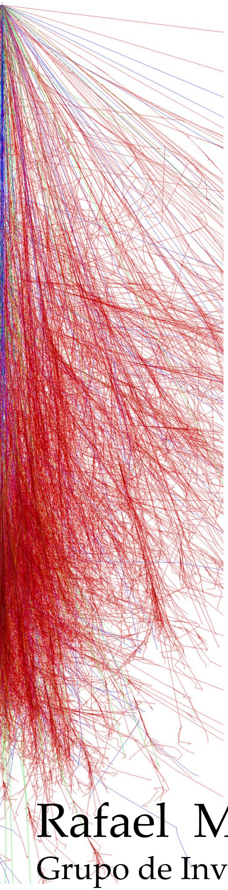


CABRIALES: Physics-informed AI muography simulation system

Rafael Martínez Rivero
Grupo de Investigación en Relatividad y Gravitación (GIRG)
Laboratorio de Investigación para la Detección de Radiación y Astropartículas (LiDERA)
Universidad Industrial de Santander. Bucaramanga Colombia

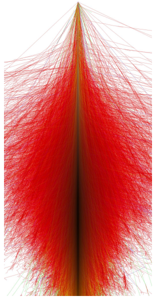
2 June, 2026
Muographers26, Budapest

rafael2248058@correo.uis.edu.co

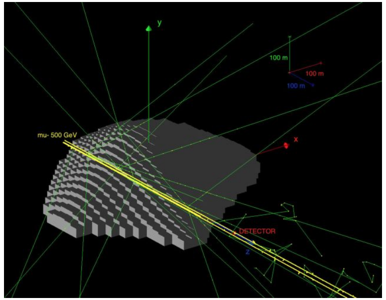
Cosmic-ray **A**I **B**ackpropagation and **R**ay-tracing with **I**ntegrated **A**ngular scattering for **L**ow-cost **E**mulation and **S**imulation

The Forward Problem in Muography simulation

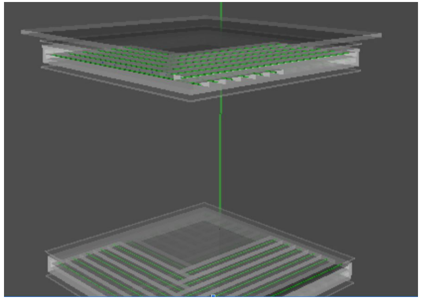
air-shower source (CORSIKA)



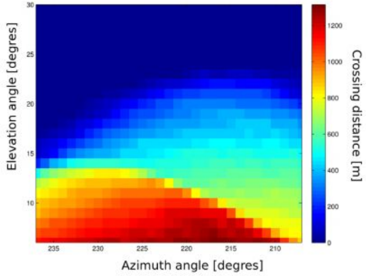
Particle interactions and transport



Detector response



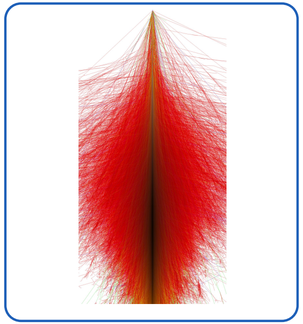
Muogram



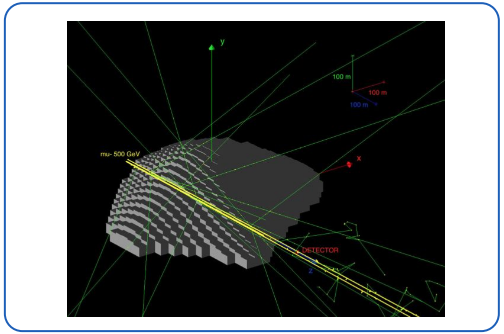
Monte Carlo is detailed but expensive 💲

The Forward Problem in Muography simulation

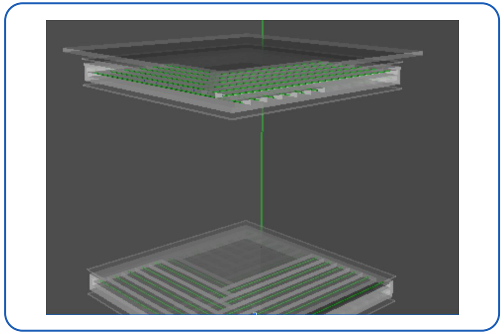
air-shower source (CORSIKA)



