Simulation of Two-site Coincident Cosmic-ray Muons at Daya Bay

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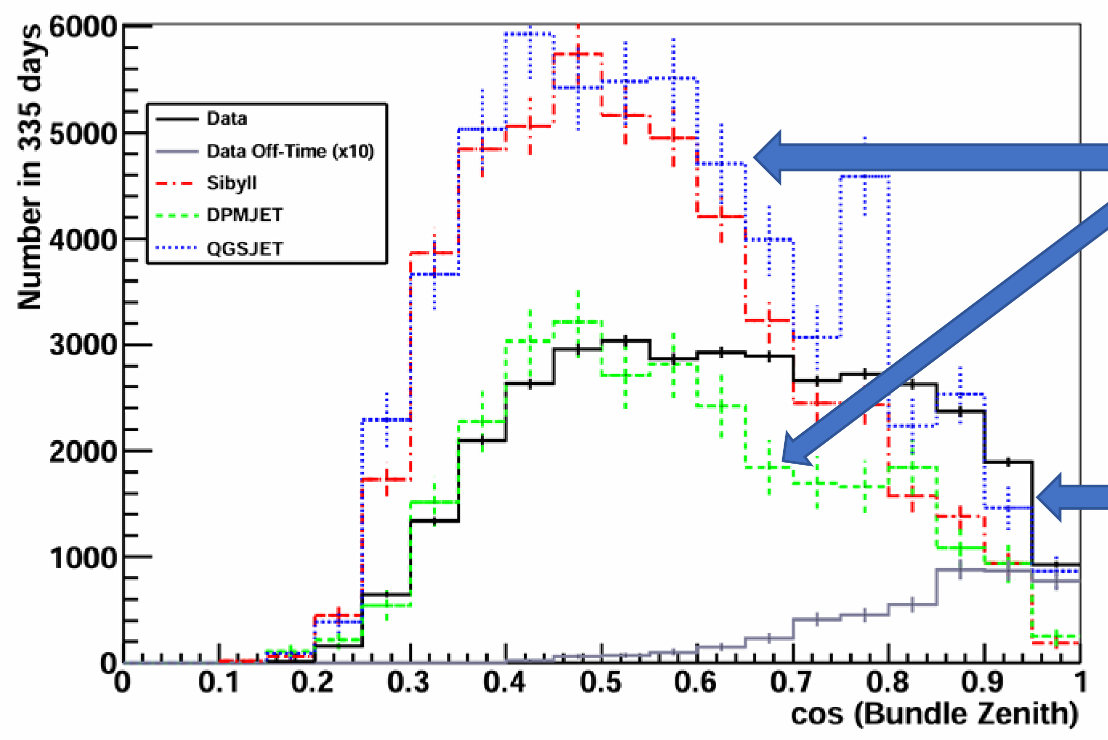
Outline

- Introduction
- Cosmic-ray Simulation Study
- Summary

Introduction

Motivation

- Lateral distribution of muons in IceCube cosmic-ray events
- Muon puzzle problem
- Seasonal variations of the underground muon flux



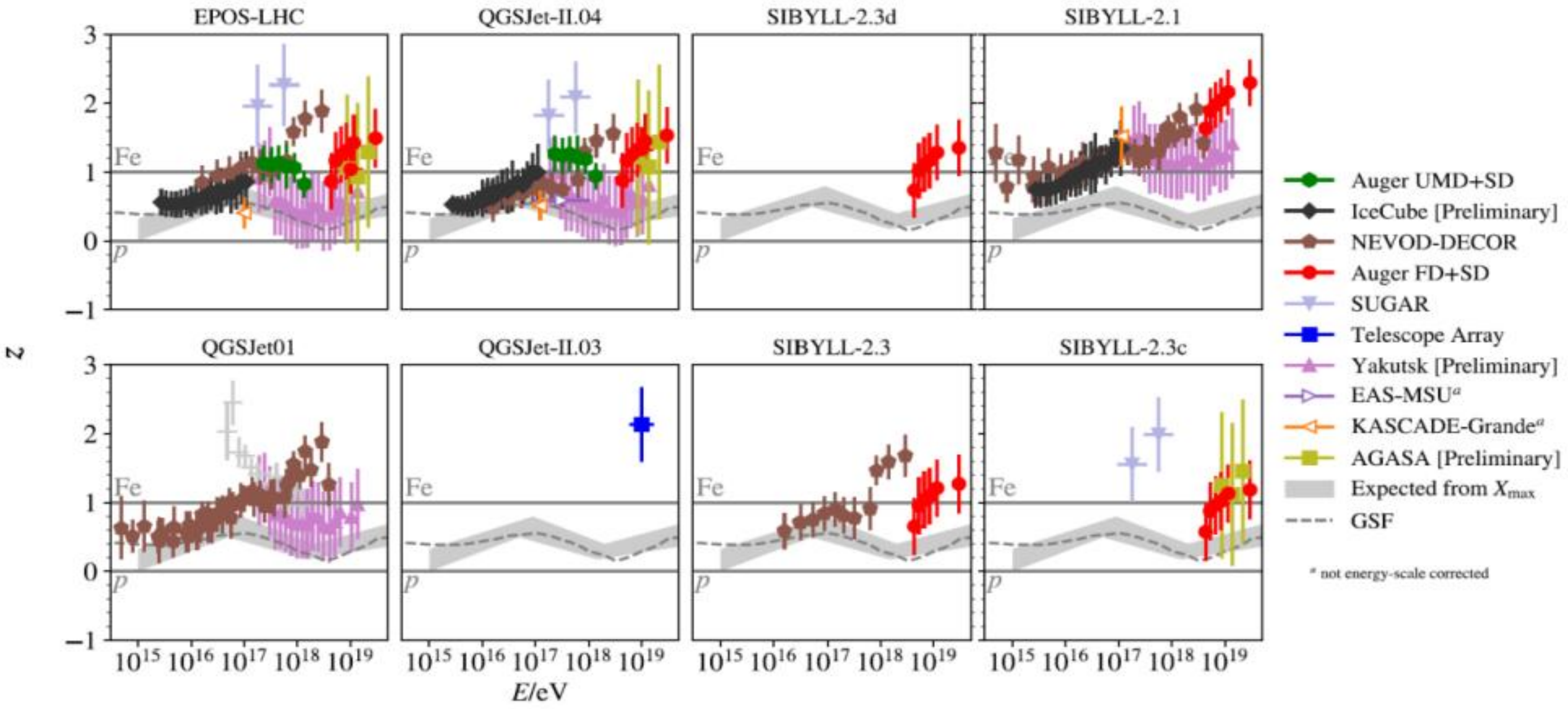
Simulation based on different QCD models

Data

DOI: 10.1103/PhysRevD.87.012005

Motivation

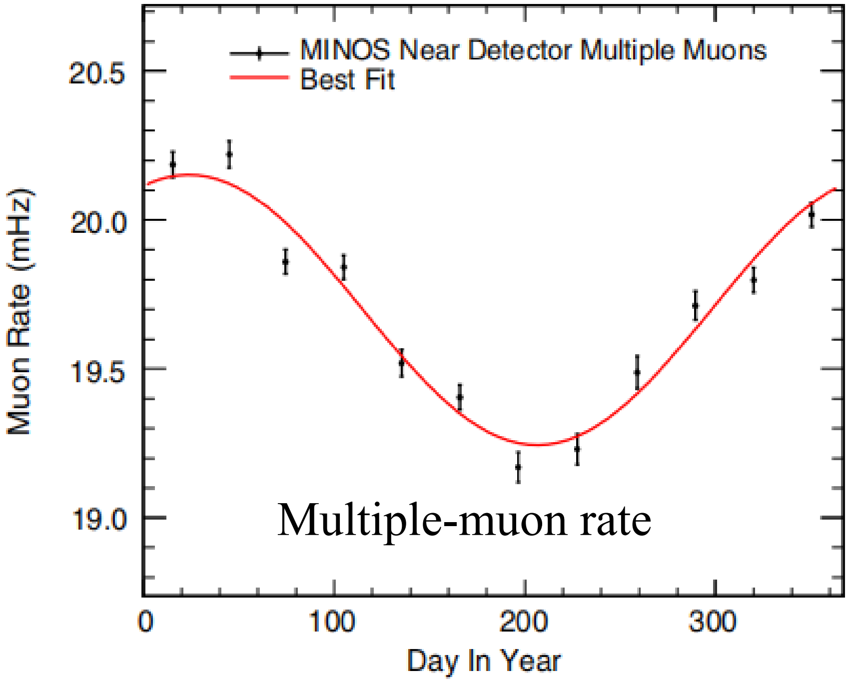
- Lateral distribution of muons
- Muon puzzle problem. Data > MC
- Seasonal variations of the underground muon flux

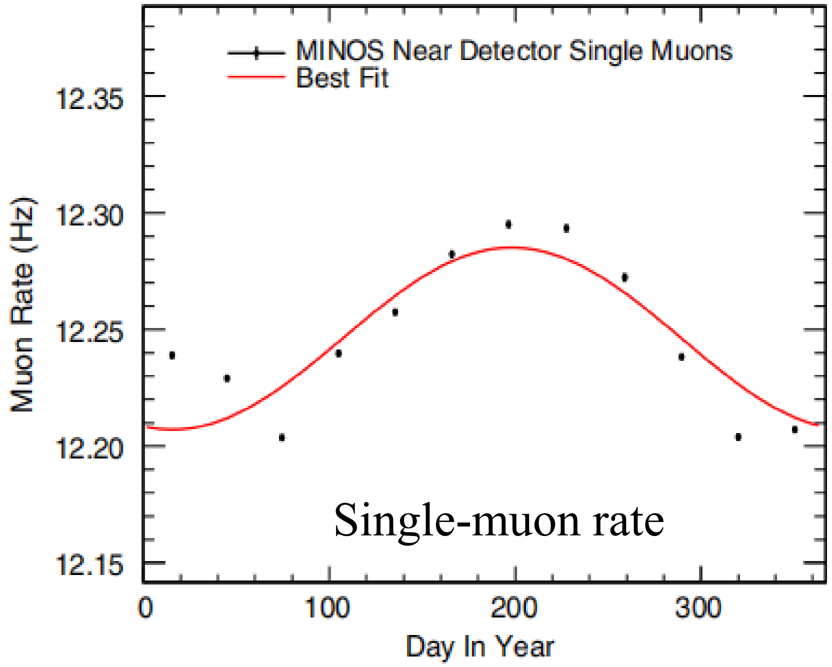


DOI: https://doi.org/10.48550/arXiv.2105.06148

Motivation

- Lateral distribution of muons
- Muon puzzle problem
- Seasonal variations of the underground muon flux



