Underground Multi-Site Detectors

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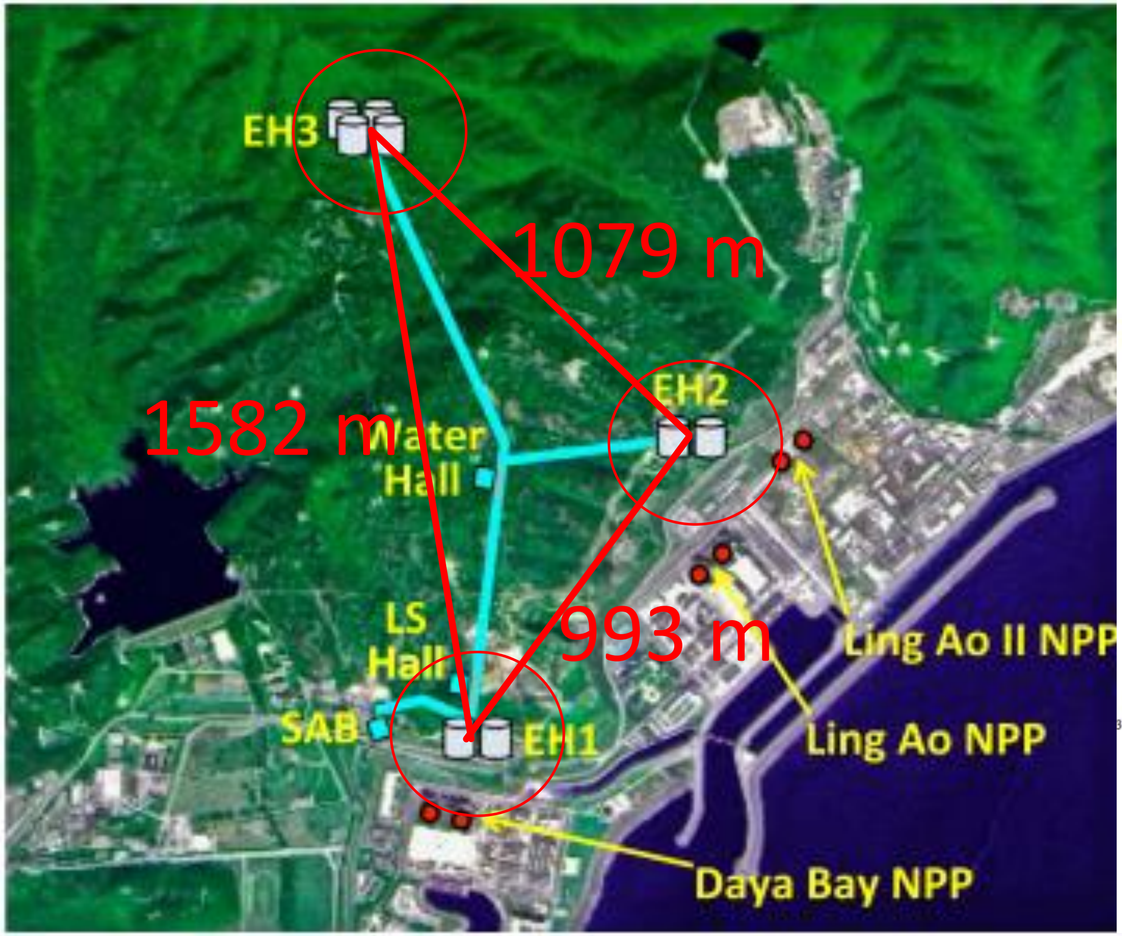
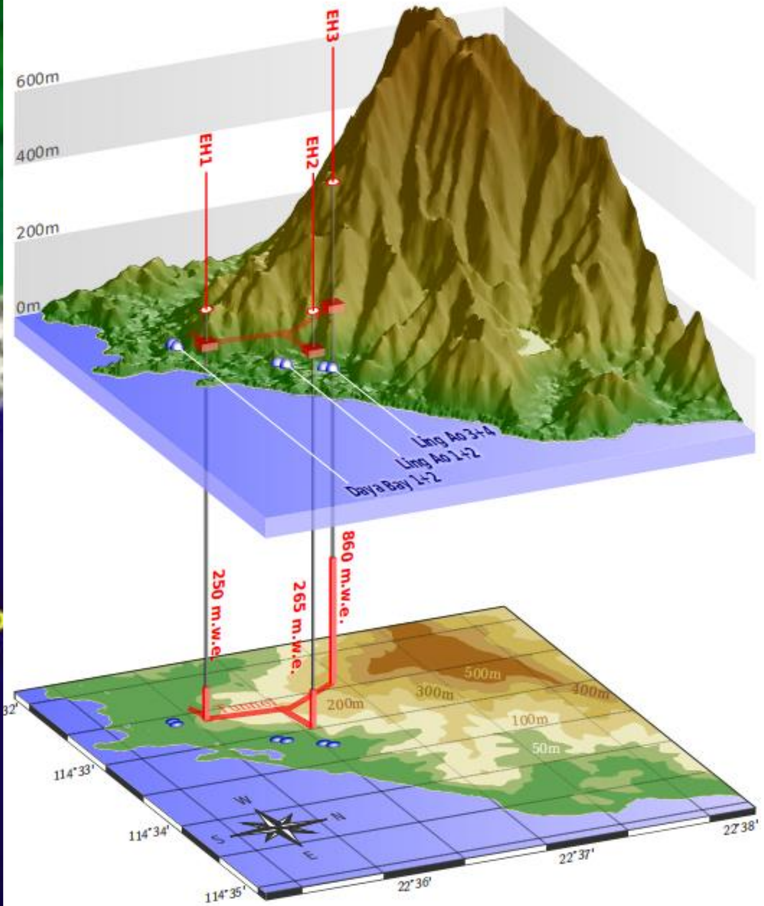
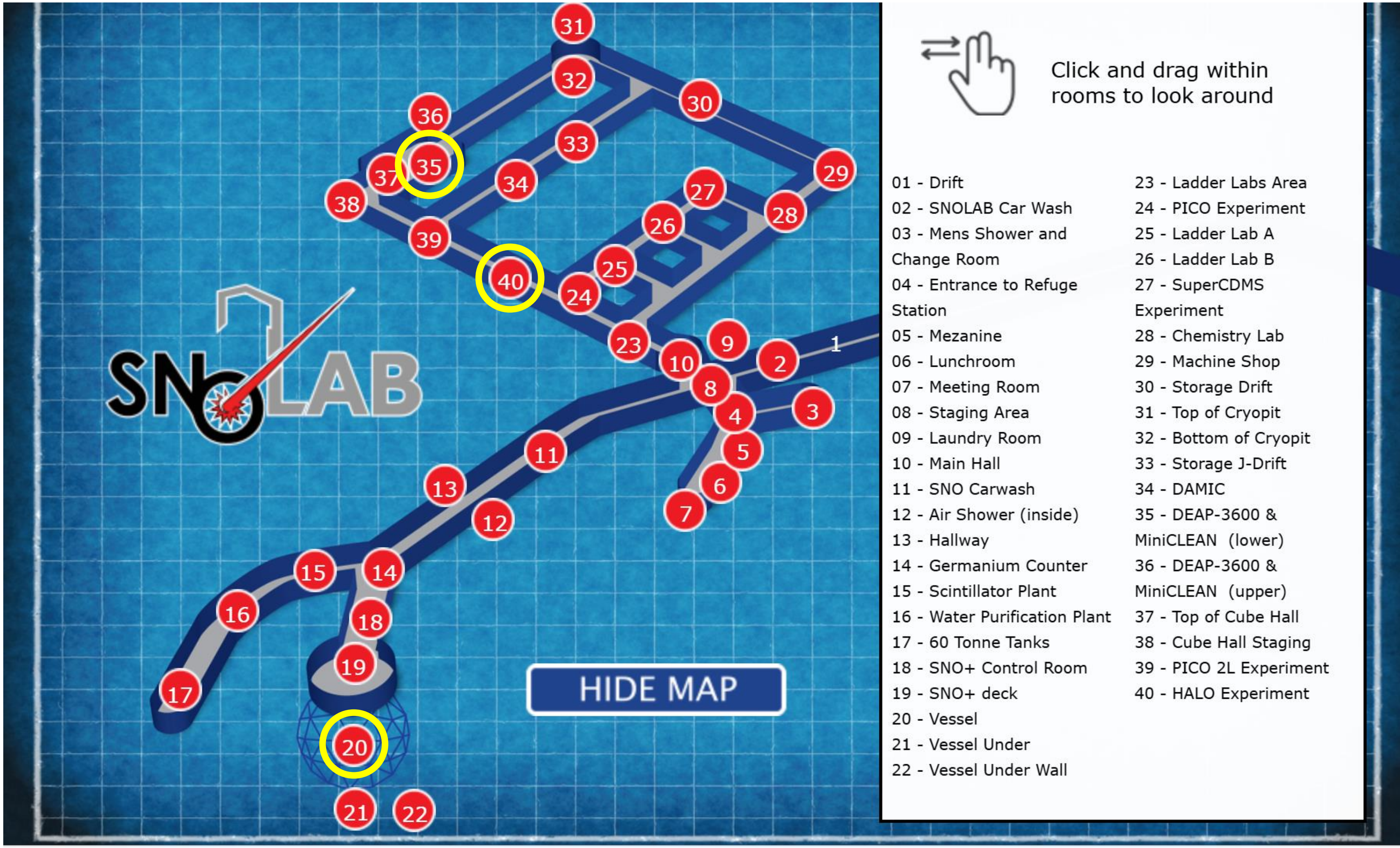
Daya Bay Experiment-3Site-8Detectors

