DEPARTMENT OF PHYSICS AND ASTRONOMY
EXPERIMENTAL PARTICLE PHYSICS GROUP

Simulation Tools for the MURAVES Experiment

on Behalf of the MURAVES Collaboration

INGV

INFN
Istituto Nazionale
di Fisica Nucleare

VUB VRIJE UNIVERSITEIT BRUSSEL

UCLouvain

GHENT UNIVERSITY

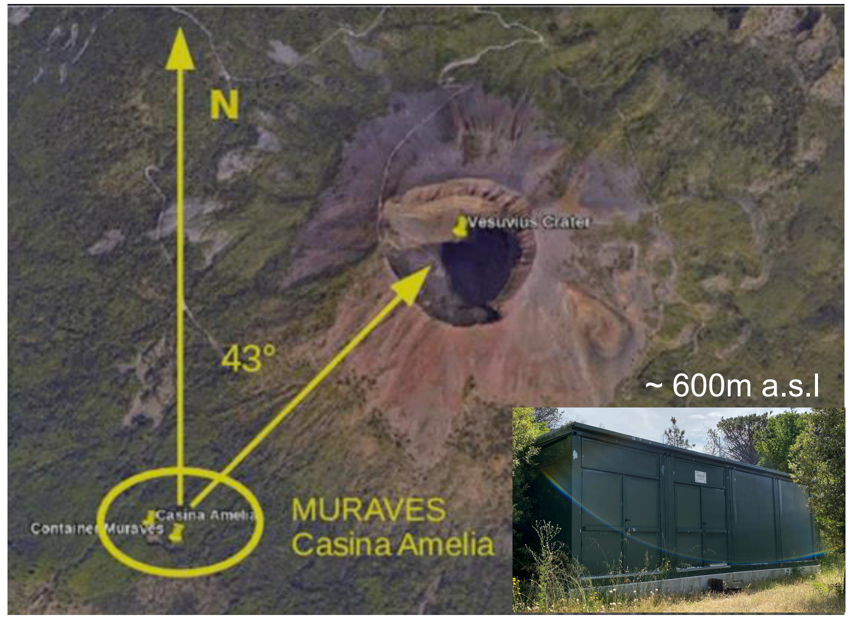
Yanwen Hong
Supervisor: Prof. Michael Tytgat
Muographers’23 Naples, 20.06.2023

MUOGRAPHERS ’23
Naples, 19-22 June
International workshop on Muography

The MURAVES Experiment

see also the talk given by Andrea Giammanco

- The **MURAVES** (MUon RAdiography of Mt. VESuvius) experiment aims to apply muon radiography to study the density distribution of the summit of the Mt. Vesuvius.



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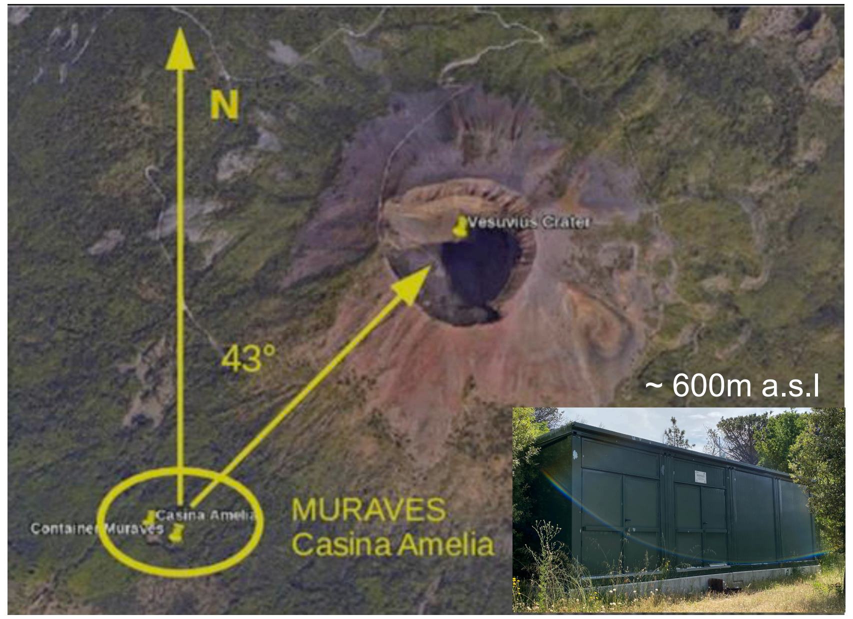
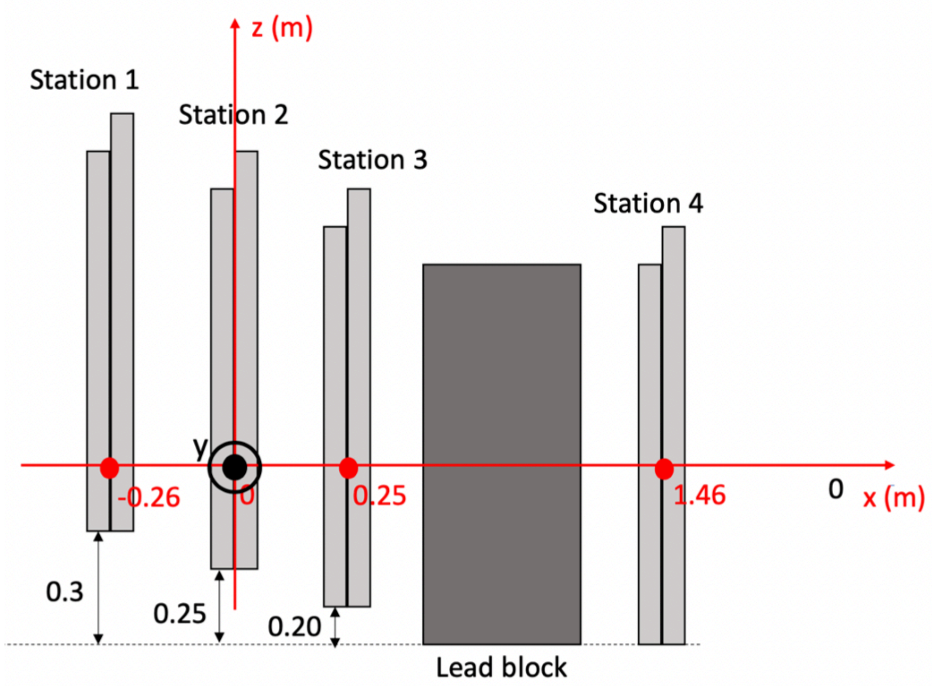


- The **MURAVES** (MUon RAdiography of Mt. VESuvius) experiment aims to apply muon radiography to study the density distribution of the summit of the Mt. Vesuvius.
- **Muon Hodoscope**:
  4 tracking stations of 1m^2 active area, distributed over ~2m;
  60cm of lead block in between two downstream stations;
  each station consists of a pair of orthogonal planes;
  each plane composed of 64 triangular adjacent scintillator bars;
  scintillator light is collected via optical fiber and later read out by SiPM.



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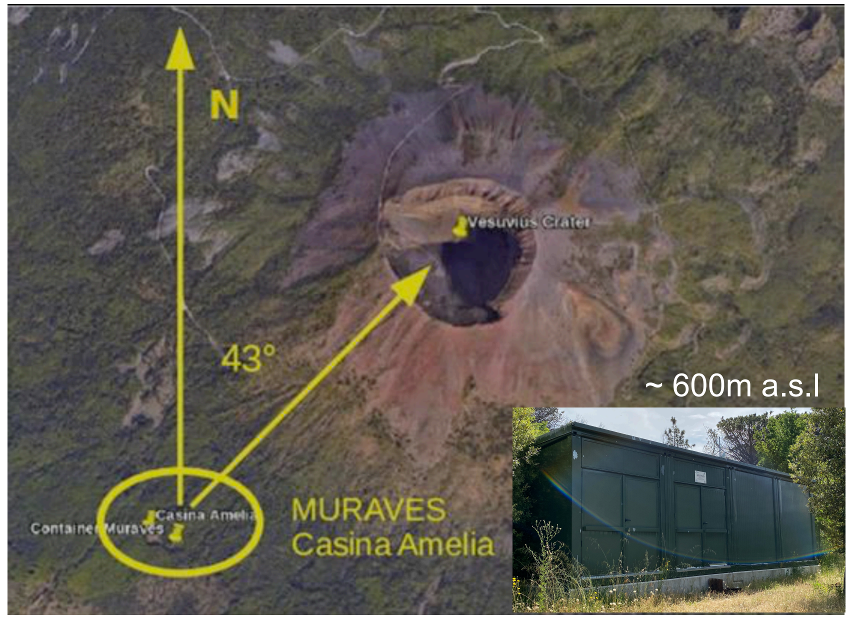

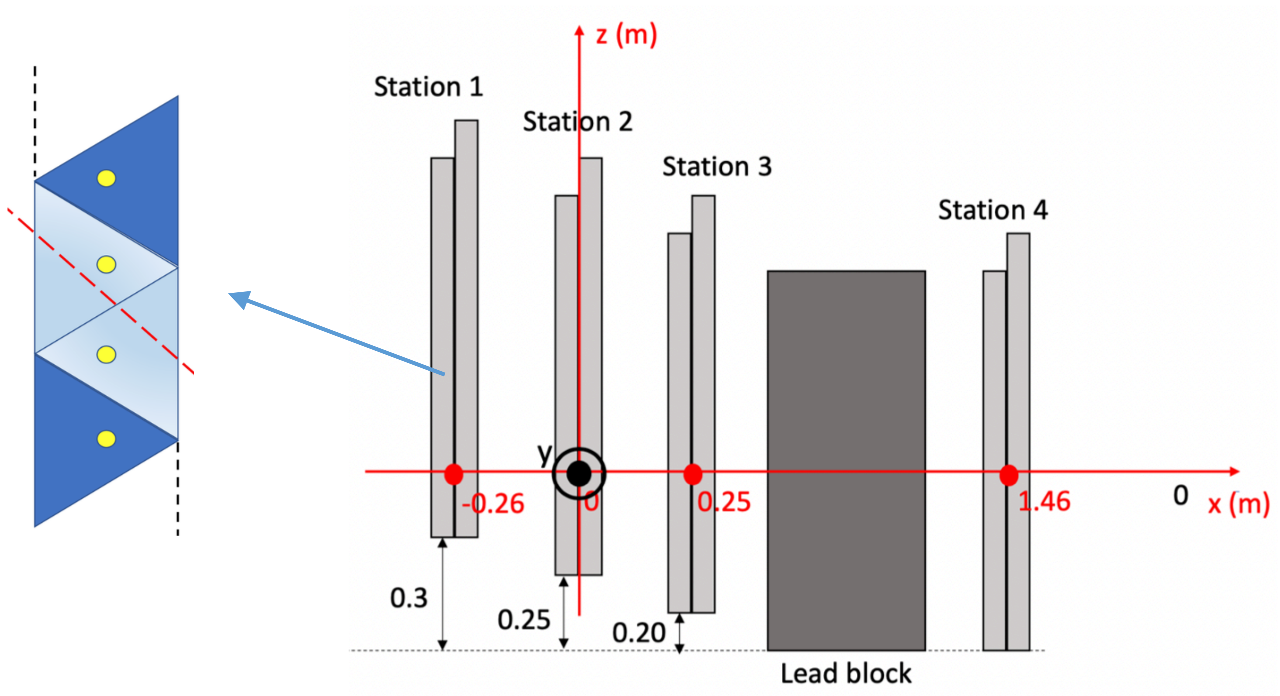

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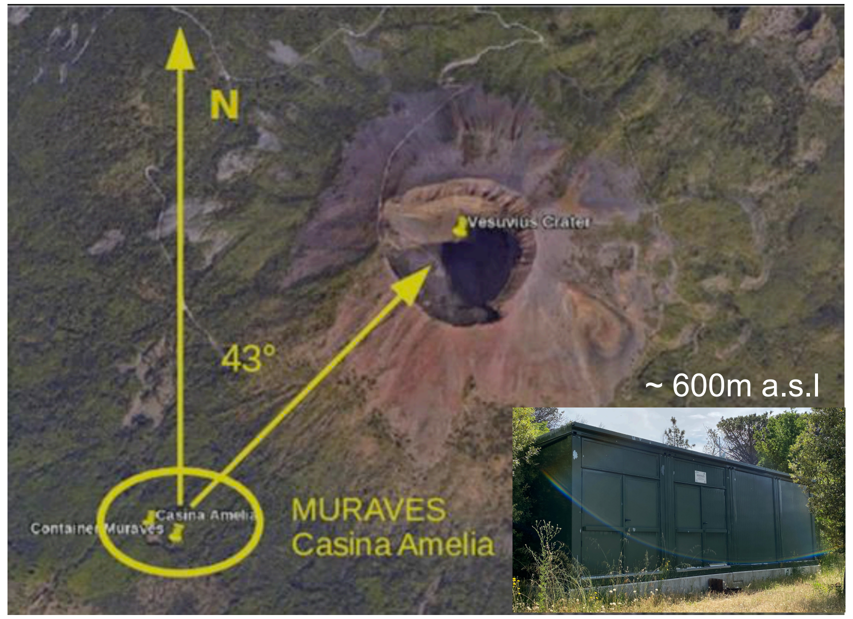

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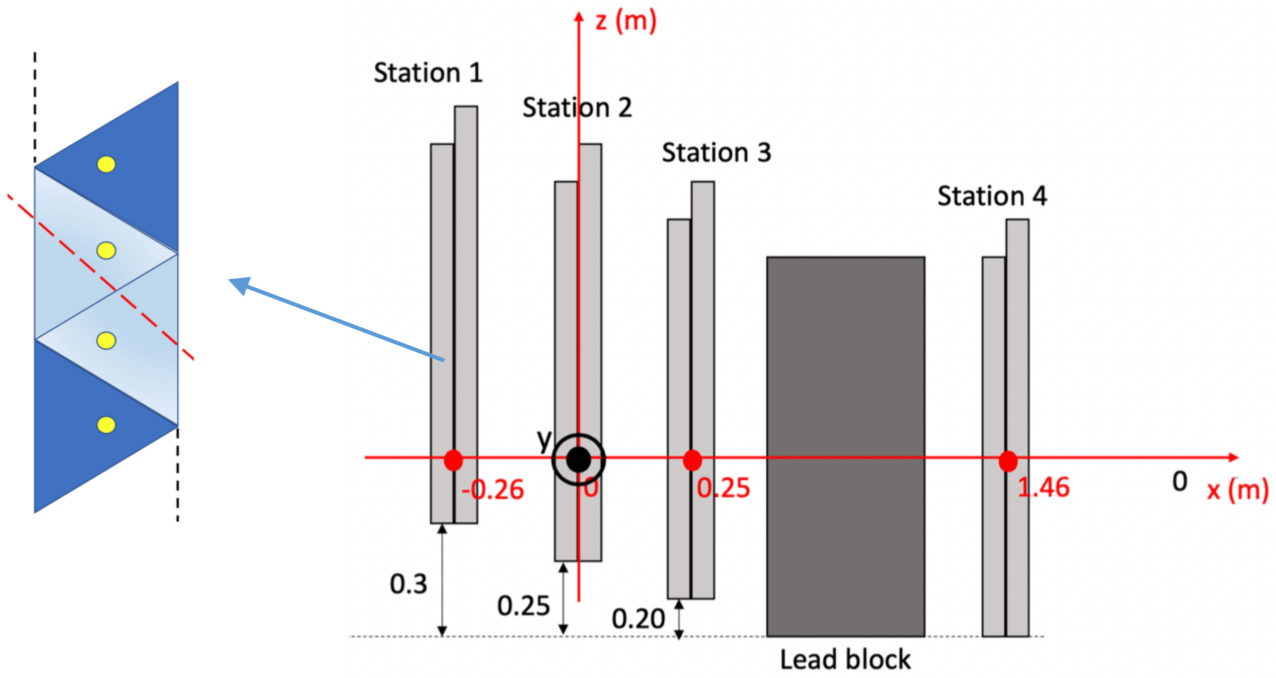
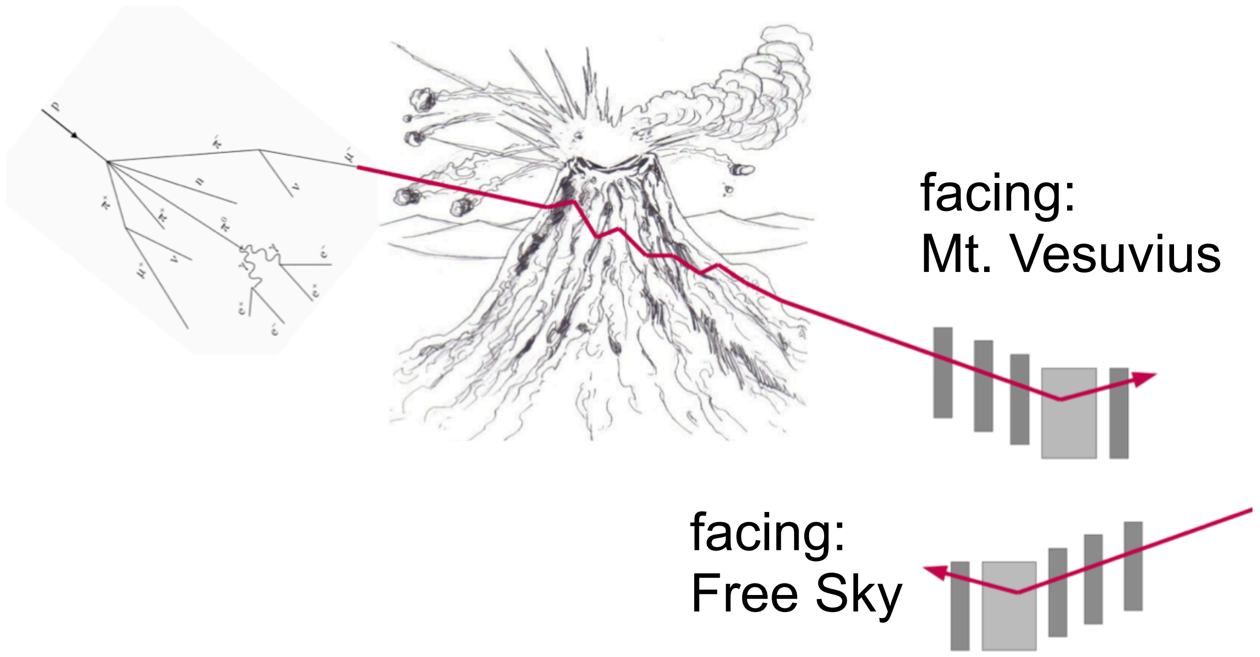
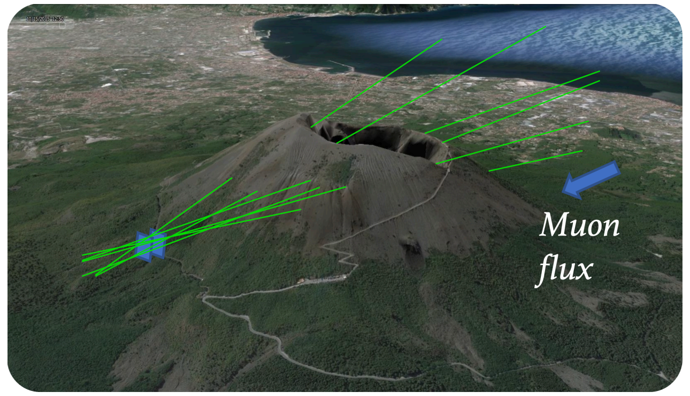
  scintillator light is collected via optical fiber and later read out by SiPM.
- Three installation positions facing the Mt. Vesuvius, while one facing free sky for calibration. Three hodoscopes alternately occupy the free-sky position.





