High-Energy Atmospheric Muon Study with TRIDENT

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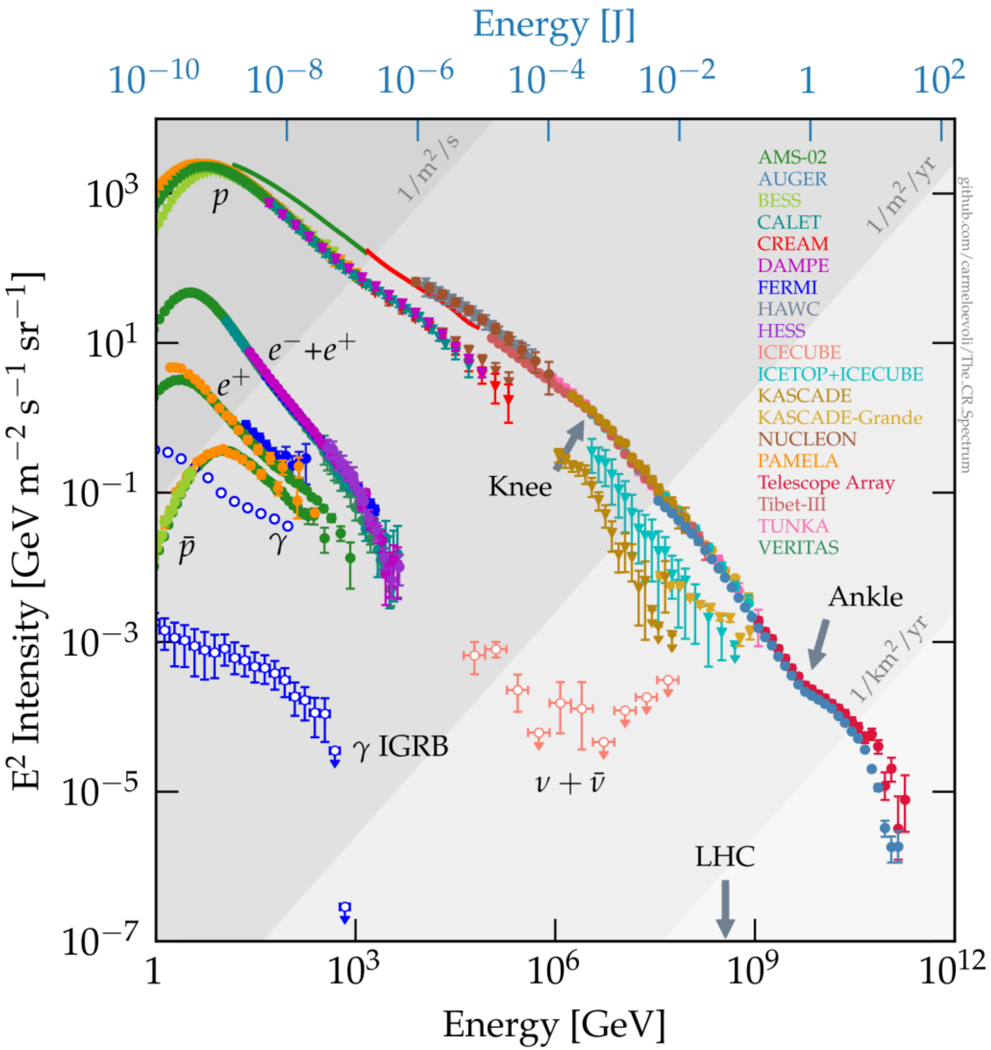
Cosmic Ray

Cosmic ray

- High energy charged particles.
- Composed of p^+, He and some other heavy nucleus.
- Energy ranges from MeV to EeV.

- **Where are they from?**



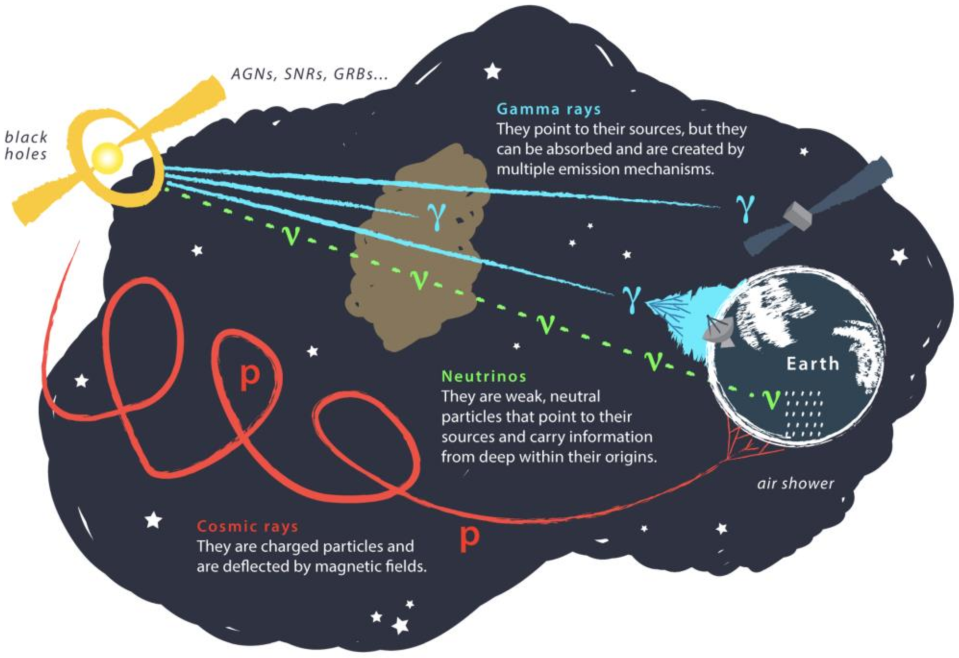
The Cosmic Ray Spectrum (2023)

Neutrino Telescopes

Probe origins of cosmic ray with **astrophysical neutrino:**

Pros:

- Neutral: not deflected by magnetic field
- Weak: not absorbed

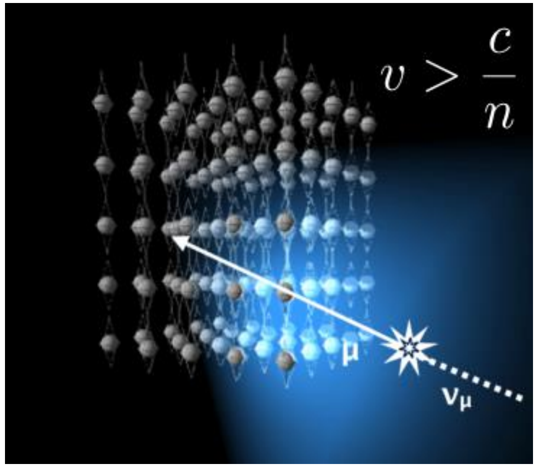


Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Cons:

- Small flux: $E_\nu \Phi_\nu < 2 \times 10^{-8} GeV cm^{-2} s^{-2} sr^{-1}$
- Small cross section: $\sigma \sim 10^{-33} cm^2$ for $E_\nu \sim 10 PeV$

Use sea water as target



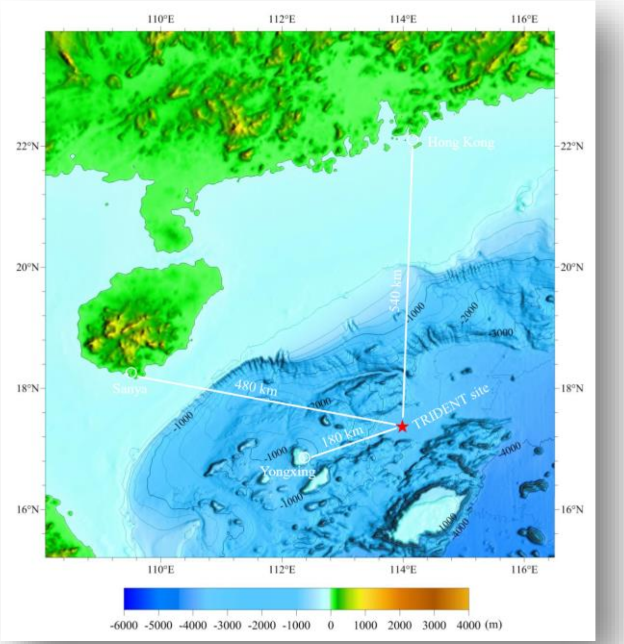
- Neutral-current interaction
  $\nu_l + N \to \nu_l + X$
- Charged-current interaction
  $\nu_l + N \to l + X$

TRIDENT

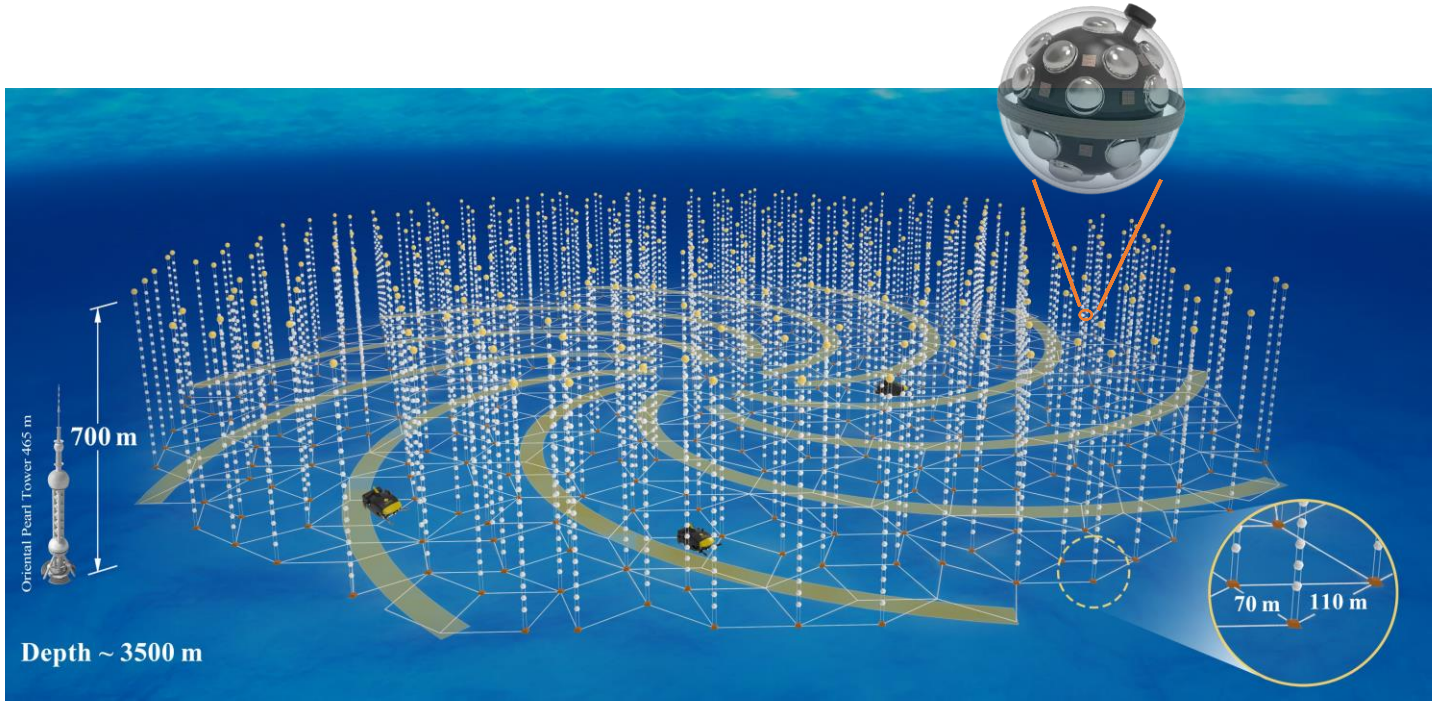
- **TRIDENT (海铃计划)**: **TR**oplcal **DE**ep-sea **N**eutrino **T**elescope.

