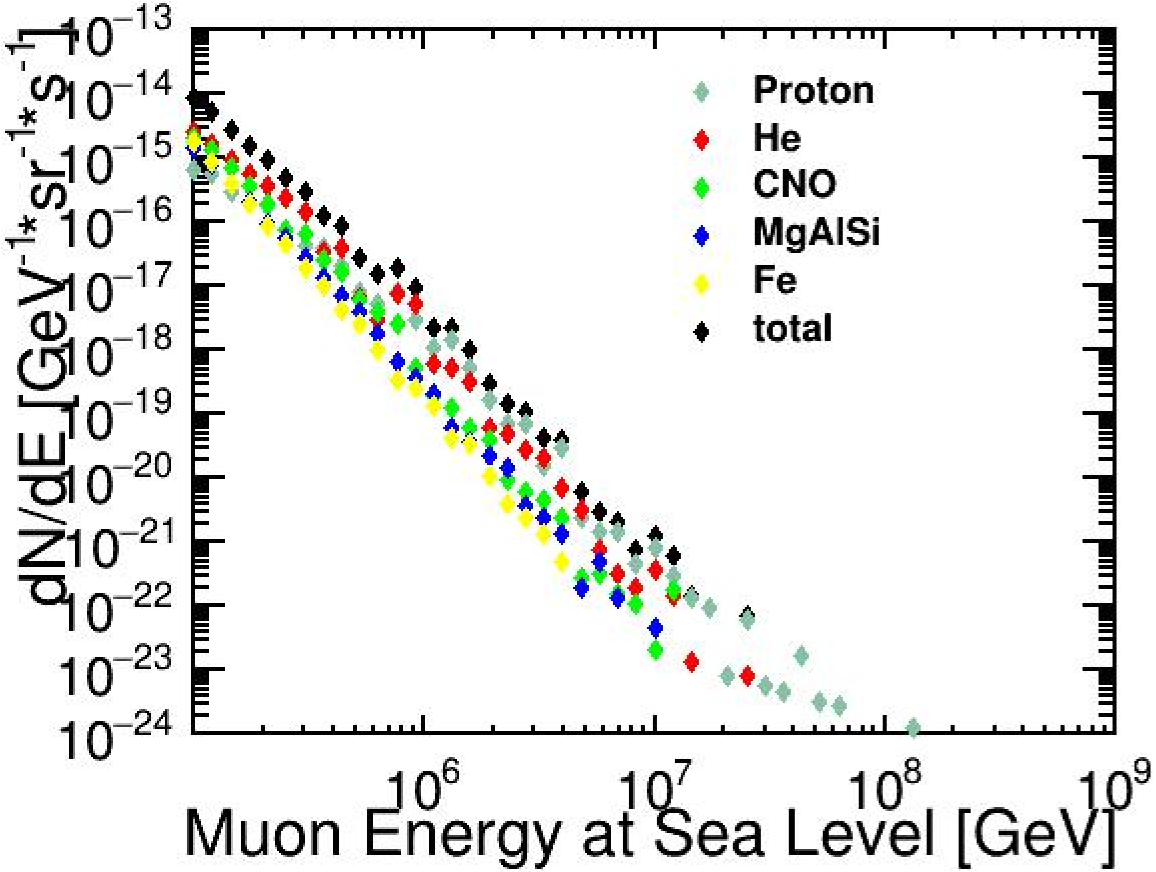
Surface High Energy Muon Spectrum

- We first calculate the muon energy spectrum at the earth surface

$$\phi_{muon}(E_{muon}) = \sum_{i=1}^{5} \frac{\int \phi_i(E_i) \cdot dE_i \cdot \eta_{i,E_{muon}}}{E_{muon}}$$

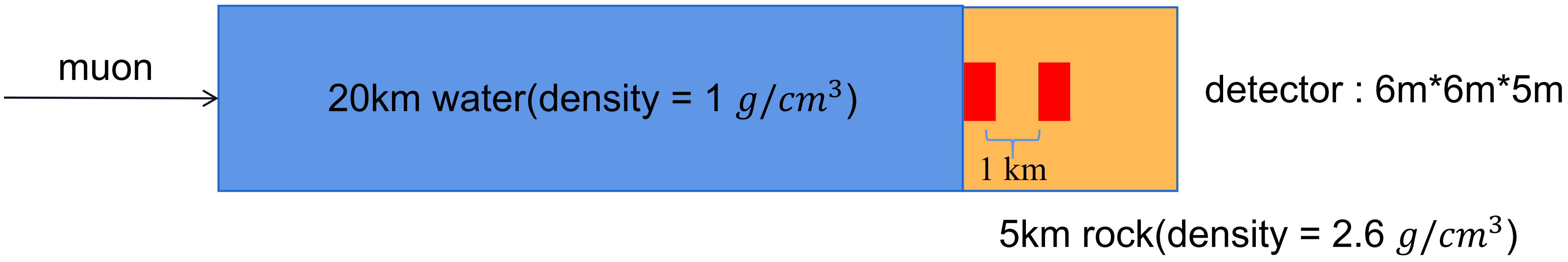
- i=1, 2, 3, 4, 5 represents protons, He, CNO, MgAlSi, Fe five parts.
- $\eta_{i,E_{muon}}$ represents "conversion probability", which means what is the probability that when the incident particle energy is E_i and the outgoing muon energy is E_{muon} at earth surface.

- Initial particle energy range is $[10^7, 10^9]$ GeV
- Flux result as right graph
- The simulation results give the muon surface flux as at $E_{min} = 10^5\ GeV$ for $8.549 \times 10^{-15}\ GeV^{-1} \cdot sr^{-1} \cdot s^{-1}$ and at $E_{max} = 1.318 \times 10^8\ GeV$ for $1.302 \times 10^{-24}\ GeV^{-1} \cdot sr^{-1} \cdot s^{-1}$



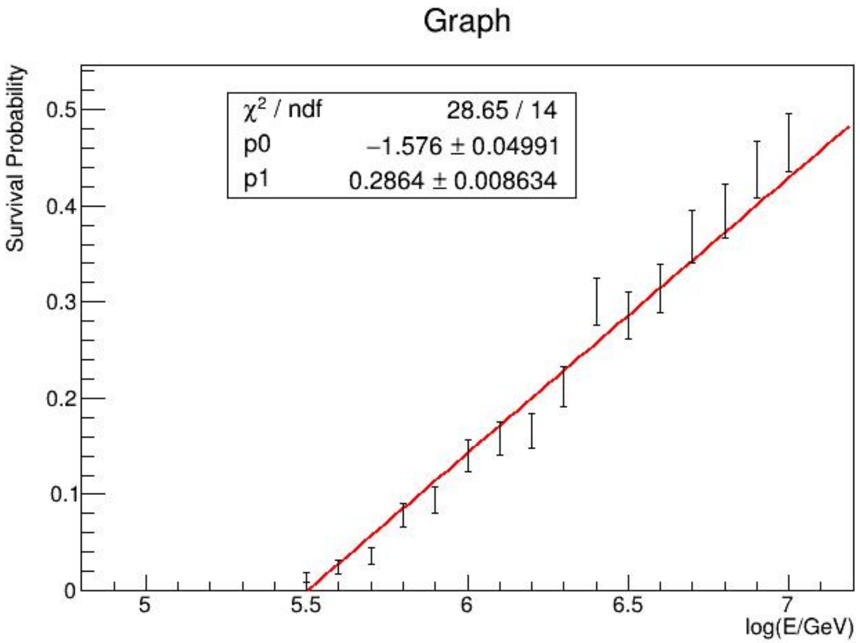
Energy Threshold for Deep Underground Muon