Motivation

- Muography applied to volcanology is also challenging,
  because typical rock thicknesses of volcanoes can be up to few km;
  high energy muons are needed.
- Accurate simulation based predictions are necessary.



Observed muons flux through target:

$$N_\mu(\theta,\phi) = \Delta T \cdot \epsilon(\theta,\phi) \cdot A(\theta,\phi) \cdot \int_{\underset{\uparrow}{E_{min}(X)}}^{\infty} I(E;\theta,\phi)\,dE$$

≡ density * thickness

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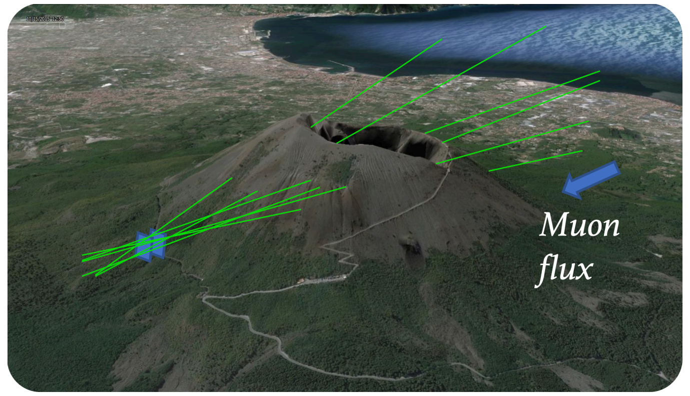

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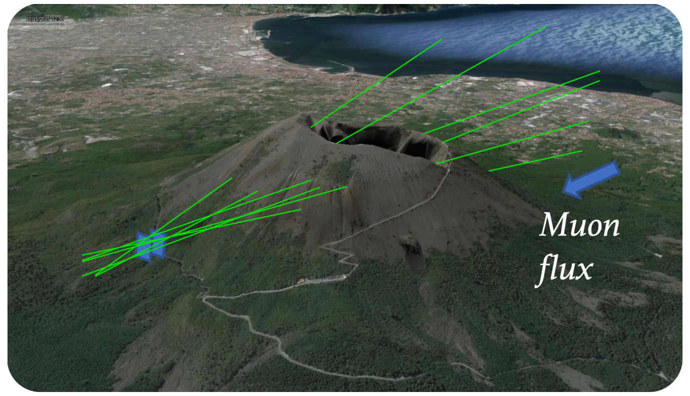

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List of the Simulation Tools

I. **Cosmic Muon Generation**
   1. CORSIKA
   2. CRY
   3. EcoMug

II. **Detector Simulation and Data Processing**
   GEANT4
   Digitization, Clustering and Tracking

III. **Muon Transport Through Mt. Vesuvius**
   1. MUSIC
   2. PUMAS

I. Cosmic Muon Generation

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Comparison of Three Cosmic Muon Generators

Generator	EcoMug [4]	CRY [3]	CORSIKA [2]
Principle	parametric single-particle simulation	parametric particle simulation	complete step-by-step evolution of a cosmic shower
Modeling	based on ADAMO experiment [6]	based on MCNPX simulation [5]	various low- and high-energy hadronic interaction models provided
Help in developing tracking algorithms	not designed for multiple muons or for backgrounds, but possible to improve	single sample muon properties from pre-defined distributions	more realistic on multi-muon events
Generation Surface	flat, cylindrical and hemispherical ensuring angular and momentum distributions	flat	flat
Speed 10^5 muons	O(sec)	O (min)	O(hour)
Integration with GEANT4	easy	easy	complex but possible

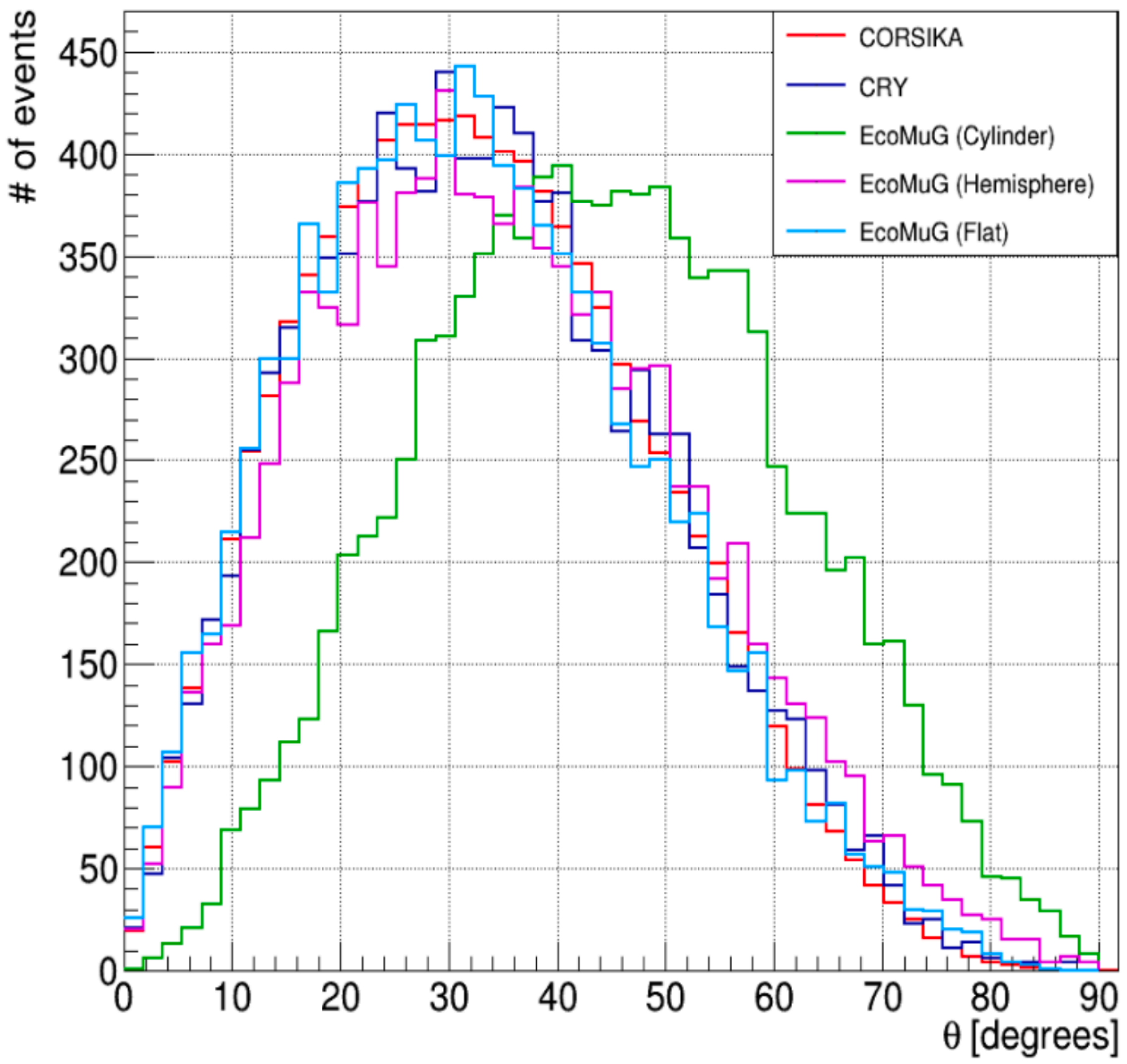
maintain for estimating systematic uncertainties

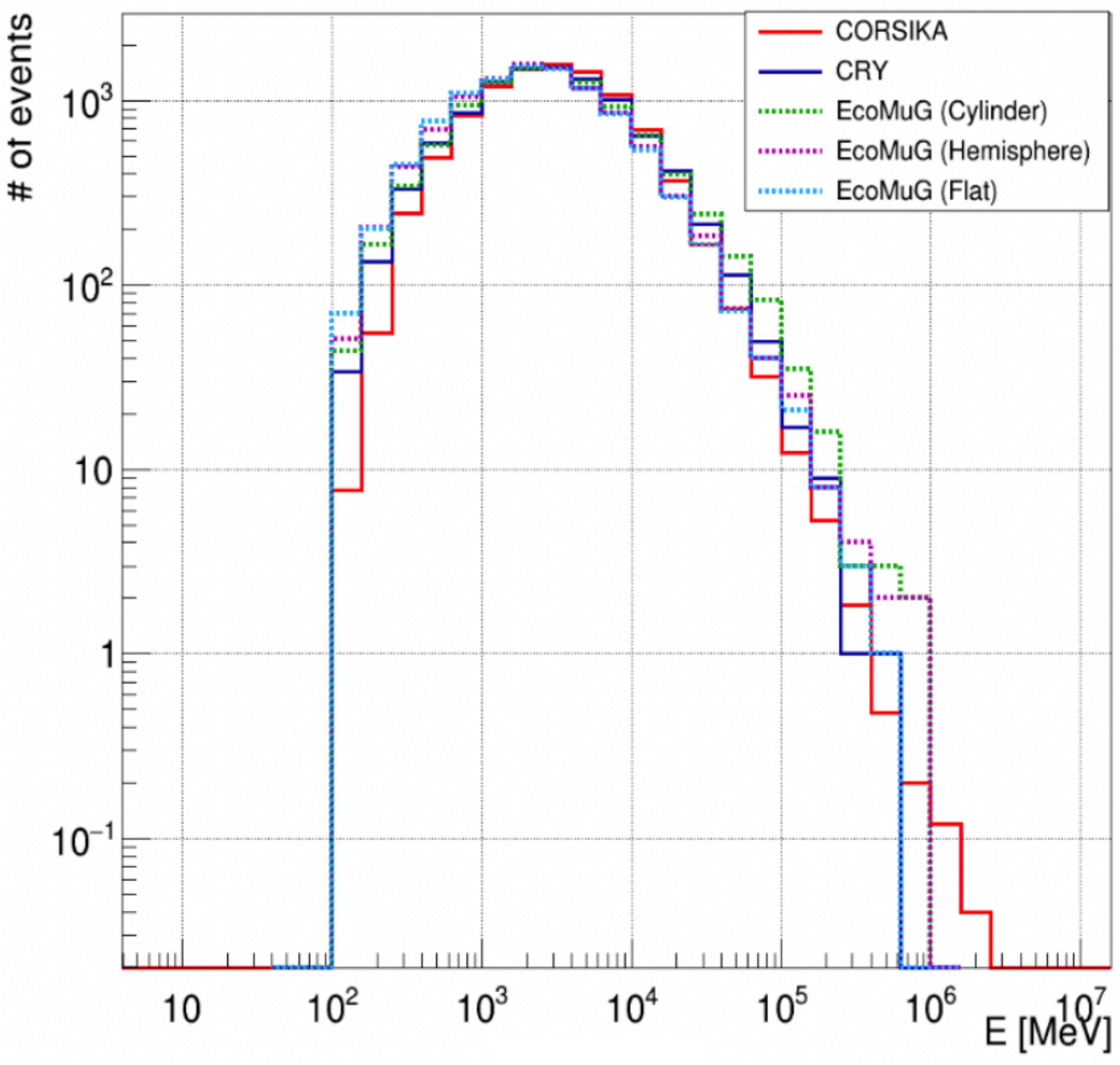
main generator

maintain for estimating systematic uncertainties

Comparison of Three Cosmic Muon Generators

Distribution of zenith angle and energy of cosmic muons generated using CORSIKA, CRY and EcoMug with three generation surface, flat, hemispherical and cylindrical[1].





* In CORSIKA, the DPMJET and GHEISHA hadronic interaction models are used for high and low energy collisions in the atmosphere respectively.
* In CRY, a.s.l is set to 0m.

– Three generators shows consistency.

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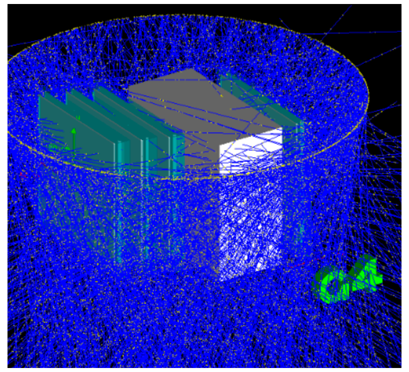