  A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean. *Nat Astron* (2023).

- To be located in the South China Sea.
- Penrose tiling structure with 2000m radius, 700m height (8.7 km^3). 3500m deep under sea level.

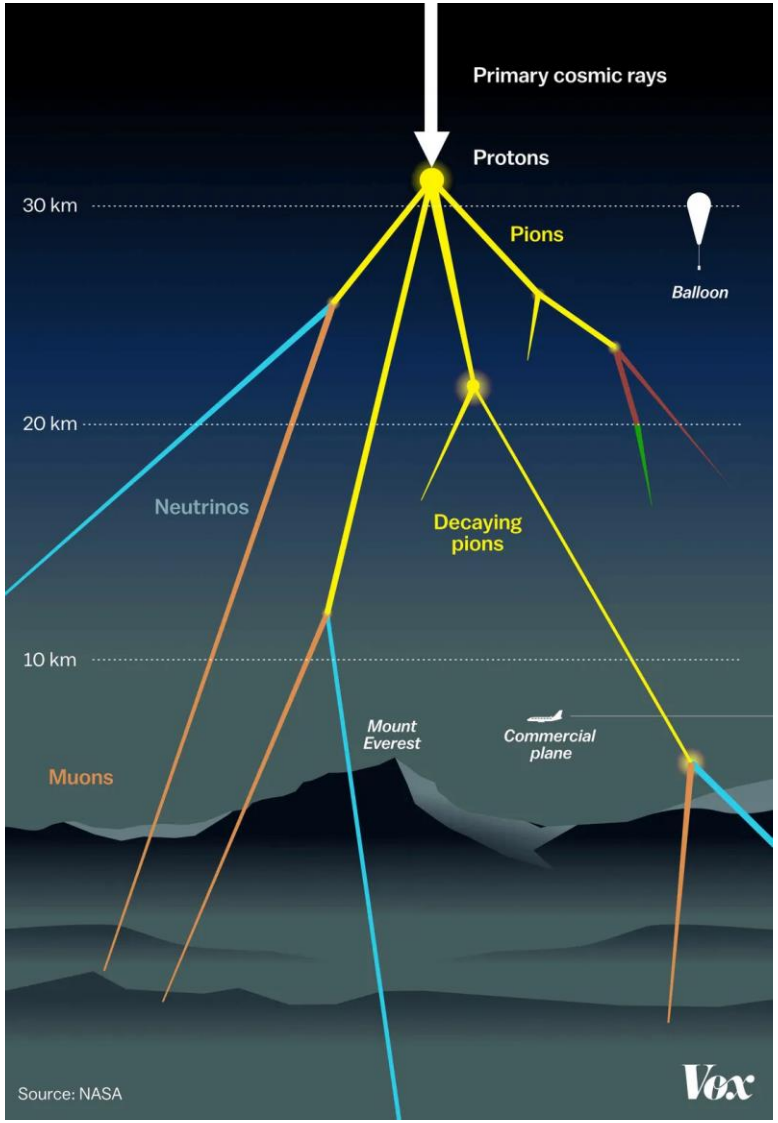


hDOM
(hybrid digital optical module)



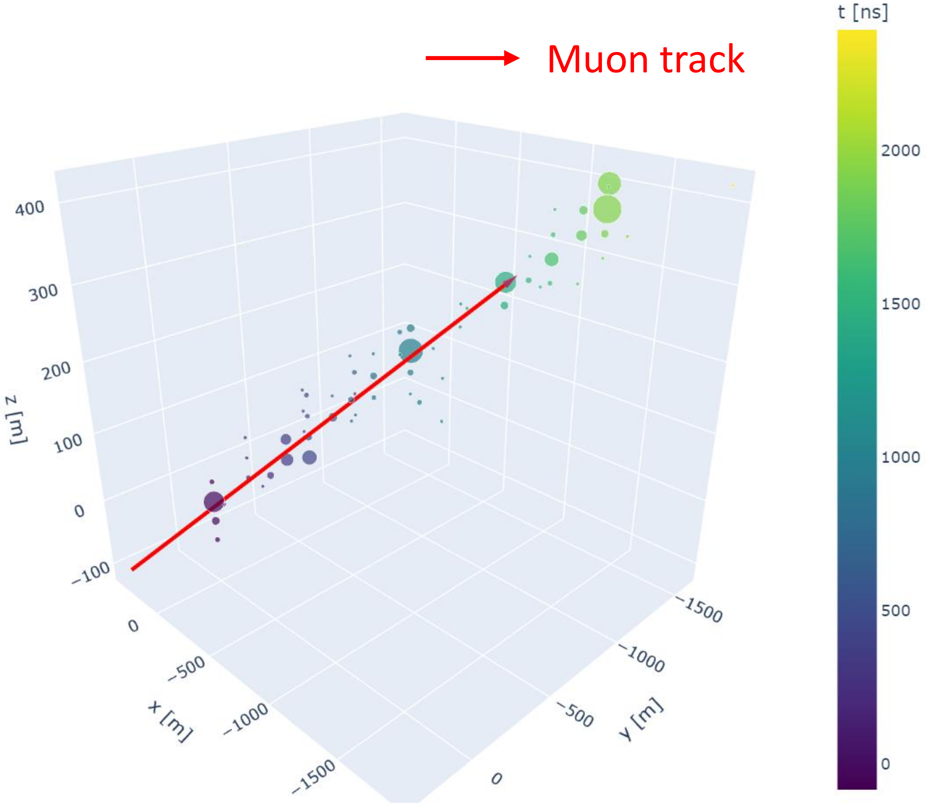
TRIDENT

Atmospheric Muons



Background for neutrino telescope: **atmospheric muons**

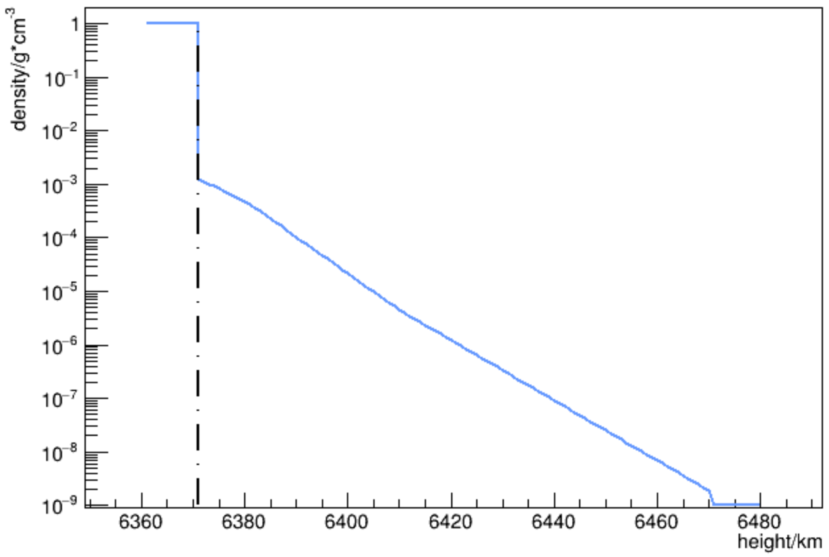
- High flux
- Indistinguishable from μ originating from ν_μ charge-current interaction.



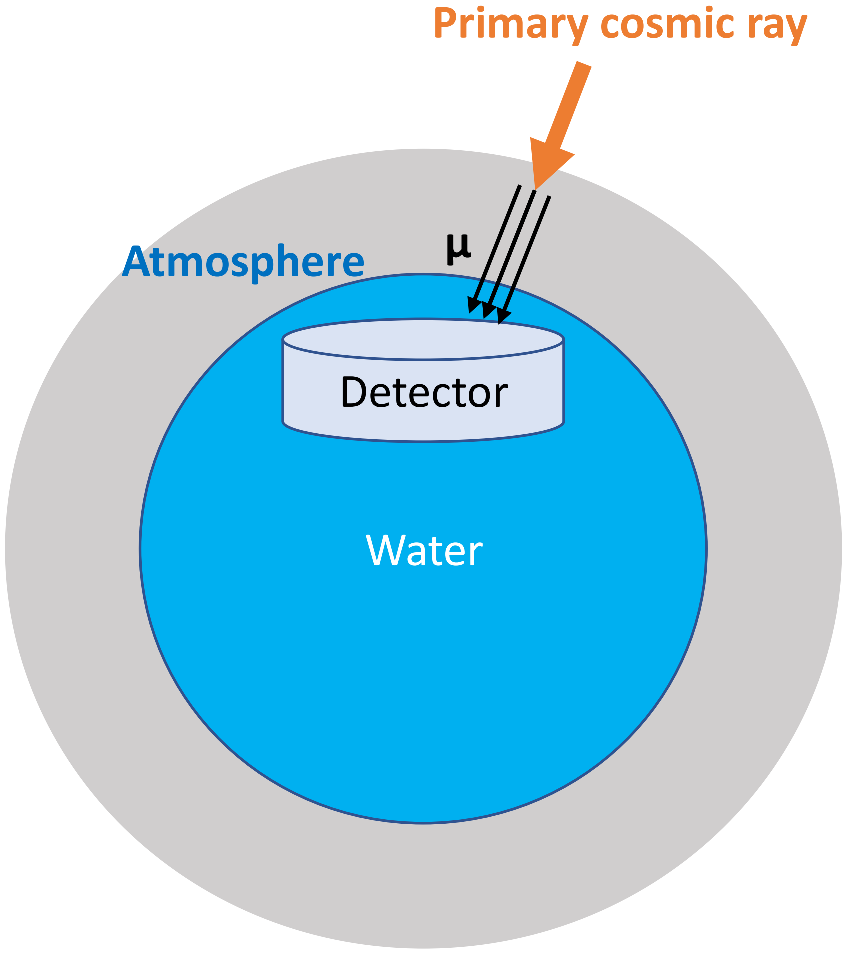
Simulation of Atmospheric Muon

Based on CORSIKA8 (arxiv:2208.14240):

- The next-generation air shower simulation framework.
- Built a **water ball** with a radius of 6371 km.
- **Outer surface**: atmosphere with a thickness of 110 km.
- Density of the atmosphere: **U.S. Standard Atmosphere model.**



Radius / km



Monte Carlo Simulation

Physics models

- Hadronic interaction models: **SIBYLL 2.3d**
- Continuous EM energy loss: **PROPOSAL**
- Decay Process: **Pythia**