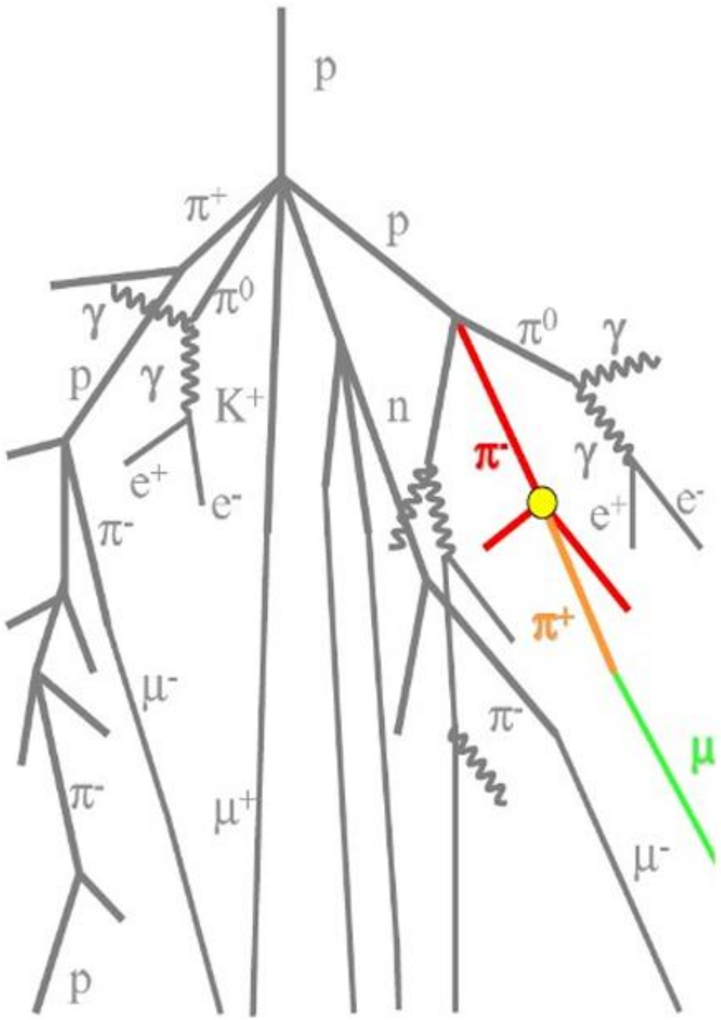


Different seasonal variations

DOI: https://doi.org/10.1103/PhysRevD.91.112006

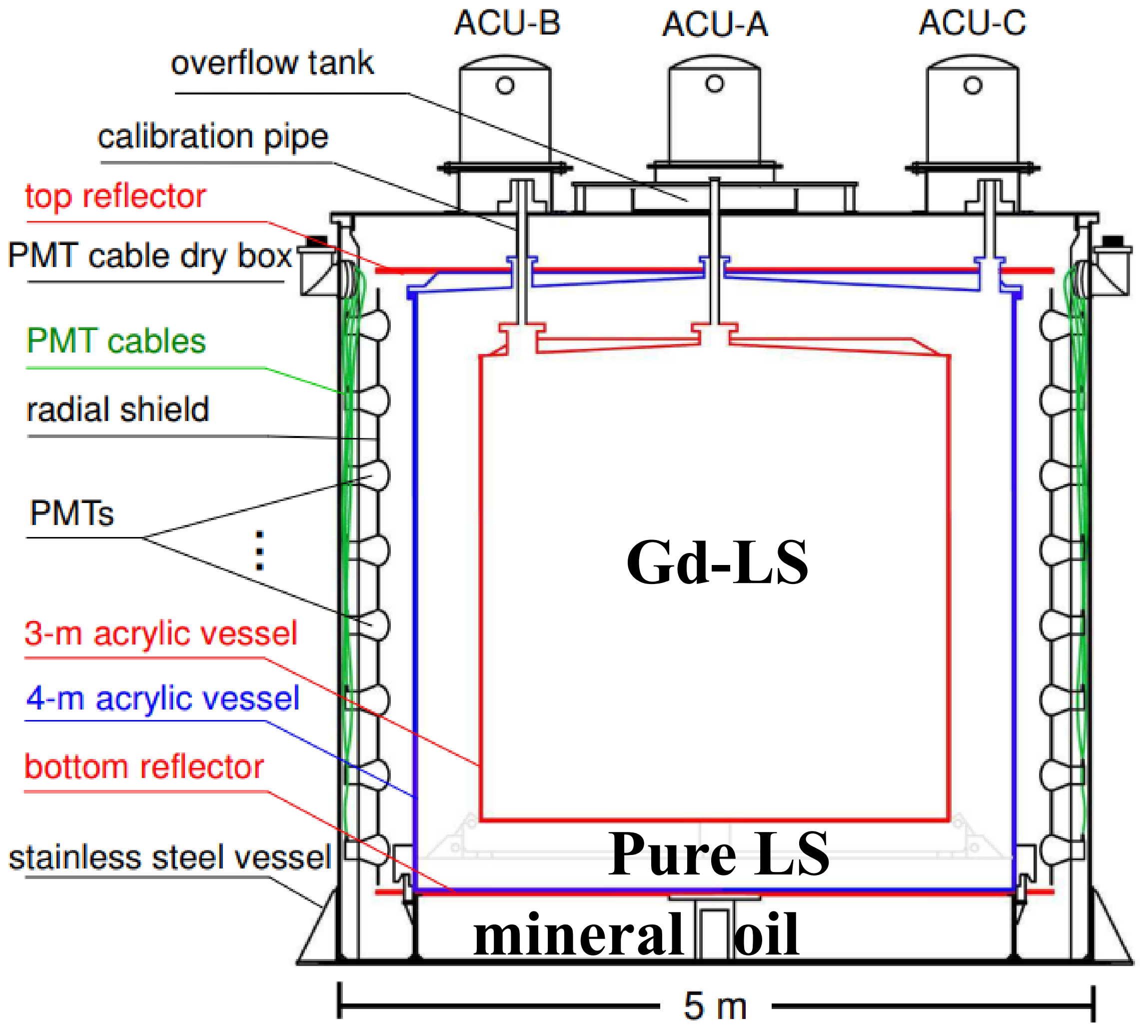
Extensive Air Shower

- Extensive air showers are cascades of secondary particles produced by high-energy cosmic rays interacting with the atmosphere.
- The shower contains hadronic and electromagnetic cascades, generated through repeated interactions and particle decays.
- High-energy muons can penetrate deep underground, making them useful probes of primary cosmic rays and high-energy hadronic interaction models.



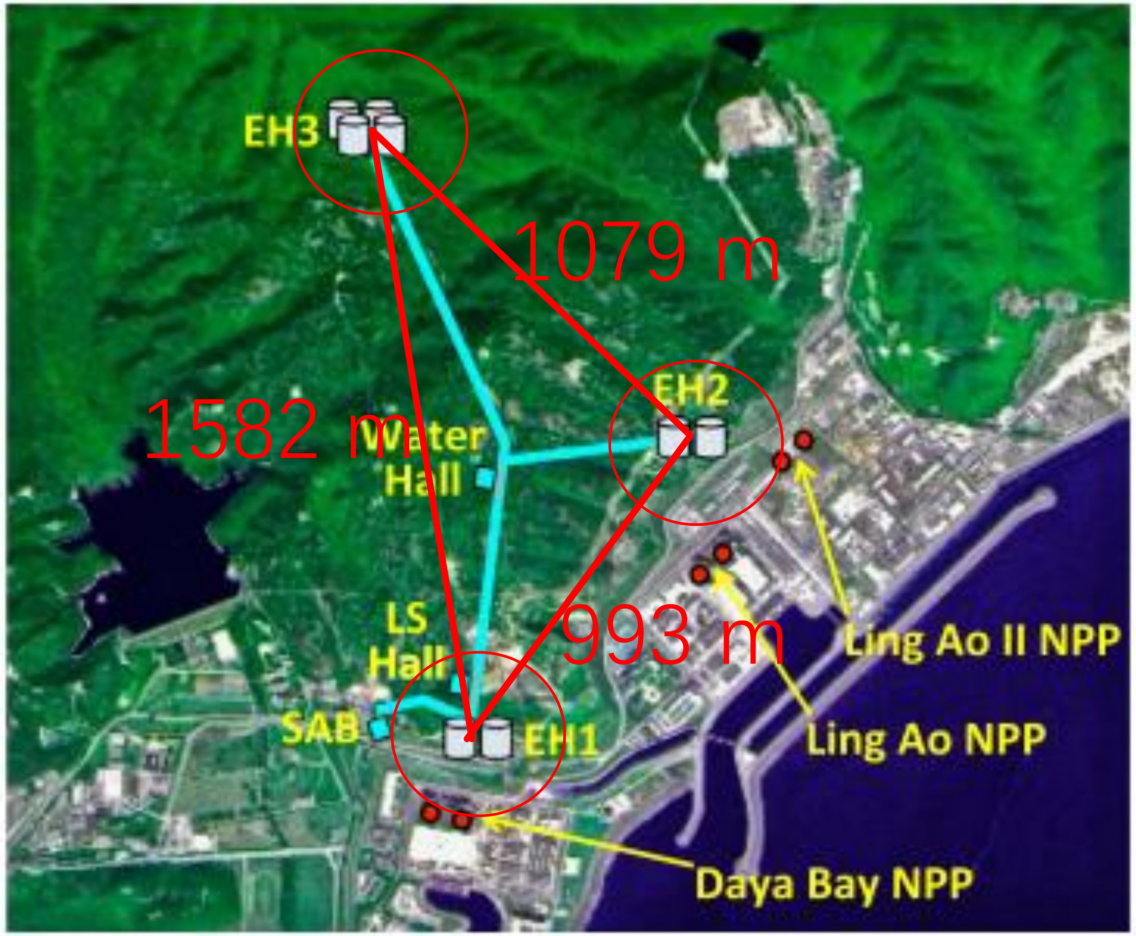
From R. Ulrich (KIT)