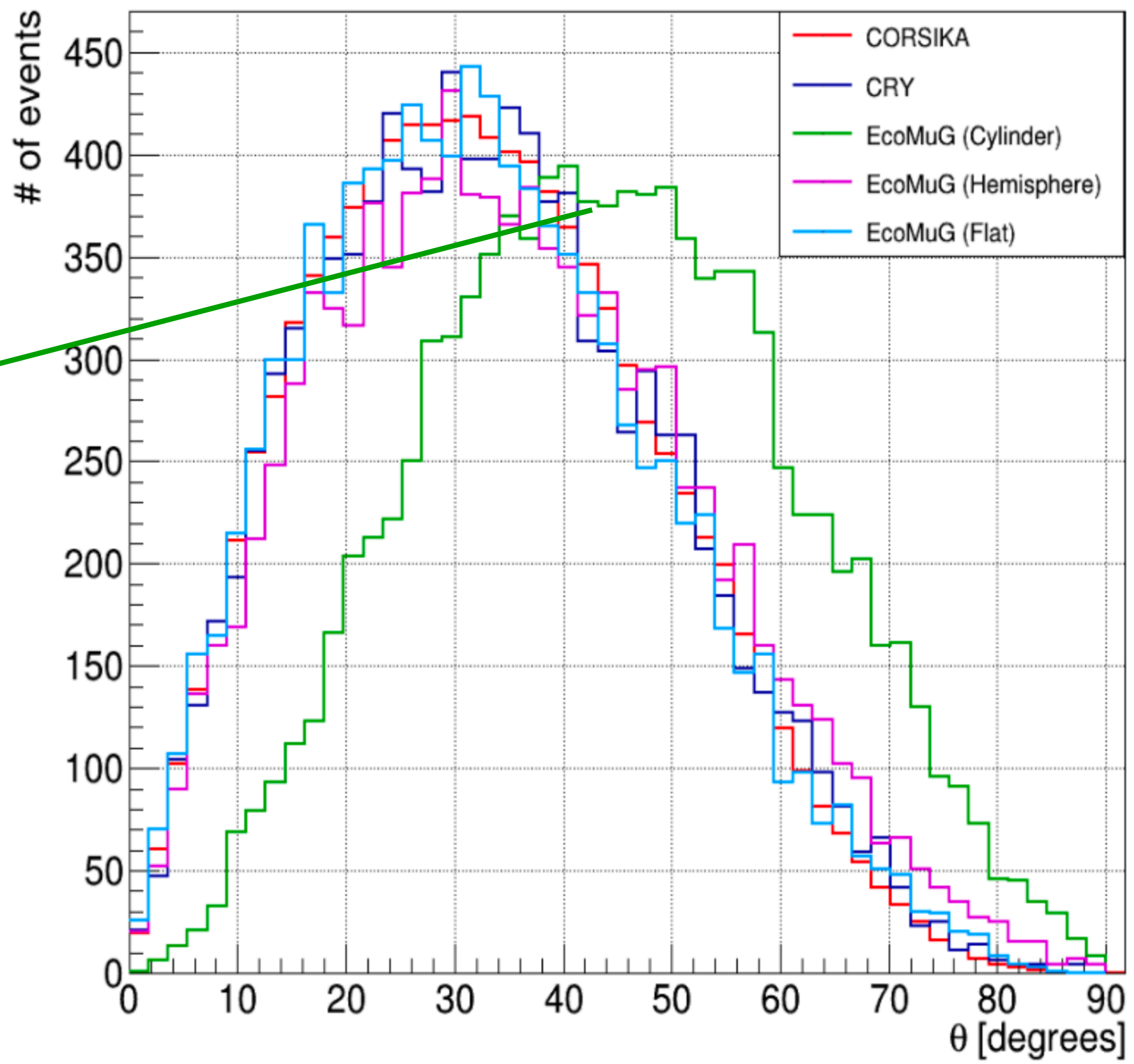

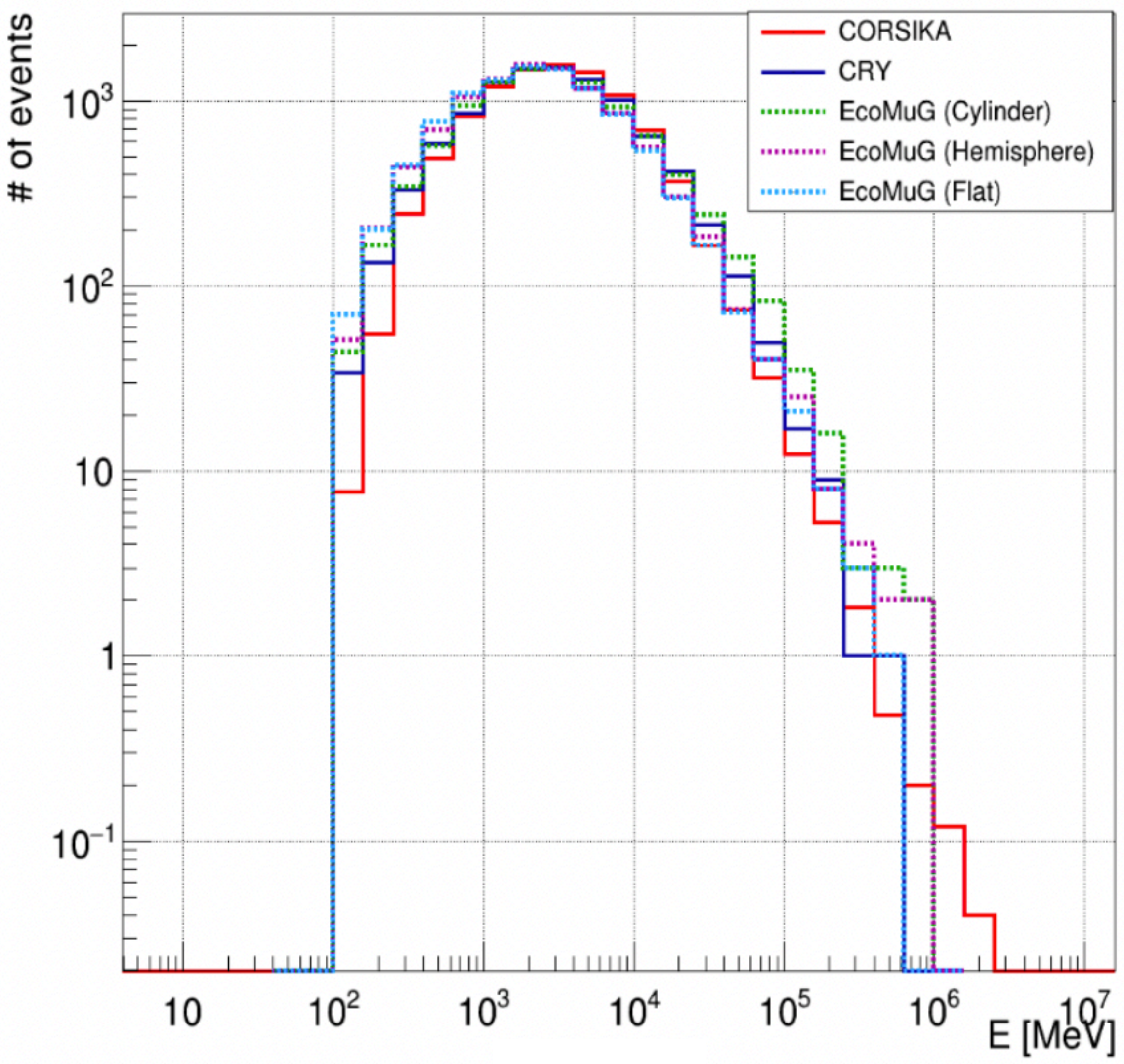

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- Three generators shows consistency.
- Offset of peak from the cylindrical generation surface with EcoMug at zenith angle distribution can be explained by angular bias of the geometry -> lack of source from the top.

II. Detector Simulation and Data Processing

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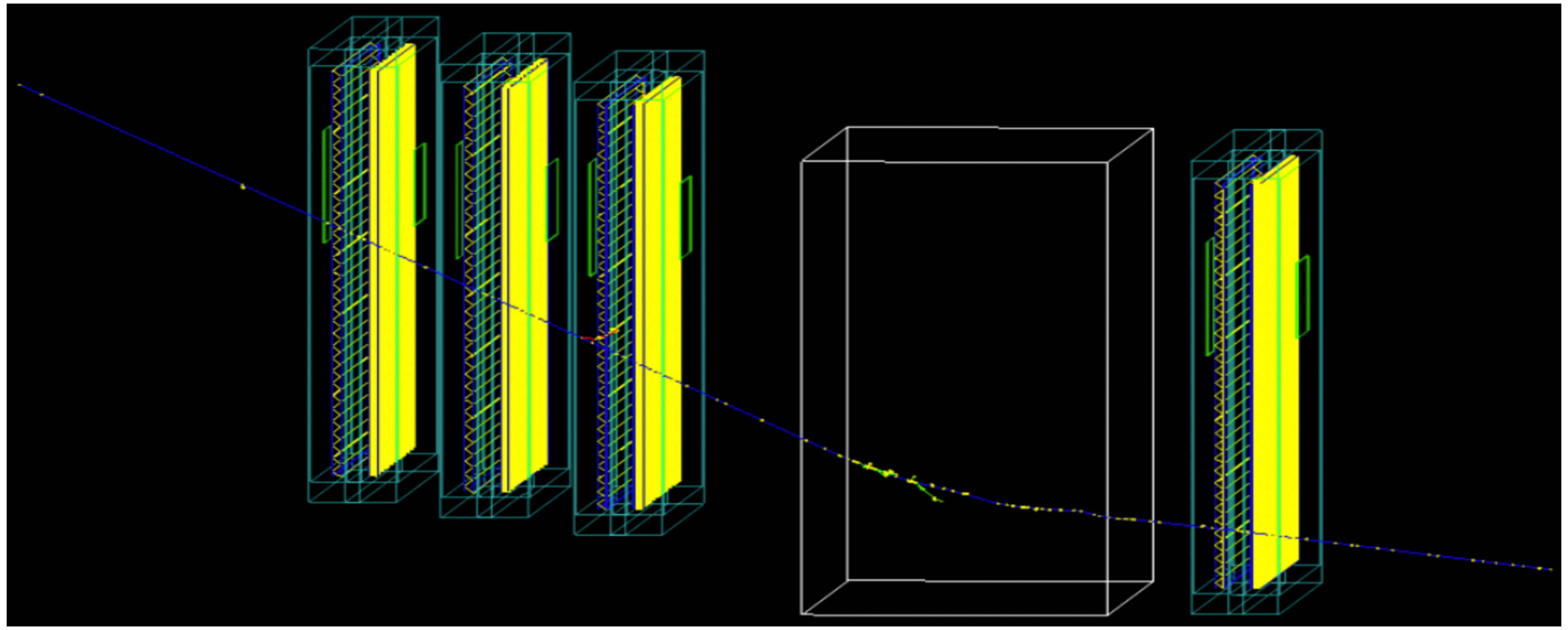
Simulation Data Processing Chain

i. Muon passing through detector: **GEANT4**[1].

Simulated interaction of a 1 GeV muon with the MURAVES hodoscope in GEANT4 [2].



Simulation Data Processing Chain

i. Muon passing through detector: **GEANT4**[1].
   -> **HITS** (simulated interaction with detector):
   3D position, time, energy deposition and identity of the particle…

ii. **Digitization**: quantisation of positions and energy deposits.
   -> **Simulated Detector Output**

iii. **Clustering**:
   A cluster is a collection of adjacent bars whose signals pass a certain threshold.
   -> **Analysis Data Objects**:
   total energy deposit & position

iv. **Tracking**:
   3D tracking method

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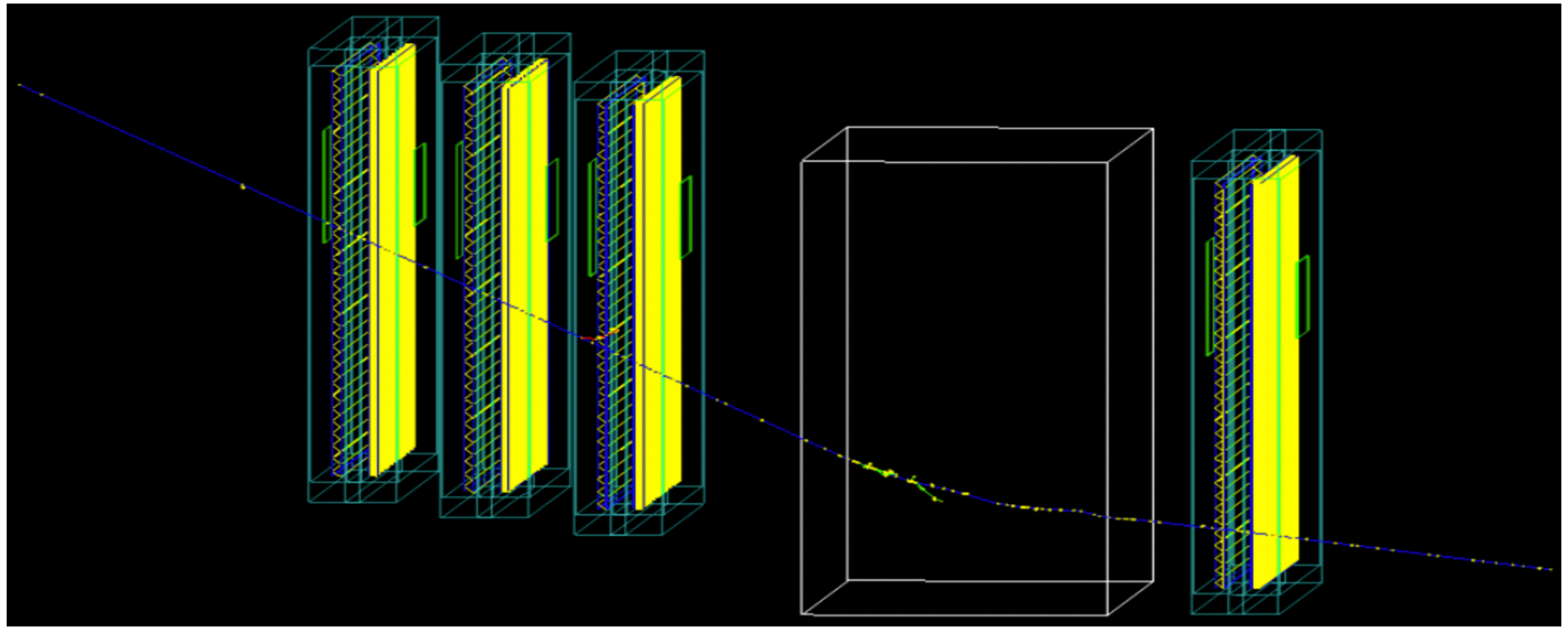

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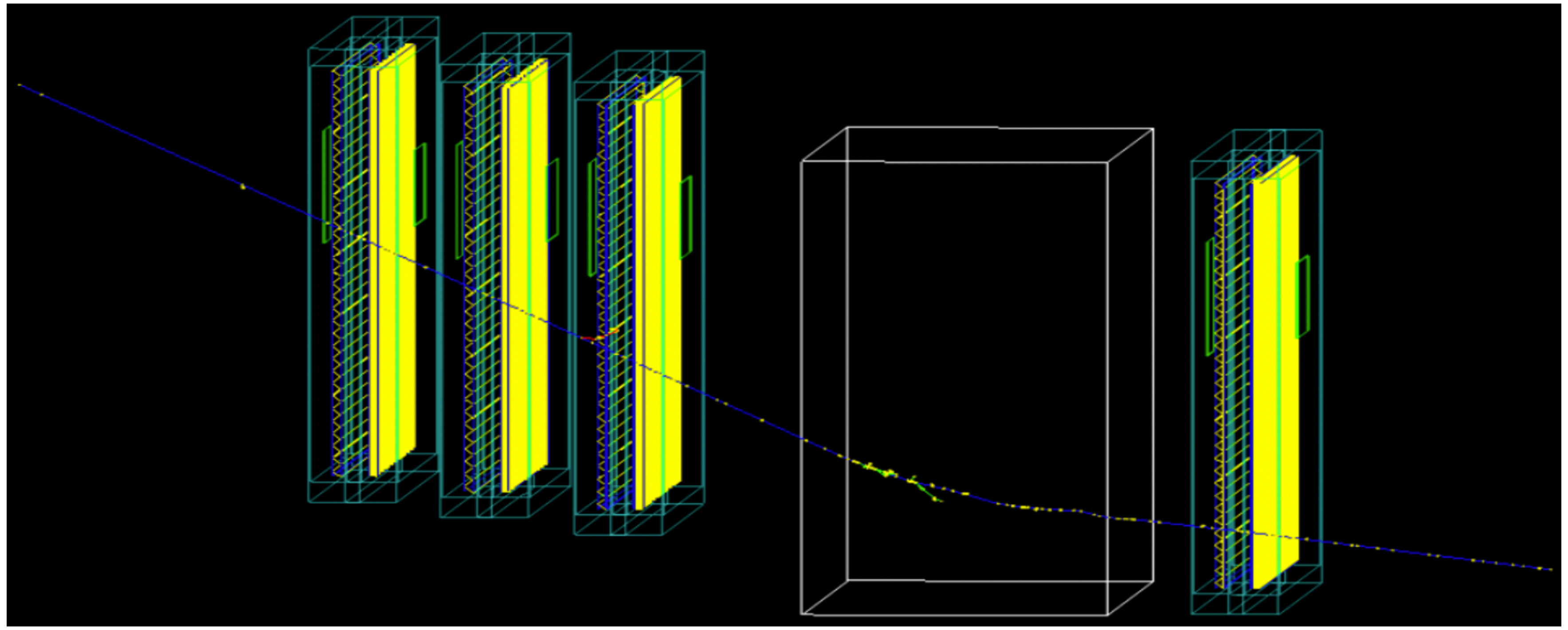
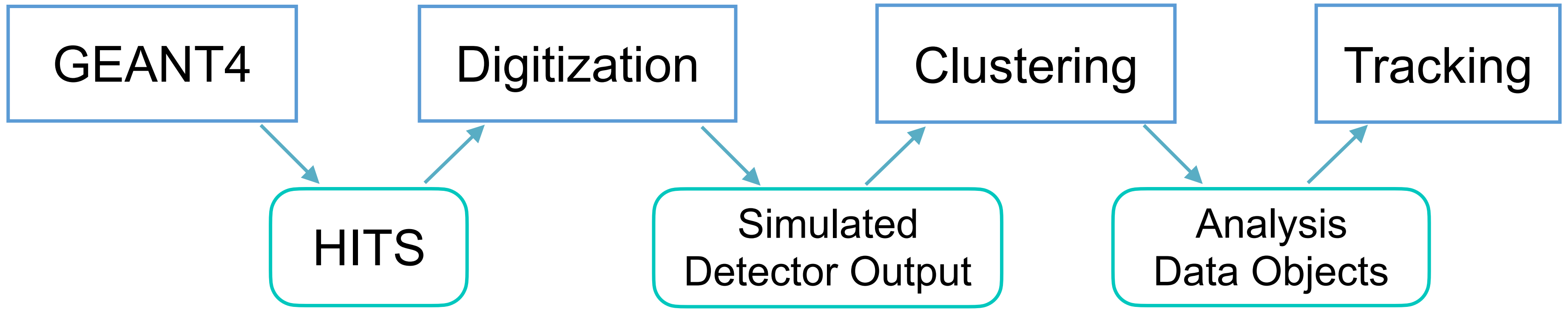
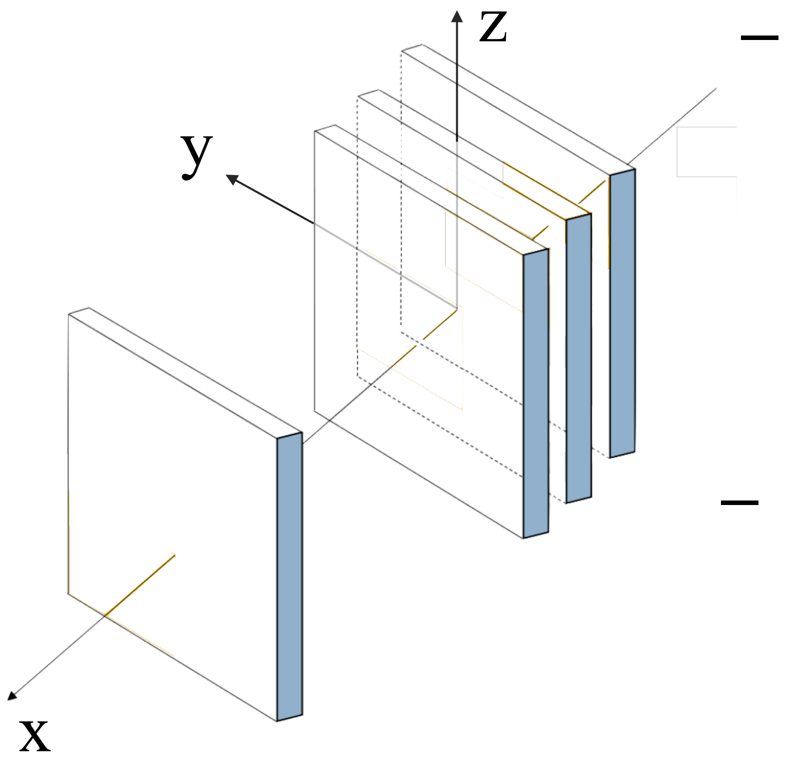