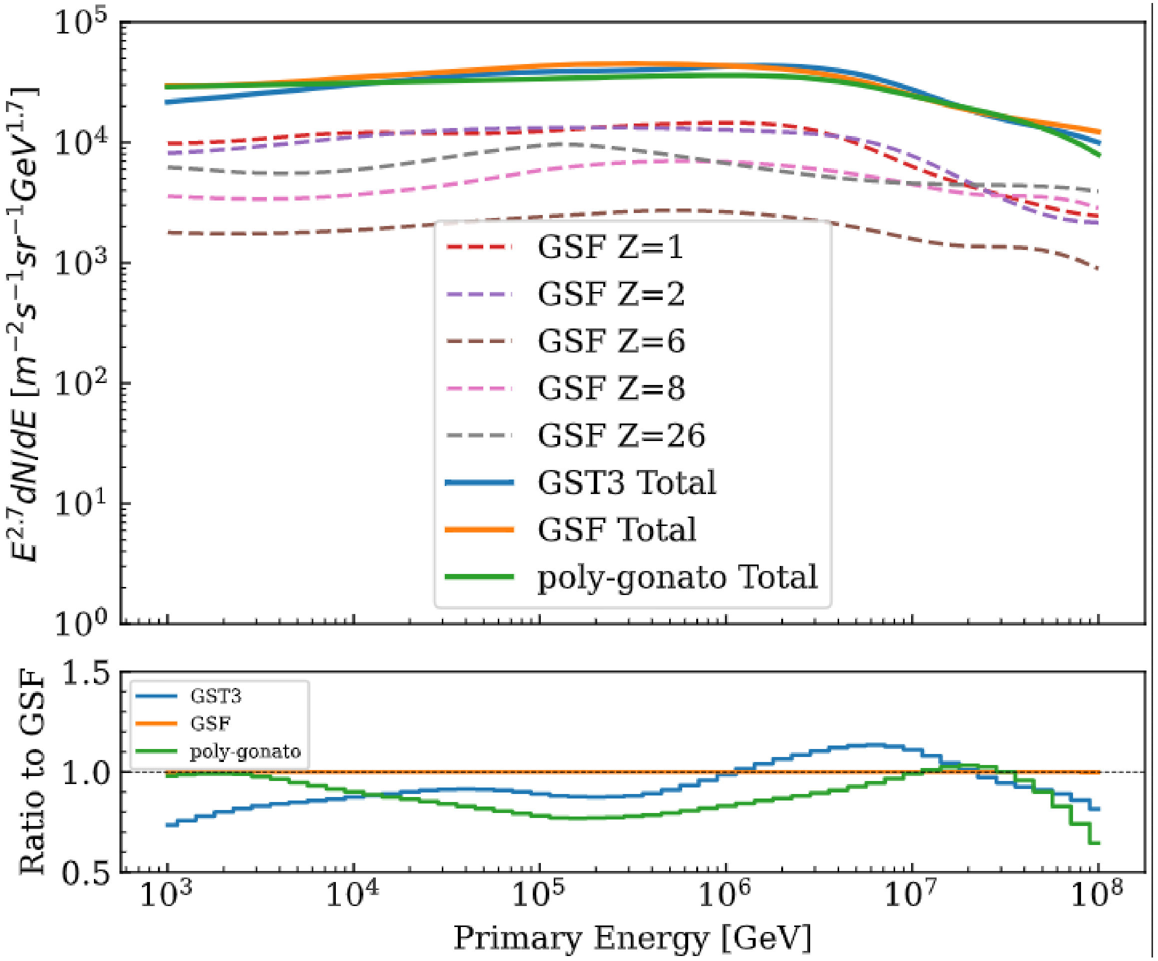
MC Energy spectrum: $f(\mathrm{E}) \propto \mathrm{E}^{-1}$

MC sample counts of primary particle / energy range / direction

		P	He	C	O	Fe
	Energy: 1-100 TeV cosθ: (0, 1)	5e5	5e5	1e5	1e5	1e5
	Energy: 100 TeV – 100 PeV cosθ: (0.8, 1)	2e5	1e5	5e4	5e4	4e4
	Energy: 100 TeV – 100 PeV cosθ: (0.4, 0.8)	2e5	1e5	5e4	5e4	4e4
	Energy: 100 TeV – 100 PeV cosθ: (0, 0.4)	5e4	5e4	2e4	2e4	2e4

Cosmic Ray Flux Model

- A cosmic ray flux model describes the flux of (p, He, C, O and Fe)
- Three models were investigated:
  - **Global Spline Fit (GSF)** [arxiv 1711.11432]: data-driven
  - **GST3** [arxiv 1303.3565]: with an assumption of 3 populations of particle sources:
    - Supernova remnants
    - Other galactic sources.
    - Extragalactic sources
  - **Poly-gonato** [arxiv 0210453]: phenomenological model



Muon Flux at Sea Level

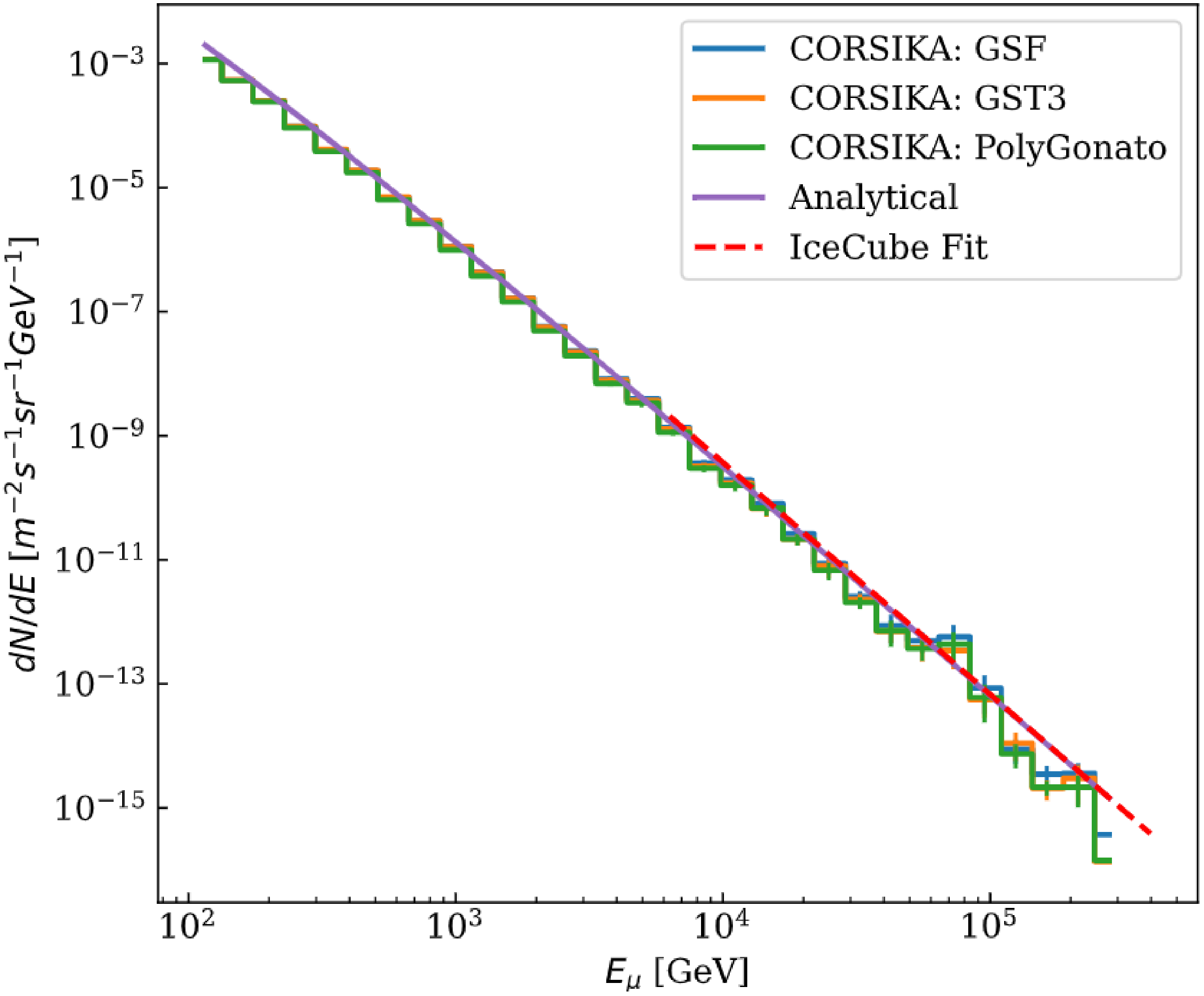
- Vertical muon flux at sea level.
- Analytical function:

Gaisser analytical parametric model

(Particle Data Group) **2022**, 083C01 (2022)

$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0.14\,E_\mu^{-2.7}}{\text{cm}^2\ \text{s sr GeV}} \times \left\{ \frac{1}{1+\frac{1.1 E_\mu \cos\theta}{115\,\text{GeV}}} + \frac{0.054}{1+\frac{1.1 E_\mu \cos\theta}{850\,\text{GeV}}} \right\}$$