- We constructed the following geometric model (Daya Bay)



- The muon first passes through 20 km of water and then enters 5 km of rock, and muons are detected only if the deposition energy is greater than 10 MeV in both detectors.
- Scan incident muon energy with FLUKA

Energy Threshold Result

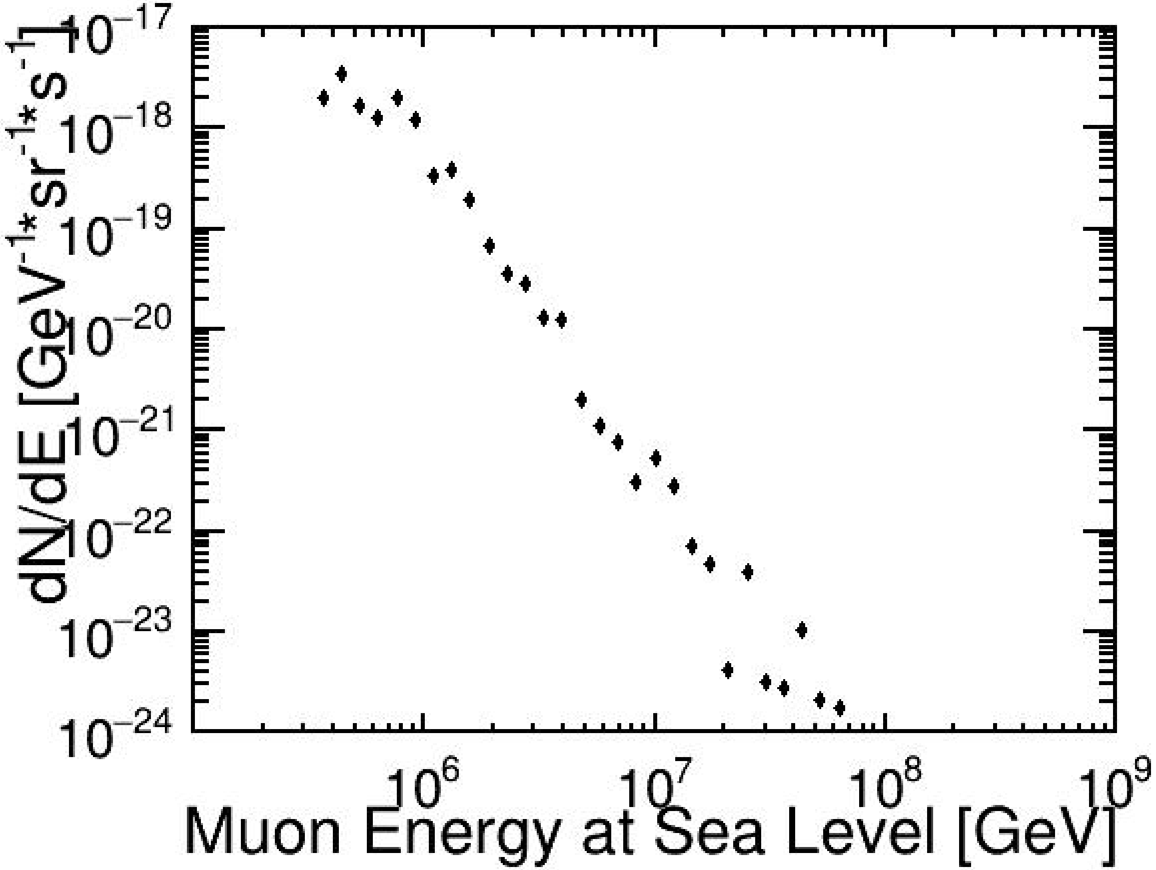


$$Detect\ Probability = 0.2864 \cdot log(E/GeV) - 1.576$$

- The fitting results give an energy threshold for horizontal direction $3.18 \times 10^5\ GeV$

Deep Underground Muon Flux Based on above Model

- Based on the above model, the deep underground muon flux energy spectrum for horizontal direction flight is shown in right Fig.



To do

- For energy threshold simulation part
  - Vary the incident angle direction to give all other angles result
- Neutrino Simulation
- Validating the QCD model
  - Change different hadronic interaction models like SIBYLL, QGSJET, EPOS, DPMJET
  - Comparing the results of data and simulations
- Change atmosphere density model(represent seasonal changes)
  - Validation of seasonal variations in muon fluxes
  - Calculation Charged π/K ratio

Summary

- We give a method to calculate muon flux from primordial cosmic rays, for initial particle energy range is $[10^7, 10^9]$ GeV. the muon surface flux as at $E_{min} = 10^5\ GeV$ for $8.549 \times 10^{-15}\ GeV^{-1} \cdot sr^{-1} \cdot s^{-1}$and at $E_{max} = 1.318 \times 10^8\ GeV$ for $1.302 \times 10^{-24}\ GeV^{-1} \cdot sr^{-1} \cdot s^{-1}$
- Based on the horizontal geometric model, the corresponding energy threshold for horizontal muon is $3.18 \times 10^5\ GeV$ (Applicable to Daya Bay), the full angle results will be given later
- The flux of deep underground muons can be estimated based on the model
- The next simulation will calculate seasonal variations muon flux and charged π/K ratio