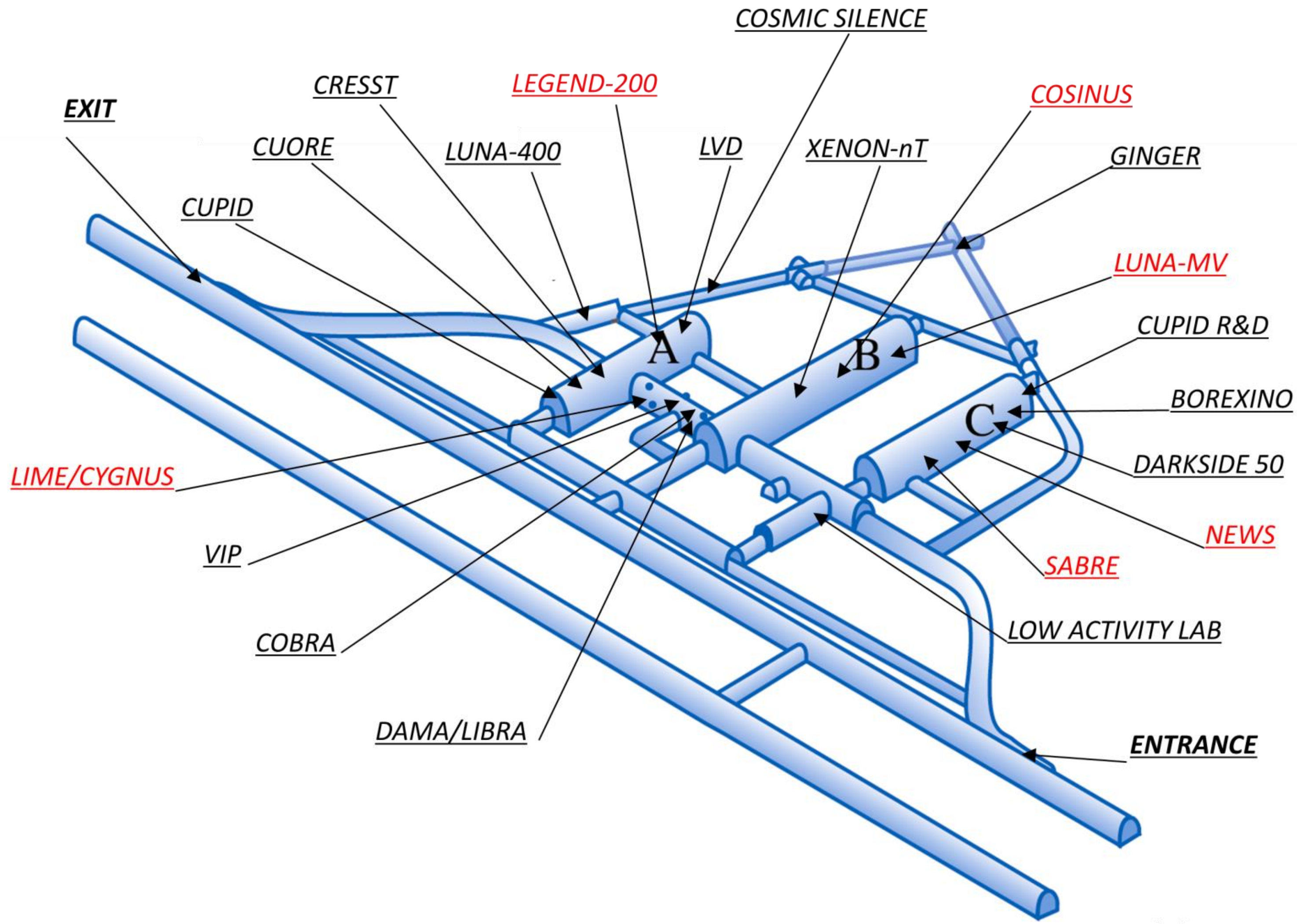




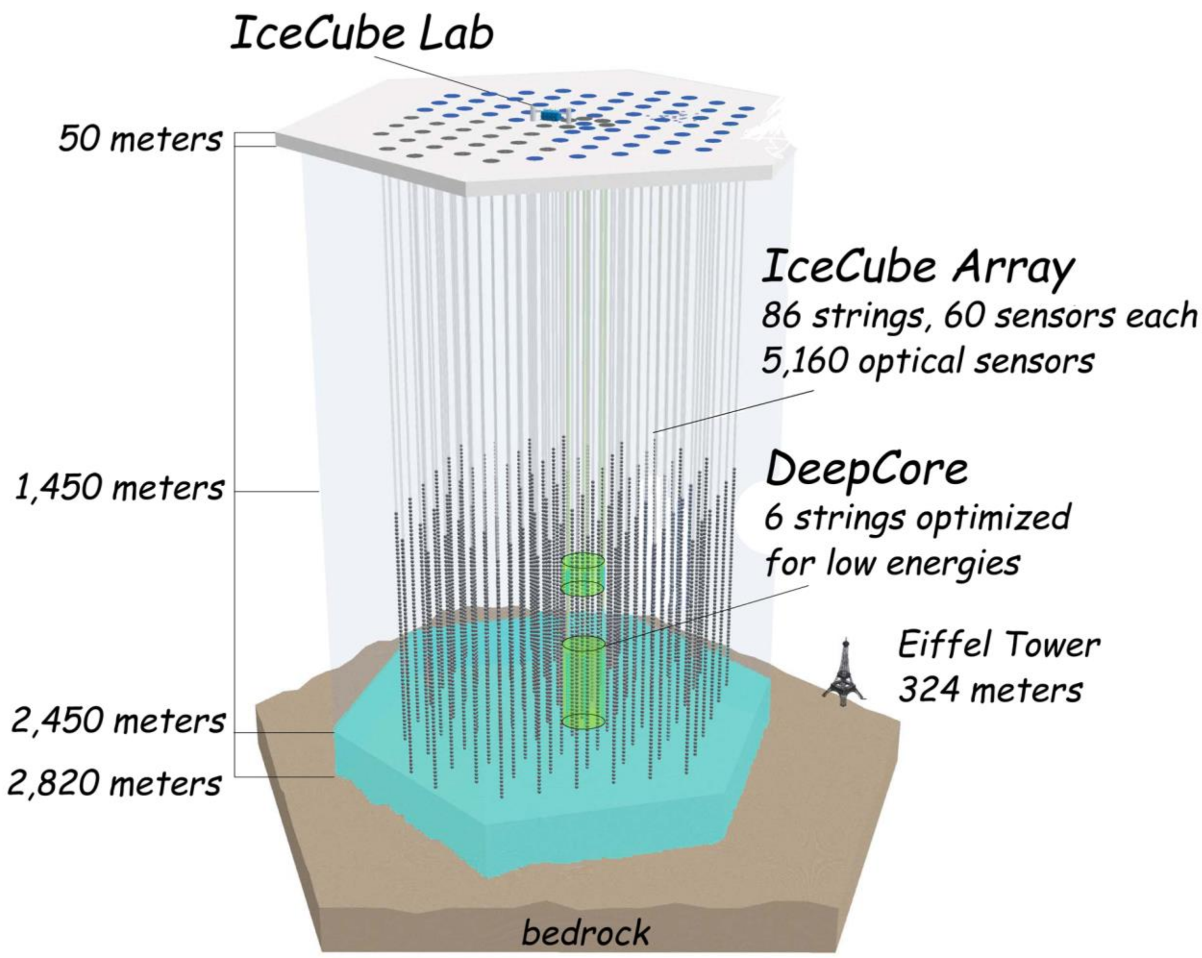
SNO Laboratory-Several Detectors



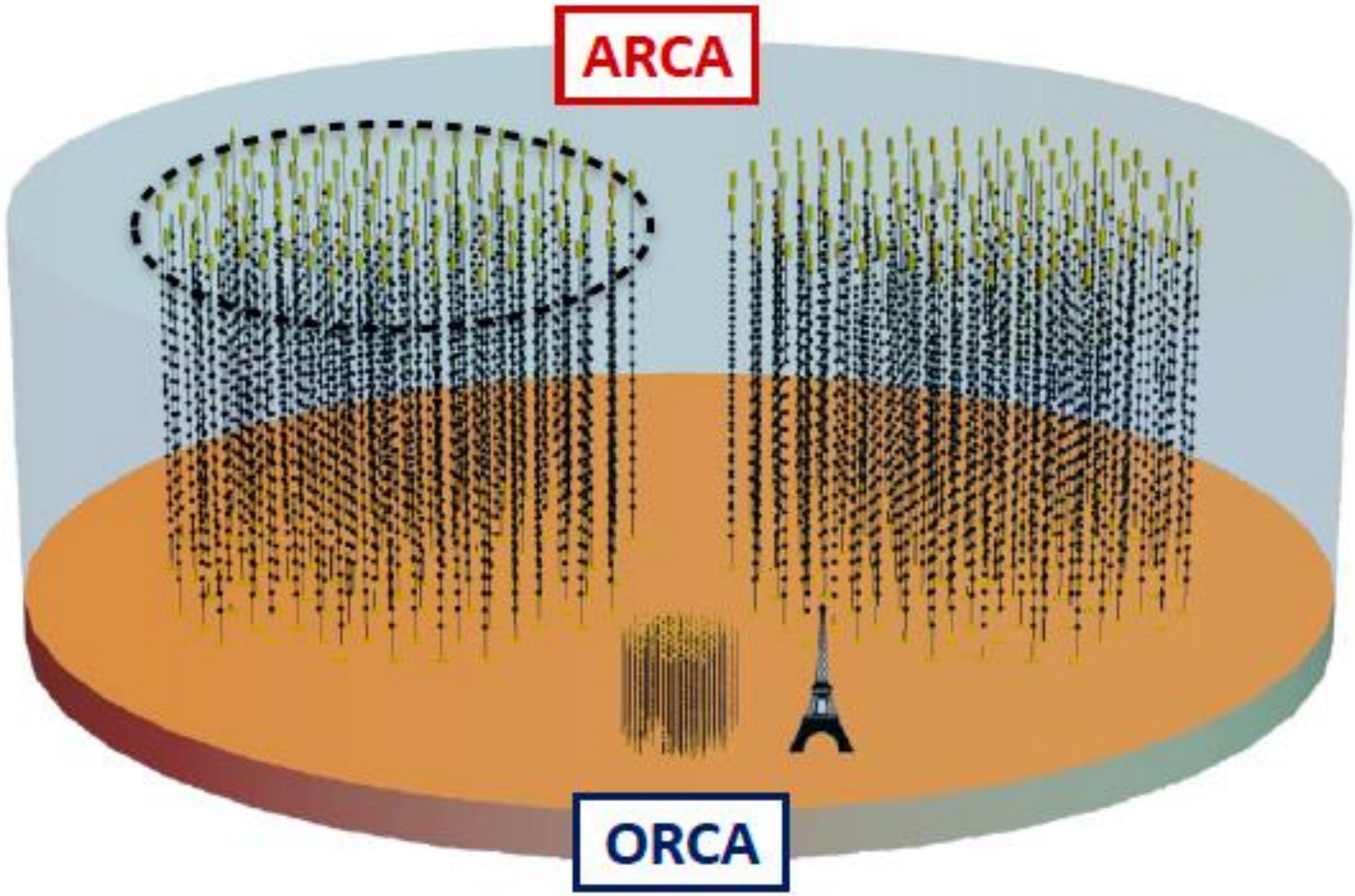
Gran Sasso-Several Detectors



IceCube – in ice experiment



KM3Net – in water experiment



Similarity between them?

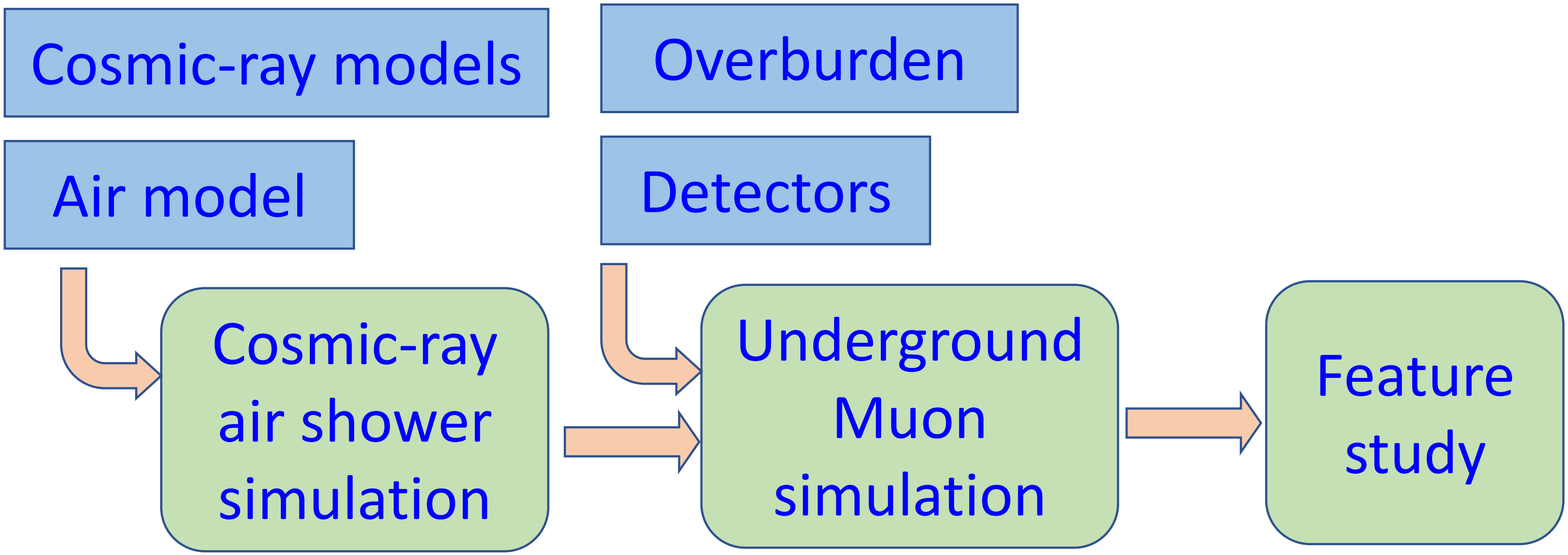
Motivation

- Underground laboratory – hosting multi experiments
- All synchronized to sub μs with GPS timers
- All with muon detection capability
- Use them jointly as a giant shower detector
- Dimension – comparable to IceCube and KM3NeT
- Medium – transparent vs opaque
- Cost – could be lower than remote in-ice in-ocean experiment
- Deficiency – low granularity, can be improved

In this talk

- Use Daya Bay underground experiment as an example
- 3 underground sites: EH1 (2 detectors), EH2 (2 detectors), and EH3 (4 detectors)
- Report the ability to measure cosmic-ray showers
- Features including the event rate, time structure, energy scale, related QCD models

Study method flow chart



Cosmic-ray models

- H3A model

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

j=1: acceleration of supernova remnants

j=2: high-energy galactic component of unknown origin

j=3: extragalactic origin

		p	He	CNO	MgAlSi	Fe
$j=1$	$a_{i,j}$	7860	3550	2200	1430	2120
$R_c = 4PeV$	$\gamma_{i,j}$	1.66	1.58	1.63	1.67	1.63
$j=2$	$a_{i,j}$	20	20	13.4	13.4	13.4
$R_c = 30PeV$	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4
$j=3$	$a_{i,j}$	1.7	1.7	1.14	1.14	1.14
$R_c = 2000PeV$	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4