Pion **Kaon**

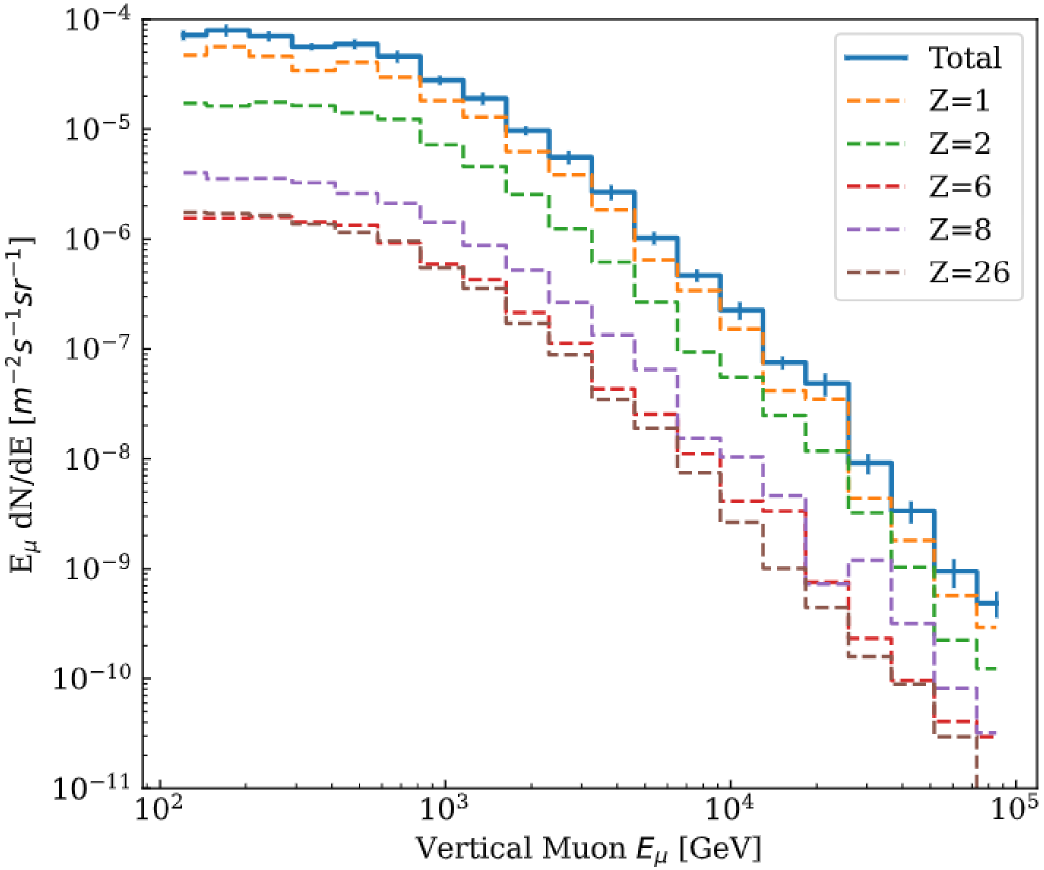


Muon Flux in TRIDENT

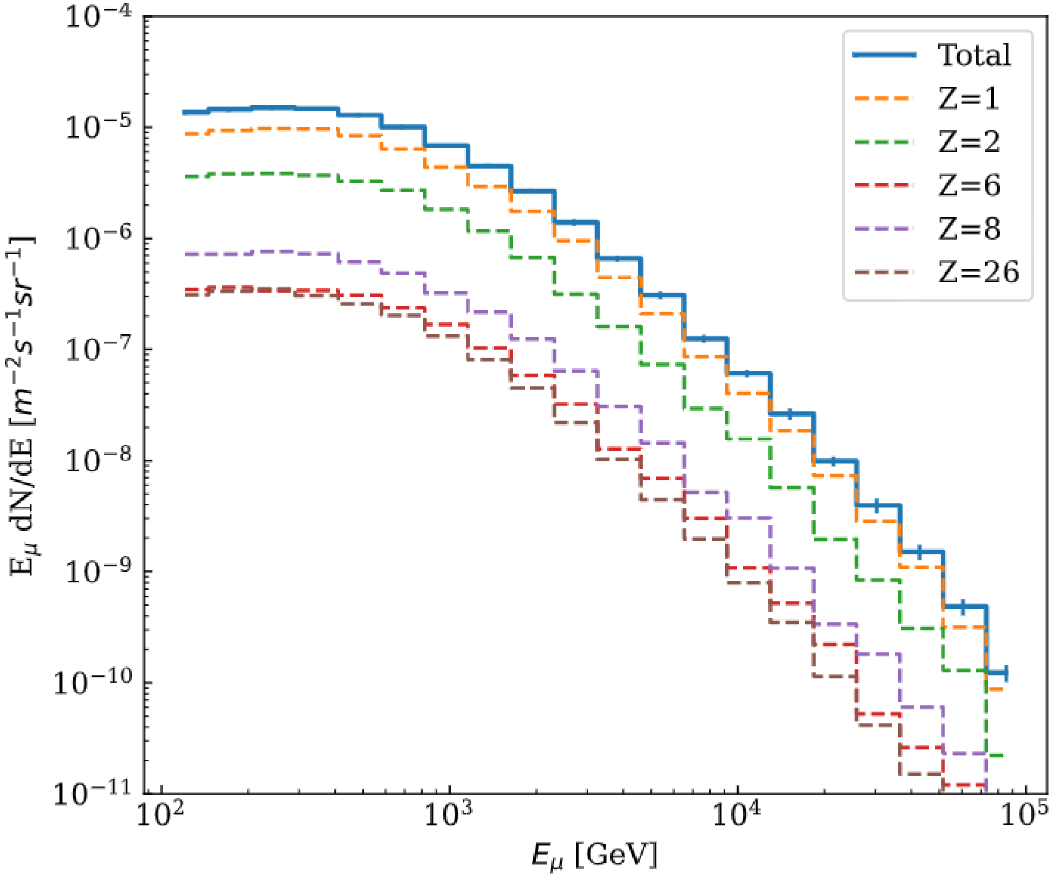
Muon flux at a depth of 2.5 km beneath the sea level as a function of muon energy.

- Types of primary nucleus are shown in dashed line
- Rate of atmospheric muon (0.1-100TeV) for a plate with 2 km radius: 2672.15Hz.

Vertical muon

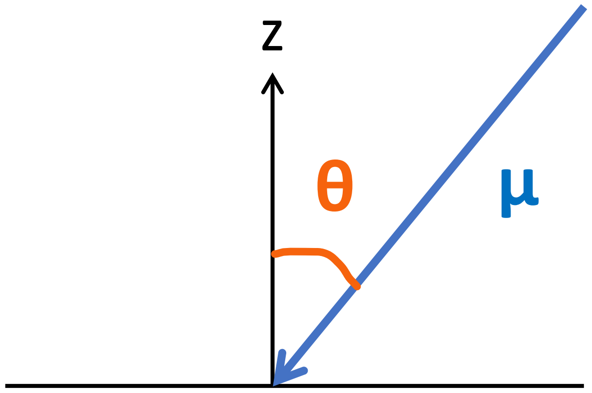


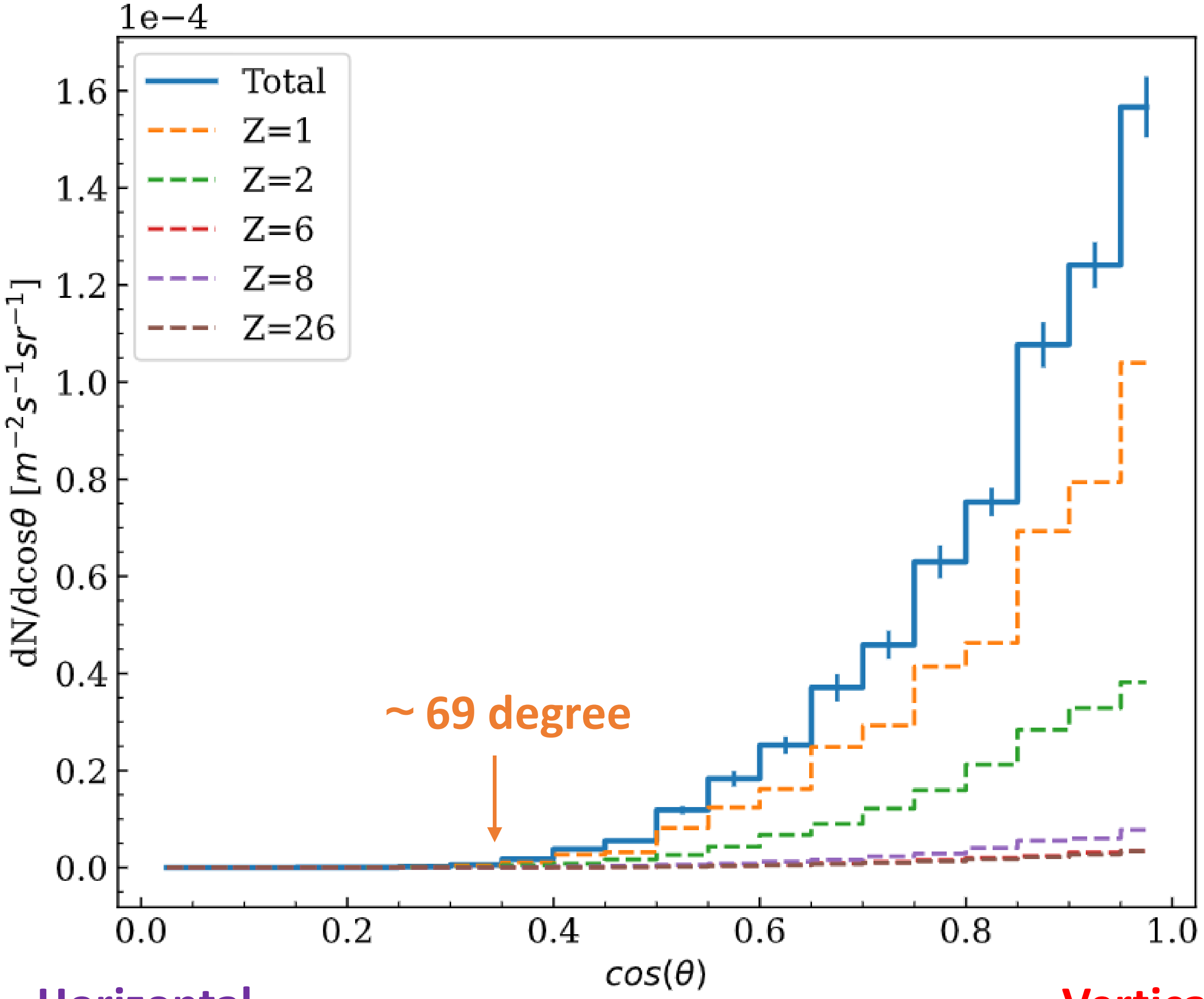
Muon from all direction



Muon Flux in TRIDENT

Muon flux at a depth of 2.5 km beneath the sea level as a function of $\cos(\theta)$