MURAVES Simulation Data Processing Chain



GEANT4
HITS
Digitization
Simulated Detector Output
Clustering
Analysis Data Objects
Tracking

Comparison of Simulation and Data



- **2D tracking:**
  - first linear fits applied to the upstream three hit points on planes xy and xz are considered separately;
  - intersected with the 4th station.
- **New 3D tracking Method:**
  - all possibility of combination of hits position of *y z* at each station (position is calculated with weighted deposited energy);
  - Take the minimum of sum of χ^2 of the linear fits performed on the xy and xz plane;
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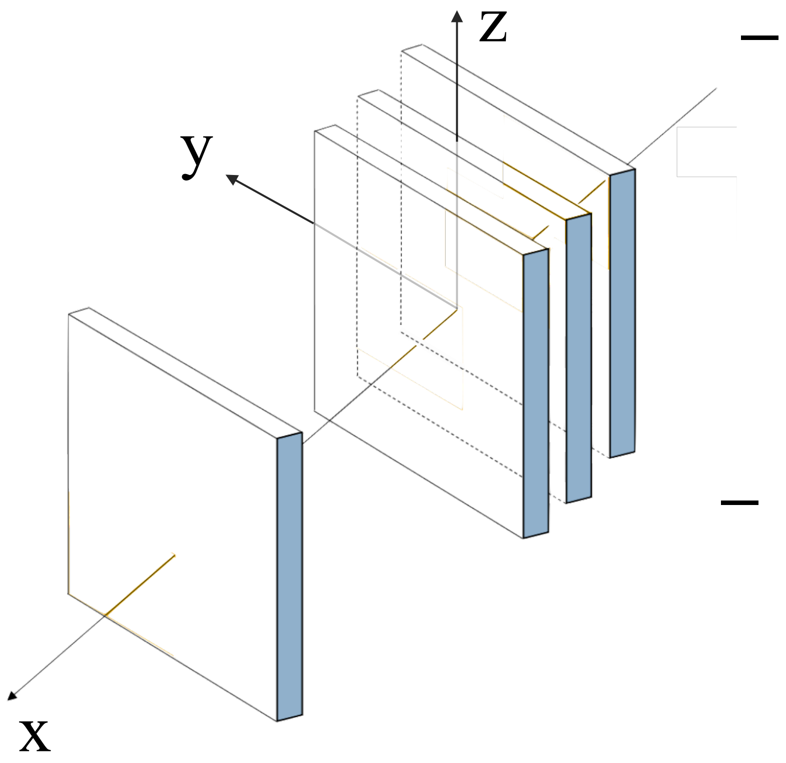

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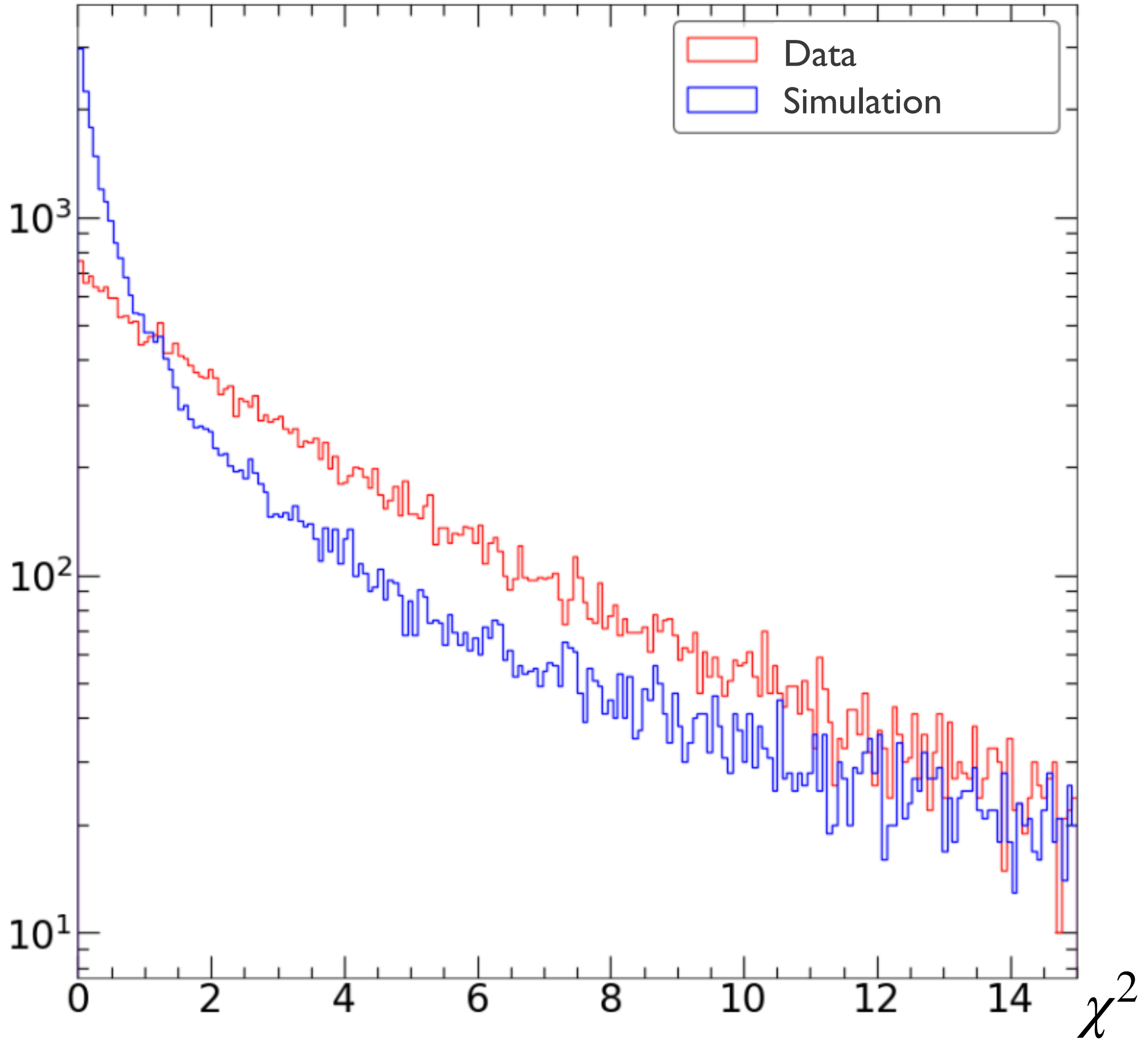
Comparison of χ^2 of Tracking Reconstruction between Simulated and Real Data



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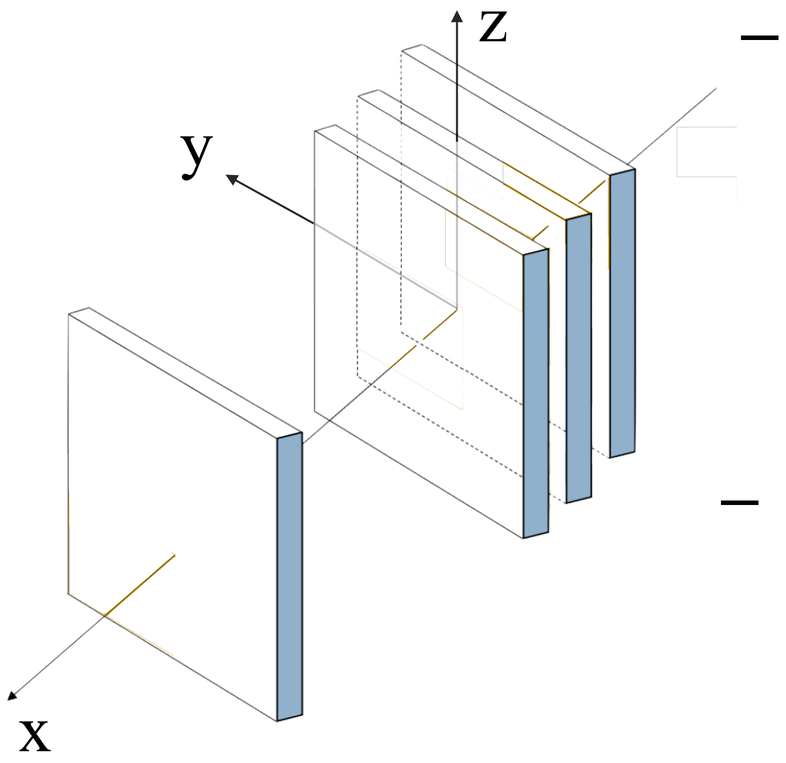

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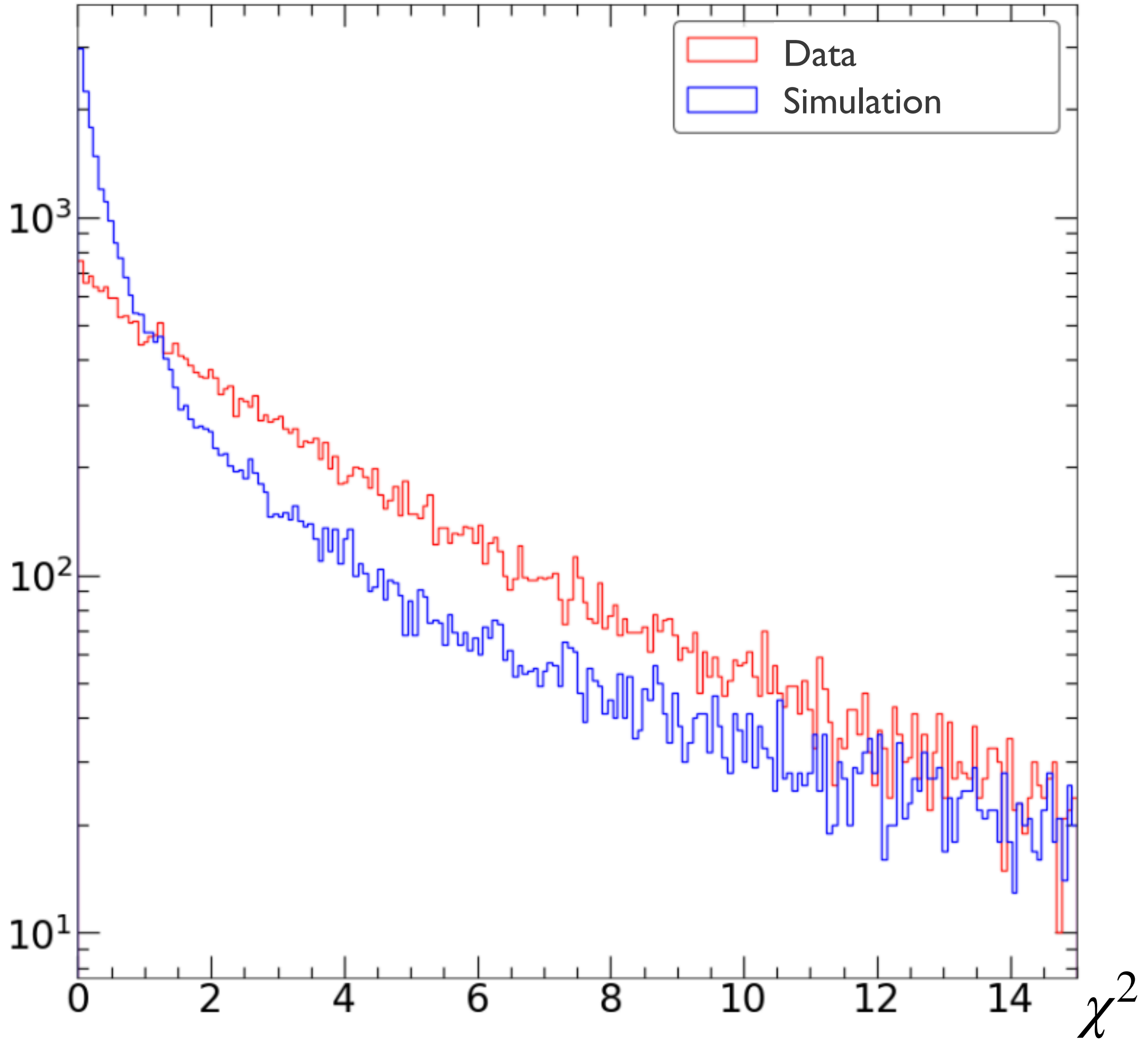
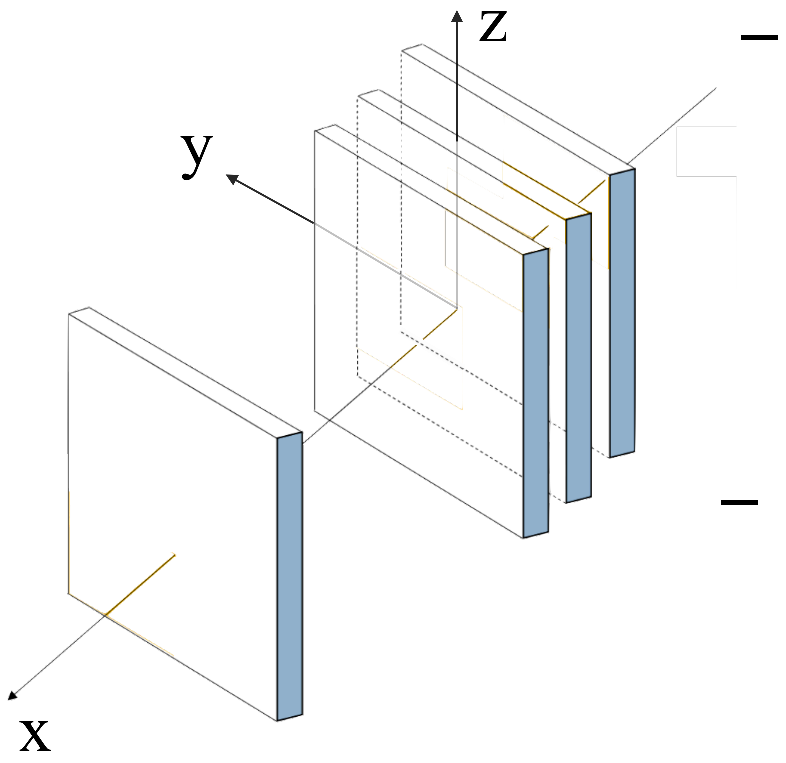


- 10^5 muon events generated with CRY, full data processing chain applied. Compared with free-sky calibration run data.
- selection of track candidates.