Daya Bay Detector

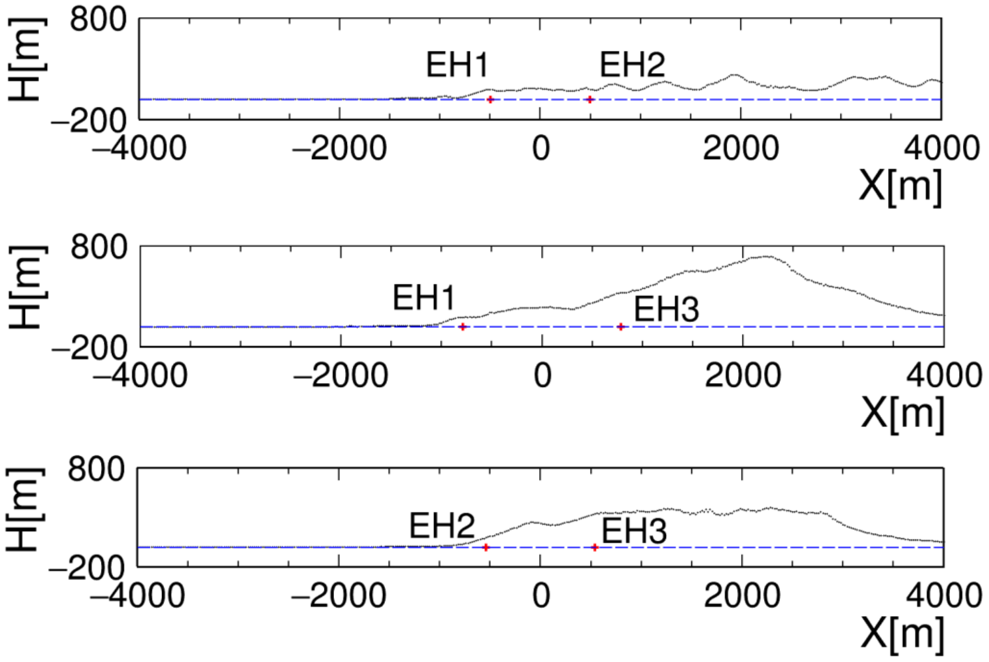


Daya Bay Geometry

- Three separate halls, ~1 km apart



	Overburden [m]	Overburden [m.w.e.]
EH1	93	250
EH2	100	265
EH3	324	860

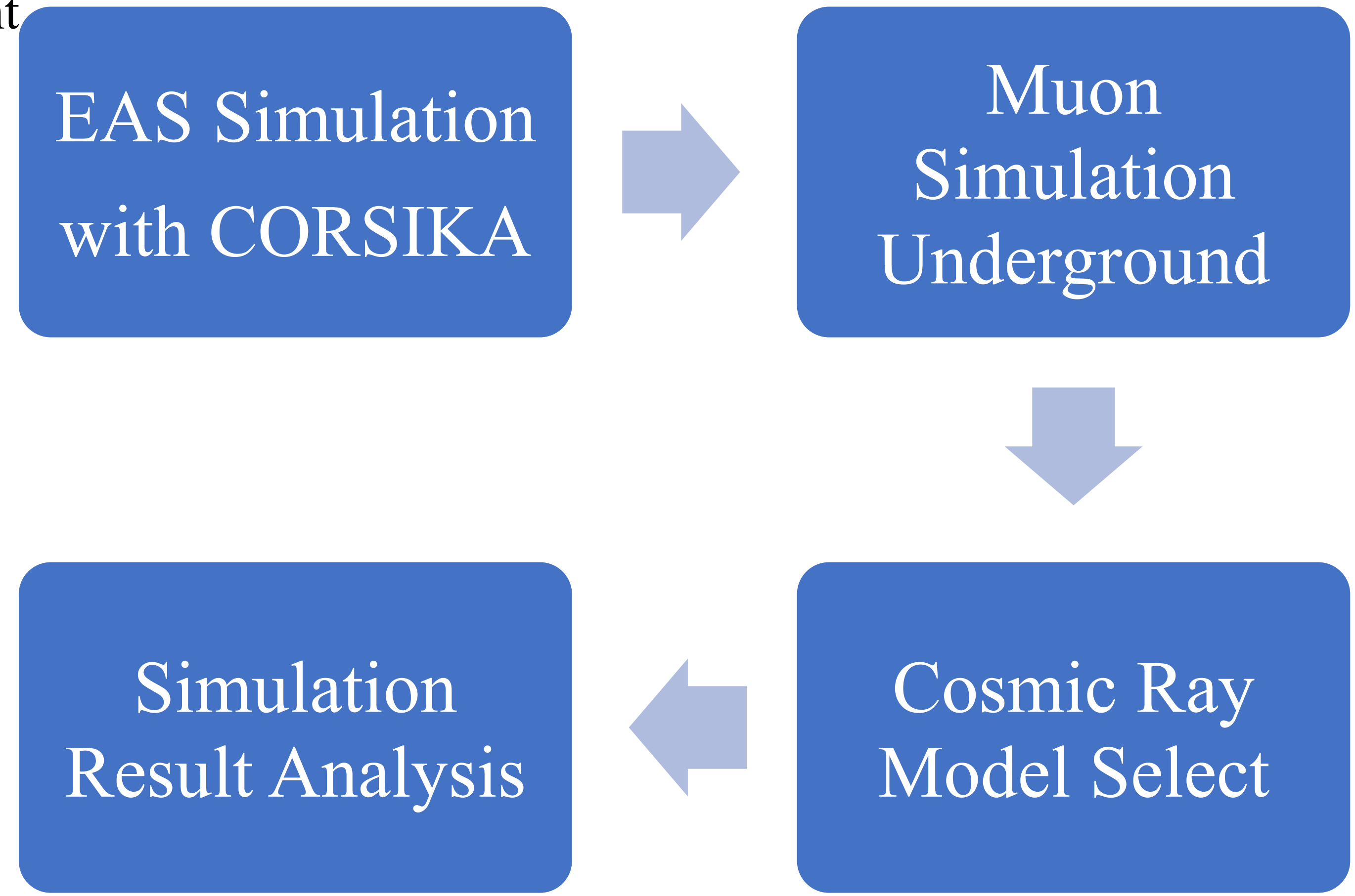


Topographic profile between Daya Bay sites

Muon Simulation of Two-site Coincidence Events

Muon Simulation

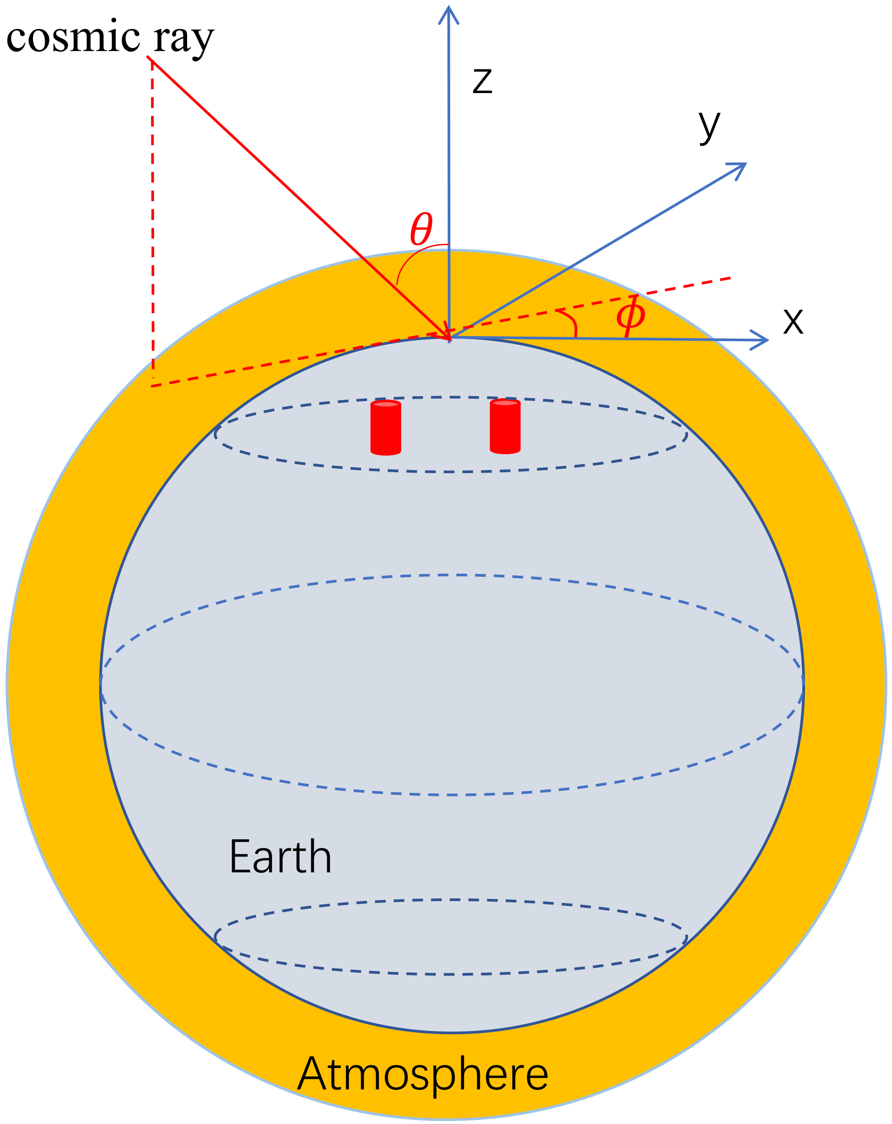
- Obtain event-by-event muon distributions using different high-energy hadronic interaction models: SIBYLL, DPMJET, and QGSJET.



- Provides the energy spectrum of primary particles (e.g., P, He, CNO, Mg-Al-Si, Fe).