Thank You

Back Up

QCD model related to EAS

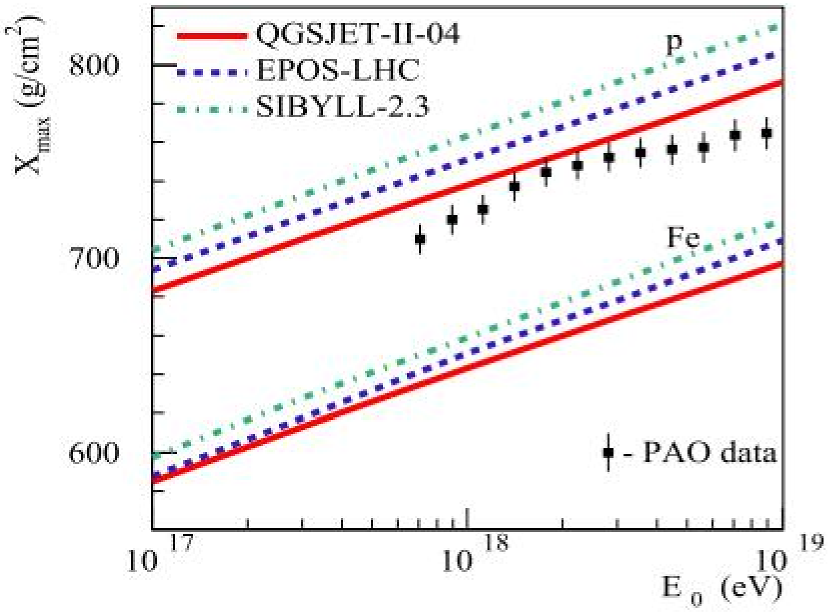


Fig. 2. Primary energy dependence of X_{max} for proton- and iron-initiated vertical EAS, calculated using the QGSJET-II-04, EPOS-LHC, and SIBYLL-2.3 models (solid, dashed, and dashed-dotted lines, respectively), compared to the data of the Pierre Auger Observatory (PAO) (Aab et al., 2014a) (squares).

Xmax is the depth of shower maximum.

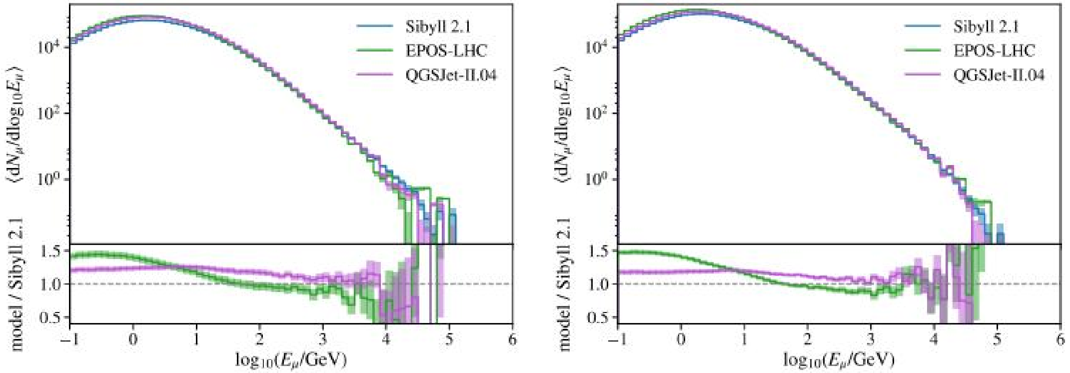


Figure 1: Muon spectrum in vertical proton (left) and iron (right) showers with primary energy around 10 PeV for Sibyll 2.1, QGSJet-II.04 and EPOS-LHC.

ICECUBE result

Seasonal variations and Charged π/K ratio

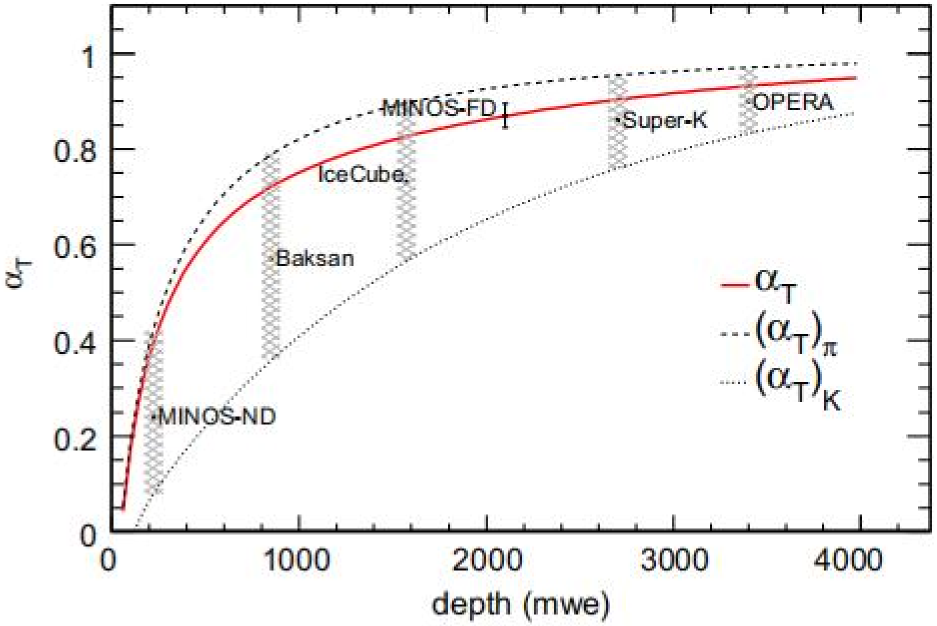


Fig. 3. The theoretical $\langle\alpha_T(X)\rangle$ (solid curve), the $\langle\alpha_T(X)\rangle_\pi$ (dashed curve), the $\langle\alpha_T(X)\rangle_K$ (dotted curve) for slant depths up to 4000 mwe. The MINOS data point is from [5]. The cross-hatched regions indicate the sensitivity (separation between the three models for a particular depth) that current underground detectors have to measurements of $\langle\alpha_T(X)\rangle$.