Comparison of Simulation and Data



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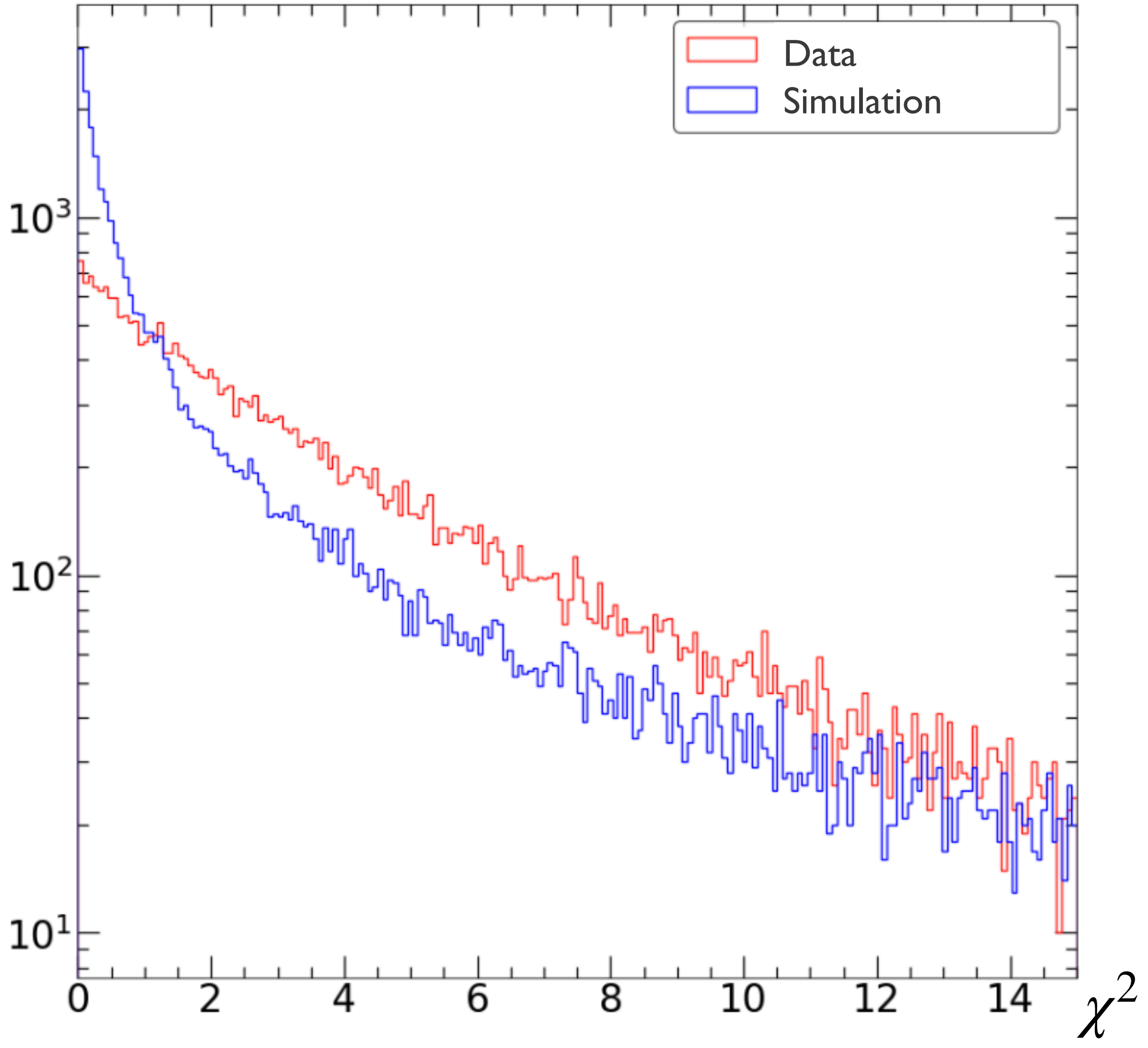

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III. Muon Transport Through the Mt. Vesuvius

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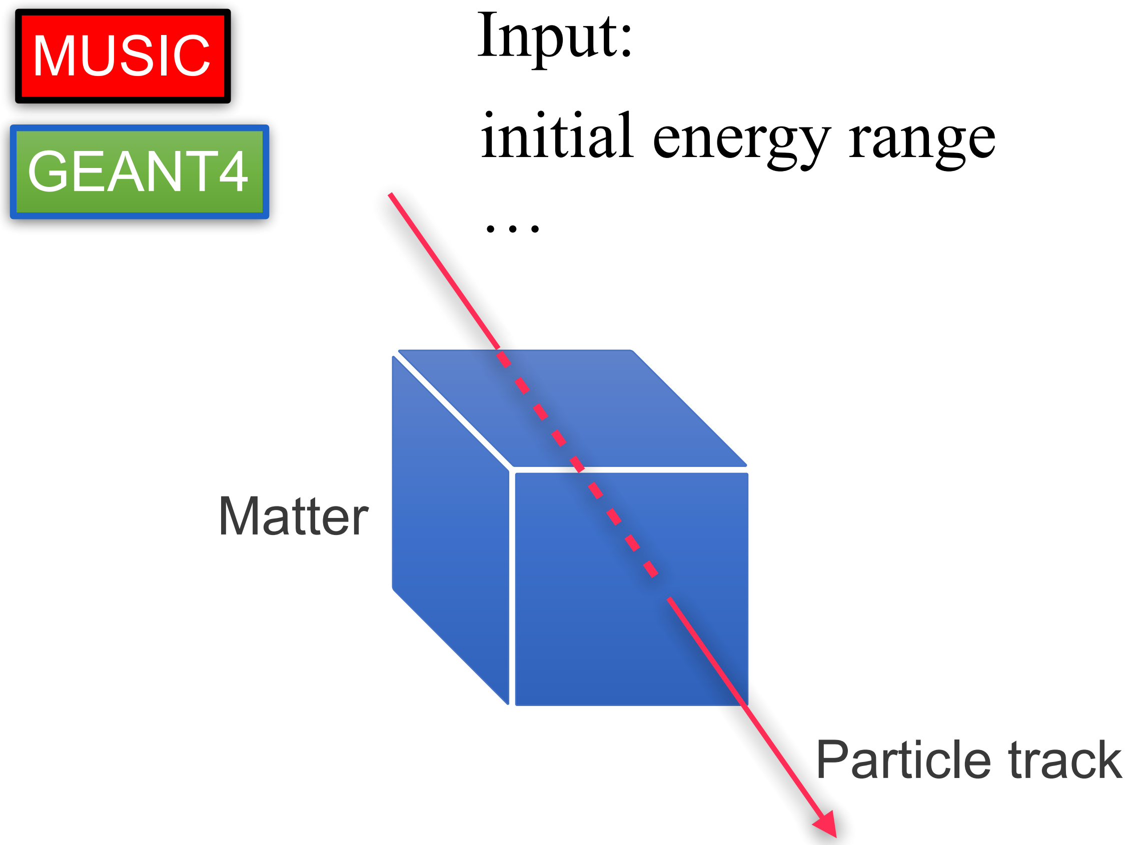
Muon Transport Engines: MUSIC & PUMAS

Same purpose:

- **MUSIC** is a transport engine for propagating muons through large thickness of rock or water [1].
- **PUMAS** library allows one to transport muon or tau leptons in matter by forward or backward Monte Carlo [2].


MUSIC

GEANT4

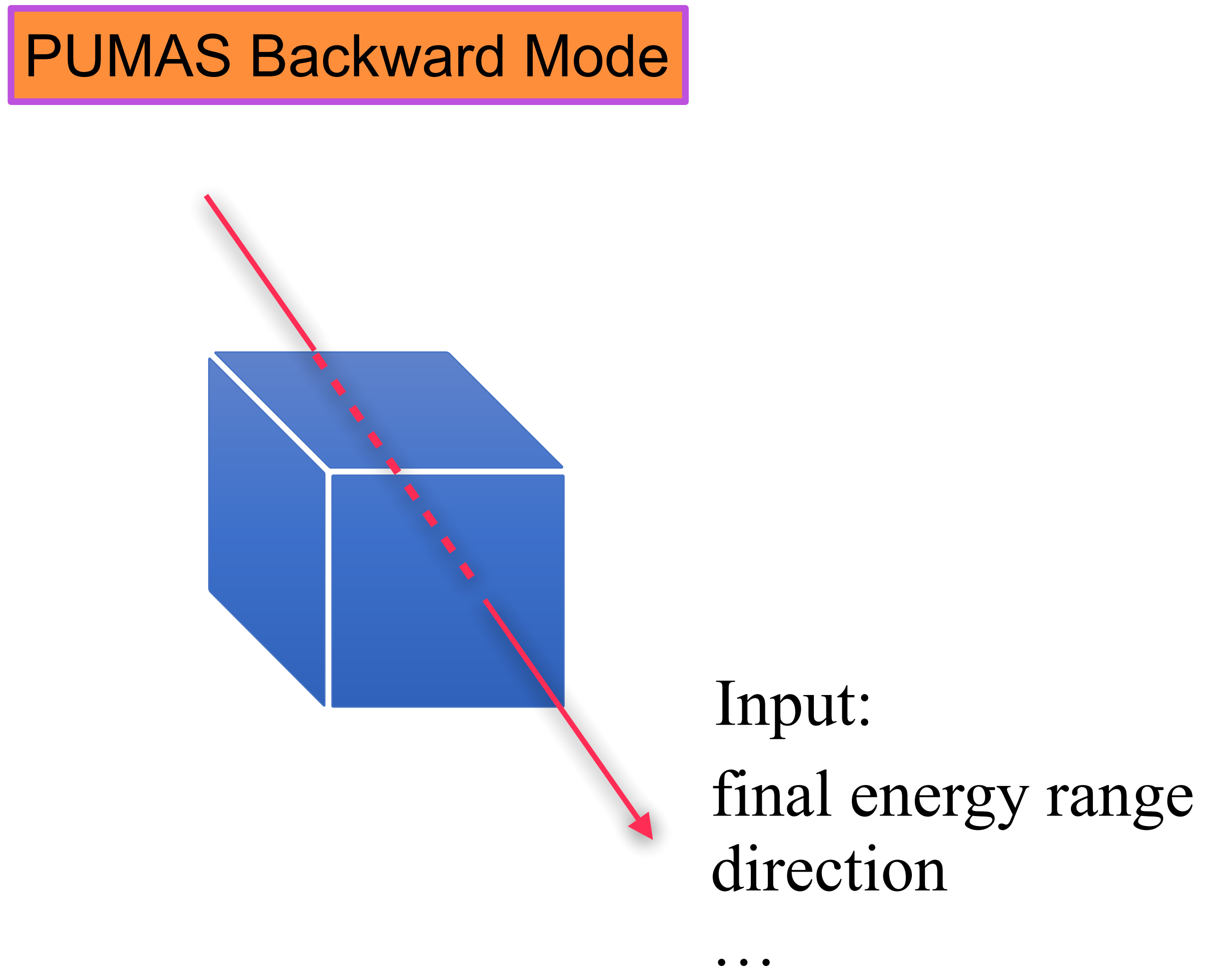
Input:

initial energy range

…

Matter

Particle track


PUMAS Backward Mode

Input:

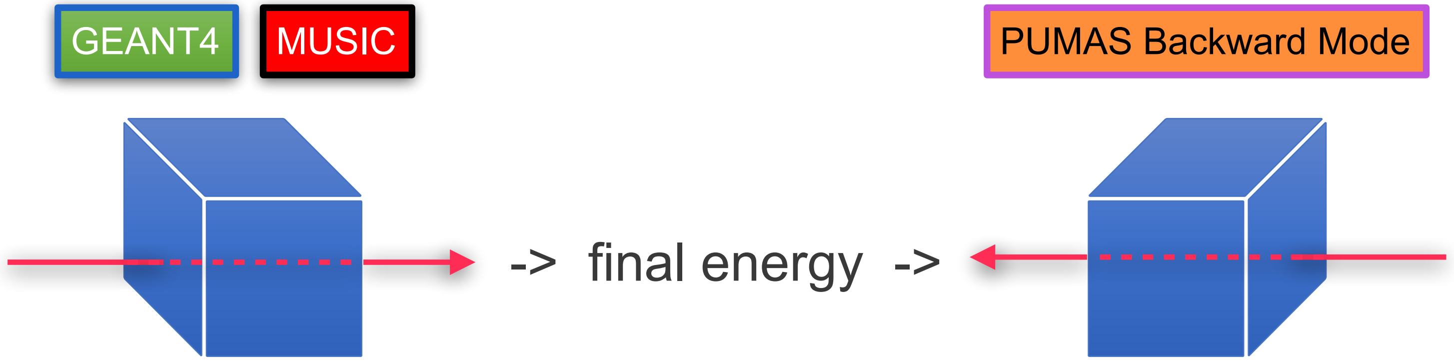
final energy range

direction

…

Comparison Study of Transport Engine MUSIC and PUMAS with GEANT4

- Simulation of 0 - 20 GeV initial energy Muon passing through a 10 m thick standard rock (ρ = 2.65 g/cm^3), with ~ 40,000 events.
- The output of the final energy range is feed in PUMAS Backwards mode.
- The energy loss distribution is compared between GEANT4, MUSIC, PUMAS Backward mode.



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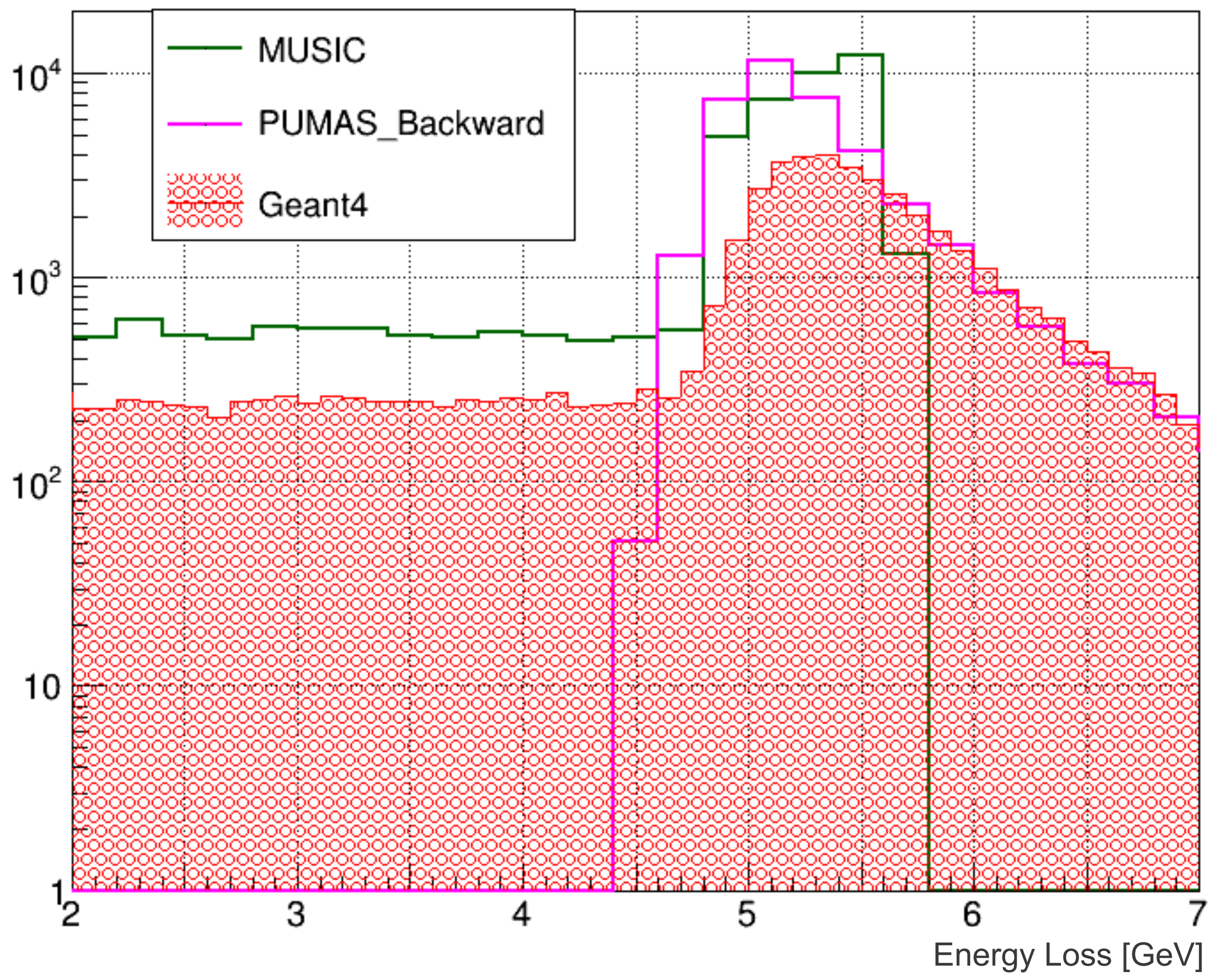

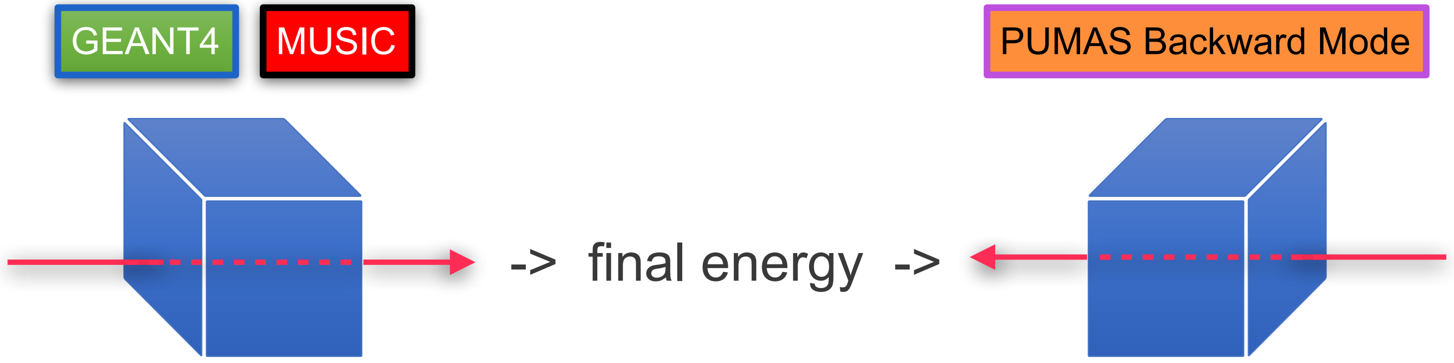

- Peak position synchronized;
- GEANT4 has the full spectrum but slow speed O(hours);
- PUMAS Backward Mode catches the particles which pass through the rock, agreement on the tail;
- MUSIC parametric simulation, simplified scattering models.