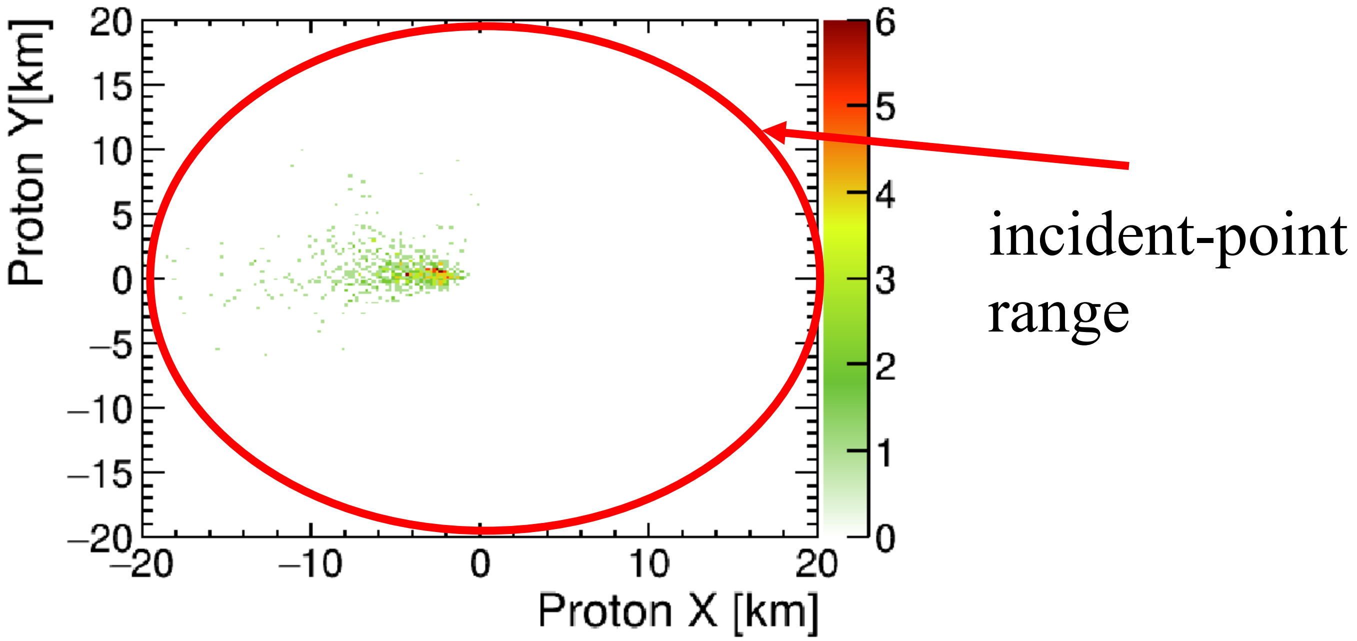
CORSIKA Configuration

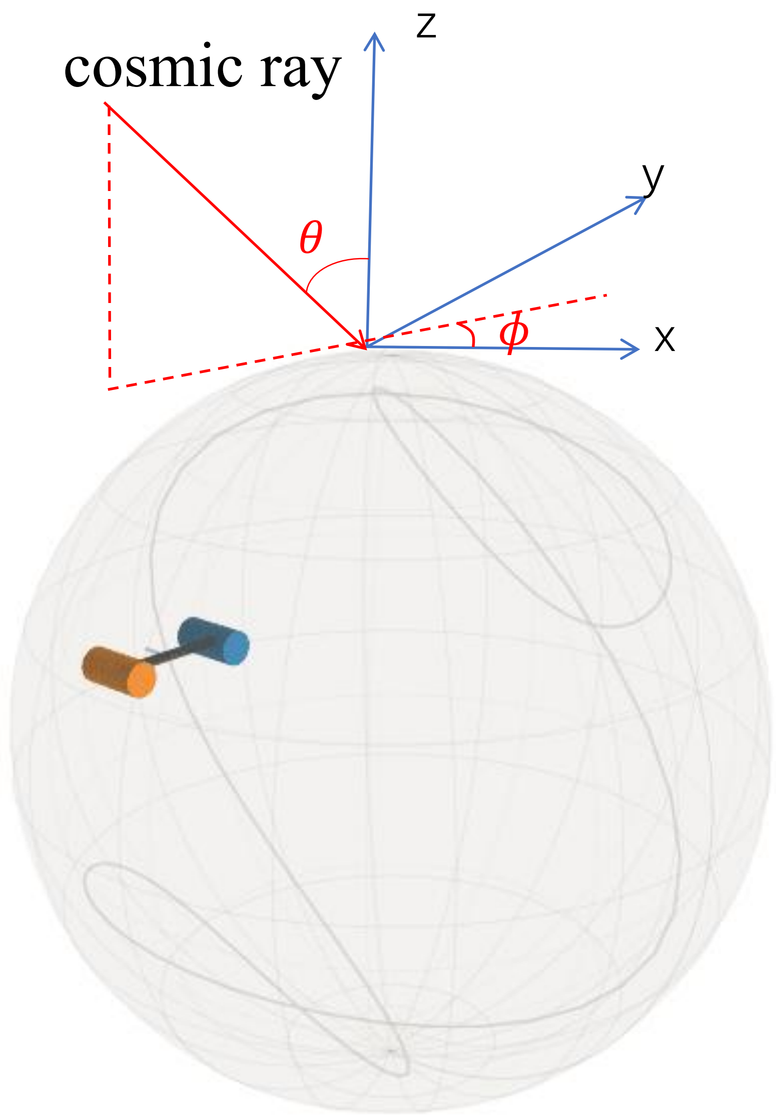
- P, He: $[10^3, 10^4, 10^5, 10^6]$ GeV
- N, Fe: $[10^4, 10^5, 10^6, 10^7]$ GeV
- Ecut: 50 GeV
- Angle: $\theta \in [0°, 90°]$, $\varphi \in [-180°, 180°]$
- Obslevel: 0 m
- CORSIKA make option
  - High-Energy Hadronic Interaction Models: **SIBYLL/DPMJET/QGSJET**
  - Low-Energy Hadronic Interaction Models: URQMD
  - Electromagnetic Interactions: NKG
- Atmosphere: South Pole atmosphere
- Magnet: No



Muon Simulation Underground

- Keep each CORSIKA shower fixed
- Generate multiple EH-geometry positions for fixed showers. (equivalent to keeping the EH fixed while translating the shower and rotating it around the (z)-axis)
- Ignore triggers outside the incident-point range



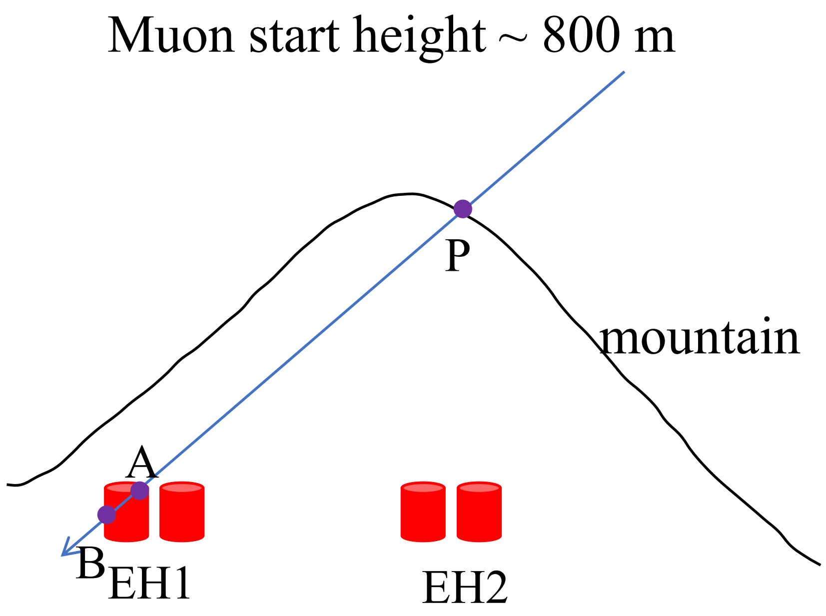


Muon Simulation Underground

- Start height: approximately 800 m (above the highest local terrain).
- Energy loss: the Bethe-Bloch formula, use the destiny of rock is $2.6 g/cm^3$. Used to calculate The maximum propagation distance (L_{max}) in rock.

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

- Trigger Request:
  - $L_{max} \geq$ truly propagation distance PA.
  - The track length inside the detector AB > 1.5 cm (~ 60 MeV).
- Trigger event: muons from the same primary cosmic ray trigger two experimental halls.



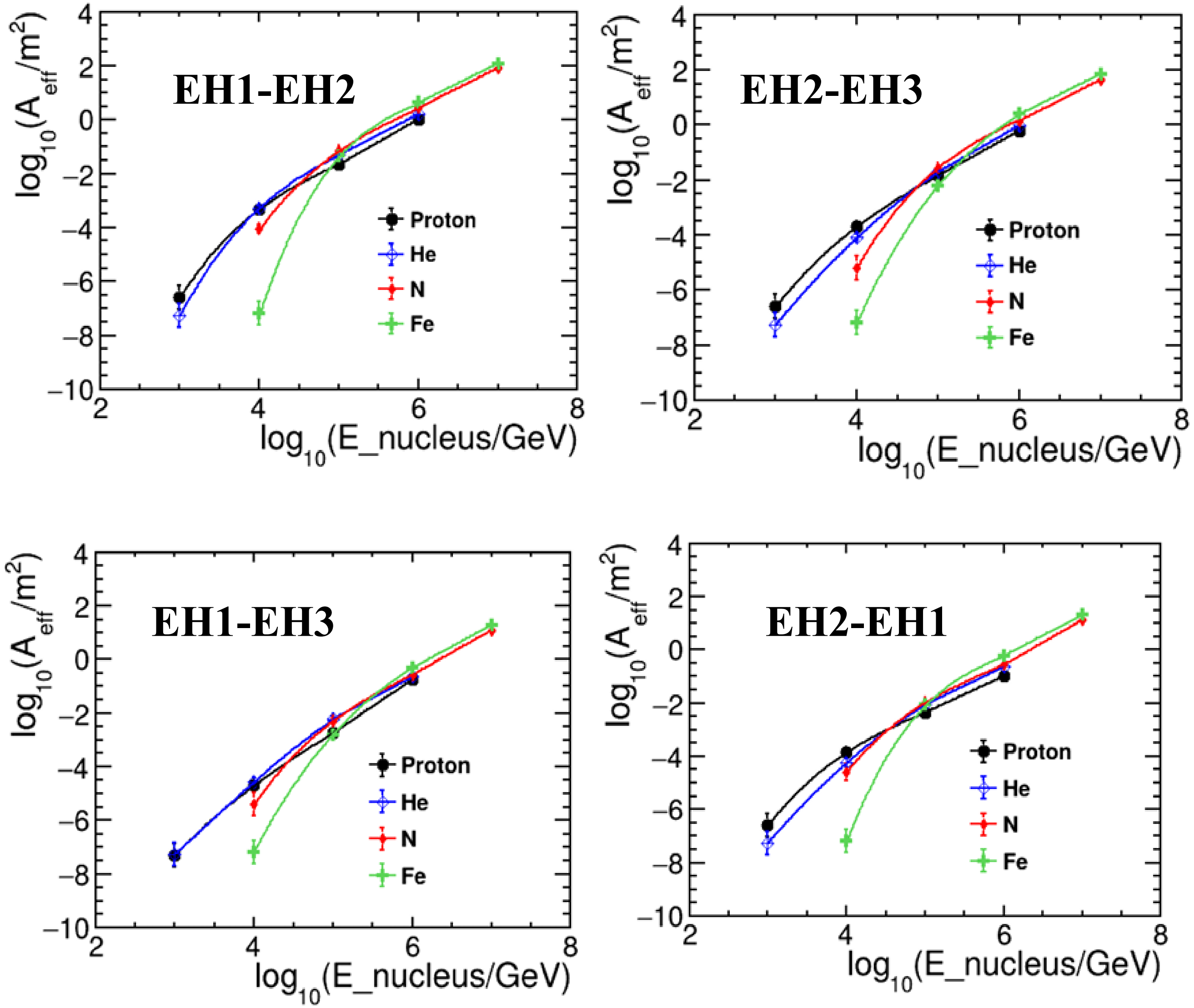
Result Analysis

- Effective detection area is used for linear interpolation.

$$A_{eff,i,j} = A_{incident-range} \times \frac{N_{trig,i,j}}{N_{incident,i,j}}$$

- To limit runtime, points with zero triggers after extensive simulation are assigned one effective trigger.