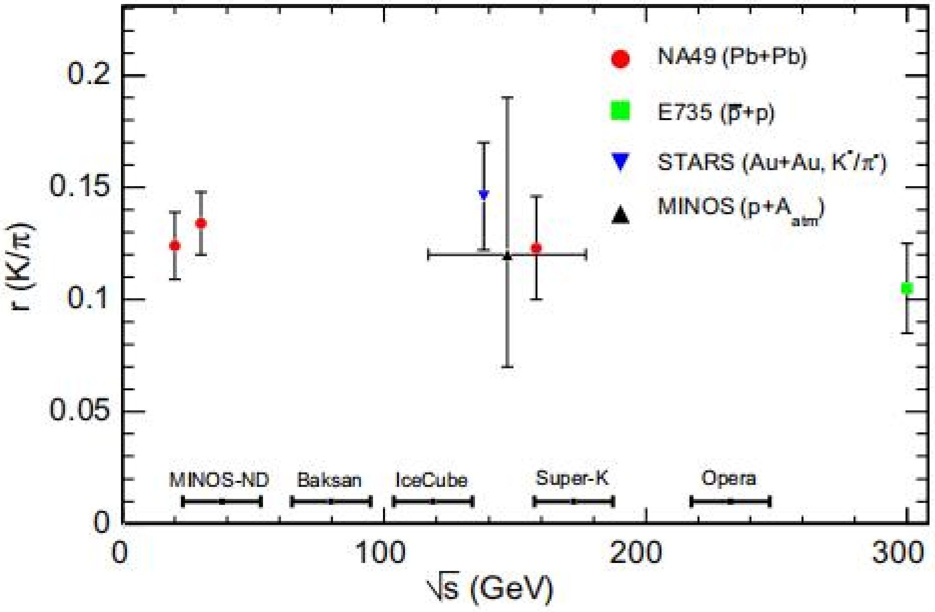
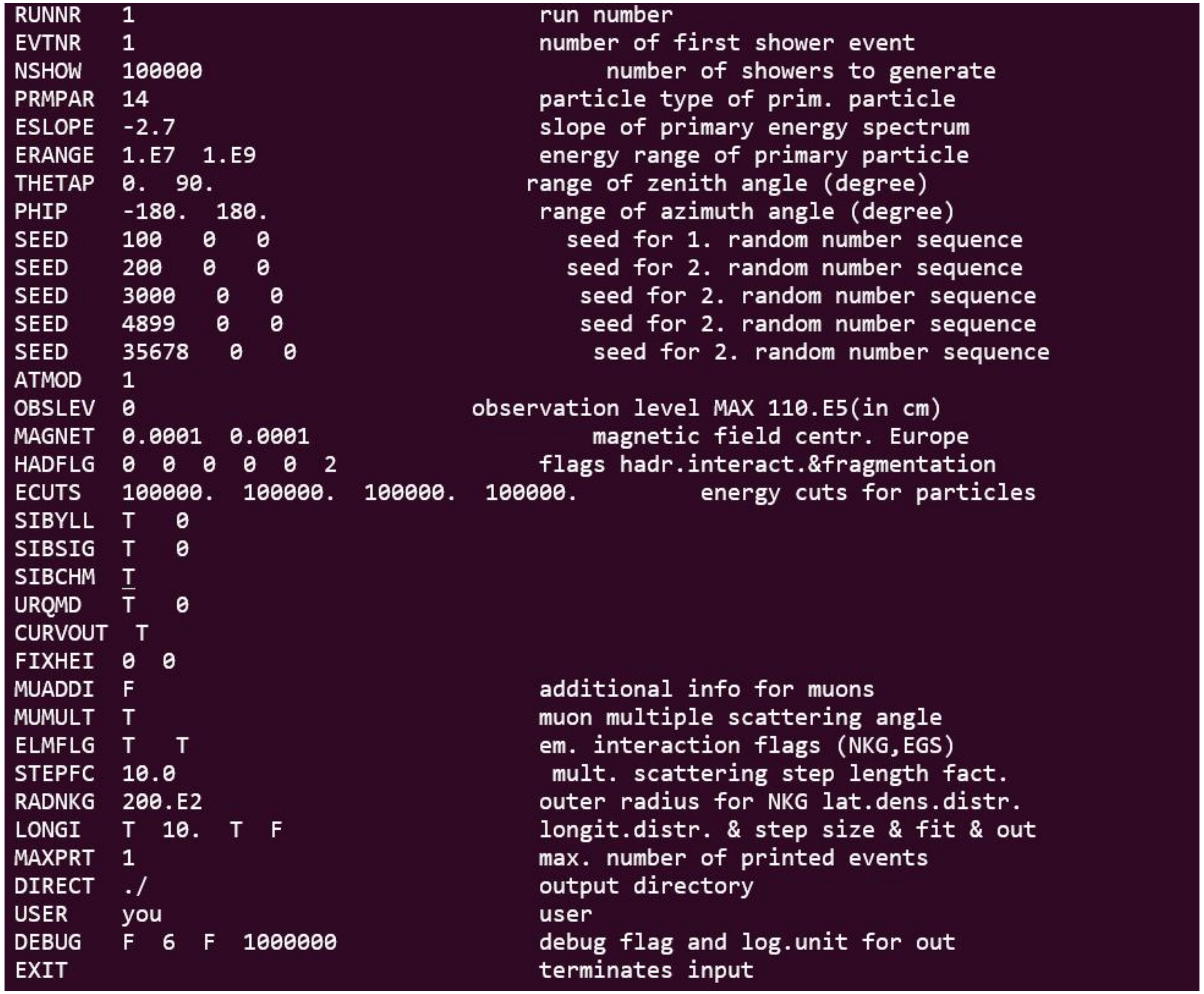


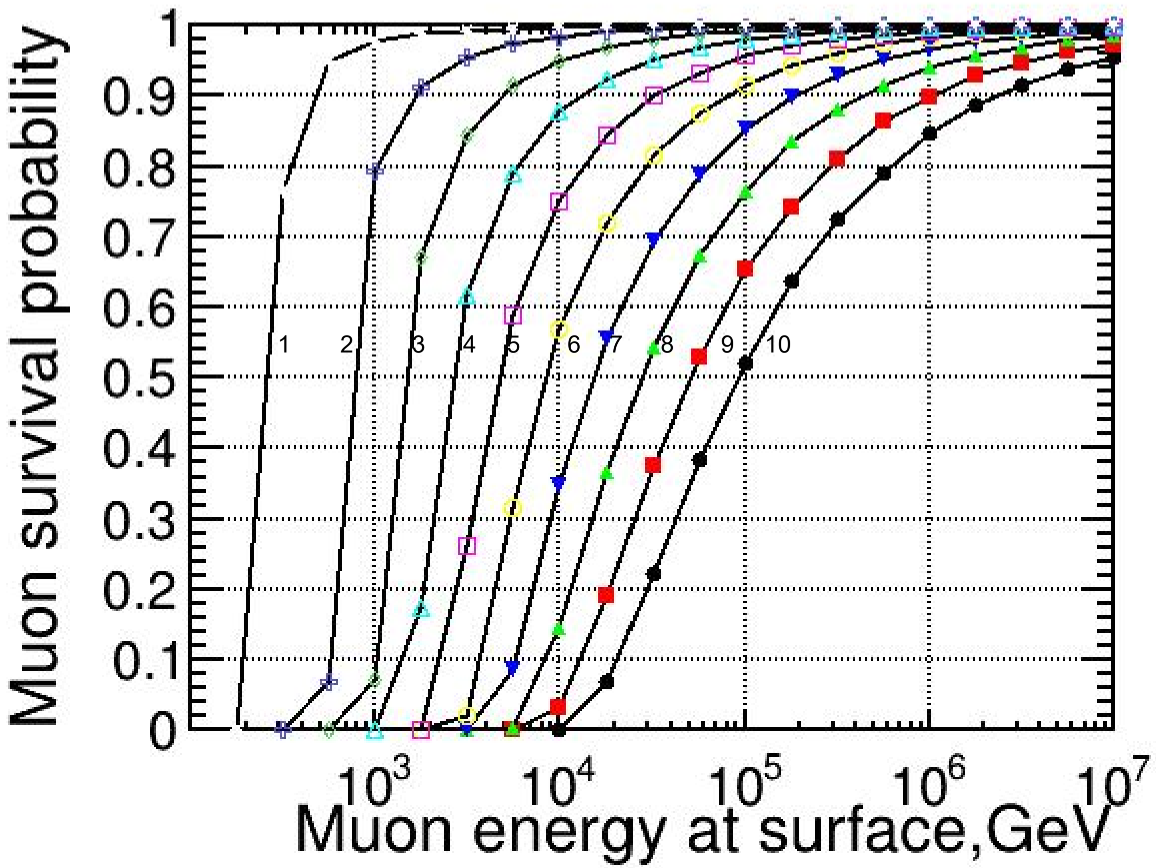
Fig. 4. A compilation of selected measurements of $r(K/\pi)$ for various primary particle center of mass energies ($\sqrt{s}$). The STARS value was from Au + Au collisions at RHIC [18], the NA49 measurement was from Pb + Pb collisions at SPS [19,20], the ISR measurement was from p + p collisions [17], and the MINOS value was from cosmic ray primaries + atmospheric nuclei collisions [5]. The thick horizontal bars near the bottom of the graph show the typical ranges of cosmic ray primary energies for the collisions that produce muons observed by the underground detectors indicated.