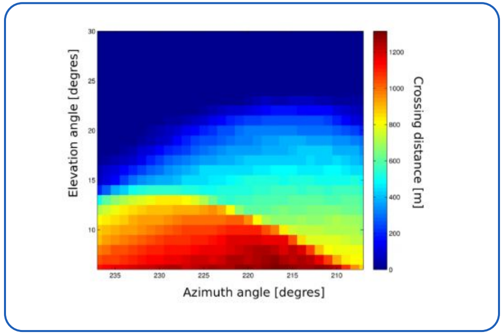
Particle interactions and transport



Detector response



Muogram

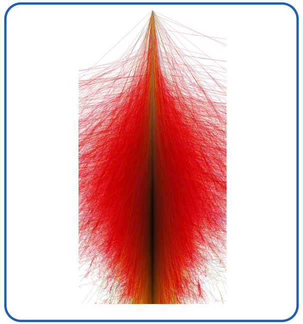


Monte Carlo is detailed but expensive $

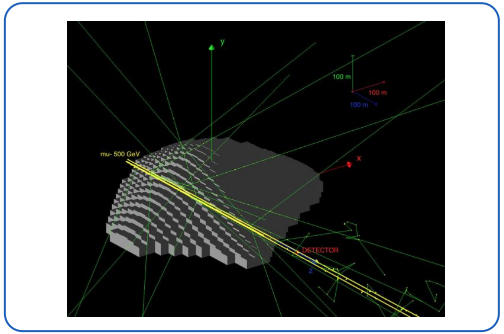
How can we keep the key physics without running a full Monte Carlo every time?

The Forward Problem in Muography simulation

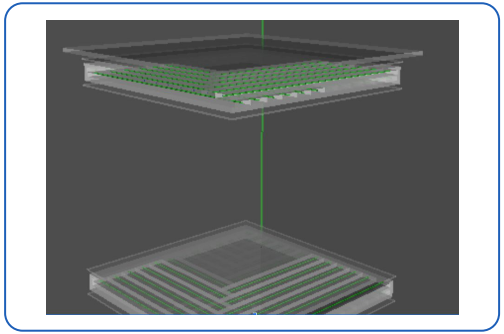
air-shower source (CORSIKA)



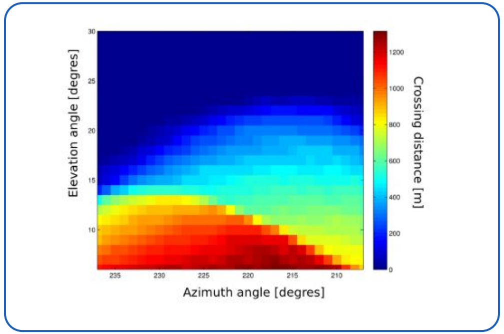
Particle interactions and transport



Detector response



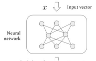
Muogram

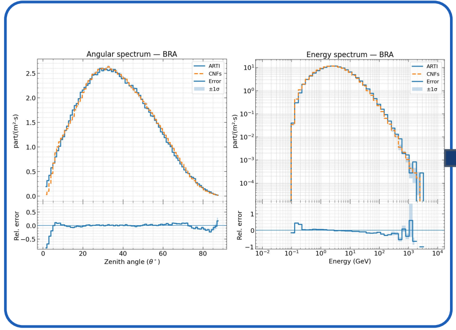


Monte Carlo is detailed in physics but it is expensive

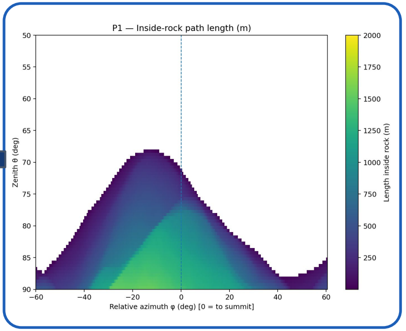
How can we keep the key physics without running a full Monte Carlo every time?