SIBYLL model



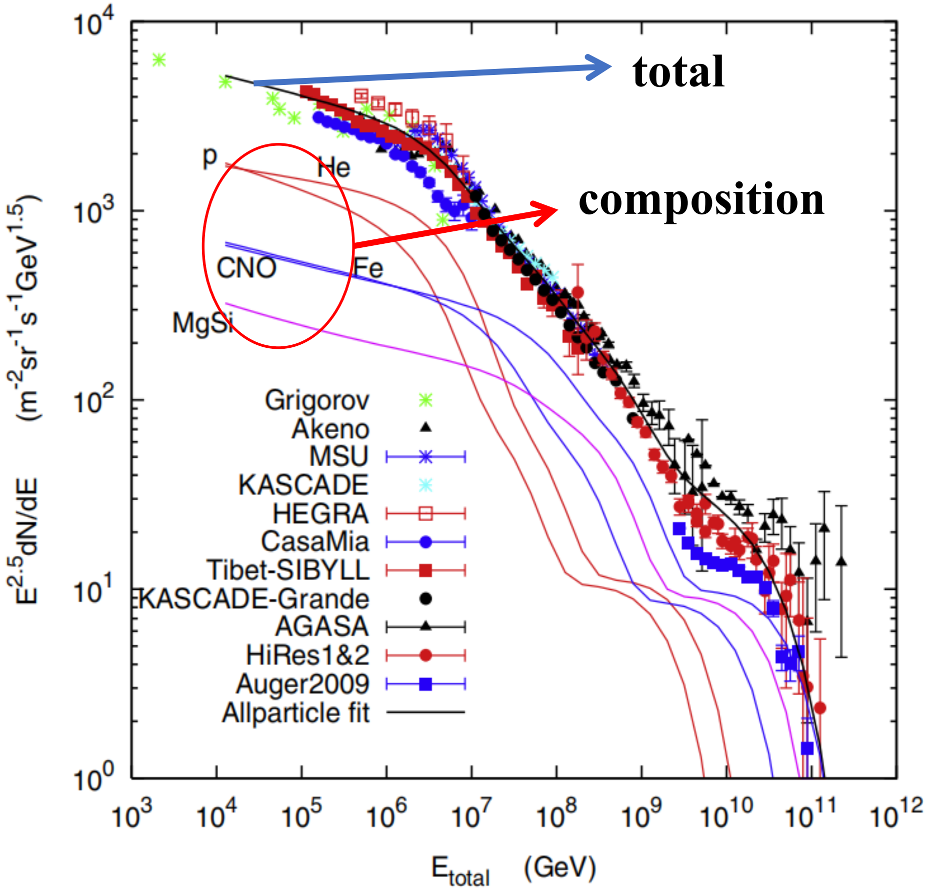
H3A model

		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

- H3A model assume high energy cosmic-ray comes from three different origins.
- Get flux $\phi_i(E)\ [m^{-2}sr^{-1}s^{-1}]$ by

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

- The MgAlSi component is ignored in the simulation because its contribution to the triggered events is smaller than those of the other components.



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

Result Analysis

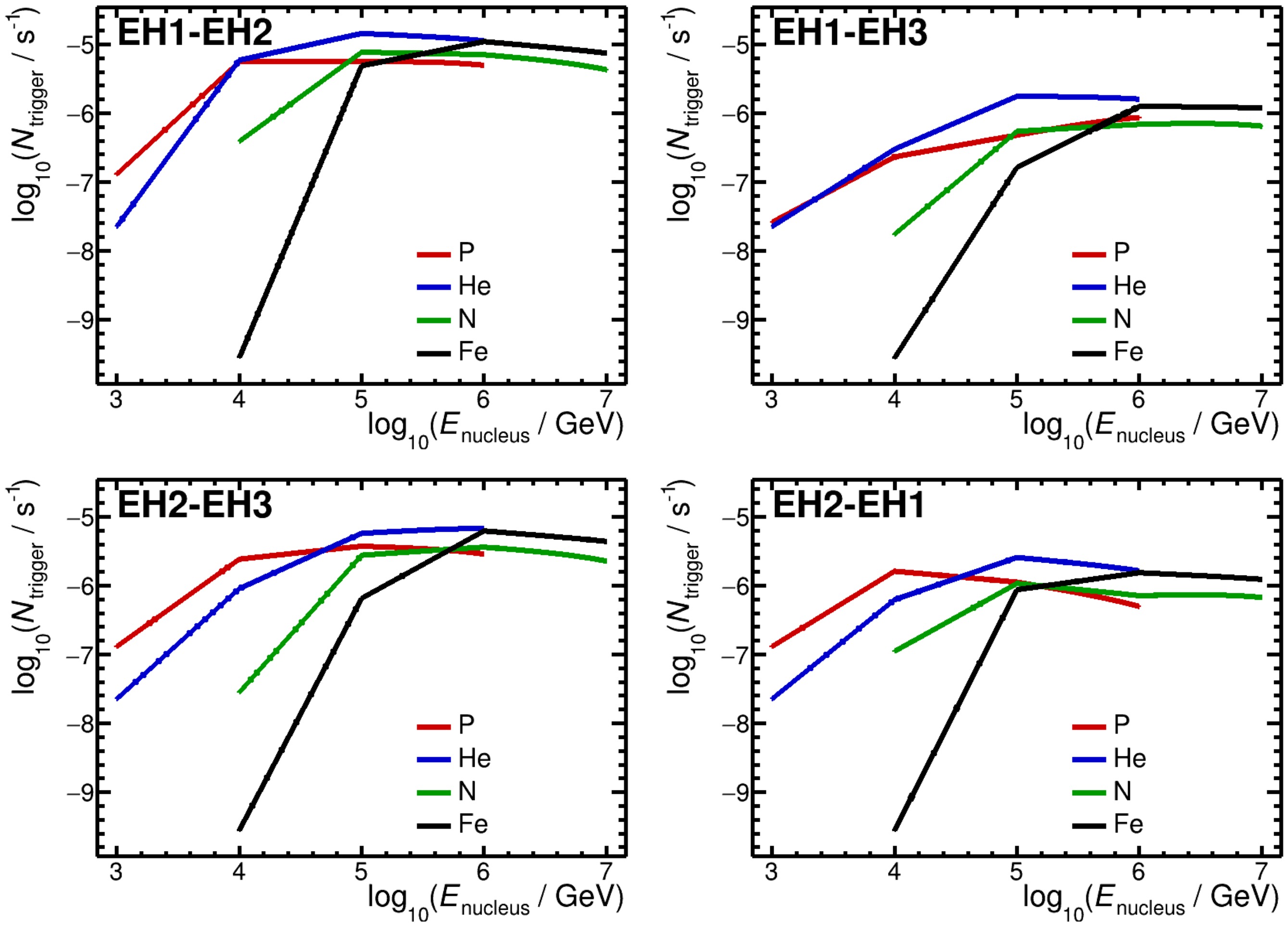
SIBYLL model

- Use the H3A model, we can get $N_{trigger,i}$ in the right figure by

$$N_{trigger,i} = 2\pi \cdot \phi_i \cdot A_{eff,i} = \frac{dN}{dlnE} [s^{-1}]$$

- N_{total} can be get from right figure

$$N_{total} = T \sum_{i=1}^{4} \int N_{trigger,i} \cdot dlnE$$

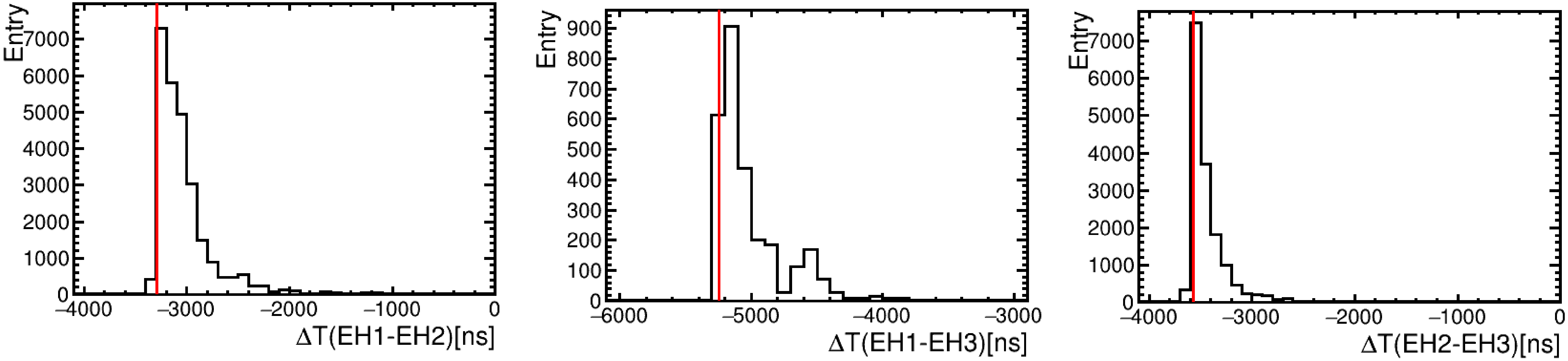


Distribution of ΔT

- The summed ΔT distribution shows a pronounced peak and a clear right-side long tail, with the peak slightly below distance/c.
- This feature may be validated with real data.

	distance [m]	distance / c [ns]
EH1-EH2	993	3294.8
EH2-EH3	1079	3570.0
EH1-EH3	1582	5246.9

Example in SIBYLL Model



Triggered Cosmic-ray Particle Comparison

- The statistical uncertainty is dominated by the effective detection area.

$$\sigma_{A_{eff,i,j}} = \frac{A_{eff,i,j}}{\sqrt{N_{trig,i,j}}} = A_{incident-range} \times \frac{\sqrt{N_{trig,i,j}}}{N_{incident,i,j}}$$

- For interpolation points, the statistical uncertainty is taken as the maximum uncertainty among nearby simulated points.
- Under the three different QCD models, the total coincidence-trigger results calculated with the H3a cosmic-ray model show significant differences.

Time ~ 9 years	EH1-EH2	EH2-EH3	EH1-EH3	EH2-EH1
MC SIBYLL	27291 ± 1559	15764 ± 1620	2795 ± 759	4470 ± 766
MC DPMJET	42195 ± 3109	20593 ± 2656	3525 ± 905	8293 ± 1176
MC QGSJET	30376 ± 1993	16026 ± 2005	3708 ± 856	5855 ± 827

GSF(Global Spline Fit) MC Result

- GSF is a data-driven cosmic-ray model based on spline fits to direct and air-shower measurements. Different GSF models reflect uncertainties in data selection, mass composition, and high-energy extrapolation.
- All calculation use the same method as in the H3A model.
- The predicted counts from the three QCD models still show significant differences under different GSF models, with trends similar to those from H3a.

		EH1-EH2	EH2-EH3	EH1-EH3	EH2-EH1
GSF 1	SIBYLL	45522 ± 2689	24245 ± 2737	4464 ± 1169	7256 ± 1357
	DPMJET	71723 ± 6072	33356 ± 4762	5580 ± 1594	13982 ± 1924
	QGSJET	48615 ± 3221	25141 ± 3572	4598 ± 1582	10253 ± 1459
GSF 2	SIBYLL	41124 ± 2234	21966 ± 2064	3883 ± 921	6537 ± 1086
	DPMJET	64103 ± 5673	29863 ± 3572	5069 ± 1254	12795 ± 1714
	QGSJET	44323 ± 2794	22402 ± 2782	4130 ± 1290	9246 ± 1253
GSF 3	SIBYLL	43497 ± 2621	23154 ± 2717	4299 ± 1147	6980 ± 1333
	DPMJET	68753 ± 5603	31825 ± 4708	5315 ± 1558	13373 ± 1862
	QGSJET	46489 ± 3114	23999 ± 3491	4414 ± 1529	9763 ± 1408
GSF 4	SIBYLL	48045 ± 2687	25804 ± 2612	4670 ± 1139	7586 ± 1322
	DPMJET	75299 ± 6479	35549 ± 4548	6001 ± 1563	14938 ± 2027
	QGSJET	51795 ± 3347	26620 ± 3487	4862 ± 1564	10738 ± 1483
GSF 5	SIBYLL	44779 ± 2666	23896 ± 2731	4411 ± 1165	7153 ± 1351
	DPMJET	70665 ± 5970	32865 ± 4751	5497 ± 1586	13744 ± 1897
	QGSJET	47777 ± 3178	24828 ± 3558	4558 ± 1578	10078 ± 1442

A Simple Cross-Check

DOI: https://doi.org/10.48550/arXiv.2606.09116

- Previous group studies predicted single-hall trigger rates at the three Daya Bay experimental halls using MCEq and a similar rock-propagation algorithm, obtaining results consistent with Daya Bay measurements.