Cosmic-ray models

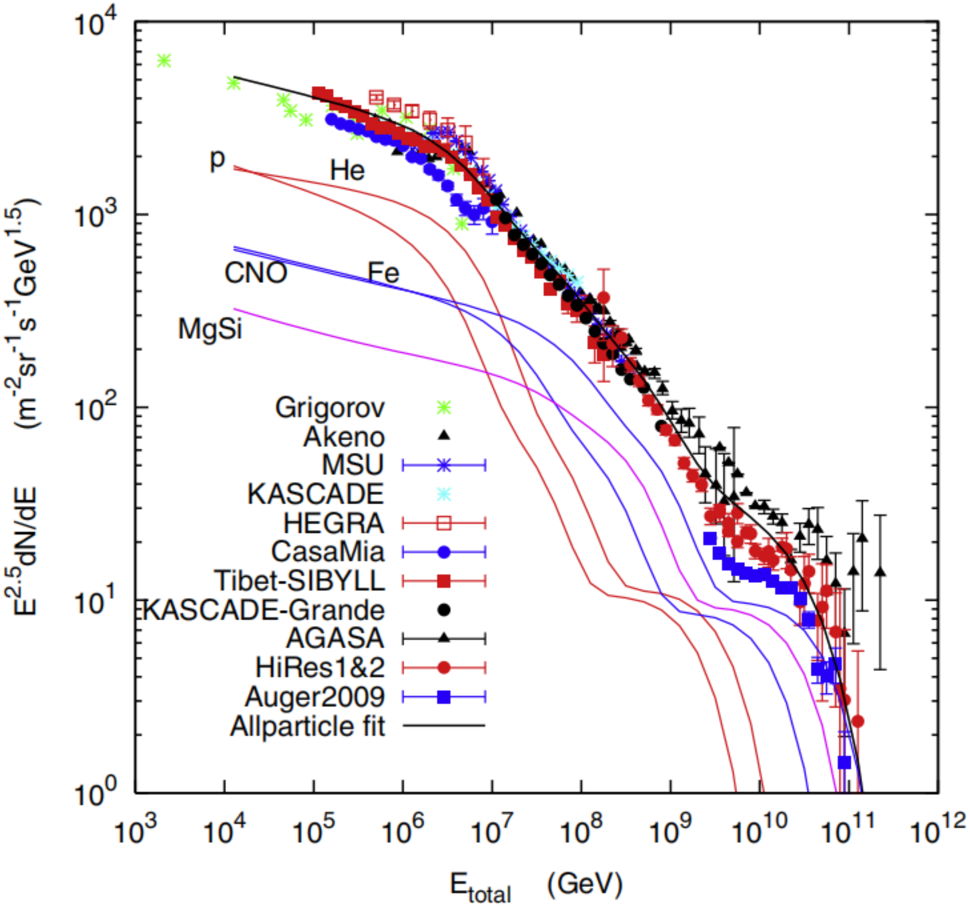
- ➢ H3A model

j=1: acceleration of supernova remnants

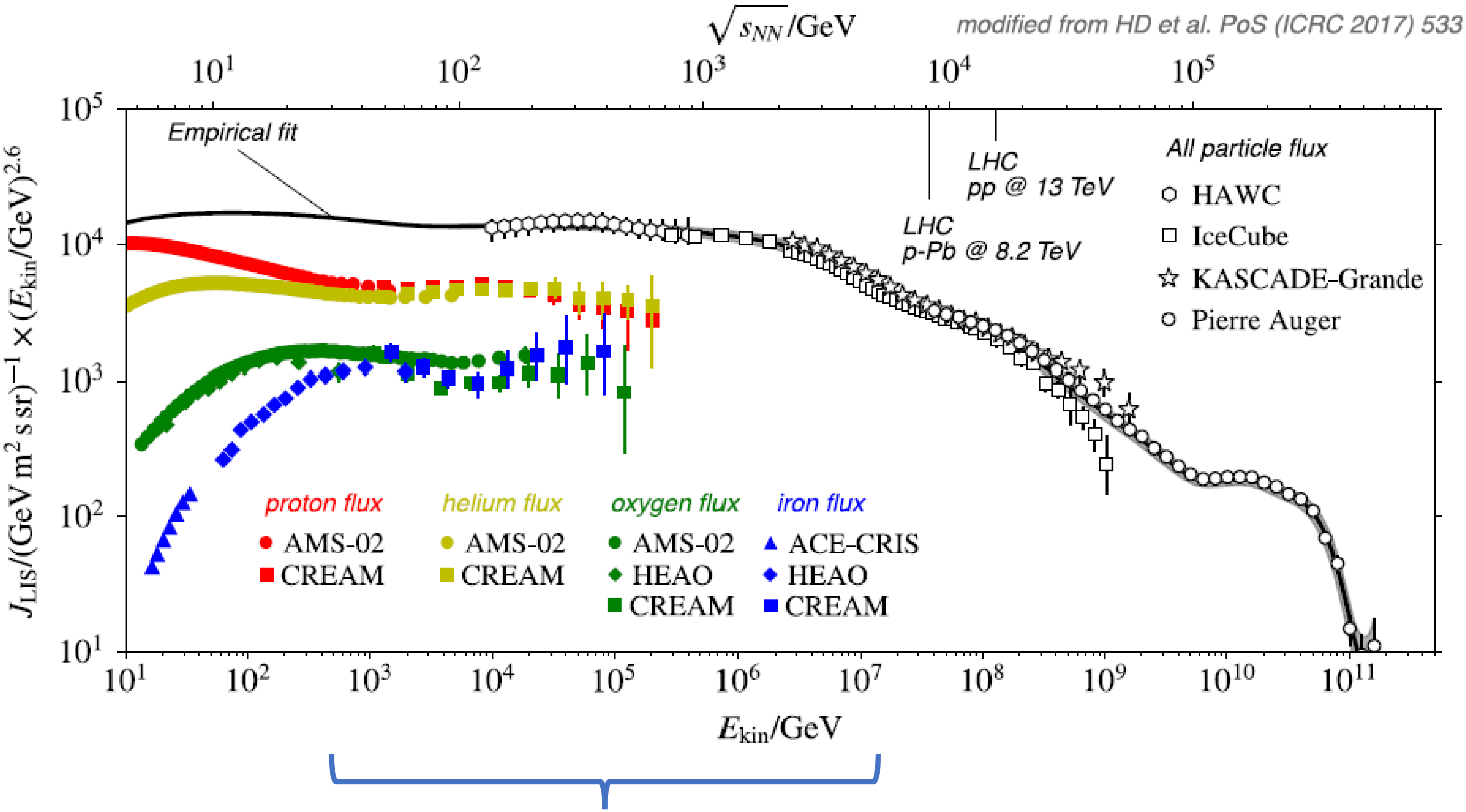
j=2: high-energy galactic component of unknown origin

j=3: extragalactic origin

- ➢ GSF model (several data set results)



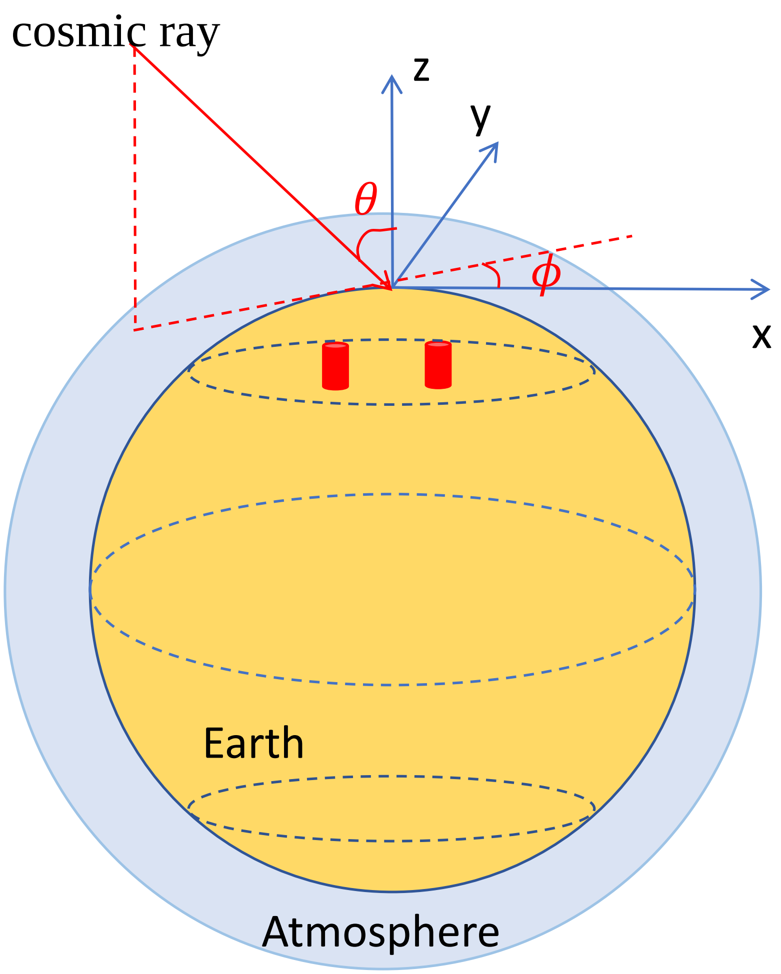
Energy region for this talk



1e3-1e7 GeV Direct and indirect cosmic ray flux measurement

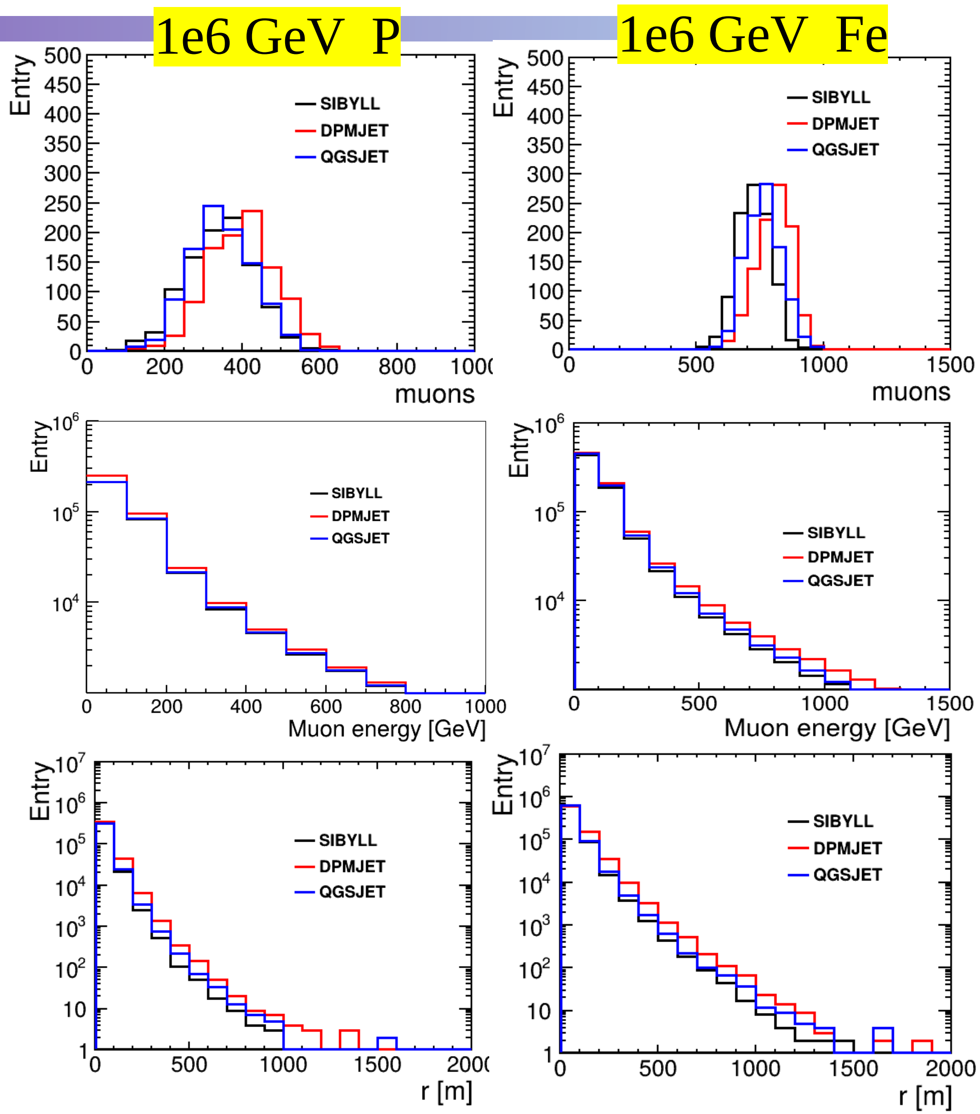
Air shower simulation with Corsika

- P, He: $[10^3, 10^4, 10^5, 10^6]$ GeV, 10^6 events
- N, Fe: $[10^4, 10^5, 10^6, 10^7]$ GeV, 10^6 events
- Ecut: 50 GeV
- Angle： $\theta \in [0,90]$, $\varphi \in [-180,180]$
- Obslevel: 0 m
- Corsika make option
  - **High-Energy Hadronic Models: SIBYLL/DPMJET/QGSJET**
  - Low-Energy Hadronic Models: URQMD
  - Electromagnetic Interactions: NKG
  - Other Non-standard Options: 4+6+7a
    - NEUTRINO version
    - CHARMed particle/tau lepton version with PYTHIA
    - CURVED atmosphere version and observation plan
- Atmosphere: **South pole atmosphere**
- Magnet: No