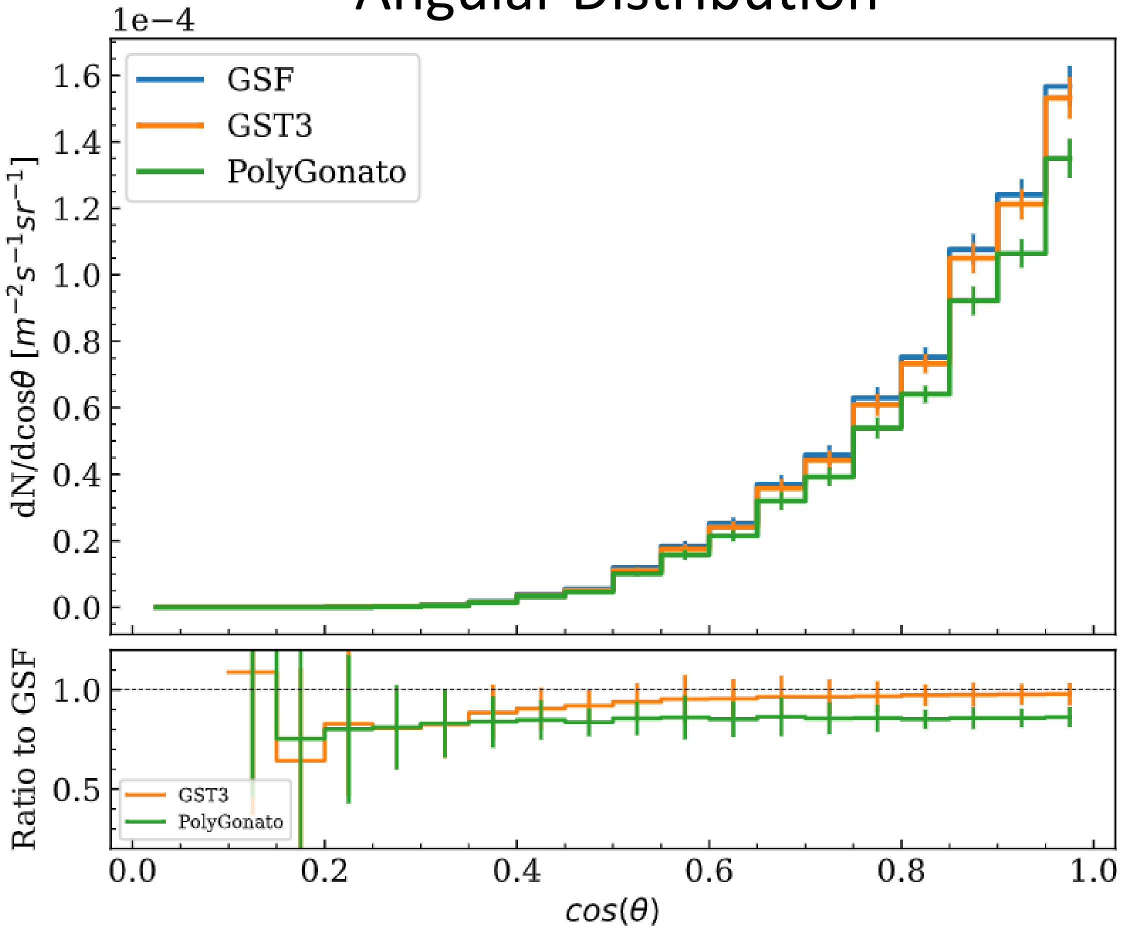


Horizontal

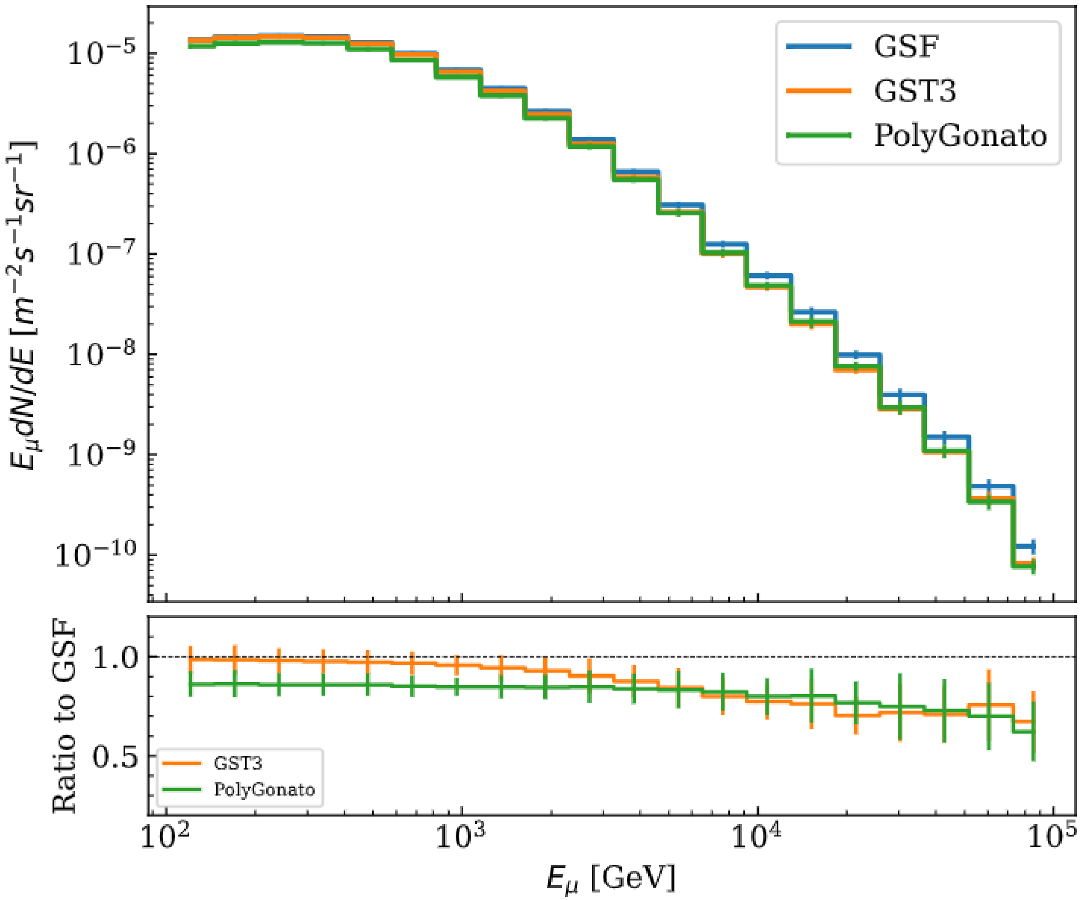
Vertical

CR Model Comparison

Angular Distribution

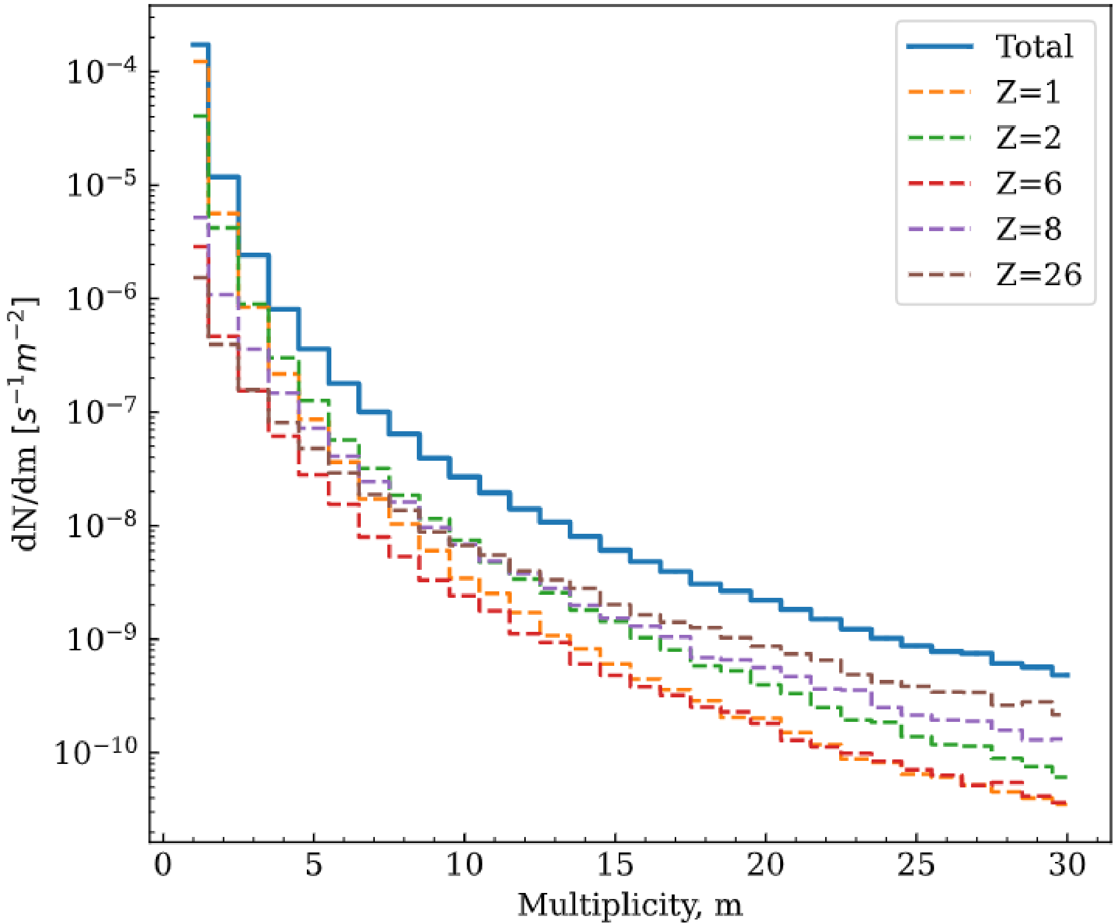


Energy Spectrum



Multiplicity distribution

- **Muon Multiplicity**: number of muons originating from the same primary particle.
- Most (91%) events contain only single muon.
- It is sensitive to Z of primary particles.



Direction Reconstruction

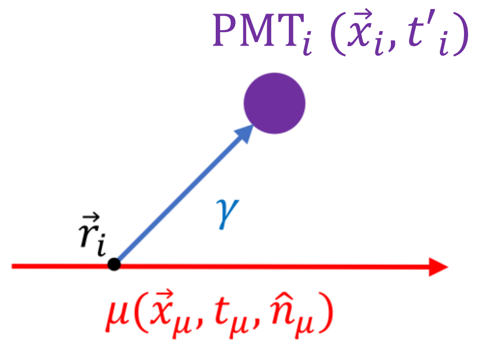
Reconstruction of muon events:

Traditional method: **Likelihood method.**

- Construct probability density function (PDF) with Monte Carlo result:

$$\text{Likelihood}(\hat{n}_\mu, \vec{x}_\mu, t_\mu; \vec{x}_i, t_i') = \Pi_i P(t_i^{res})$$

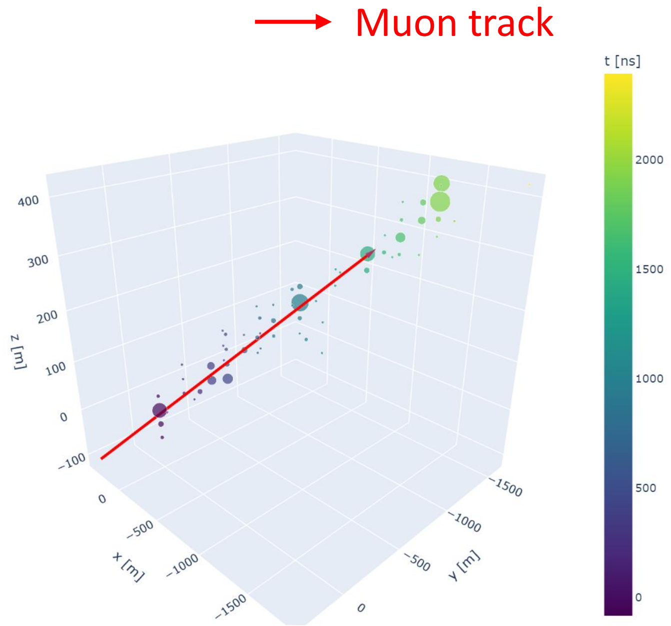
- High accuracy
- High runtime cost



μ emits photon and triggers PMT_i

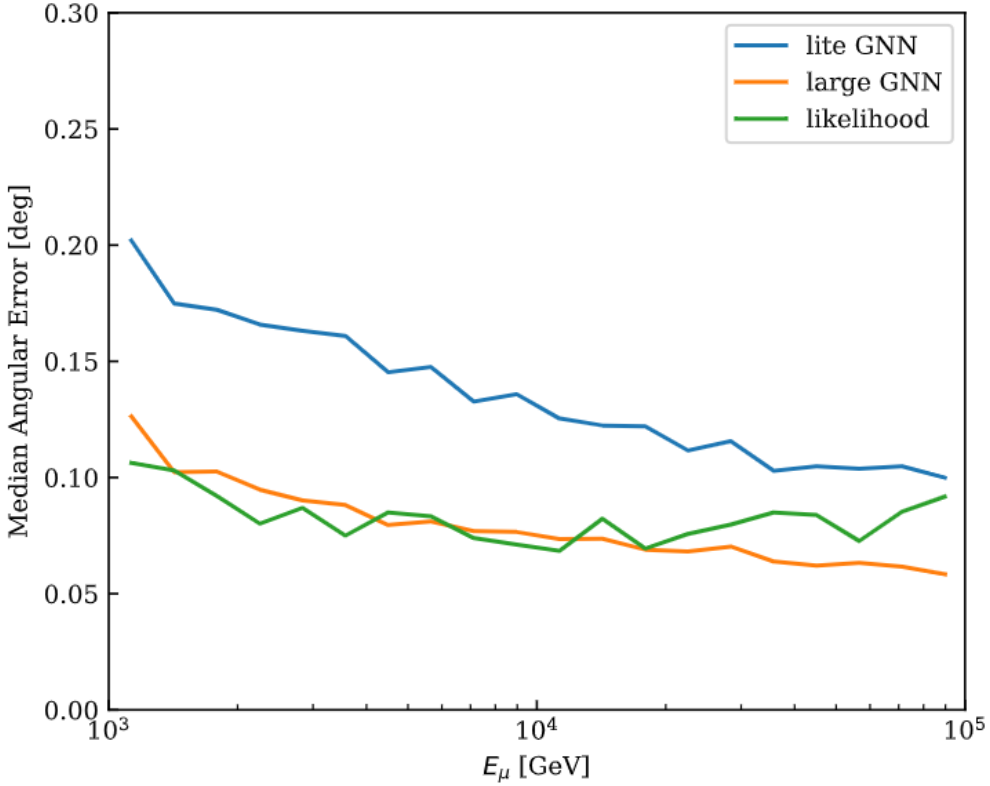
Graph Neural Network (GNN) based method:

- Represent each digital optical module as a node. Train GNN with Monte Carlo result.
- High accuracy
- Low runtime cost



Direction Reconstruction

Angular resolution of different methods



Mean runtime cost per event

Method	Time (1-10 TeV) [ms]	Time (10-100 TeV) [ms]
Likelihood	1290.52	847.27
GNN lite (GPU)	**0.27**	**0.57**
GNN large (GPU)	1.21	3.53
GNN lite (CPU)	7.26	17.87
GNN large (CPU)	95.67	231.97

Atmospheric Muons in TRIDENT

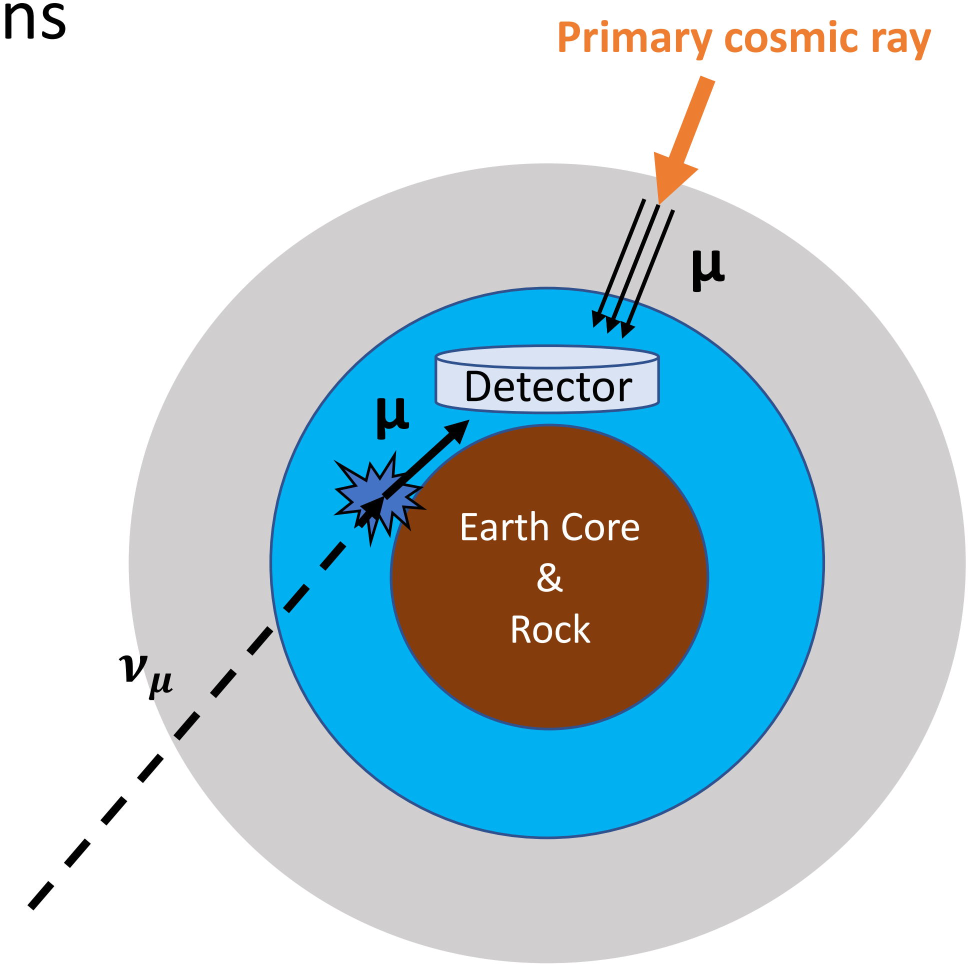
Define control region with atmospheric muons

Down-going muon events:

- Dominated by atmospheric muons **(background).**
- High flux.
- Control Region (CR).

Up-going muon events:

- Dominated by neutrino events **(signal).**
- Signal Region (SR).

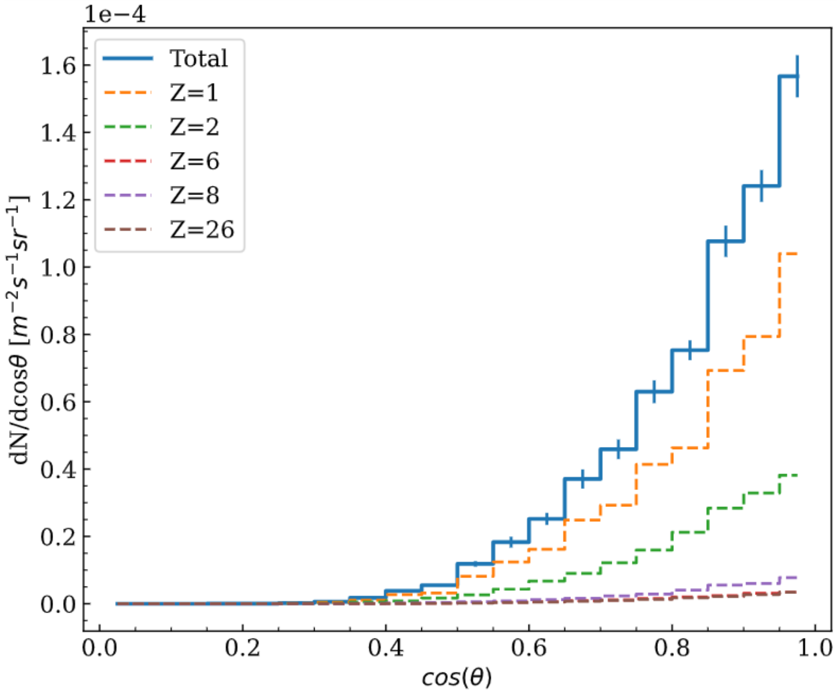


Define CR to calibrate simulation & reconstruction.

Direct Measurement

To calibrate the simulation & reconstruction algorithm:

- Measure the atmospheric muons directly.
- Compare directly measured results with:
  - Reconstructed direction.
  - Flux of different direction (from MC results).



Summary and Outlook

A study on high energy **atmospheric muon** is conducted:

- **Full simulation** of atmospheric muons were preformed with CORSIKA8.
- Results across three cosmic ray flux models were compared:
  - The choice of model can lead to ~20% variation in outcomes.
- At a depth of 2.5 km under sea water, the rate of atmospheric muon (0.1-100TeV) is approximately $2 \times 10^{-4}\mathrm{Hz}/m^2$.
- The angular resolution for high-energy muon tracks is approximately 0.1 degrees.

Outlook:

- The **composition of cosmic ray** can be inferred by reconstructing multiplicity of muon bundle.
- Muon simulation & reconstruction algorithms can be **calibrated** with atmospheric muons.

Thanks!

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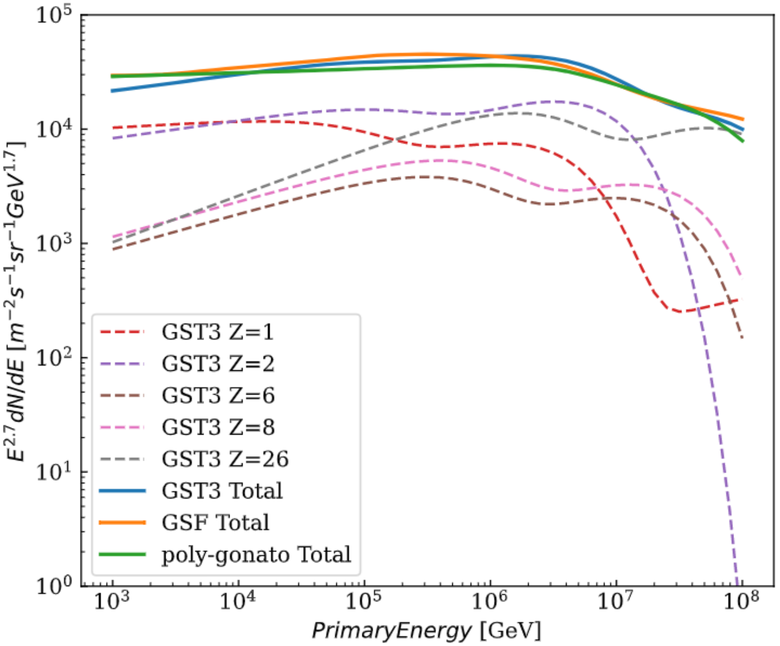
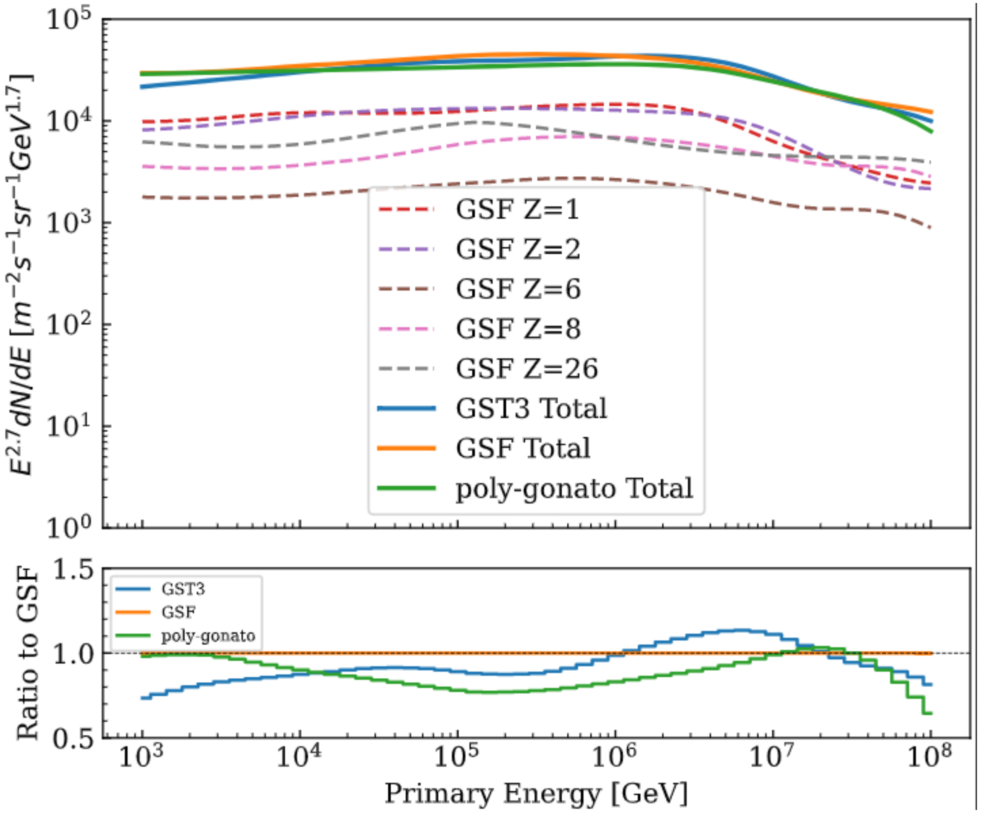
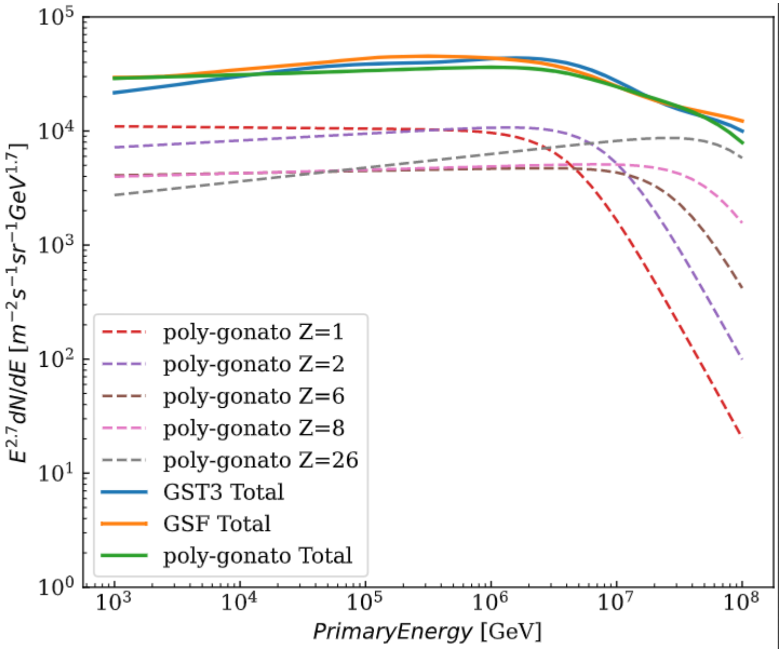
Backup