- By applying our own code framework under their topographic and atmospheric settings, but with MUSIC replacing the original rock-propagation calculation, we reproduce similar results, providing a cross-check of our simulation.

	EH1	EH2	EH3
Experiment [Hz/m2]	1.16 ± 0.11	0.86 ± 0.09	0.054 ± 0.006
MCEq Simulation [Hz/m2]	1.144	0.832	0.056
My Simulation[Hz/m2]	1.10 ± 0.04	0.79 ± 0.05	0.046 ± 0.001

Summary

- We studied two-site coincidence events using Monte Carlo simulation. And as a cross-check, the simulation was independently implemented with two separately developed code frameworks, which give consistent results at chosen energy points under the same settings.

- MC simulation shows:
  - Pronounced peak and a clear right-side long tail, with the peak slightly below distance/c.
  - Triggered primaries reach average energies beyond the PeV scale, and the remaining tension between simulation and data may offer a useful but preliminary probe of possible QCD-model limitations at these energies.

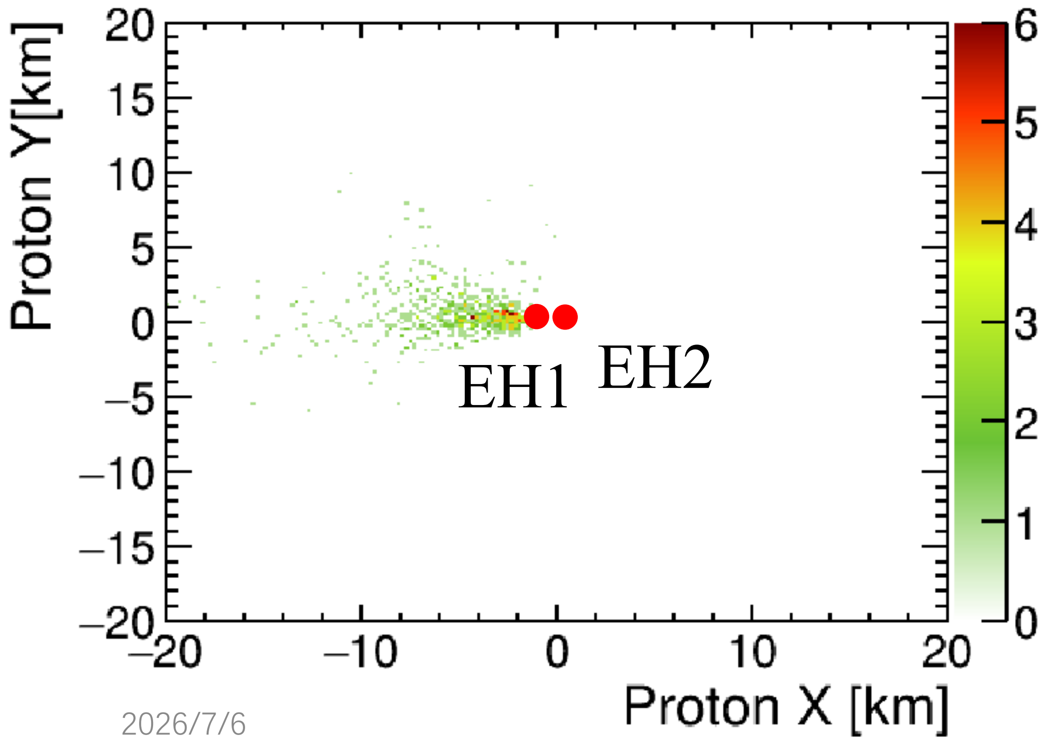
- The simulation still lacks a fully detailed like treatment of topography, realistic trigger response, and atmospheric modeling, which may lead to further corrections in future work.

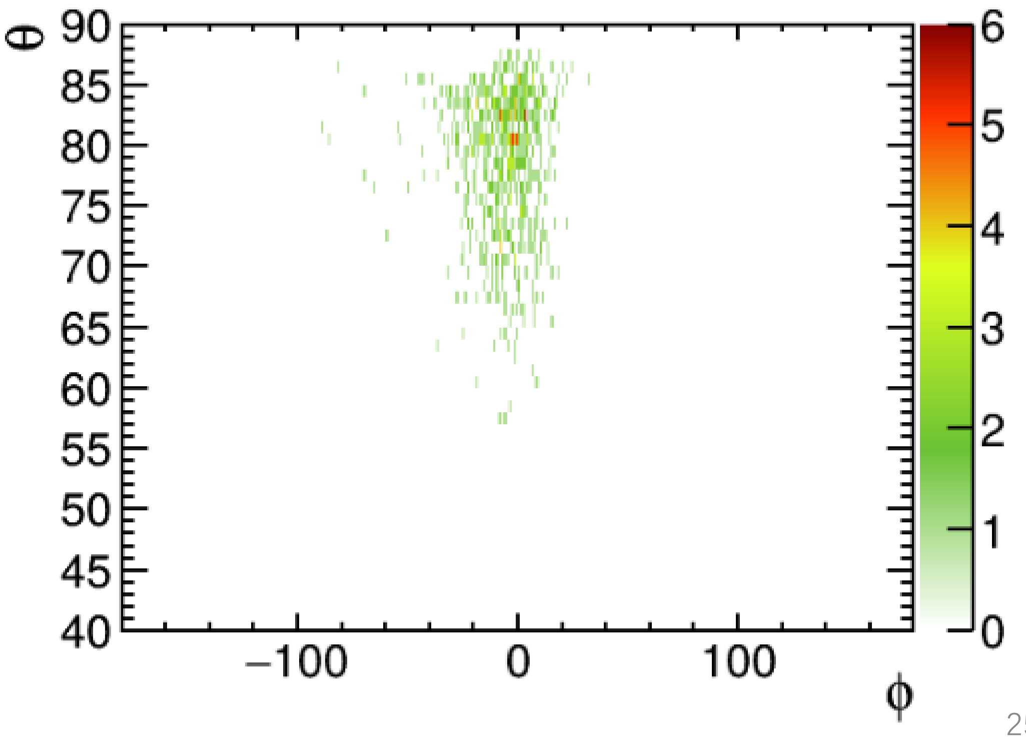
Thanks

Backup

Aiming Point and Direction

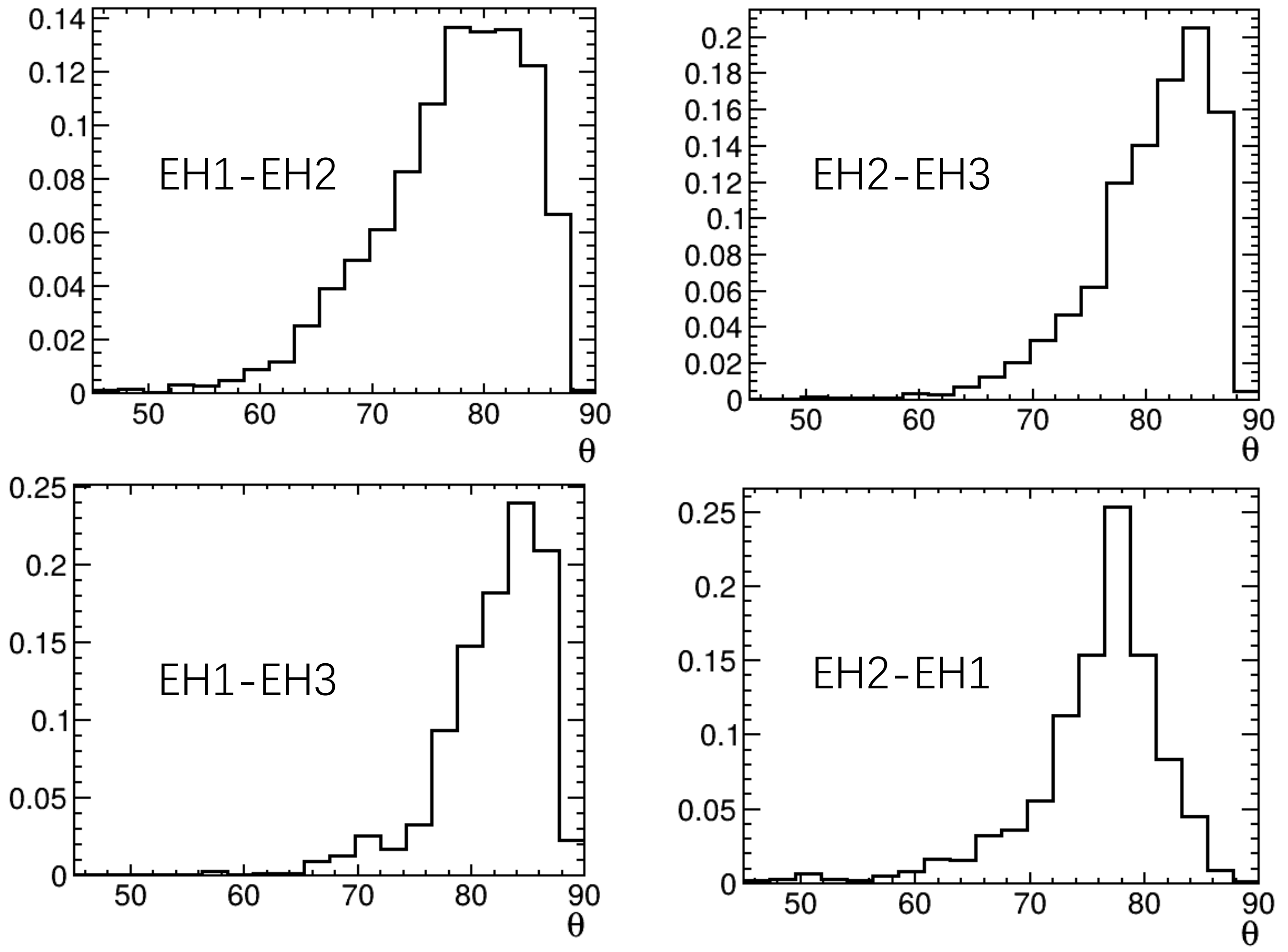
- For 10^6 GeV protons, the aiming points and directions of triggered events are shown in the figure below
- The incident cosmic rays are all highly inclined, with zenith angles between 70° and 90°, and arrive along the line connecting the two triggered experimental halls.