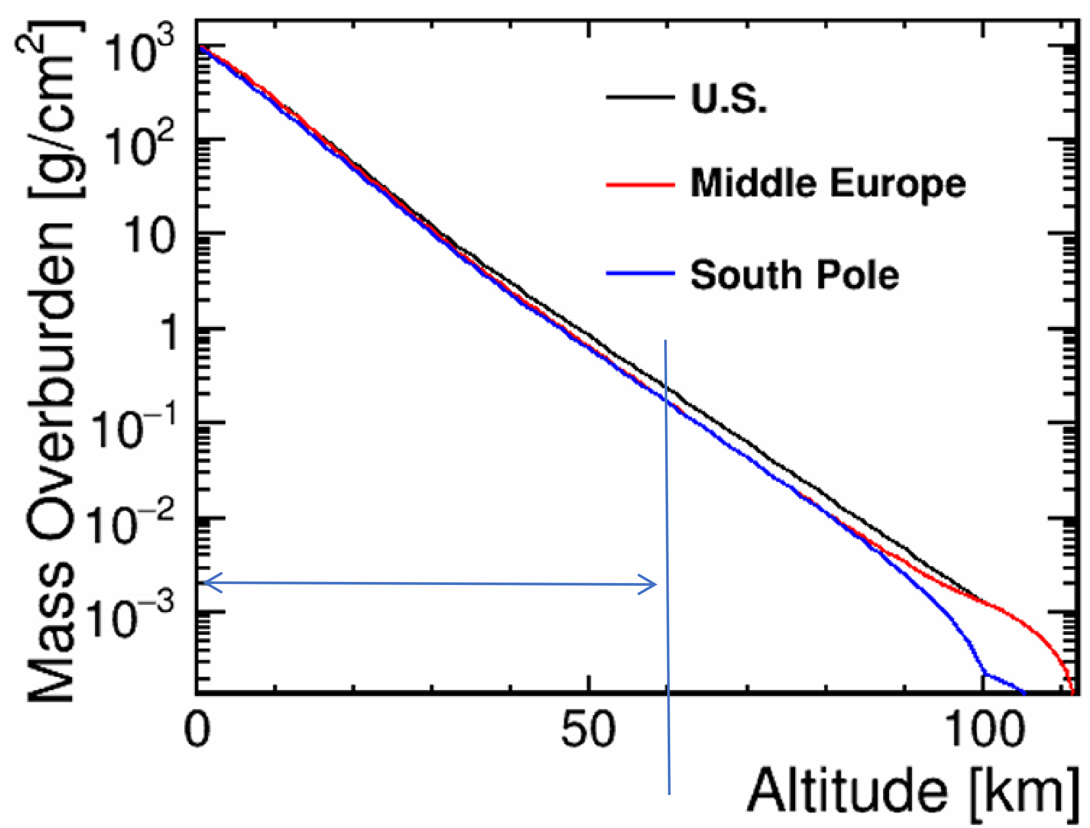
Hadronic interaction models

- P, Fe comparison
- Multiplicity
  DMPJET – more muons
  SIBYLL and QGSJEST less
- Muon energy
  DMPJET – high
- Lateral spread
  DMPJET – large



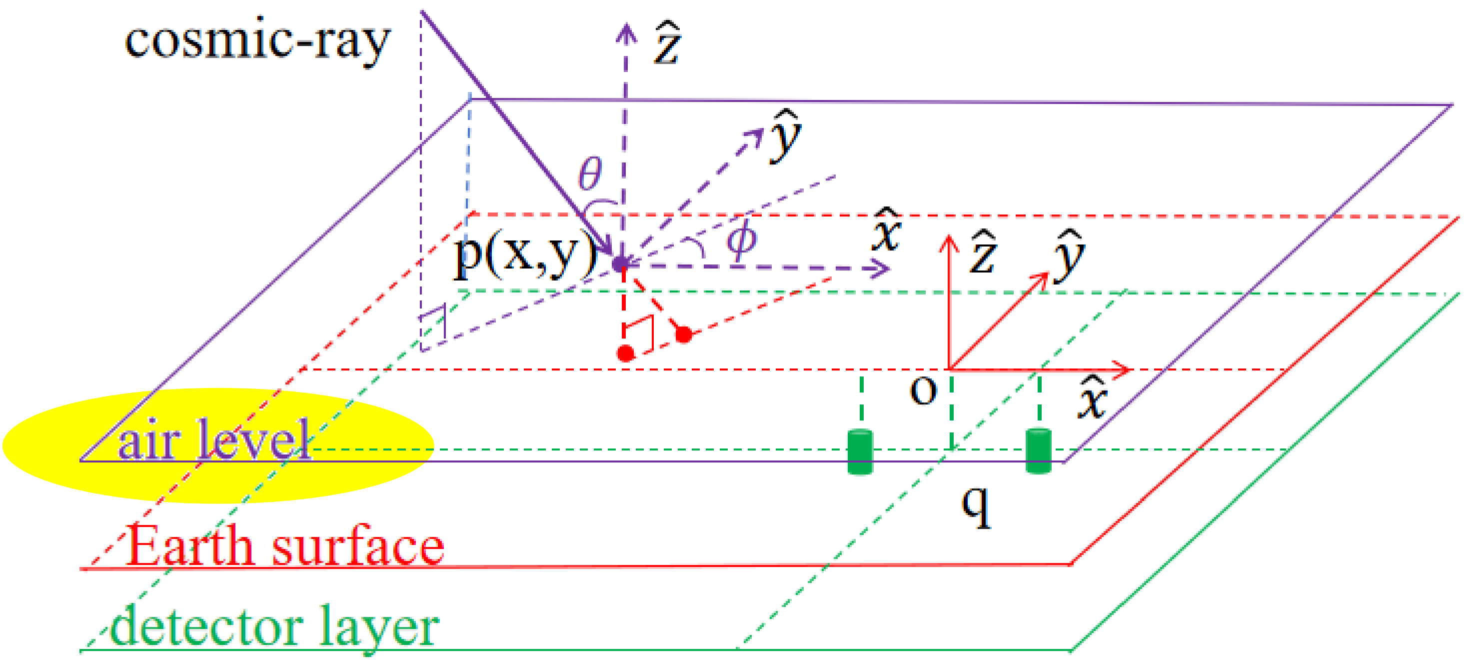
Air model

- The comparison of atmospheric models shows major differences above 90 km altitude, but agreement within 10% in the core interaction region (below 60 km).



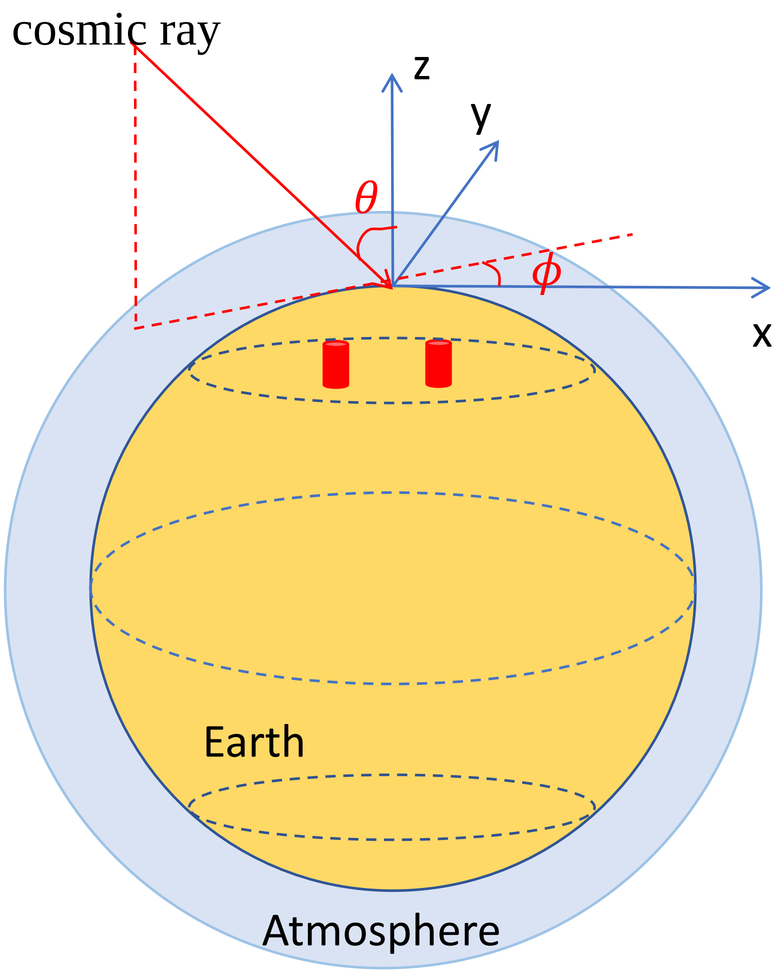
Between air and overburden simulation

- The air level is slightly above the mountains.
- The air level is the connection level of two simulation jobs – air and overburden.