Deep learning muon flux

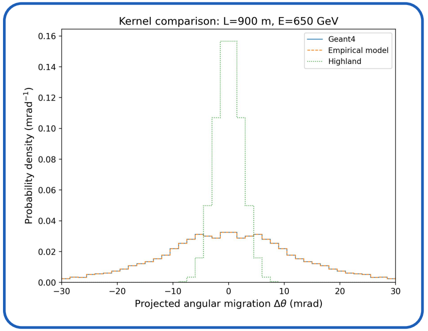




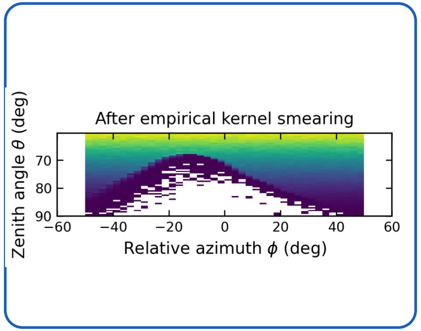
Backpropagation



Angular Scattering



muogram



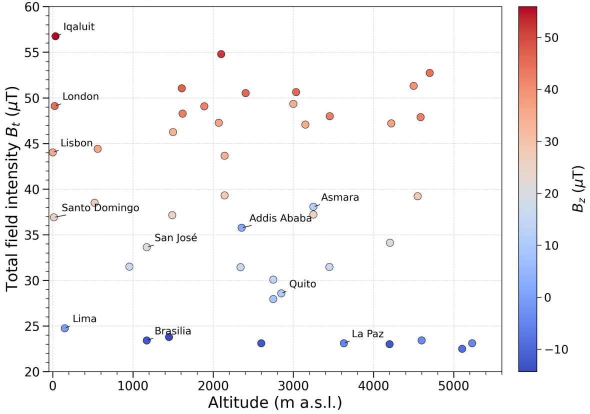
From Monte Carlo simulation to fast AI flux generation

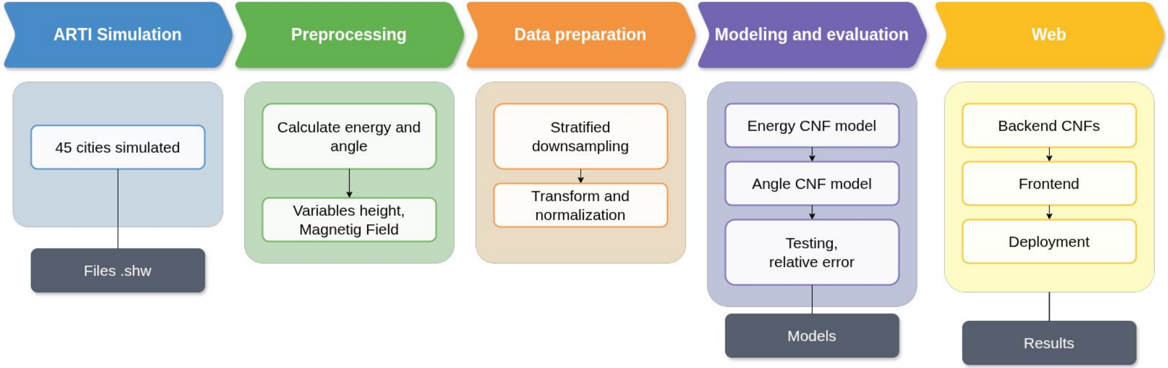
Visit poster

FAST MUON SPECTRUM ESTIMATION WITH GENERATIVE DEEP LEARNING

We use CORSIKA outputs as training data, so the AI model can generate muon fluxes faster.

- Monte Carlo simulation gives the reference muon-flux data.
- The training sites cover different altitude and geomagnetic conditions.
- The AI model learns site-dependent angular and energy spectra.
- The generated flux becomes the input of the forward model.