Use of PUMAS in MURAVES

1. Define topography with similar library:

- **TURTLE** [1]: utilities for the long range transport of Monte-Carlo particles through a topography.

Digital Elevation Model (DEM) file
observation point & azimuth elevation angles

→

rock thickness map from the
user-defined observation point.

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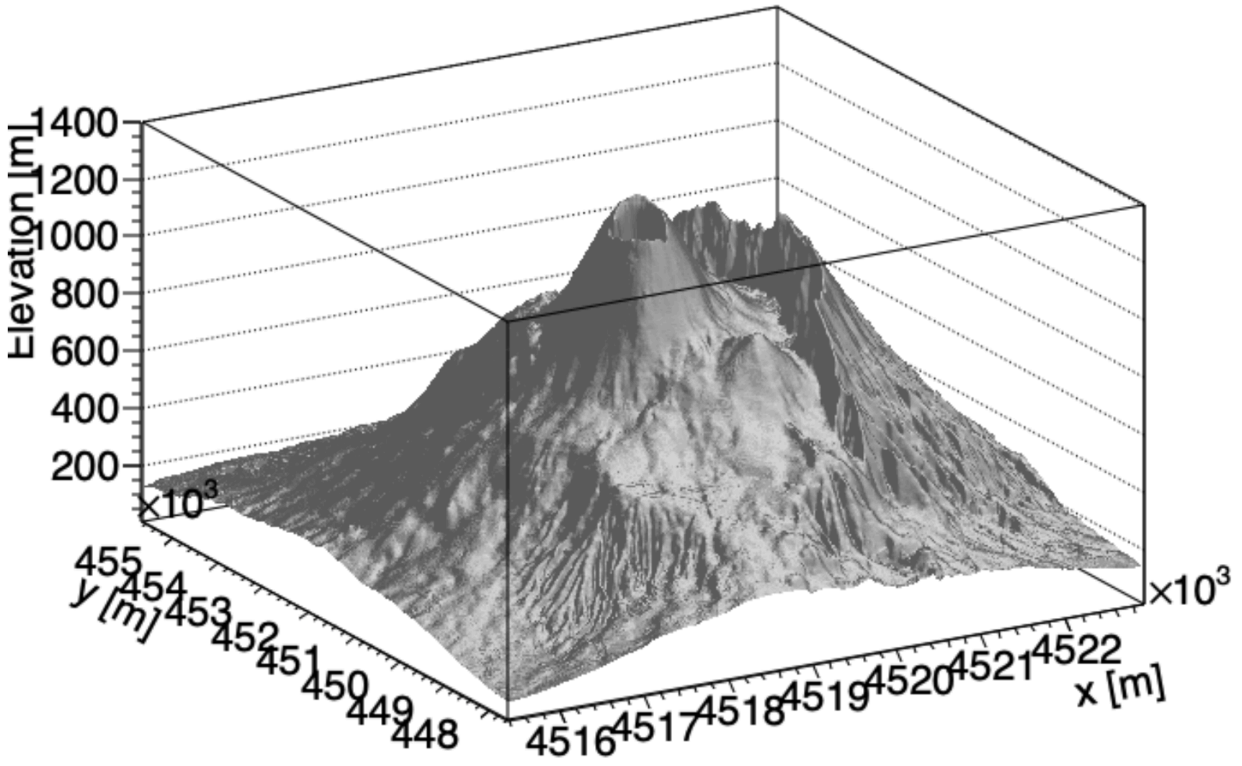
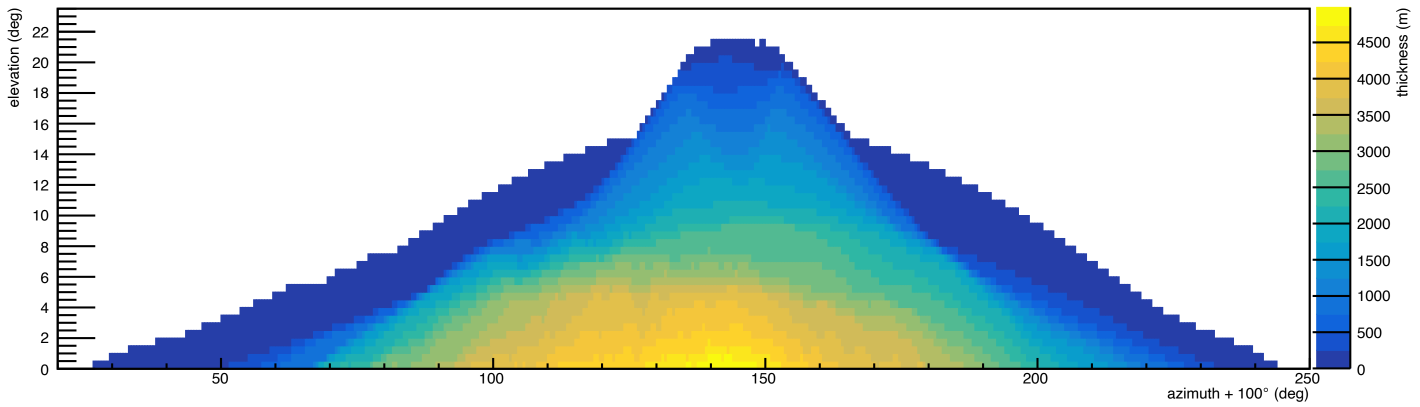


DEM of the surrounding area of the Mt. Vesuvius, with 5m precision, based on data [2].

TURTLE

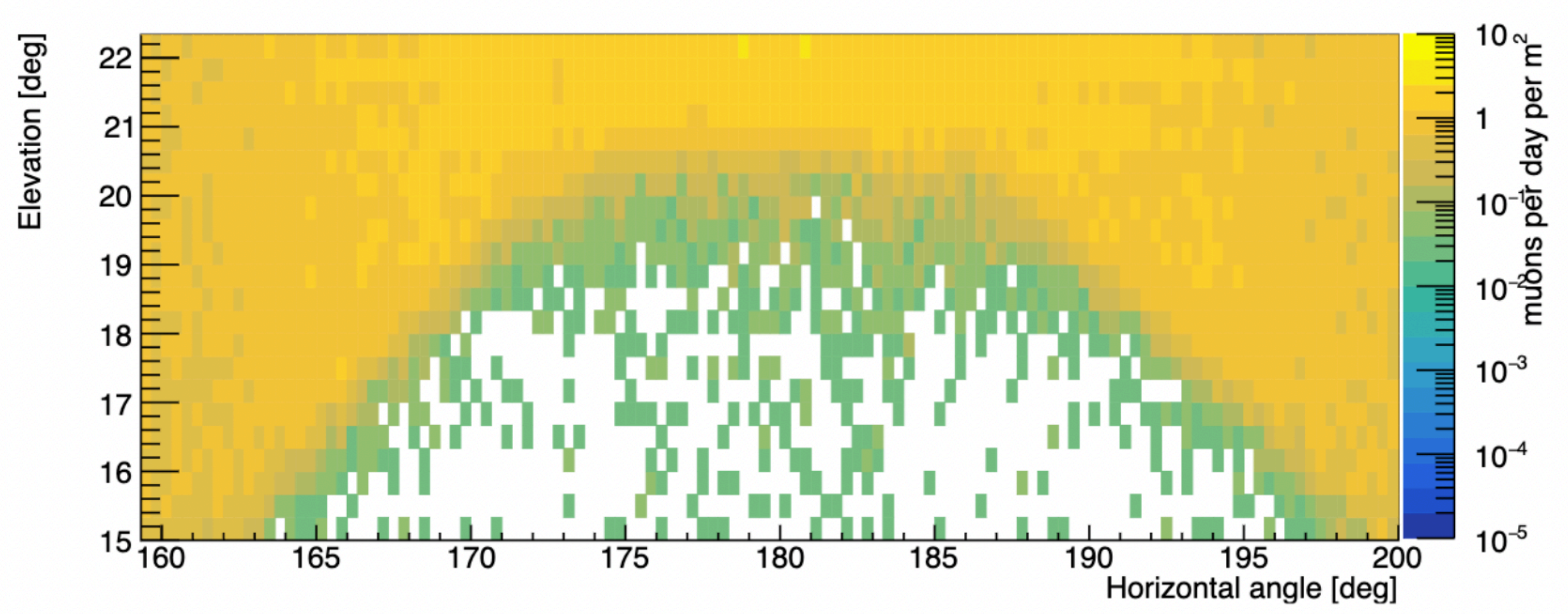


Mt. Vesuvius' thickness map observed at the location of the MURAVES experiment.

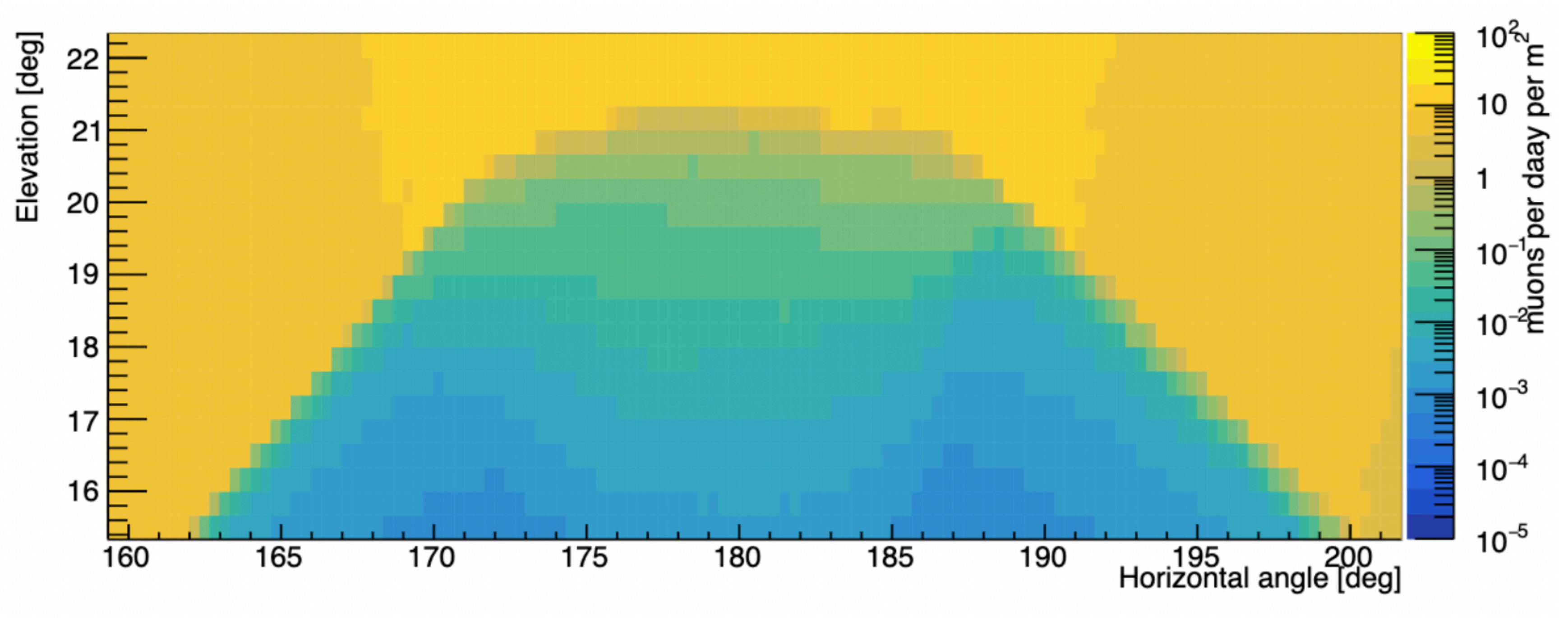
Use of PUMAS in MURAVES

2. perform backward transport simulation:

- Expected muon flux through the Mt. Vesuvius body obtained by PUMAS library.



* 51 days of data collection



* The hypothesised rock density is = 3.35 g/cm3.

see also the talk given by Andrea Giammanco

Outlook & Full MURAVES Simulation Chain

- Similar transport simulation steps can apply to PUMAS Forward Mode;
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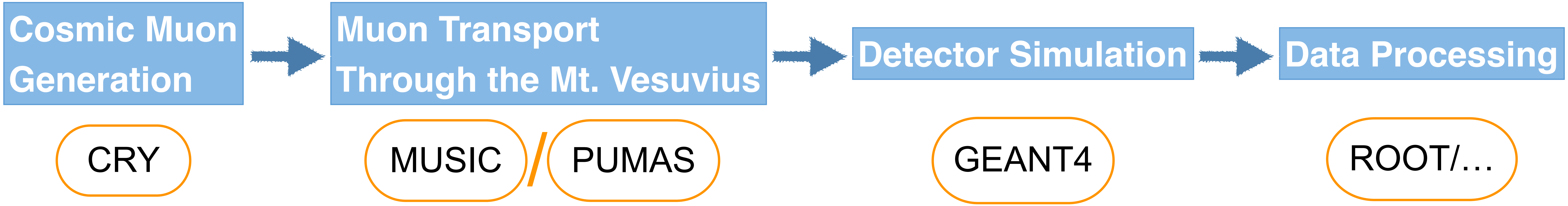

Cosmic Muon Generation → **Muon Transport Through the Mt. Vesuvius** → **Detector Simulation** → **Data Processing**

CRY

MUSIC / PUMAS

GEANT4

ROOT/…

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CRY ✓

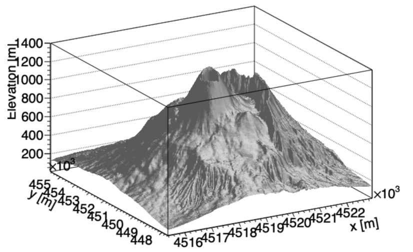
MUSIC / PUMAS

✓ GEANT4

✓ ROOT/…

<u>still missing:</u>

Defining Mt. Vesuvius Geometry by GEANT4



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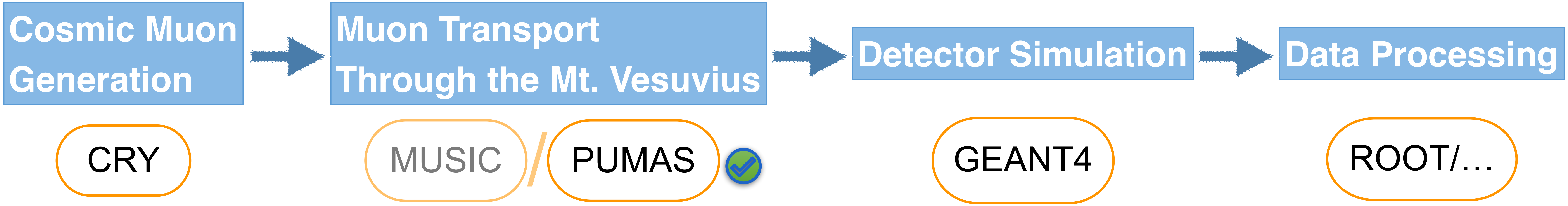

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still missing:

Integrate with Cosmic Muon Generator & Detector Simulation

Thank you for your attention!

special thanks to Marwa Al Moussawi, Andrea Giammanco, Amrutha Samalan, Michael Tytgat