cosmic ray simulation



```
RUNNR   1                              run number
EVTNR   1                              number of first shower event
NSHOW   100000                              number of showers to generate
PRMPAR  14                             particle type of prim. particle
ESLOPE  -2.7                           slope of primary energy spectrum
ERANGE  1.E7  1.E9                     energy range of primary particle
THETAP  0.  90.                       range of zenith angle (degree)
PHIP    -180.  180.                    range of azimuth angle (degree)
SEED    100   0   0                      seed for 1. random number sequence
SEED    200   0   0                      seed for 2. random number sequence
SEED    3000   0   0                      seed for 2. random number sequence
SEED    4899   0   0                      seed for 2. random number sequence
SEED    35678   0   0                      seed for 2. random number sequence
ATMOD   1
OBSLEV  0                         observation level MAX 110.E5(in cm)
MAGNET  0.0001  0.0001                     magnetic field centr. Europe
HADFLG  0  0  0  0  0  2               flags hadr.interact.&fragmentation
ECUTS   100000.  100000.  100000.  100000.         energy cuts for particles
SIBYLL  T   0
SIBSIG  T   0
SIBCHM  T
URQMD   T   0
CURVOUT  T
FIXHEI  0  0
MUADDI  F                              additional info for muons
MUMULT  T                              muon multiple scattering angle
ELMFLG  T   T                          em. interaction flags (NKG,EGS)
STEPFC  10.0                            mult. scattering step length fact.
RADNKG  200.E2                         outer radius for NKG lat.dens.distr.
LONGI   T  10.  T  F                   longit.distr. & step size & fit & out
MAXPRT  1                              max. number of printed events
DIRECT  ./                             output directory
USER    you                            user
DEBUG   F  6  F  1000000               debug flag and log.unit for out
EXIT                                   terminates input
```