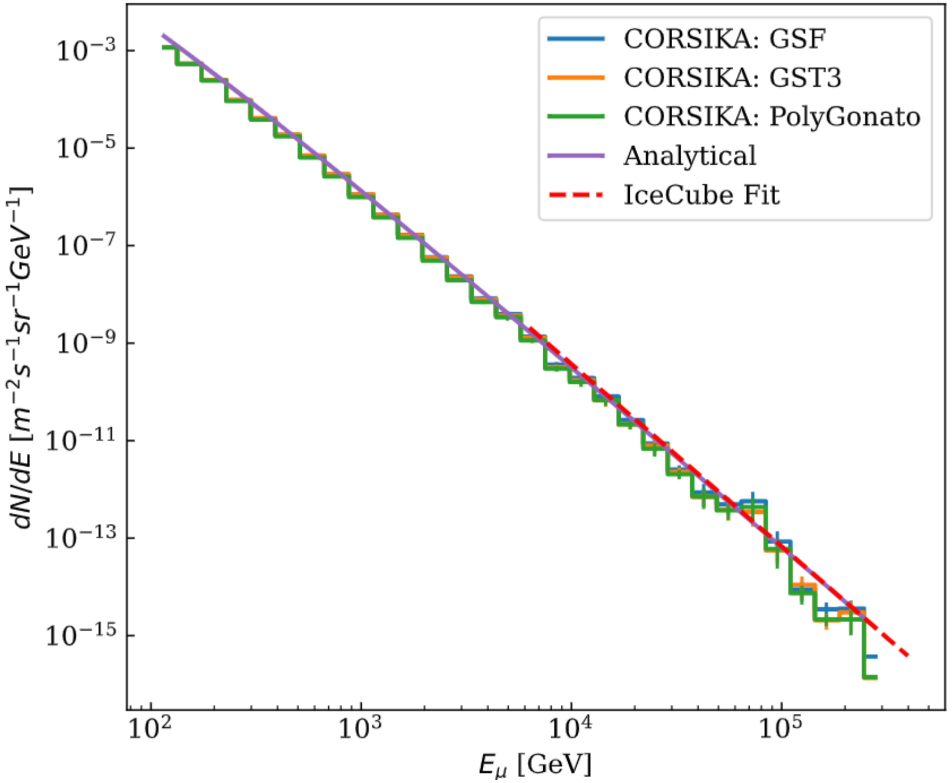
Cosmic Ray Flux Model



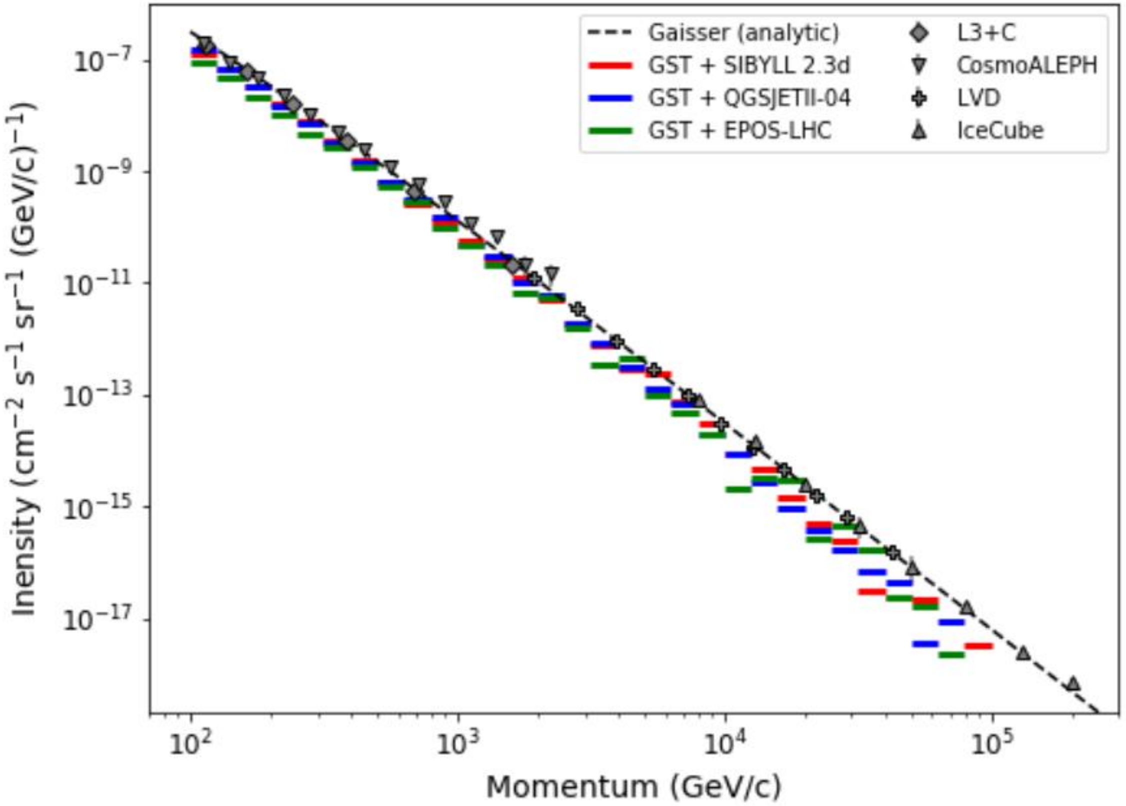




Muon Flux at Sea Level



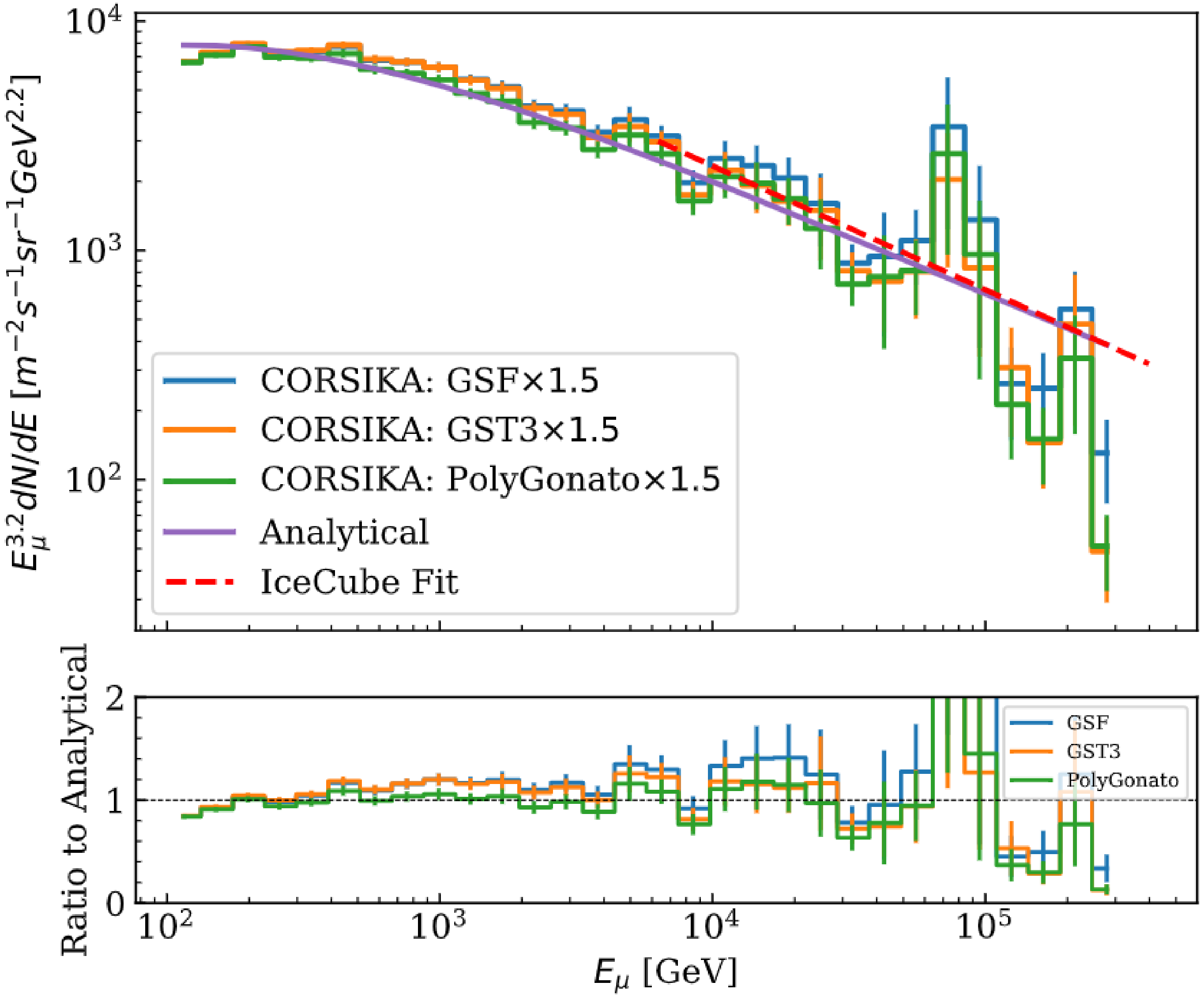
This study



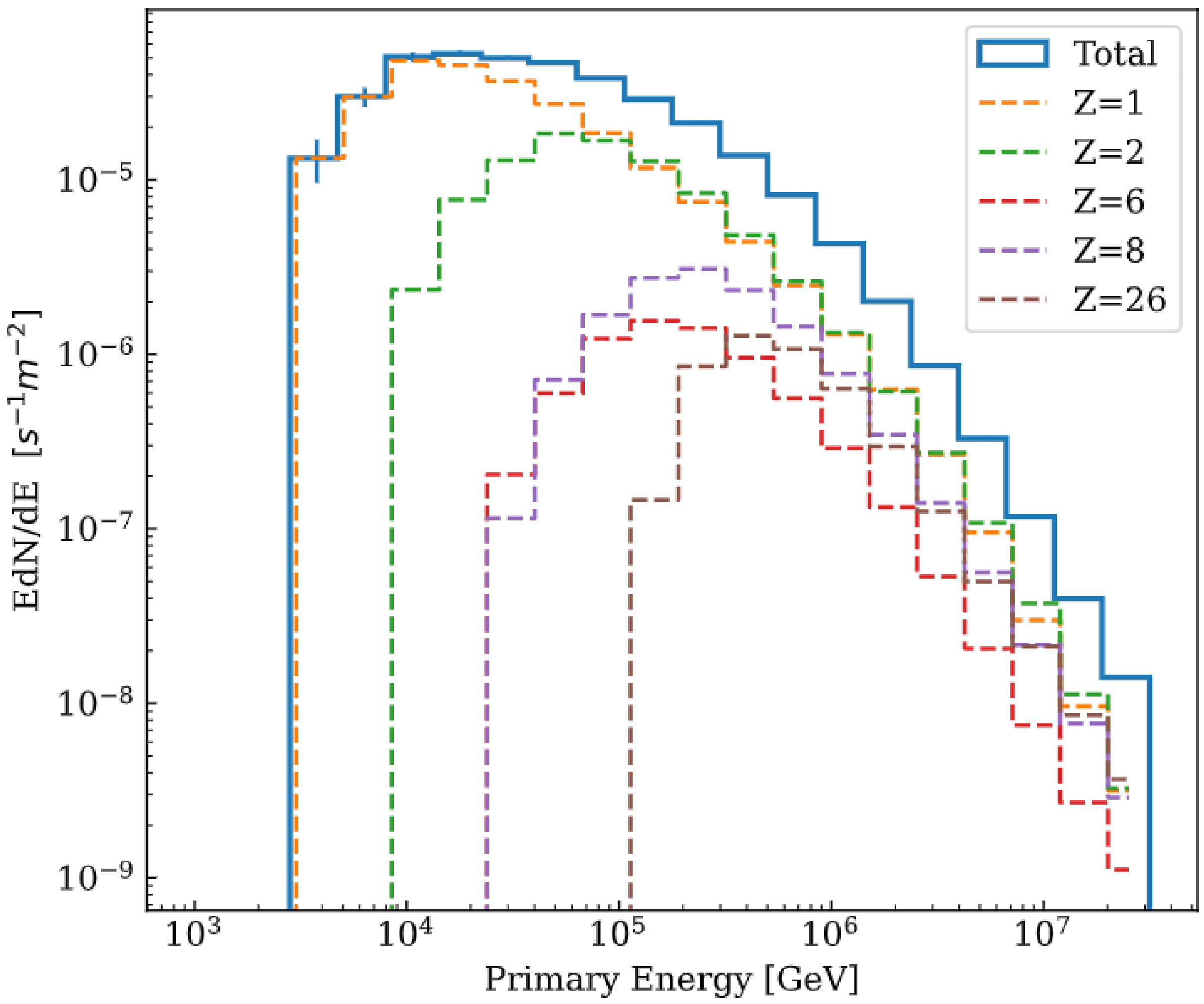
Based on CORSIKA7.741

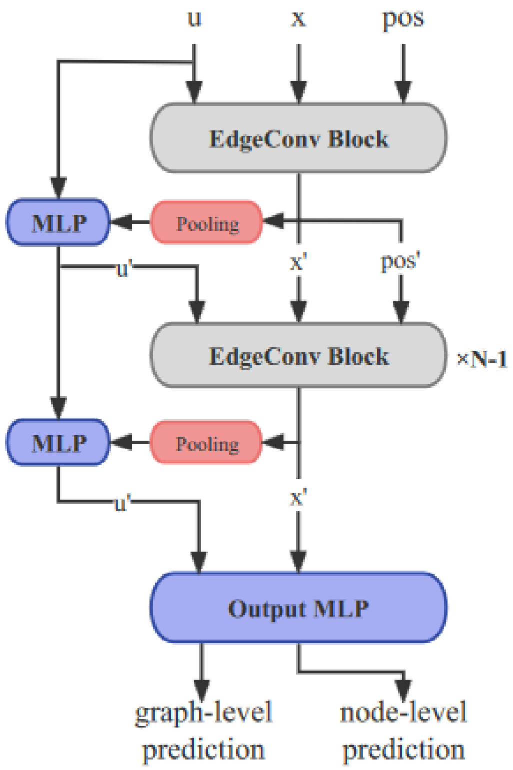
https://pos.sissa.it/423/071

Muon Flux at Sea Level

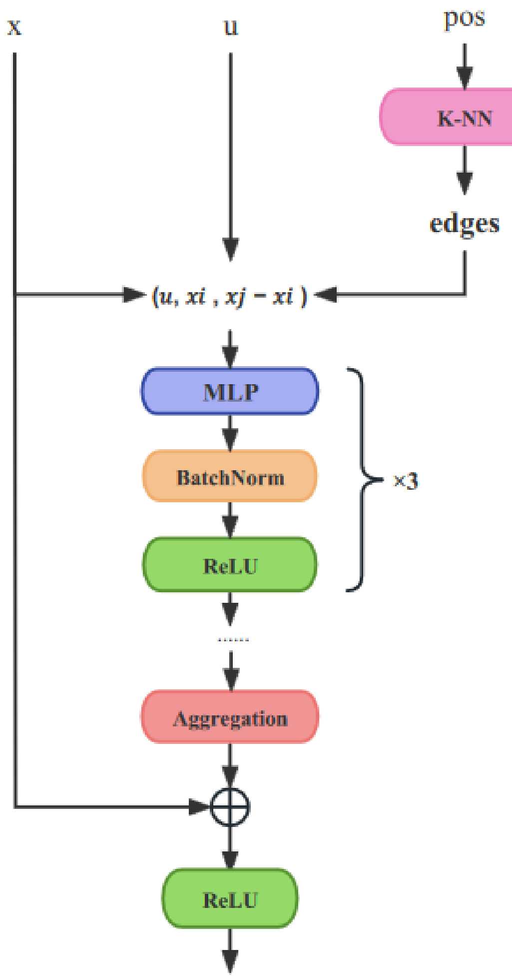


- Energy distribution of primary particles





Network Structure



EdgeConv Block

Sensitivity

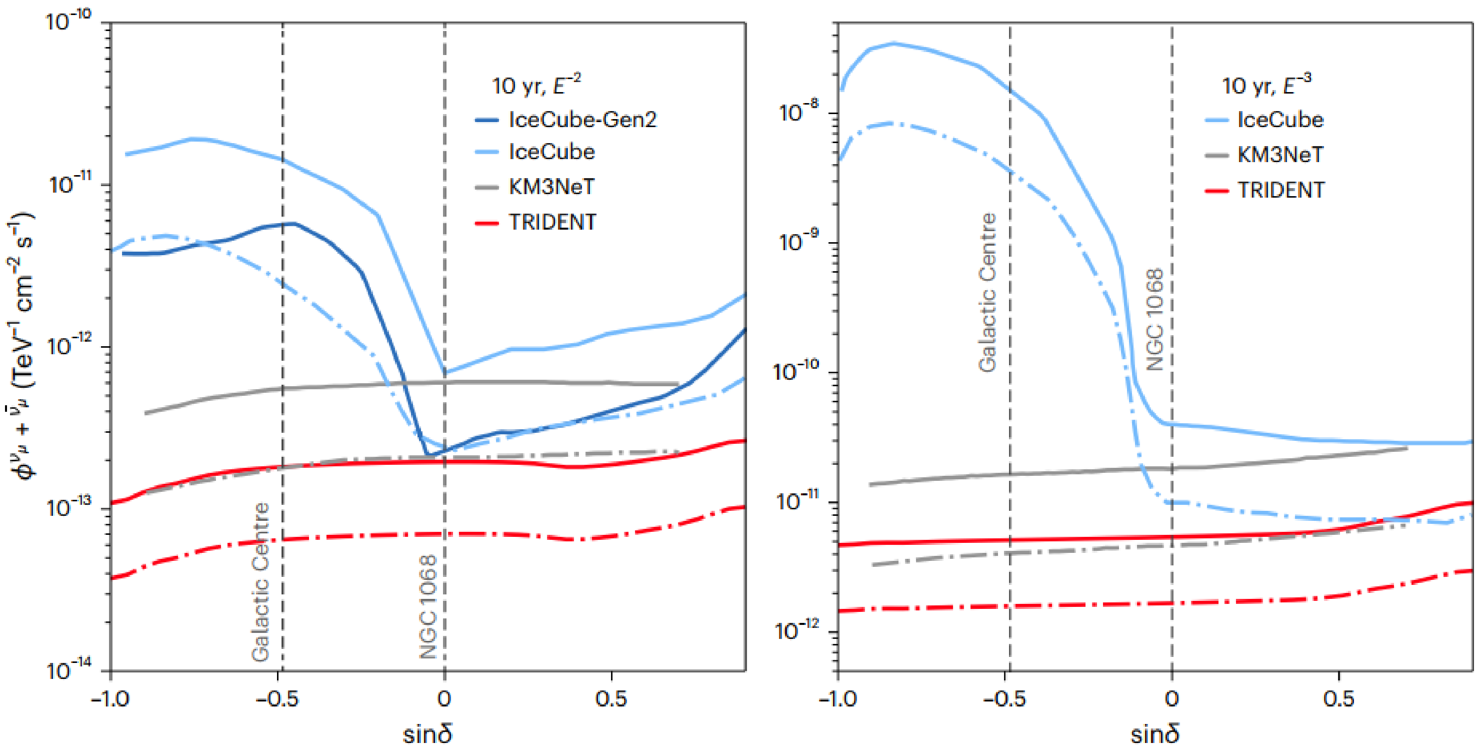


Fig. 3 | Projected point source sensitivities and discovery potentials of TRIDENT. All-sky point source 90% confidence-level median sensitivity (dashed dot lines) and 5σ discovery potential (solid lines) of TRIDENT with 10 years of data taking. The left panel corresponds to a source energy spectrum index of 2 (labelled E^{-2}) and minimum energy of 10 TeV, while the right panel assumes an index of 3 (E^{-3}) and minimum energy of 1 TeV. The *x* axis represents the sine declination (sinδ) and the *y* axis is the neutrino flux (ϕ). KM3NeT, IceCube and IceCube-Gen2 sensitivities[15,66,67] are also shown for comparison. IceCube, located at the South Pole, has increased sensitivity to the northern sky. For a source located in the southern sky with a spectral index of 3, TRIDENT will have 4 orders of magnitude improvement in sensitivity compared with IceCube. Similarly comparing to the future telescope KM3NeT located in the Northern Hemisphere yields an improvement factor of approximately 5.