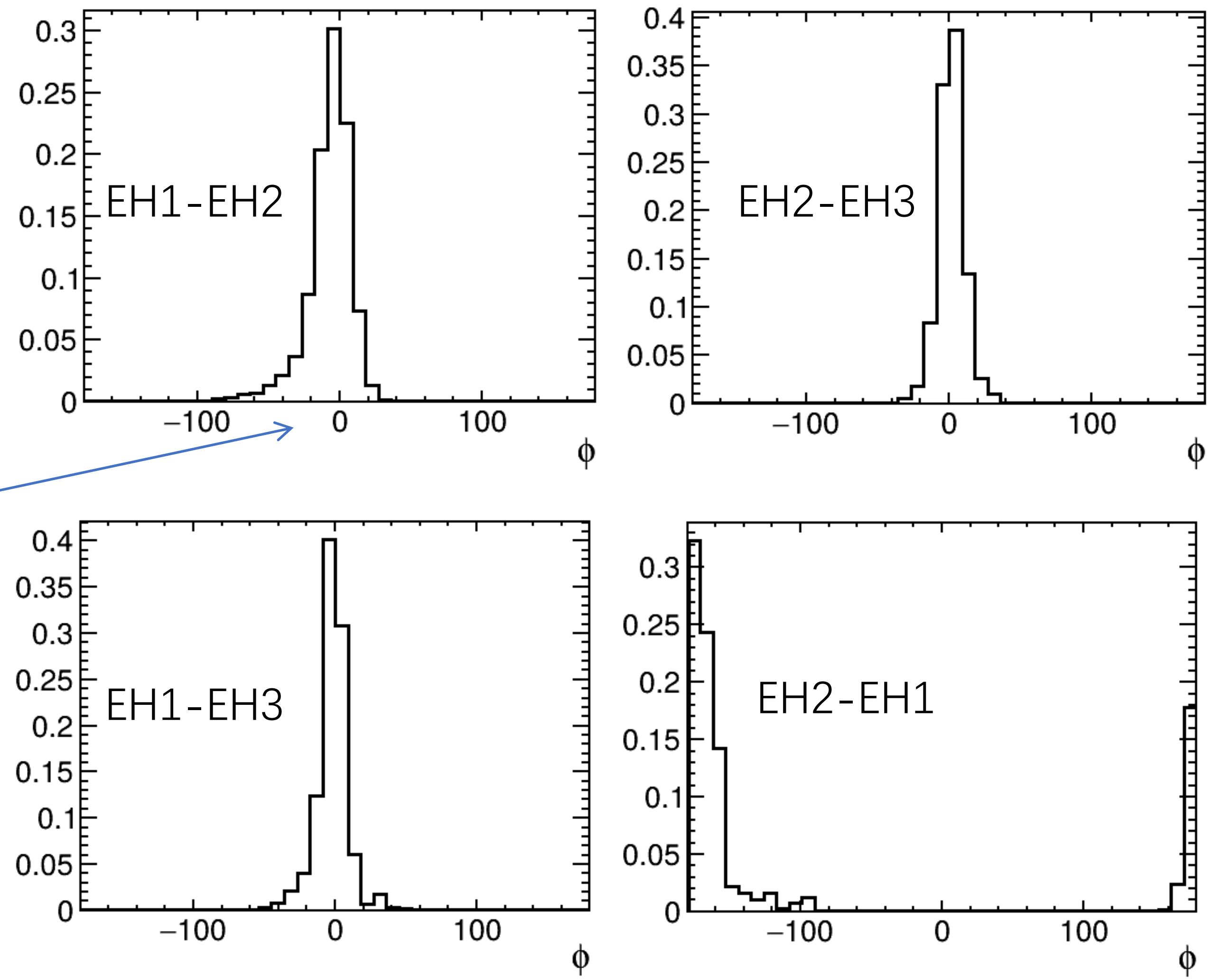
Triggered Cosmic-ray Incidence-angle Distribution

- θThe incidence-angle distribution of cosmic-ray triggers is shown in the right figure
- Triggered cosmic-ray particles are mainly concentrated at large zenith angles above 60° .
- The distribution differences are caused by variations in mountain topography along the line connecting the two halls.



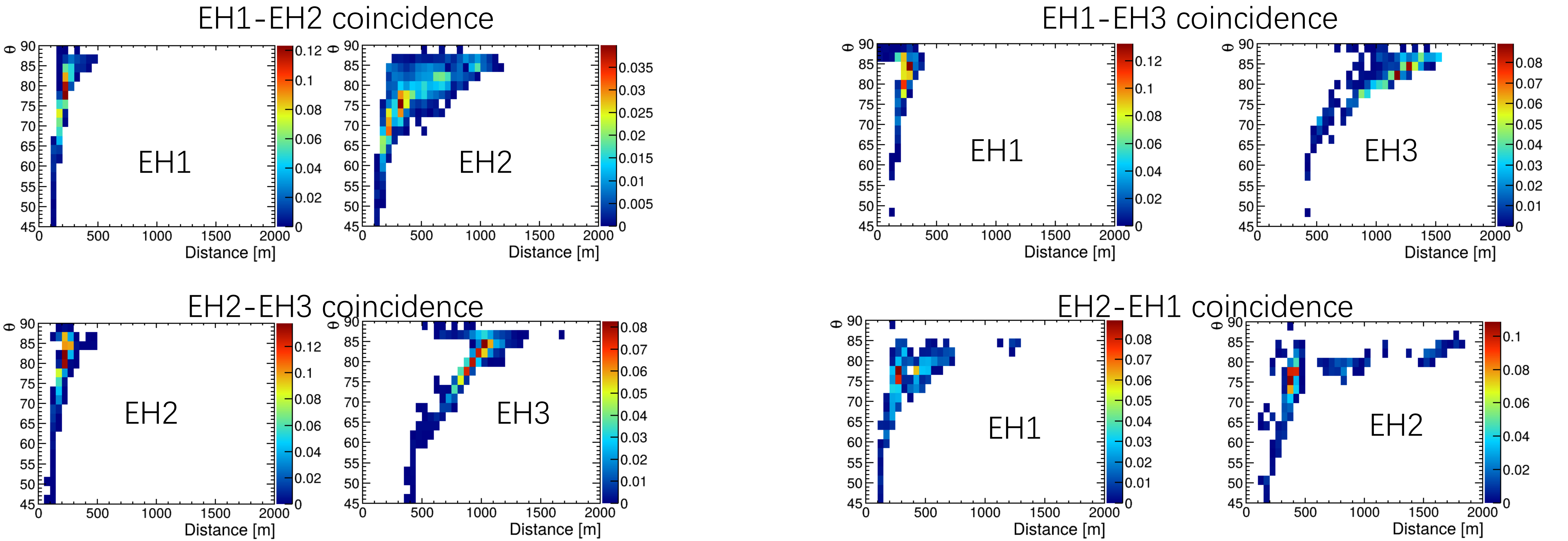
Triggered Cosmic-ray Incidence-angle Distribution

- ϕThe incidence-angle distribution of cosmic-ray triggers is shown in the right figure
- The incident-directionϕ distribution of cosmic rays is concentrated near 0° and 180°, indicating incidence along the direction connecting the two halls.
- The asymmetry in φ is caused by the asymmetric mountain overburden.



θ vs Muon Track Length in Rock

- The figure shows the distribution of cosmic-ray trigger θ vs. muon track length in rock.
- The average muon energy and average track length through rock are calculated from this distribution.



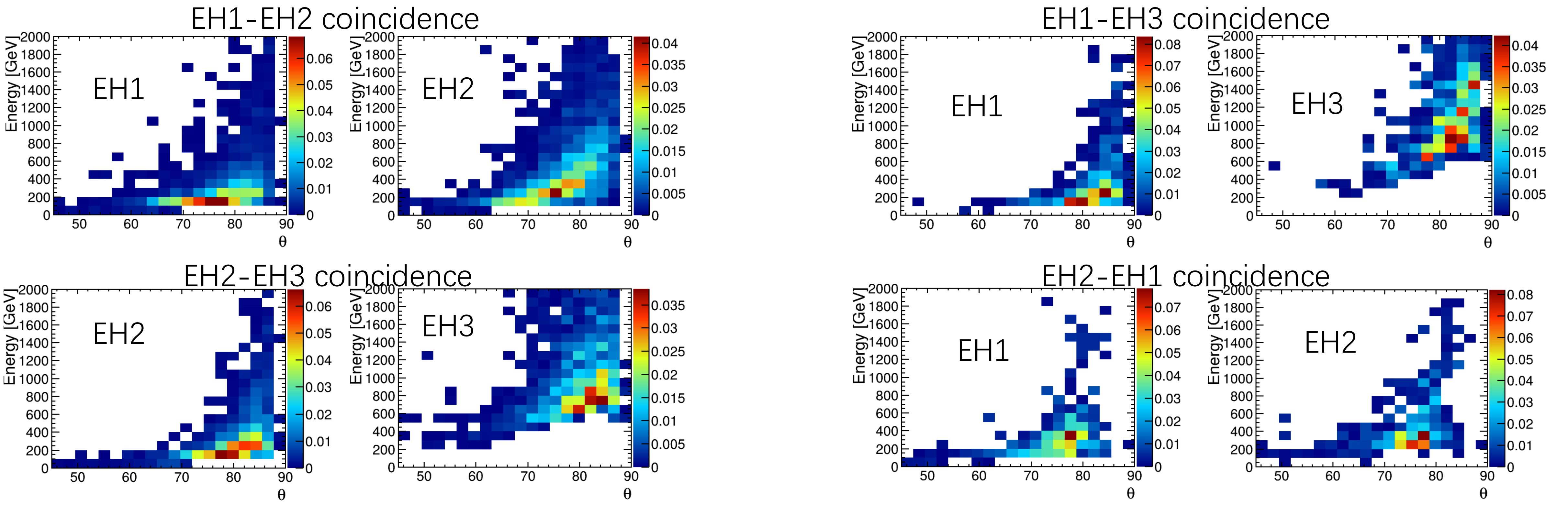
Average Energy of Coincident Muons

- The table shows the average muon energy and average track length through rock.