结果复现



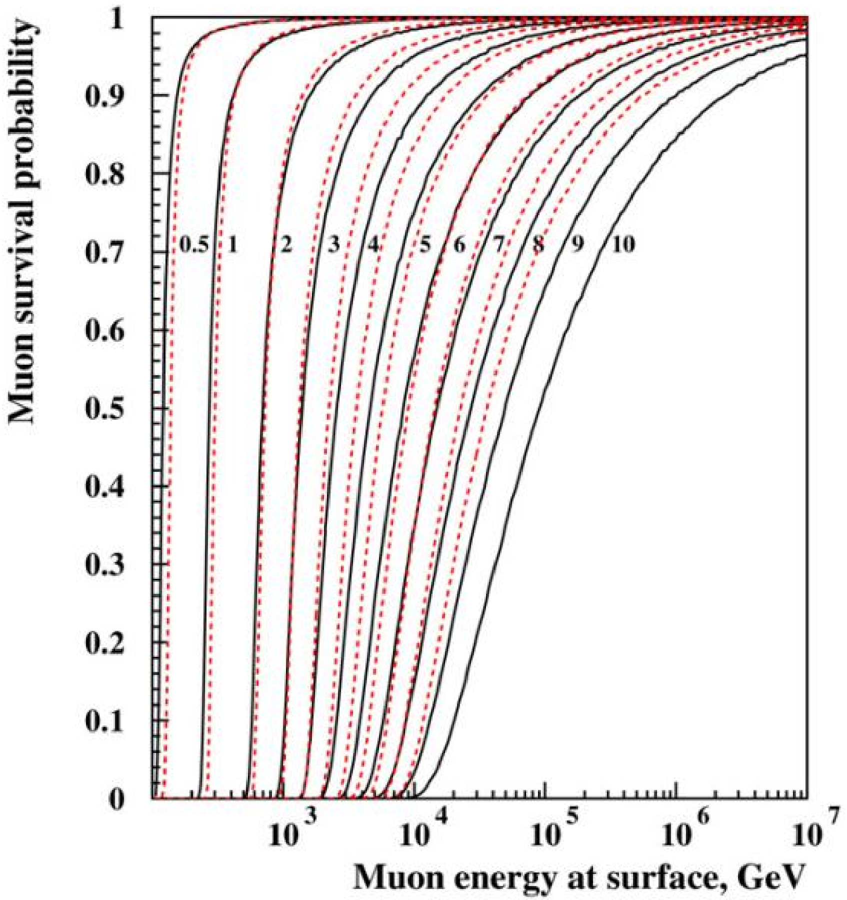
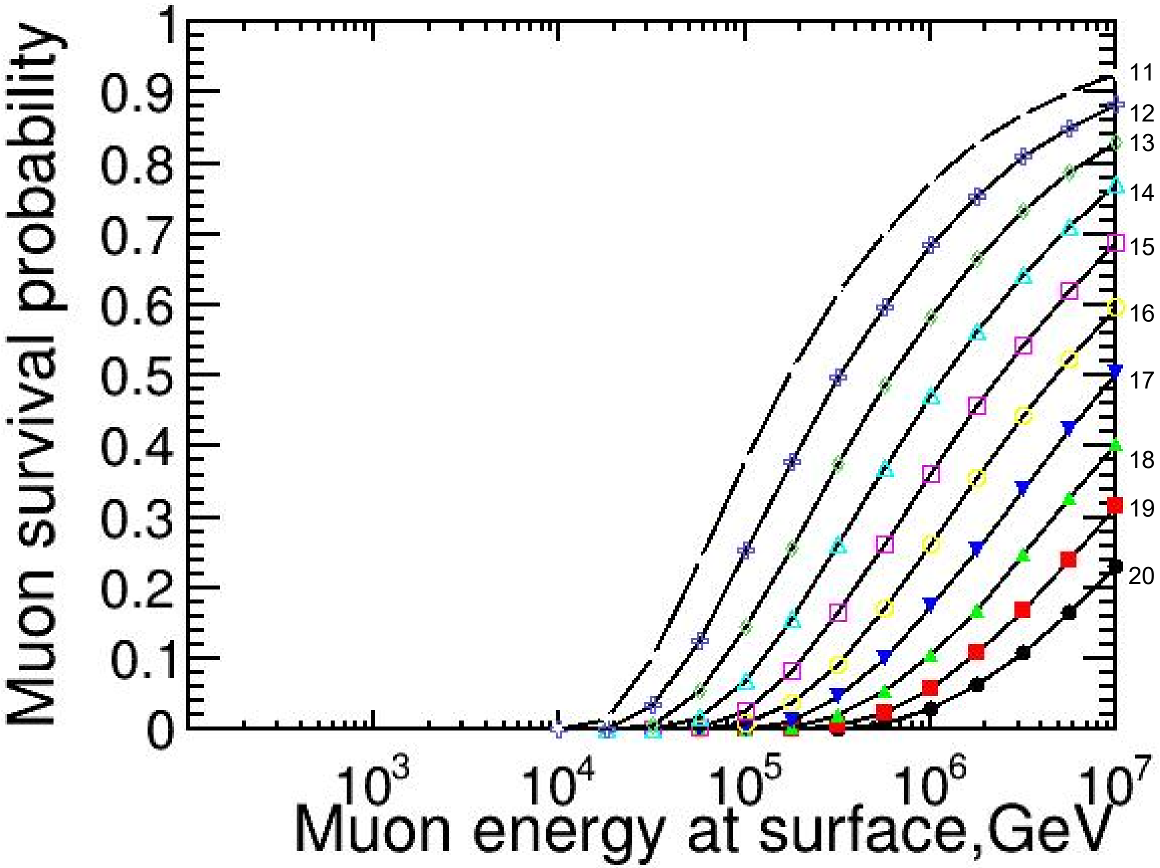
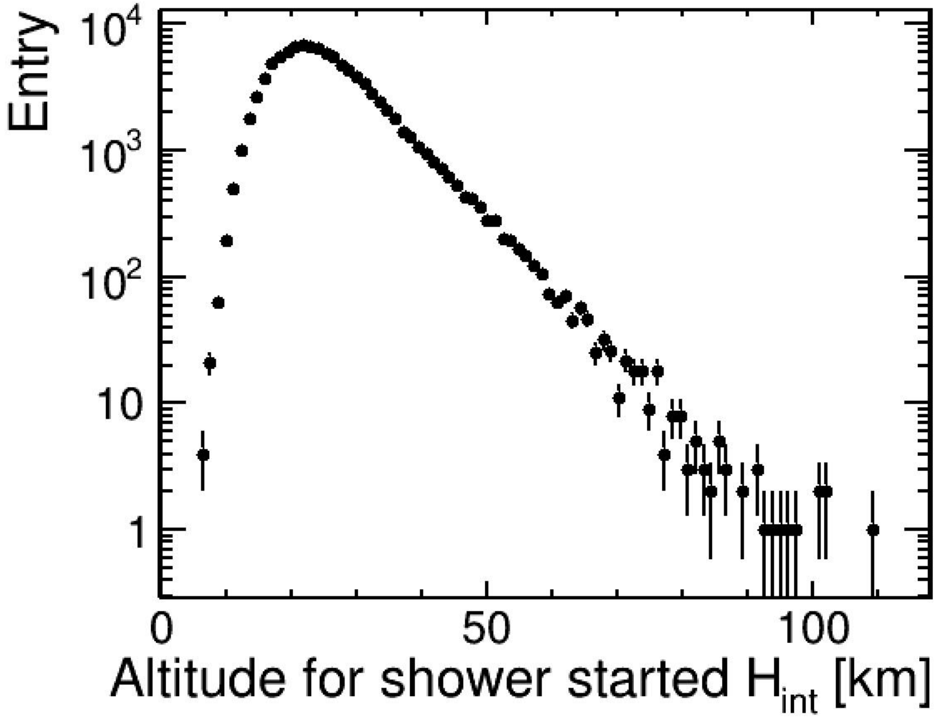
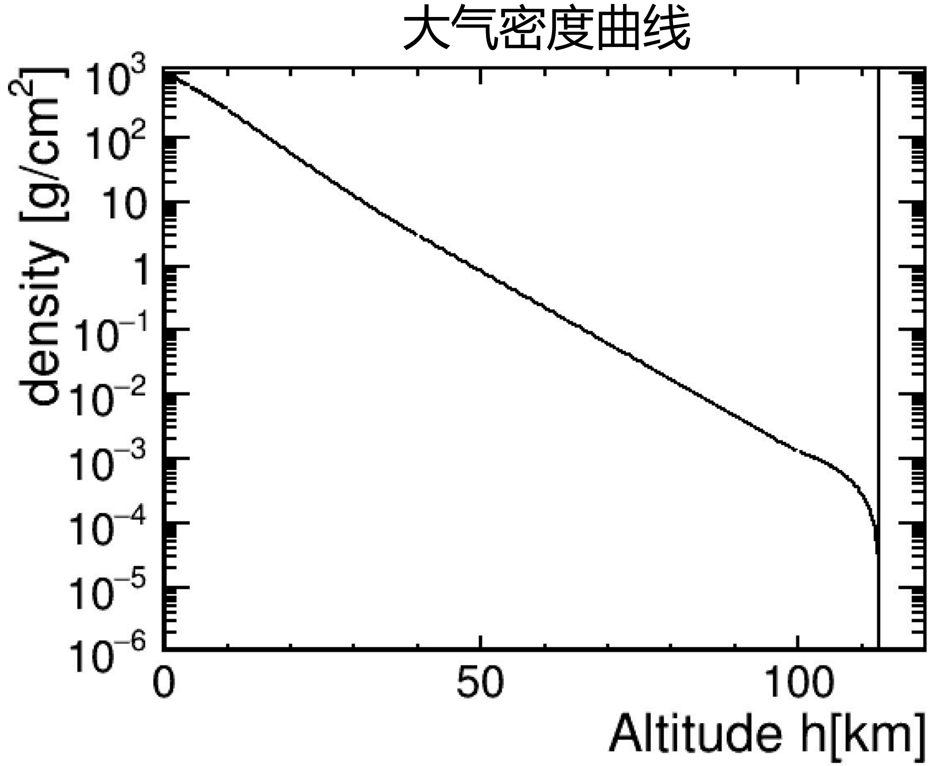


Fig. 1. Survival probabilities as functions of muon energy at surface for different depths (from 0.5 to 10 km w. e.) in standard rock (black solid curves) and water (red dashed curves). Numbers to the right from each solid curve show the depths in km w. e. for standard rock. Survival probability curves for water are shifted to the right (for small depths) or to the left (for depths larger than 2 km w. e.) relative to those for standard rock. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


Muon survival probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^3
10^4
10^5
10^6
10^7
Muon energy at surface,GeV
11
12
13
14
15
16
17
18
19
20