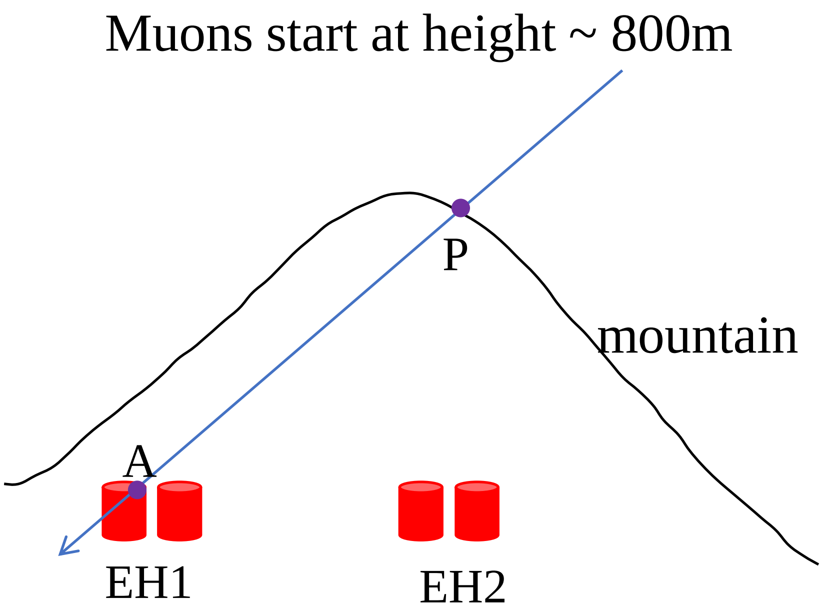
Reuse Corsika simulation events

- The aiming point, P, of one Corsika output event is randomly placed on P(x, y) of the air level.
- The phi is randomly sampled again.
- Azimuthal angle, θ, is fixed. We are on a 'curved' surface.



Underground muon simulation

- Muon start height is about 800 m.
- Muon spreads energy deposits, use Bethe-Bloch formula
- Test if muon can pass through underground detectors



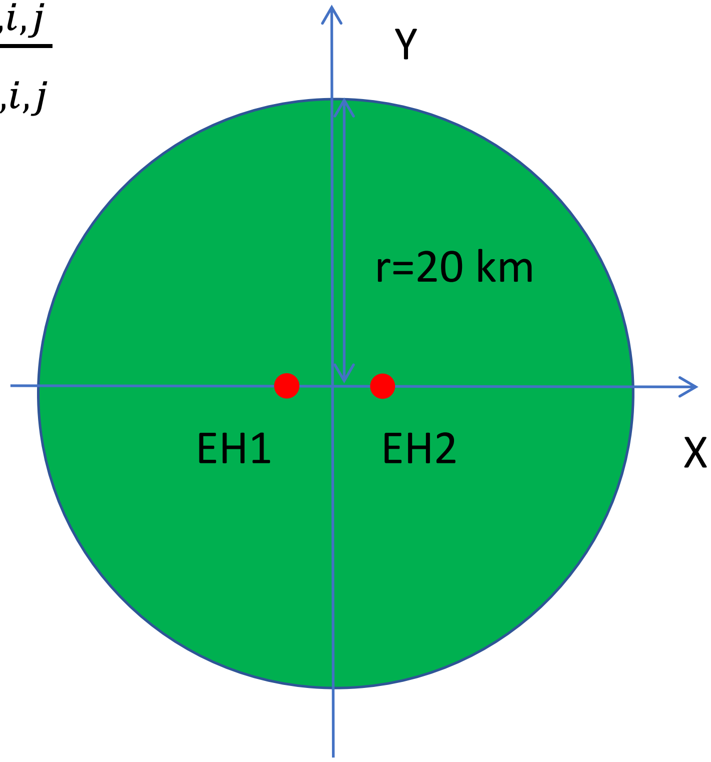
$$\frac{dE}{dX} = -[1.9 + 0.08\ln(E_\mu/m_\mu)]\ \mathrm{MeV}/\ (\mathrm{gcm}^{-2})$$

Effective Detection Area Calculation

- A_{eff} is Calculated for each element, *i*, and each energy, *j*

$$A_{eff,i,j} = A_{gen} \times \frac{N_{trg,i,j}}{N_{sim,i,j}} = \pi \times r^2 \times \frac{N_{trg,i,j}}{N_{sim,i,j}}$$

- A_{gen} is with R=20 km
- N_{trig} and N_{sim}, number of triggered and total simulated events



Two-site coincidence triggered events

- Two-site coincident events

$$N_{total} = 2\pi \cdot \sum_{i=1}^{4} \left(\int \Phi_i \cdot A_{eff,i} \cdot dE \cdot dt \right) = 2\pi \cdot T \cdot \sum_{i=1}^{4} (\sum_{j=1}^{n_{bins}} \Phi_{i,j} \cdot A_{eff,i,j} \cdot \Delta E_j)$$

- Fold in flux of each cosmic-ray flux and data taking time

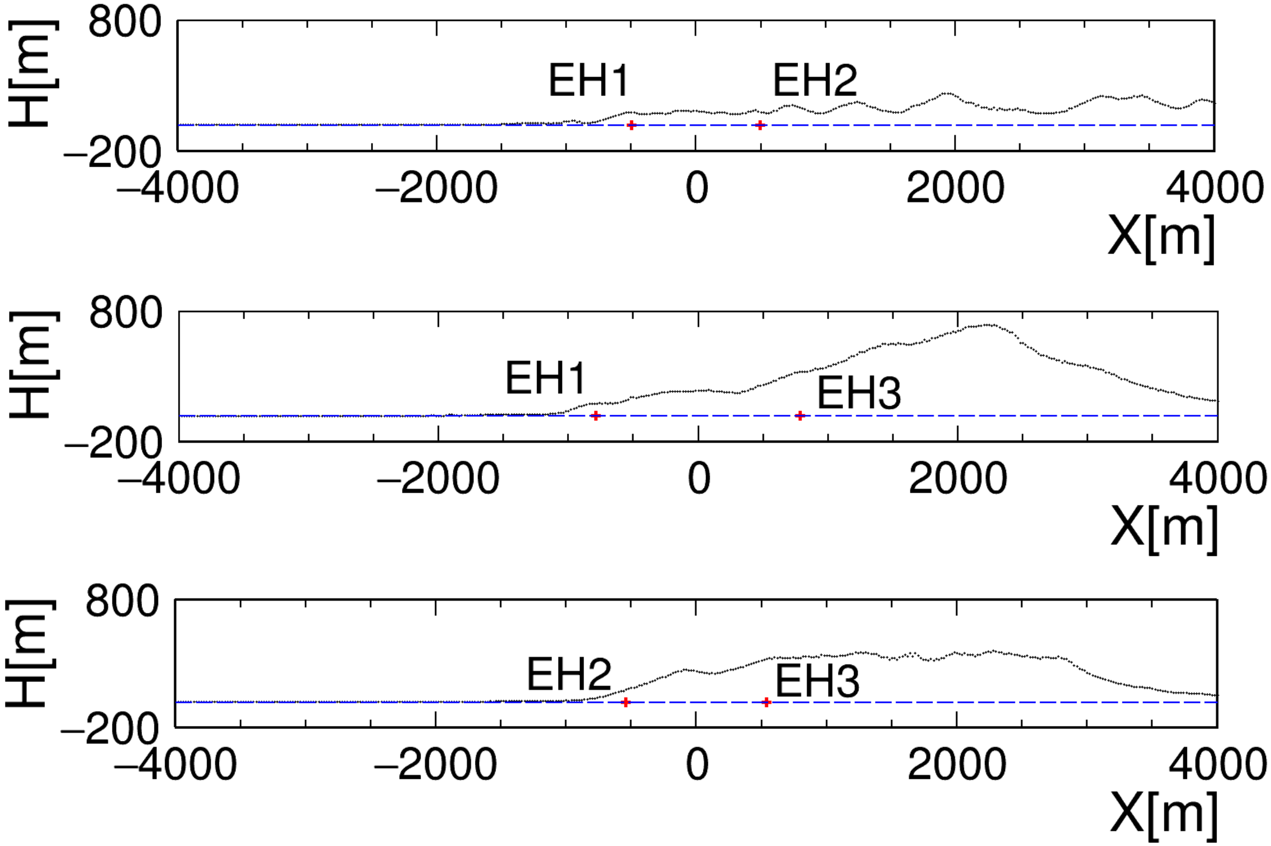
Daya Bay Geometry

Total 6 two-fold coincidences:

EH1-2; EH2-1

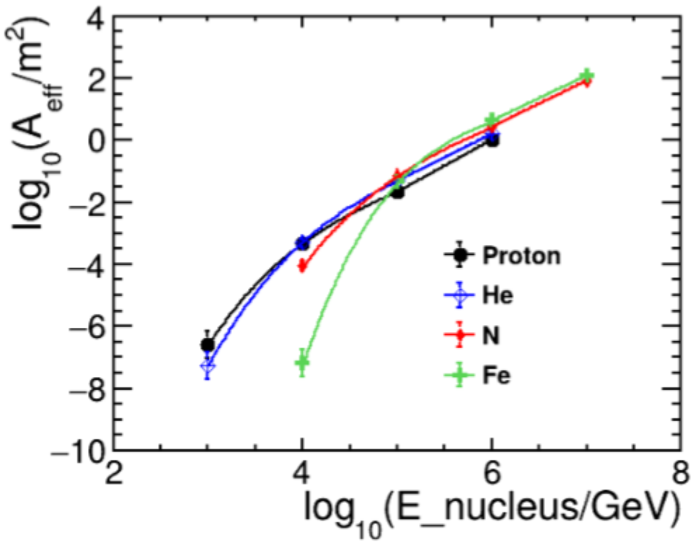
EH1-3; EH3-1

EH2-3; EH3-2

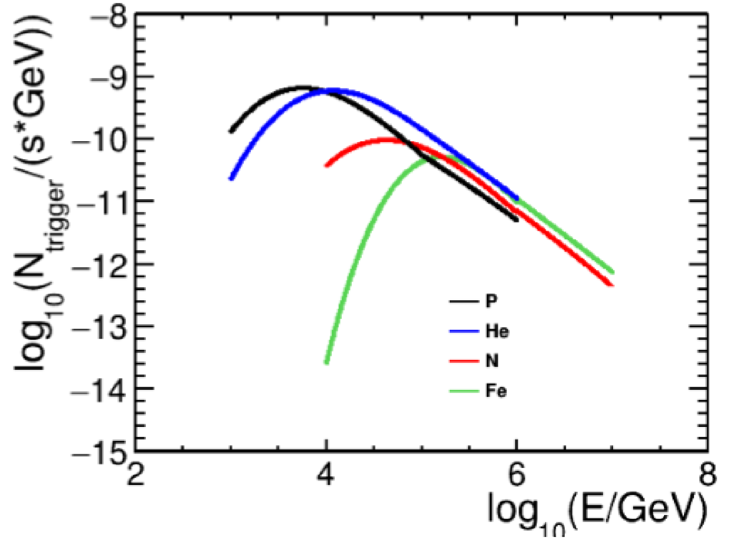


Trigger rate prediction

Effective Area (EH1-EH2)



Trigger rate (EH1-EH2)

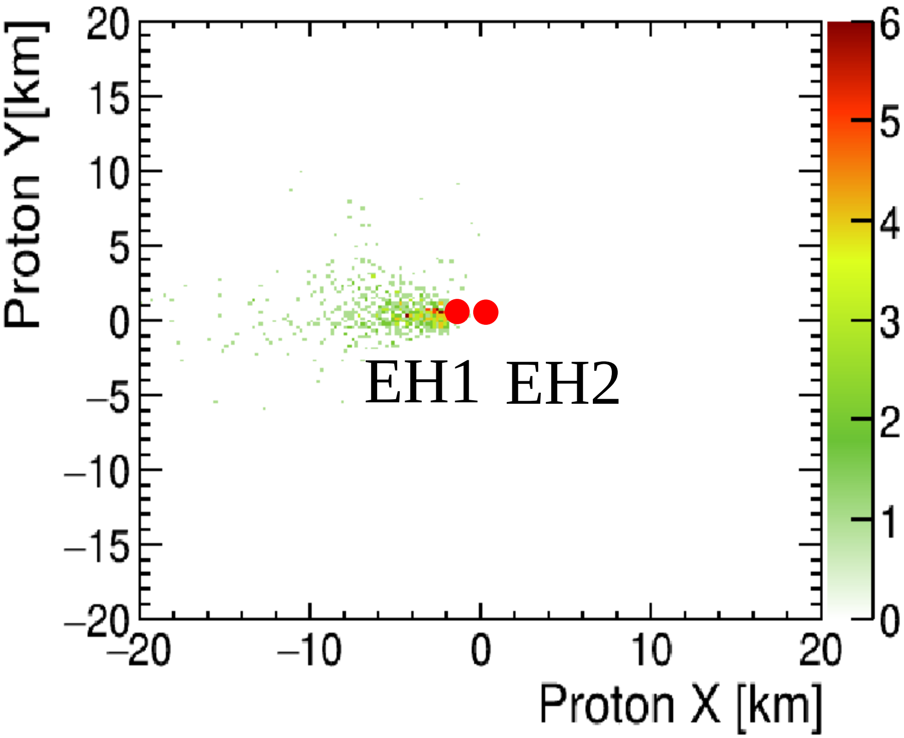


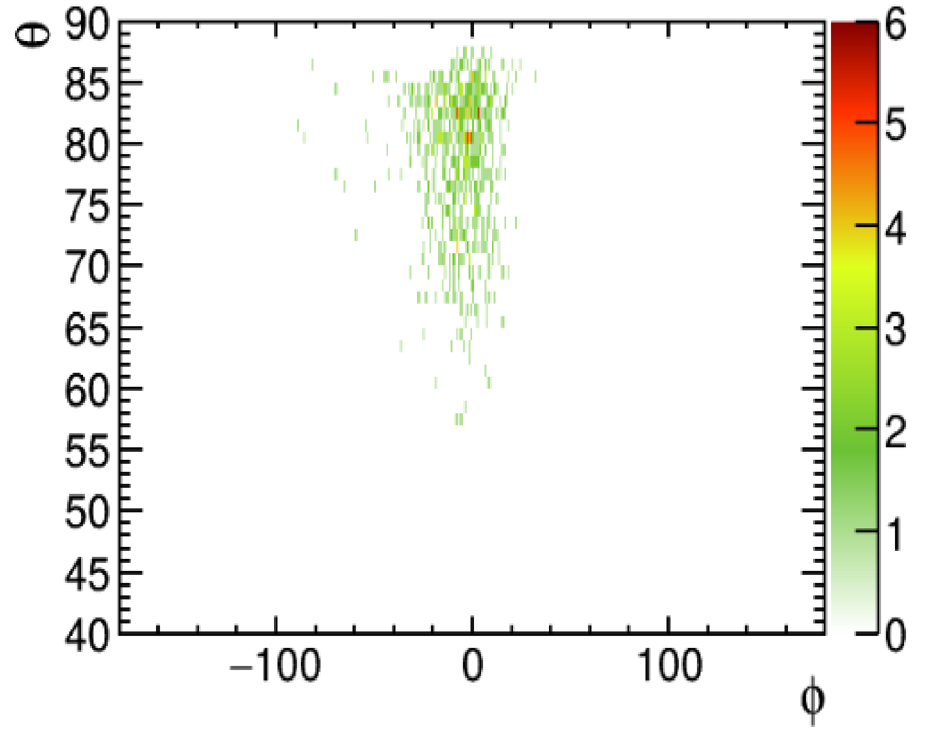
N trigger total	EH1-EH2	EH2-EH3	EH1-EH3	EH2-EH1
SIBYLL	5022 ± 308	2262 ± 198	511 ± 210	809 ± 110
DPMJET	7722 ± 640	2955 ± 359	664 ± 153	1545 ± 303
QGSJET	5573 ± 335	2303 ± 210	585 ± 93	1068 ± 159

Event rate per year

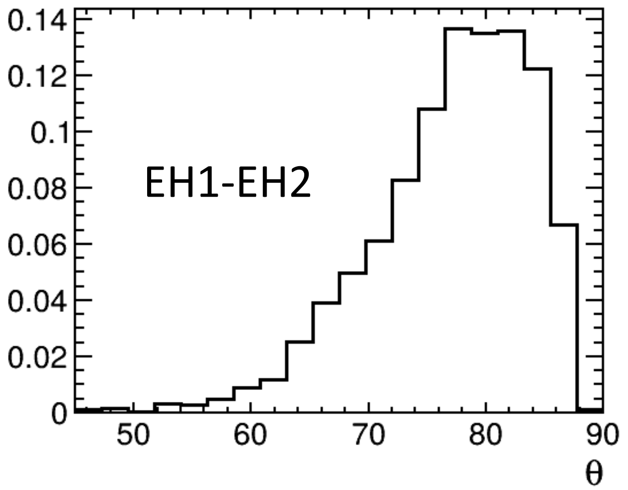
Aiming point and direction of triggers

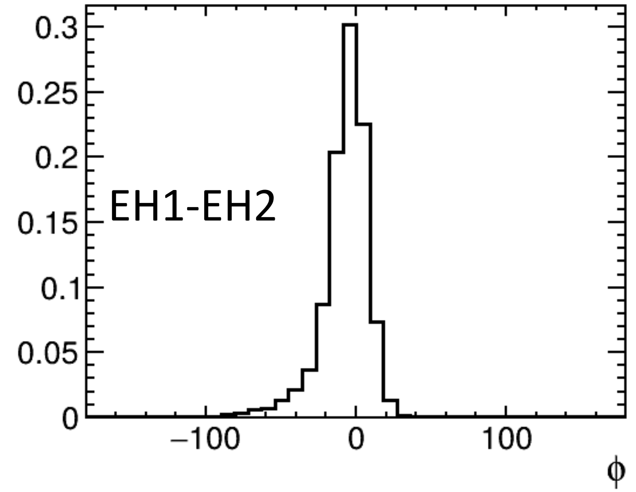
Trigger of EH1-EH2 (example):
Cosmic-ray coming from one side,
aligned with EH1-2, and with large azimuthal angle 70-90^{o}