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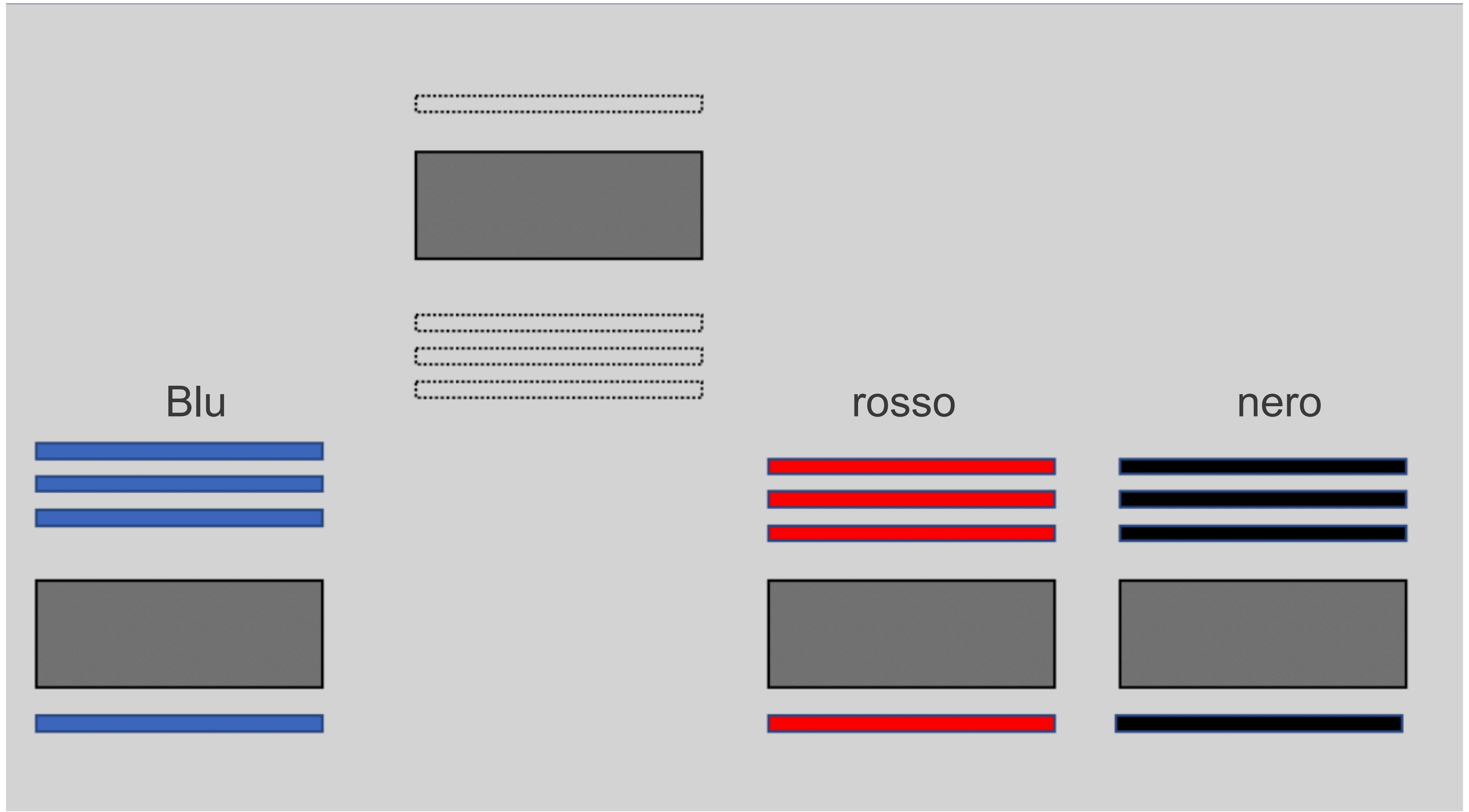
Outlook

- Expected muon flux through the Mt. Vesuvius body is obtained by PUMAS Backward Mode.

- Similar step can be done in Forward Mode,
  -> Comparison study with MUSIC,
  -> integrate with output of muon generators CRY or EcoMug, and interface with GEANT4,
  -> complete the simulation chain.

- PUMAS: Muon transport engine is predefined in the library,
  possible to define step by step like the simulation in GEANT4.

MURAVES Detector Container Plant



- Schematic representation of the container plant. Four spots have been realized to install the hodoscopes, three of which looking toward the volcano (blue, red and black rectangles) and one looking toward open sky (dotted contour rectangles) for calibration acquisition. The dark grey boxes represent the lead block.

Turtle

- **T**opographic **U**tilities for t**R**ansporting par**T**icules over **L**ong rang**E**s
- C library
- built upon a versatile optimistic ray tracing algorithm,

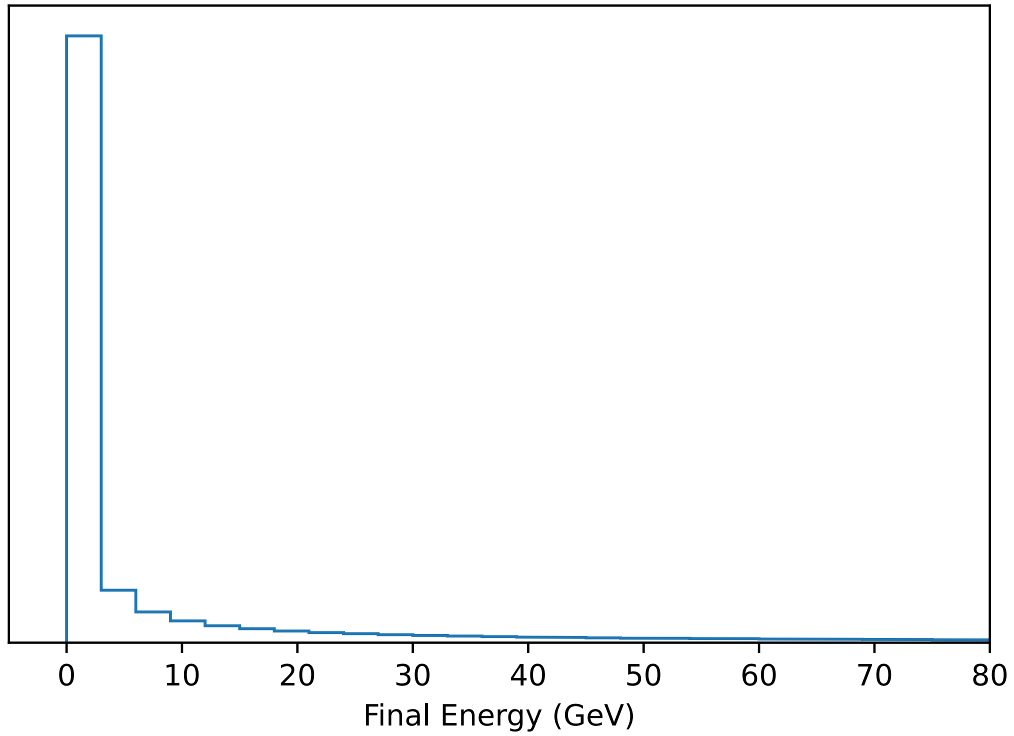
  -> only uses local topography data at each Monte-Carlo step -> efficient for scattering particles.

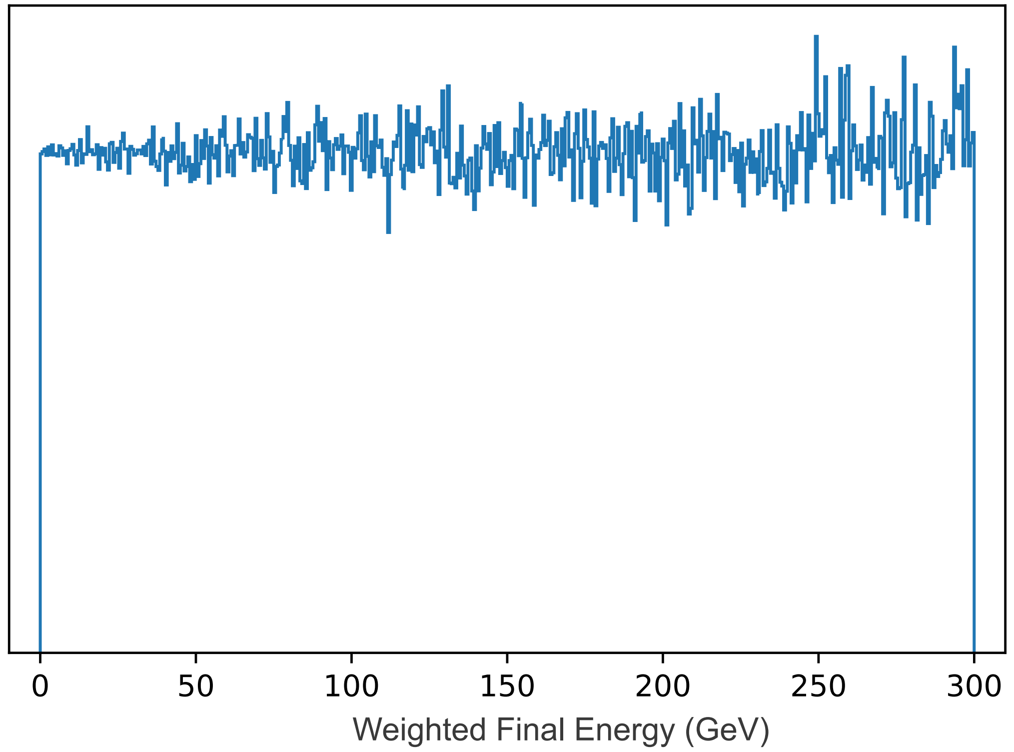
  -> allows for fast steps with an average CPU cost of only $O(500)$ instructions, i.e. a few hundreds ns per step.
- Constant traversal time,

  -> doesn't depend on the number of DEM data nodes. It only depends on the ray length and on the topography features.
- Zero Extra memory cost, the topography is built on the fly. Only the raw elevation data is required.
- Read Earth Gravitational Model (EGM96) file: ww15mgh.grd

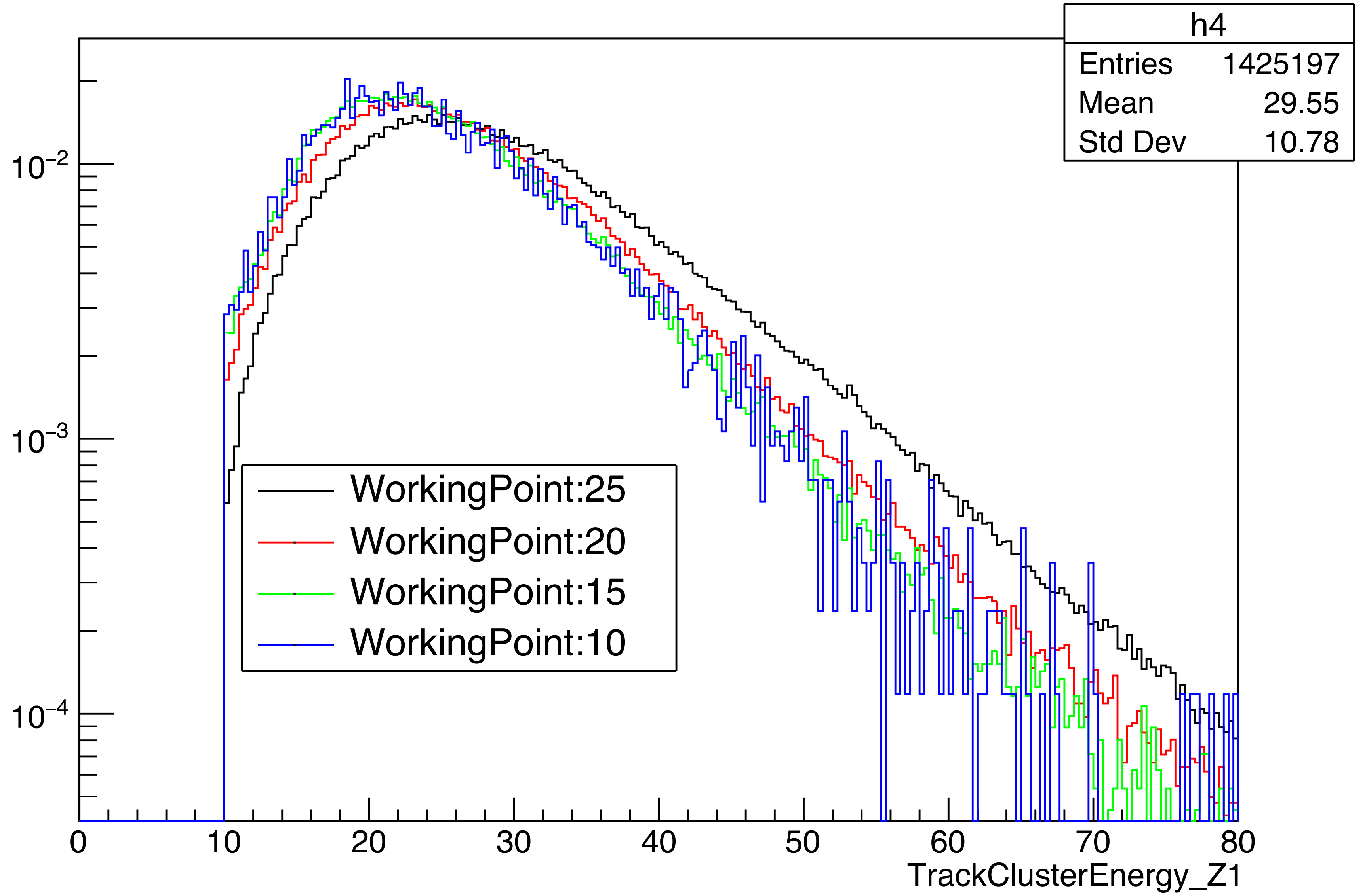
Final State Energy Distribution in PUMAS

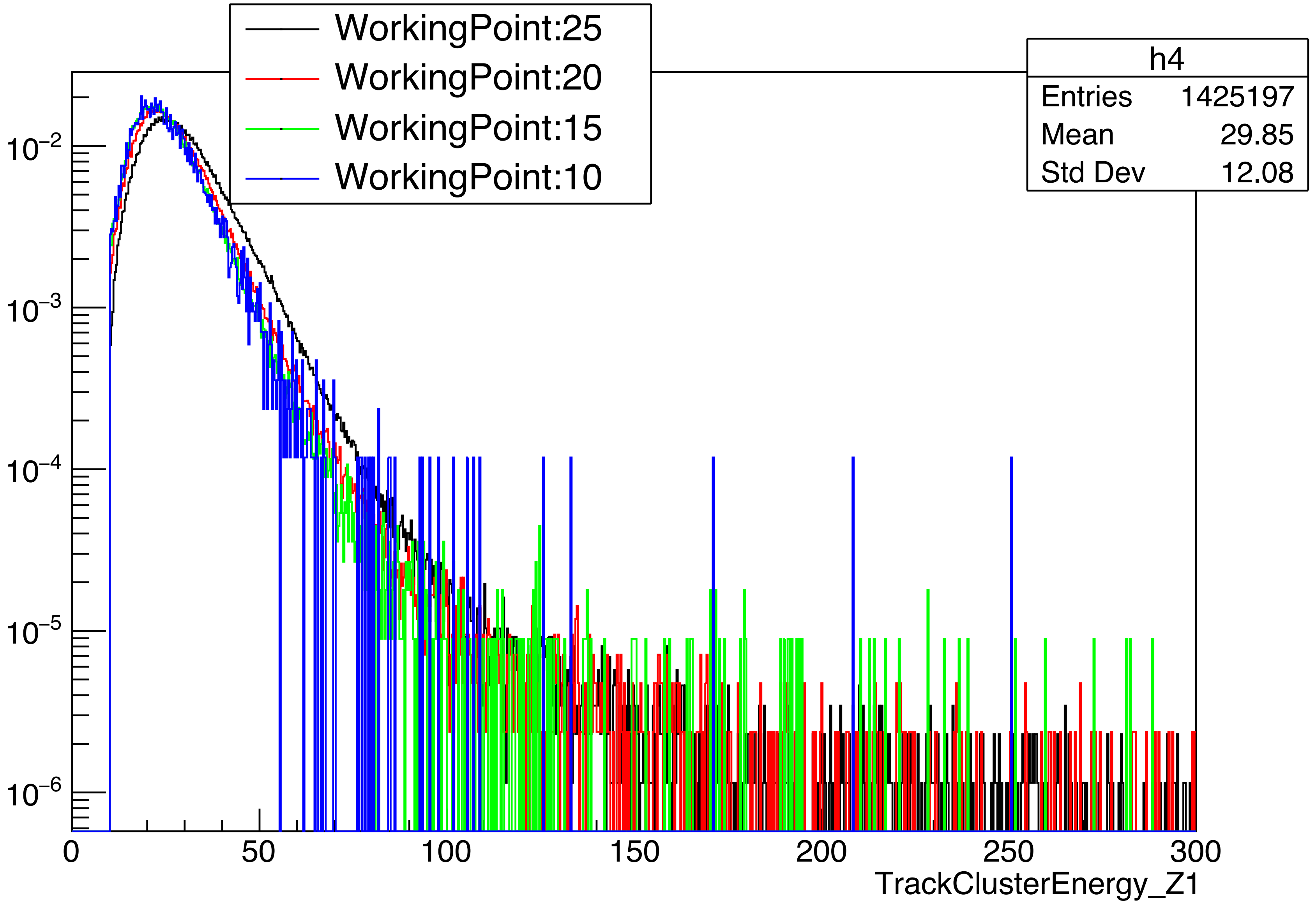
- When giving argument of the final state energy range in PUMAS, user defines the values of minimum and maximum of the energy.
  The distribution and weighted distribution are shown.
- Example: user defines final state Muon energy ranging 0.001 - 300 GeV, with 100 000 events.
- The input of final state kinetic energy is randomised over a **log-uniform distribution**. The Monte-Carlo weight is initialised according to this generating bias PDF, i.e. w = 1 / PDF(p).