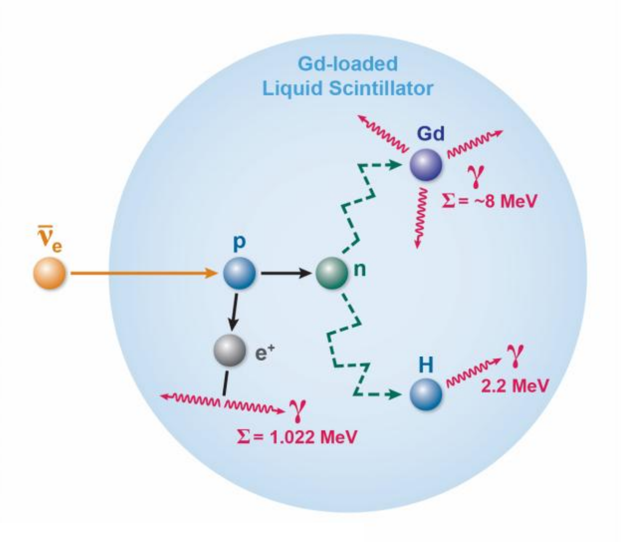
FIXHEI随机抽样

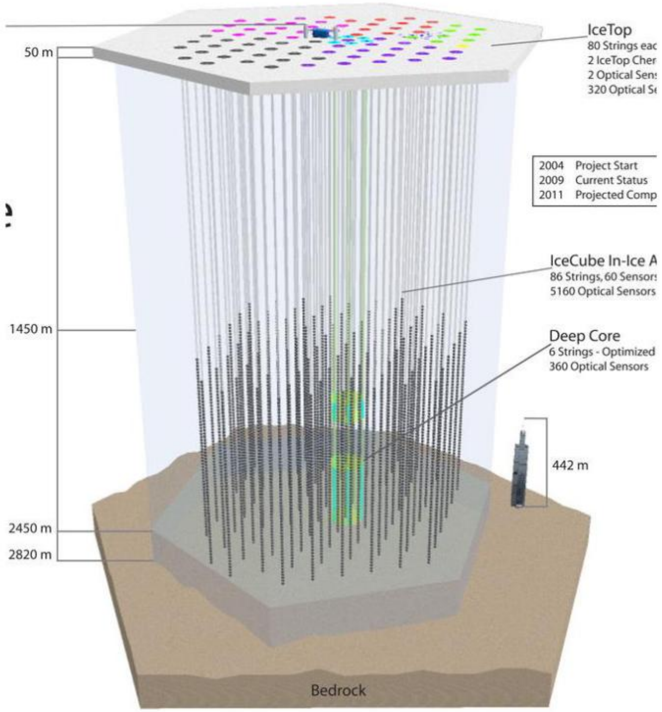

Entry
10^4
10^3
10^2
10
1
0
50
100
Altitude for shower started H_{int} [km]

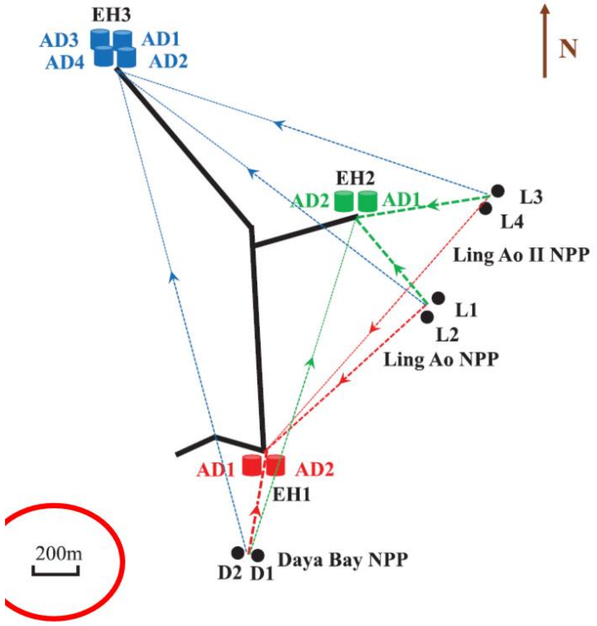

大气密度曲线
density [g/cm^2]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
50
100
Altitude h[km]

Daya Bay Experiment

- Detect neutrino with inverse beta decay
  - $\overline{\nu_e} + p \rightarrow e^+ + n$
- Three separate halls about 1 km apart
- Good underground neutrino telescope



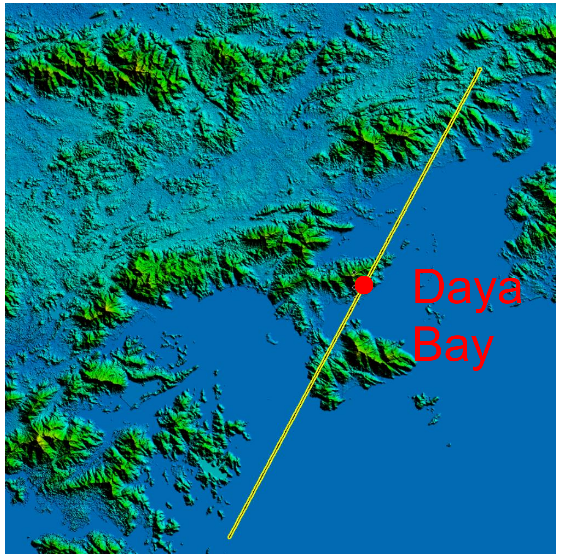




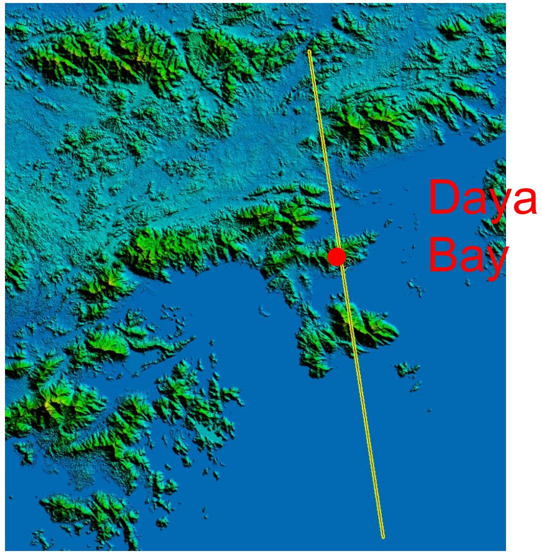
Topographic map of two-site line direction