	EH1-EH2		EH2-EH3		EH1-EH3		EH1-EH2	
	EH1	EH2	EH2	EH3	EH1	EH3	EH1	EH2
average length [m]	218.4	455.5	218.1	936.9	236.5	1117.0	364.9	544.7
average energy [GeV]	113.6	236.9	113.4	487.2	123.0	580.8	189.7	283.2

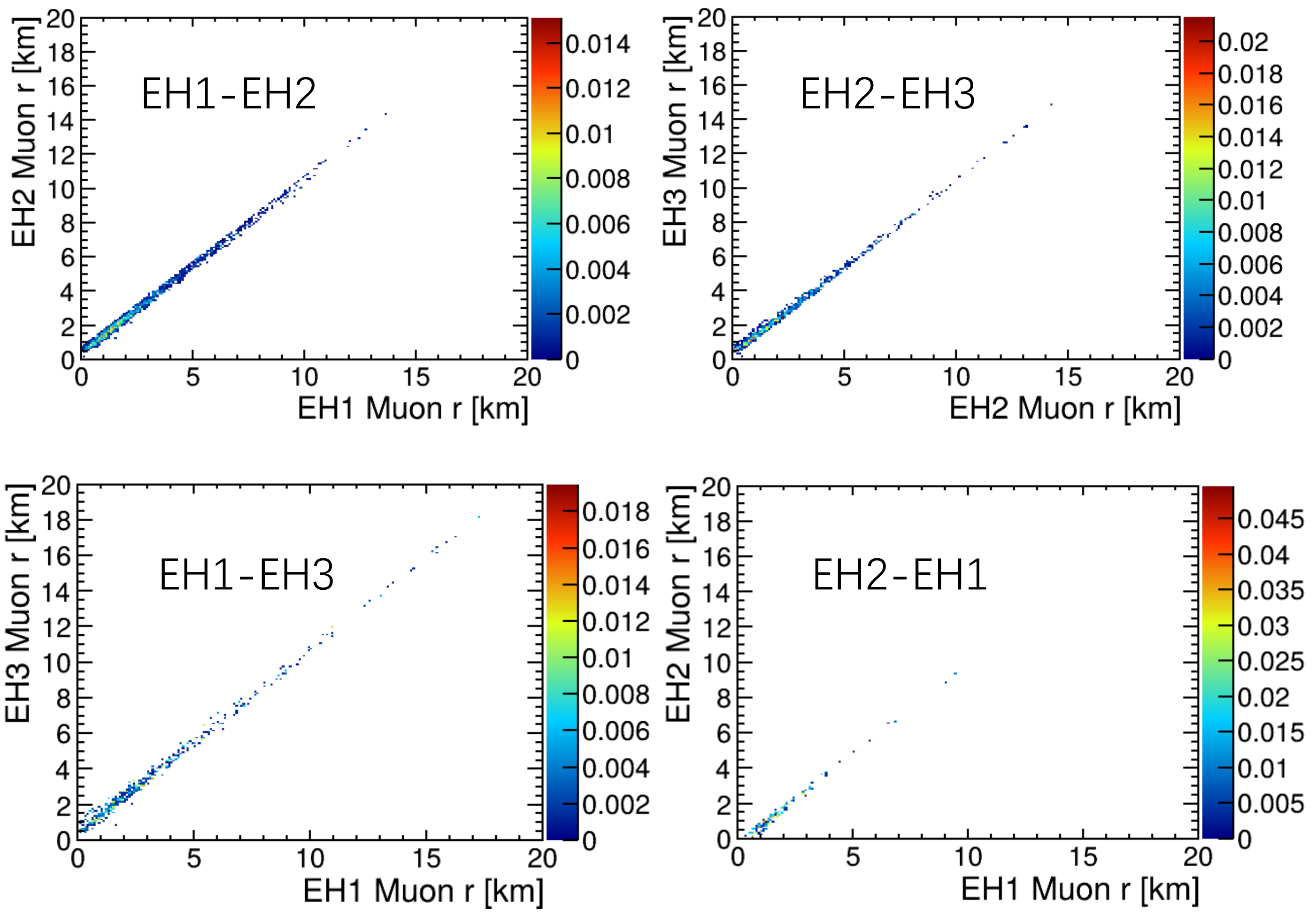
θ vs. Triggered Muon Energy

- The figure shows the distribution of cosmic-ray trigger θ versus triggered muon energy.



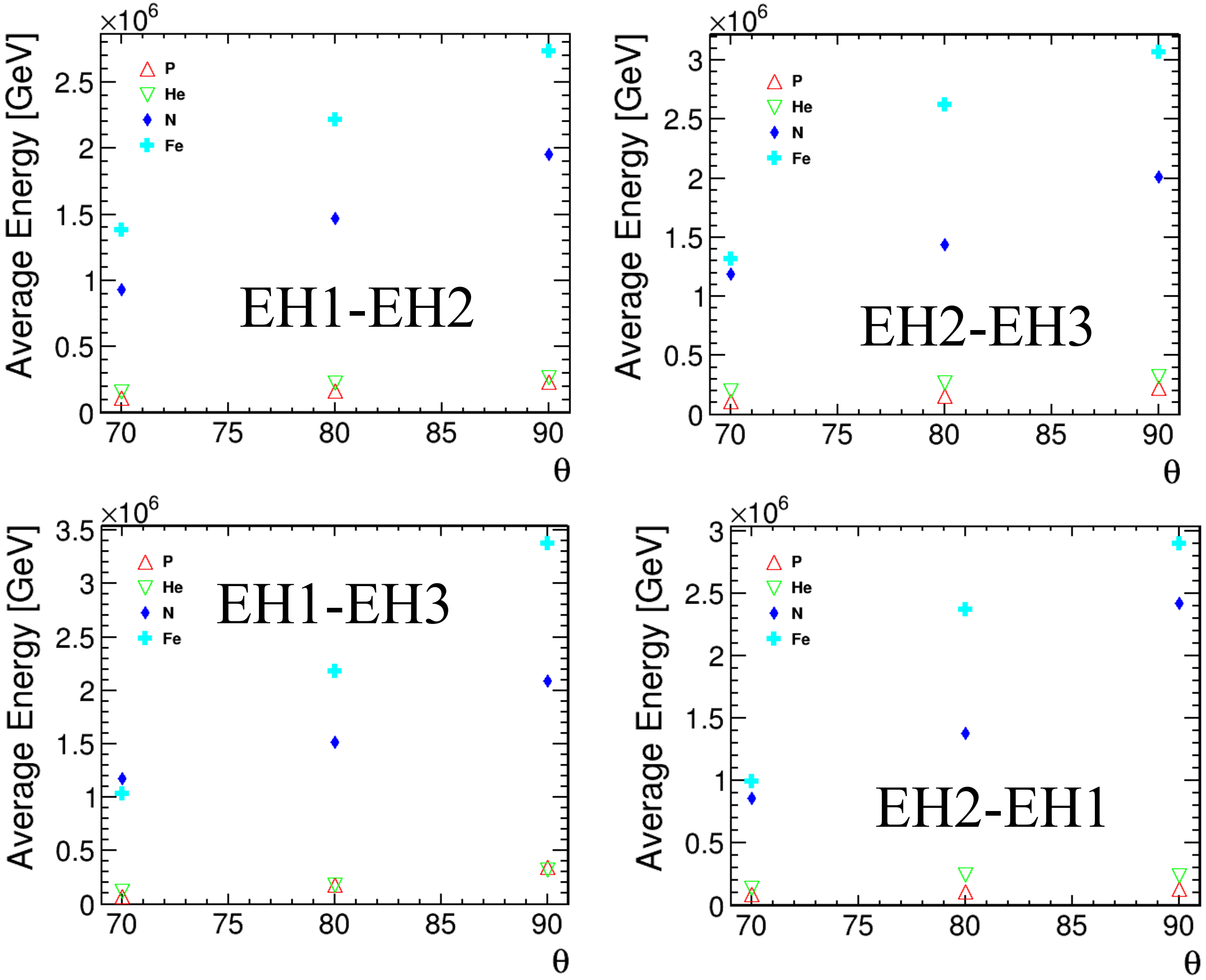
Lateral Separation of Triggered Muons

- The figure shows the distribution of lateral separation between triggered muons.
- The linear relationship suggests that the triggered muons are distributed on the same side of the cosmic-ray shower axis.



θ vs Average Cosmic-ray Energy

- The average energy of triggered iron and nitrogen cosmic-ray primaries reaches beyond the PeV level.



Comparation of Results

- For the EH13, EH12, and EH23 configurations, we simulated the several energies of selected incident particle types under different QCD models.

EH12($\Delta t_{12} < 0$)

QCD Module	Incident Particle	Energy of Incident Particle /GeV	Number of Simulations (Particles × Samples)	Trigger counts	A_{eff}/m^2 from Peiyang Liu	A_{eff}/m^2 from Huiyou Chen	Difference ΔA_{eff} $/A_{eff,huiyou}$
SIBYLL	Fe	10^7	$99400 \times (2 \times 10^4)$	362	138.5 ± 7.3	149.0 ± 8.7	-0.070
	p	10^6	$10^6 \times (3.5 \times 10^5)$	477	1.043 ± 0.047	1.114 ± 0.042	-0.083
DPMJET	N	10^6	$985000 \times (1 \times 10^5)$	583	4.53 ± 0.19	4.61 ± 0.24	-0.017
	p	10^5	$9830000 \times (4 \times 10^5)$	185	0.0360 ± 0.0026	0.0348 ± 0.0038	0.035

Comparation of Results

EH23($\Delta t_{23} < 0$)

QCD Module	Incident Particle	Energy of Incident Particle /GeV	Number of Simulations (Particles × Samples)	Trigger counts	A_{eff}/m^2 from Peiyang Liu	A_{eff}/m^2 from Huiyou Chen	Difference ΔA_{eff} $/A_{eff,huiyou}$
SIBYLL	Fe	10^7	$99400 \times (4 \times 10^4)$	351	67.6 ± 3.6	71.4 ± 6.0	-0.053
	p	10^6	$10^6 \times (5 \times 10^4)$	43	0.66 ± 0.10	0.606 ± 0.031	0.089
DPMJET	N	10^6	$997500 \times (4 \times 10^5)$	518	0.993 ± 0.043	2.27 ± 0.17	-0.56
	p	10^5	$9867500 \times (4 \times 10^5)$	88	0.0171 ± 0.0018	0.0139 ± 0.0019	0.23

Comparation of Results

EH13($\Delta t_{13} < 0$)

QCD Module	Incident Particle	Energy of Incident Particle /GeV	Number of Simulations (Particles × Samples)	Trigger counts	A_{eff}/m^2 from Peiyang Liu	A_{eff}/m^2 from Huiyou Chen	Difference ΔA_{eff} $/A_{eff,huiyou}$
SIBYLL	Fe	10^7	$99400 \times (2 \times 10^5)$	550	21.17 ± 0.90	19.35 ± 1.6	0.094
	p	10^6	$10^6 \times (5 \times 10^4)$	43	0.199 ± 0.039	0.183 ± 0.017	0.087
DPMJET	N	10^6	$987000 \times (2 \times 10^5)$	86	0.333 ± 0.036	0.533 ± 0.042	-0.38
	p	10^5	$9830000 \times (8 \times 10^5)$	22	0.00214 ± 0.00045	0.00359 ± 0.00099	-0.40

- In these comparison results, most $\Delta \mathrm{A_{eff}}/A_{eff,huiyou}$ are within 30%, especially for EH12 and SIBYLL. In other cases, however, the difference can be quite larger.

Discussion

- Using these Comparation and combining with H3a model for cosmic rays, I compare with the trigger rates of EH12,EH13,EH23 by Huiyou and estimate the trigger rates for the three cases in my dataset.

Offset	SIBYLL	DPMJET
EH12	-8.2%	3.4%
EH13	8.8%	-40%
EH23	8.7%	22%