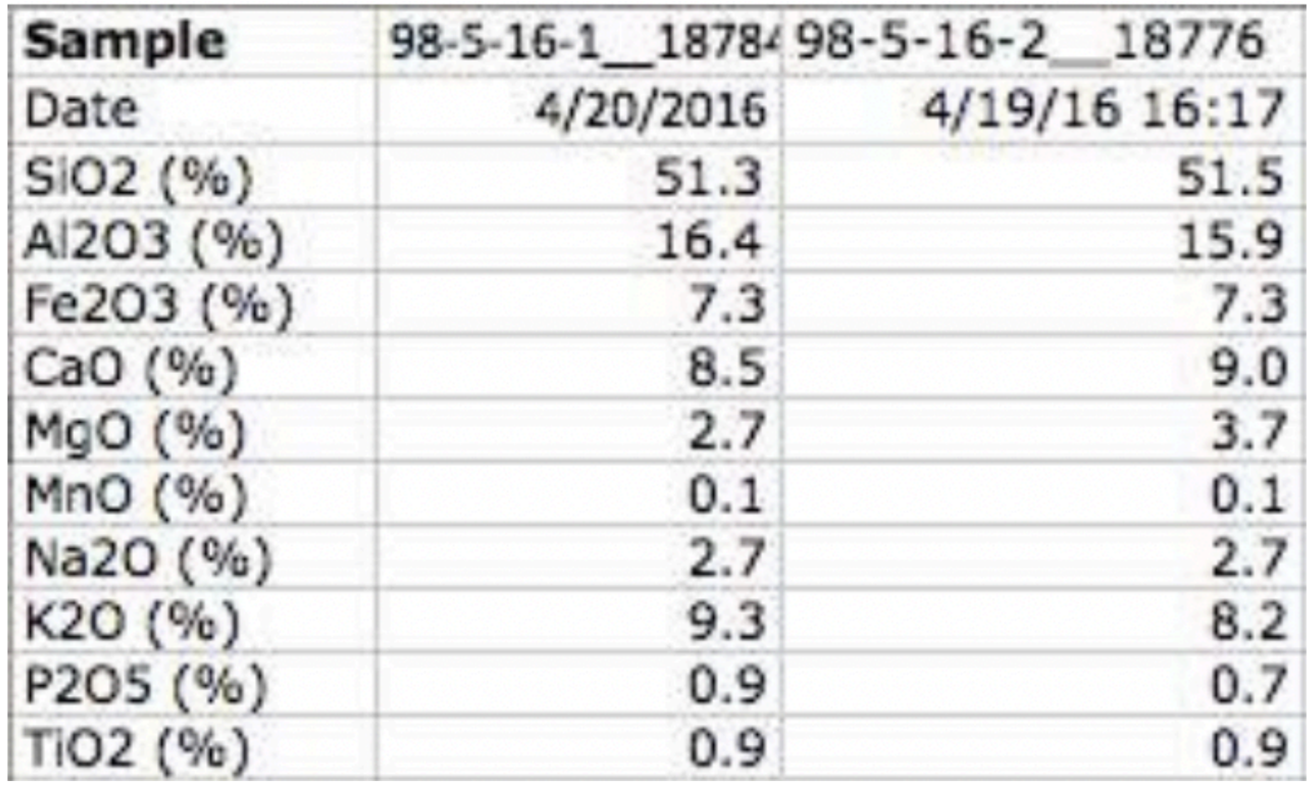
Cluster energy distribution in one axis





hypothesised rock density of Mt. Vesuvius

XRF



Sample	98-5-16-1__1878	98-5-16-2__18776
Date	4/20/2016	4/19/16 16:17
SiO2 (%)	51.3	51.5
Al2O3 (%)	16.4	15.9
Fe2O3 (%)	7.3	7.3
CaO (%)	8.5	9.0
MgO (%)	2.7	3.7
MnO (%)	0.1	0.1
Na2O (%)	2.7	2.7
K2O (%)	9.3	8.2
P2O5 (%)	0.9	0.7
TiO2 (%)	0.9	0.9

	g/cm3	Percentage1	Percentage2
SiO_2	2.65	51.3	51.5
Al_2O_3	5.95	16.4	15.9
Fe_2O_3	5.24	7.3	7.3
CaO	3.34	8.5	9.0
MgO	3.58	2.7	3.7
MnO	5.37	0.1	0.1
Na_2O	2.27	2.7	2.7
K_2O	2.35	9.3	8.2
P_2O_5	2.39	0.9	0.7
TiO_2	4.23	0.9	0.9
%		100.1	100
ρ		3.44312	3.44054

Clustering & 3D Tracking Method

Real and Simulated data comparison 4 Station tracking

- Data set used (opensky): Track4p_NERO_runs_6000_7000.root
- Data set used for simulation: Datafile with all possible primary particles (Electrons, Pions, Photons, Neutrons and Deutrons)
- No of events simulated with MURAVESSIM: ~1 million
- After applying all the cluster thresholds and selection processes, the no of events which crossed all 4-planes: 36407
- Cluster thresholds for selection:

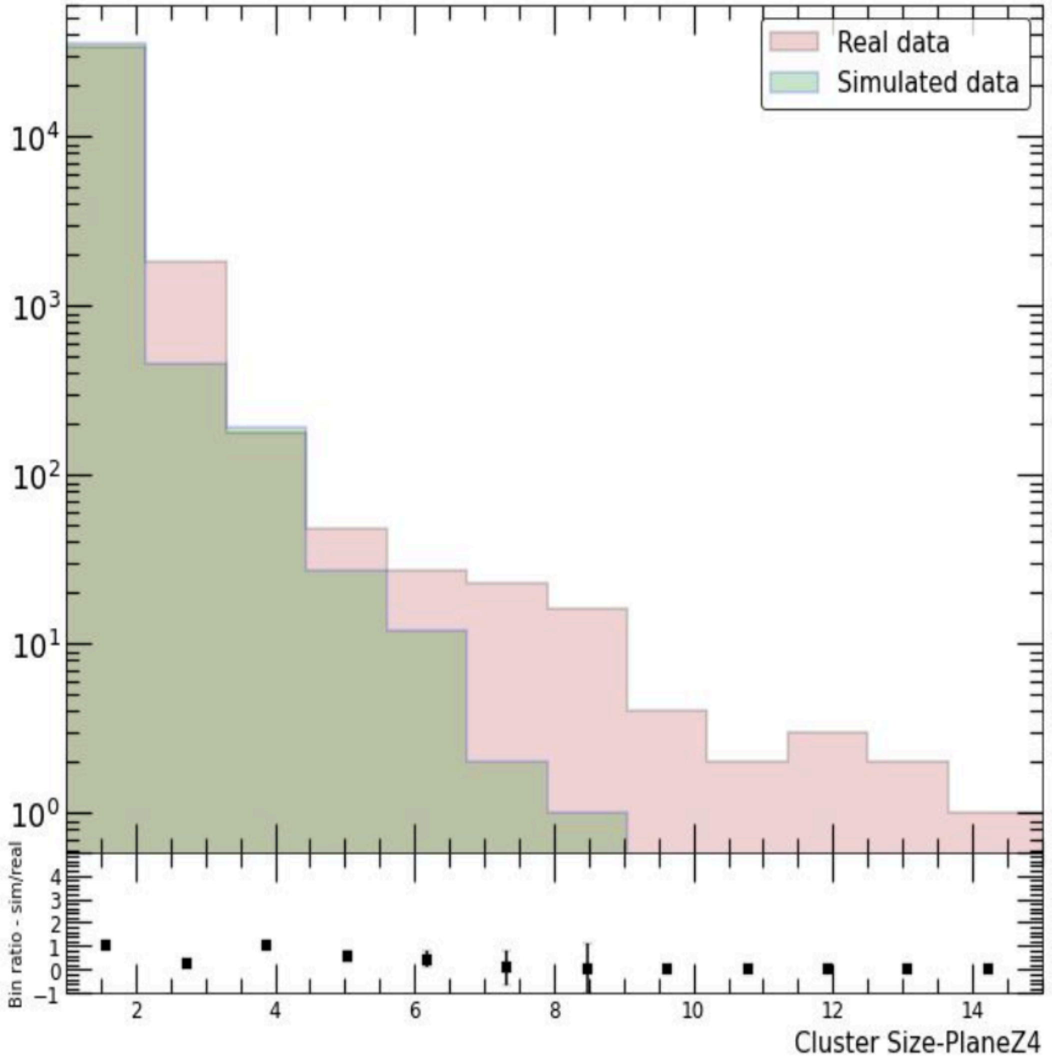
  Cluster Strip min energy = 6 phe;

  Single-strip cluster min energy = 10 phe;

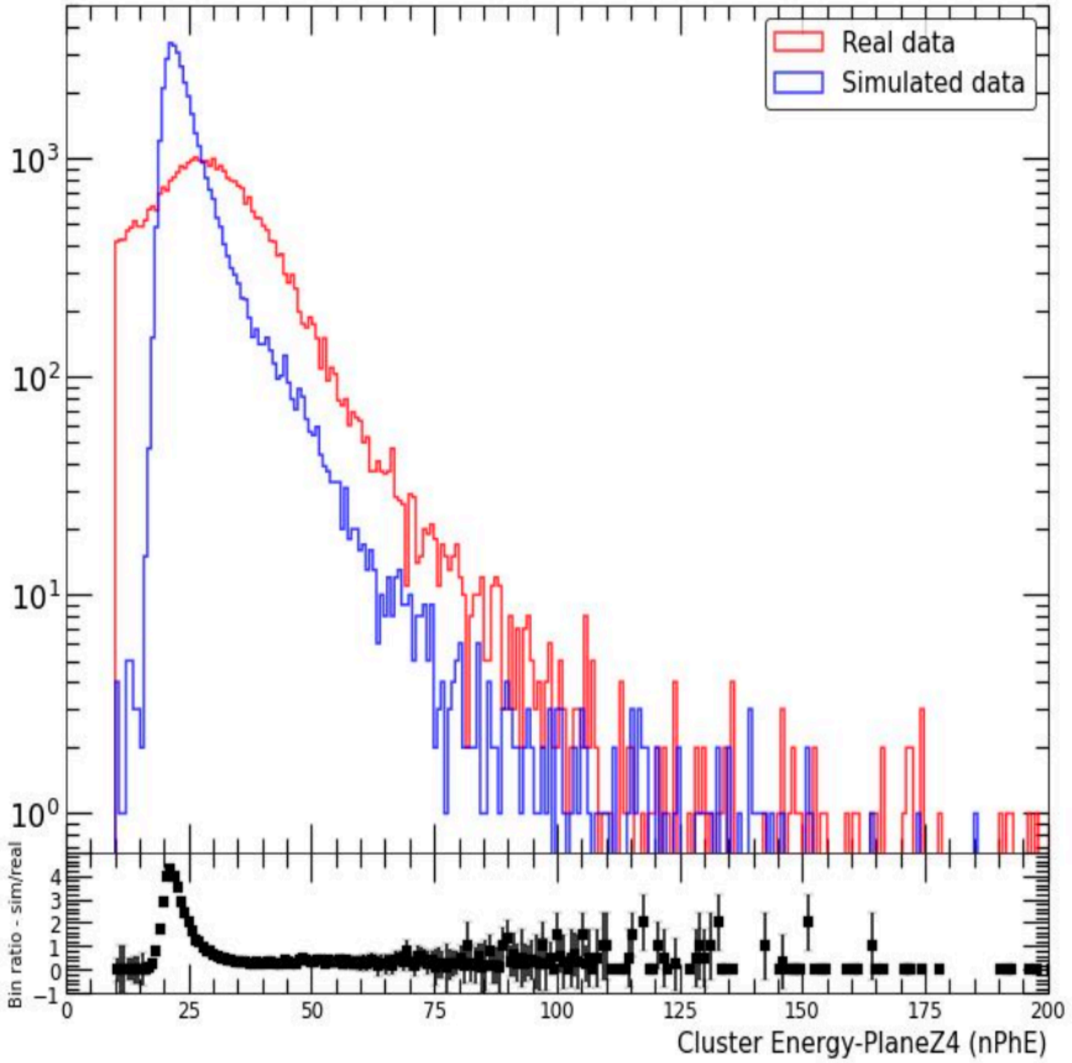
  Single strip neighbour min energy = 2 phe;
- Angle cut: 90<=phi<=270

Comparison of Cluster properties of the best tracks

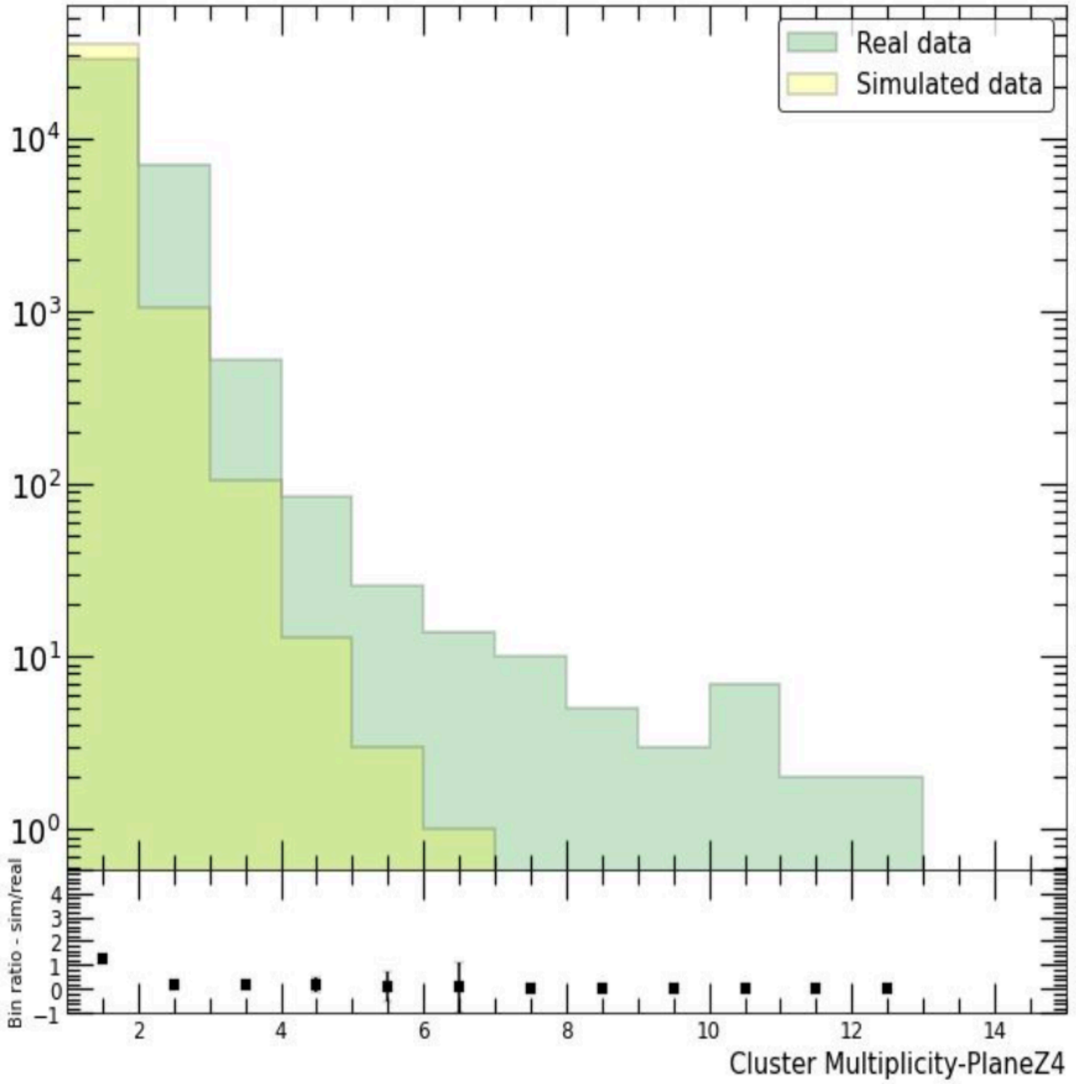
4-station tracking



Cluster size



Cluster energy



Cluster Multiplicity