- Topographic profile within ±35 km along any two sites line direction

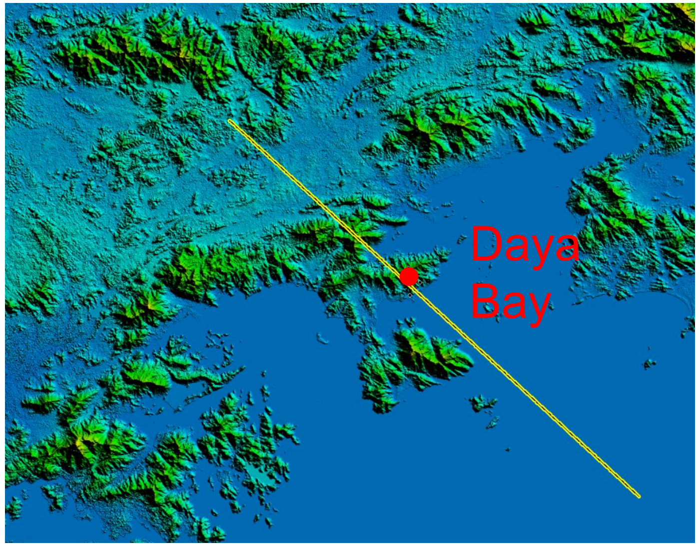
EH1EH2



EH1EH3

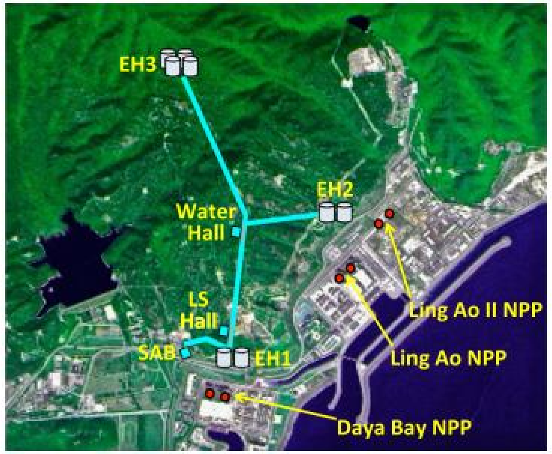


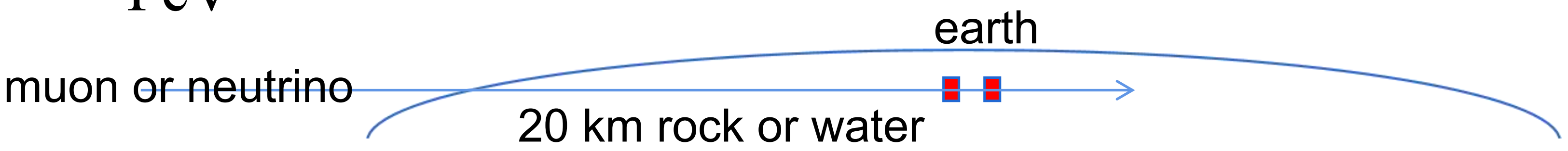
EH2EH3



Neutrino or Muon ?

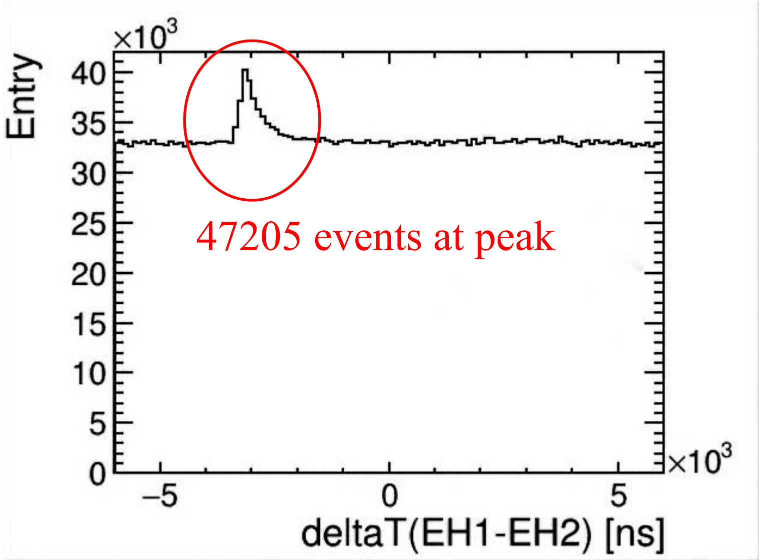
- Result for two-site coincidence events at Daya Bay
- We should simulate the two kinds of particles separately
- Expected energy threshold is above 100 TeV or even up to 10 PeV



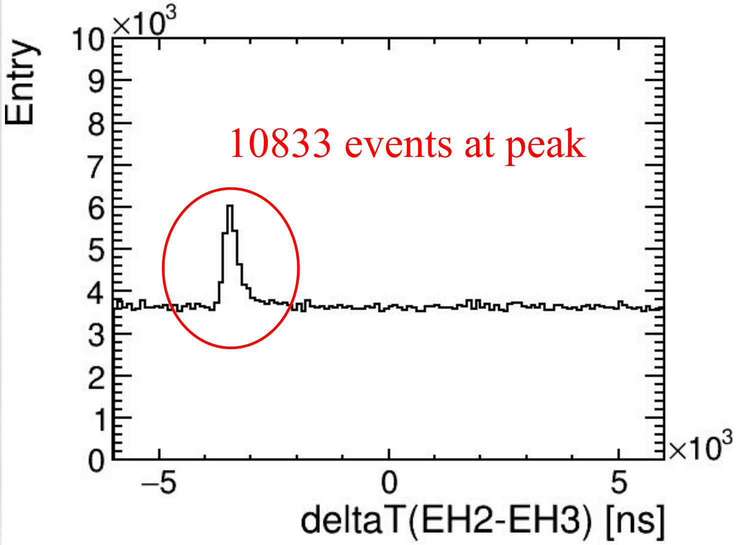

earth

muon or neutrino

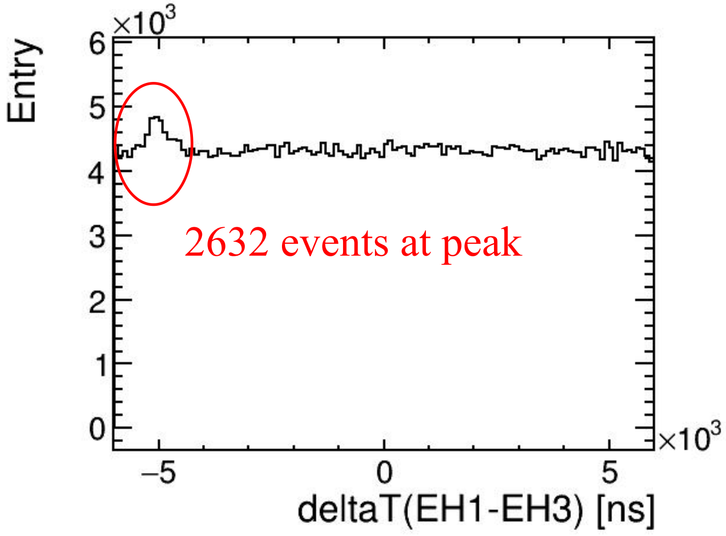
20 km rock or water



47205 events at peak



10833 events at peak



2632 events at peak