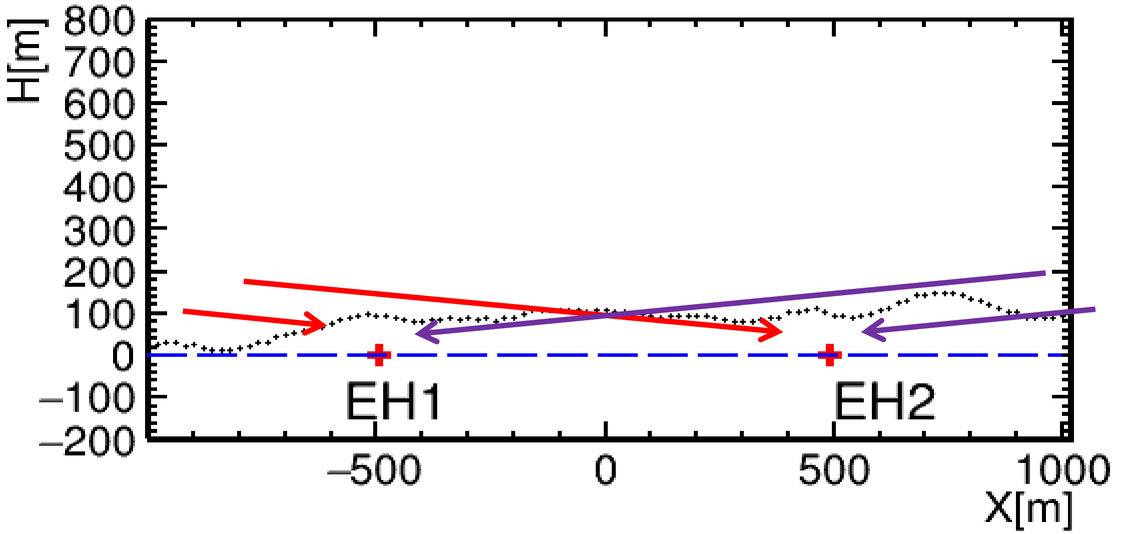




Projection on θ and ϕ and mountain

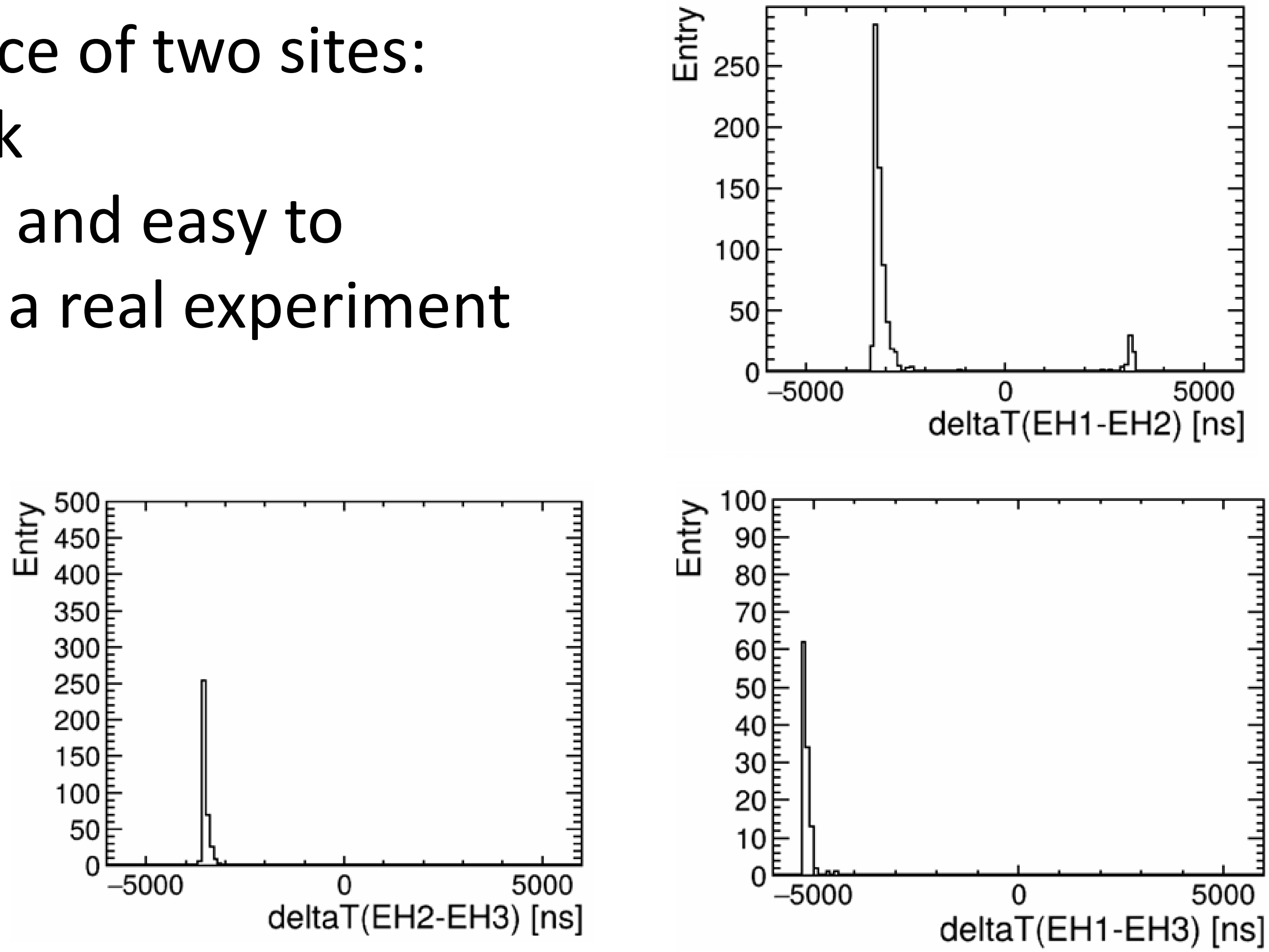






Time difference of the two sites

Time difference of two sites:
- Sharp peak
- Significant and easy to identify in a real experiment

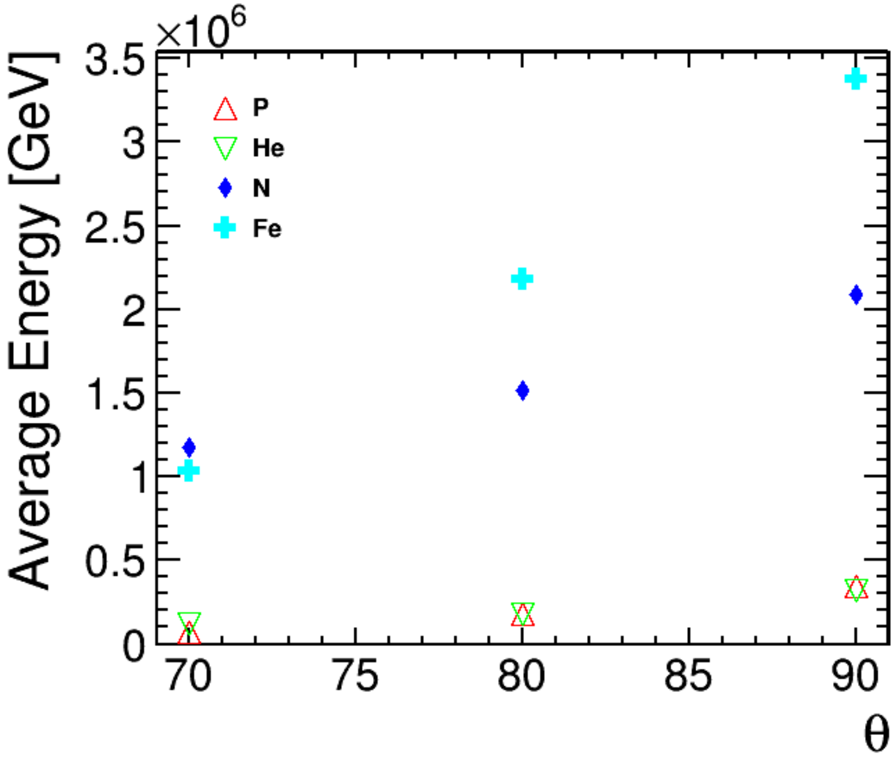


Energy scale

- EH1-3: 1e3 – 1e7 GeV
- Single site muon energy threshold:
  EH1: 40 GeV
  EH3: 200 GeV

- The energy range increased by 1000

EH1-EH3 coincidence



Discussion

- Cosmic-ray showers
  QCD models } Multi muons
  High energy } Large lateral distributions
- Cosmic rays find a balance at large average azimuthal angle of 80^{o} and PeV
  (Not 90^{o} and not teens of PeV)
- Significant timing structure
- A good chance for cosmic-ray flux and component study
- May also apply to the relevant QCD model study

Summary

Underground multi-site detectors used for cosmic-ray study

- Enhanced energy scale, cosmic-ray flux, QCD
- Low cost, at this moment
- Doing neutrino studies
- Apply to other underground laboratories

Thanks.

Questions and comments are welcome.

Broadcasting

Jinping Neutrino Experiment

- A 500 m^3 is under construction
- Geoneutrino is one of our major goals (Tibet-Sichuan Area including Himalayas)
- Collaborators are invited (Please email Shaomin Chen or me)

Directional liquid scintillators

- Under development
- Exploring mantle and potassium