Geomagnetic conditions of simulated sites


ARTI Simulation

45 cities simulated

Files .shw

Preprocessing

Calculate energy and angle

Variables height, Magnetig Field

Data preparation

Stratified downsampling

Transform and normalization

Modeling and evaluation

Energy CNF model

Angle CNF model

Testing, relative error

Models

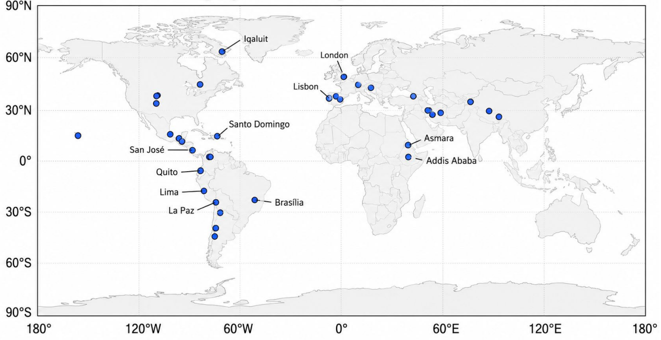
Web

Backend CNFs

Frontend

Deployment

Results


Geographic coverage of simulated sites

Deep learning flux generation and web deployment

Visit poster

FAST MUON SPECTRUM ESTIMATION WITH GENERATIVE DEEP LEARNING

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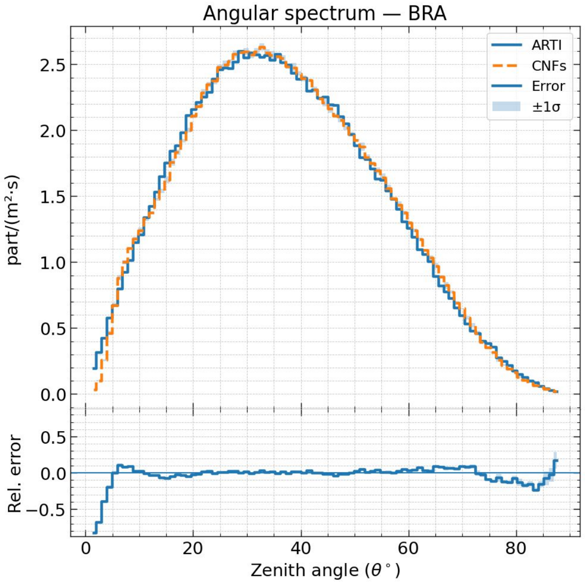
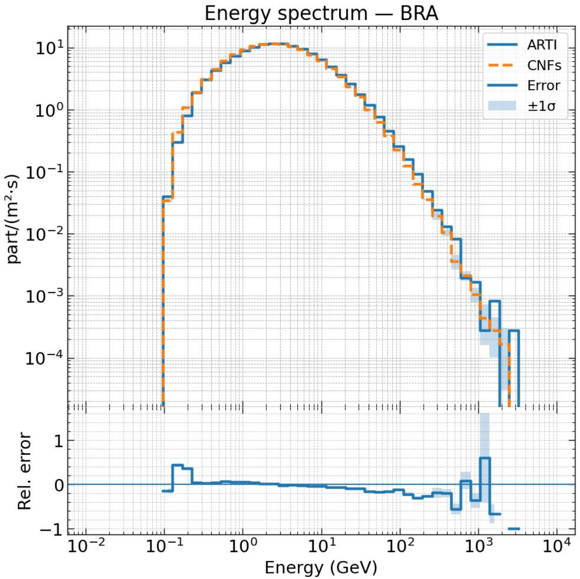




https://muon-generator.vercel.app/

Generador global del flujo de muones

Inicio Simulador Descripción

Generador global del flujo de muones

Estime y visualice la distribución de muones cósmicos para cualquier ubicación del planeta.

IA

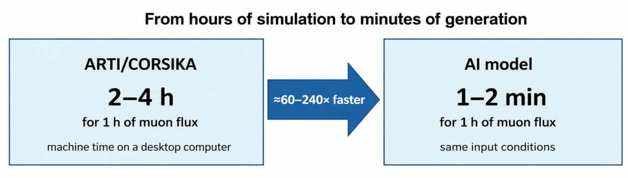
Basado en CNFs entrenados con simulaciones ARTI/CORSIKA

Resultados instantáneos

Genere distribuciones angulares y energéticas en segundos

Exportación flexible

Descargue resultados en formato CSV o



From hours of simulation to minutes of generation

ARTI/CORSIKA

2–4 h

for 1 h of muon flux

machine time on a desktop computer

≈60–240× faster

AI model

1–2 min

for 1 h of muon flux

same input conditions

Warning: Web runs may take ~3–4 min in this pilot phase.

Now that we have the flux, we can propagate it through the volcano.

Backpropagation through the volcano

We convert detector directions into rock thickness, and then into a muon survival condition.

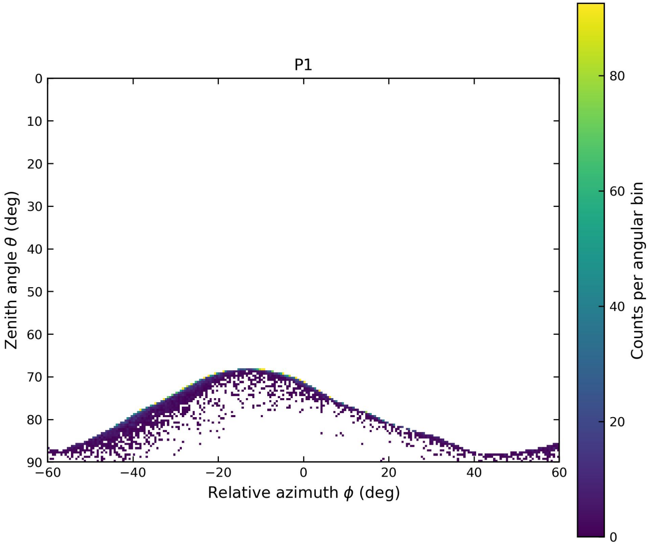
- Detector angles are traced through the volcano geometry.
- Each direction gives a rock thickness.
- CSDA converts rock thickness into a critical energy.
- Muons survive only if $E_\mu \geq E_{\text{crit}}(L, \rho)$

Geometry Filtering

Ray Back propagation

CSDA

Energy condition



Now we know which muons survive. But they do not travel in perfect straight lines.

Backpropagation through the volcano

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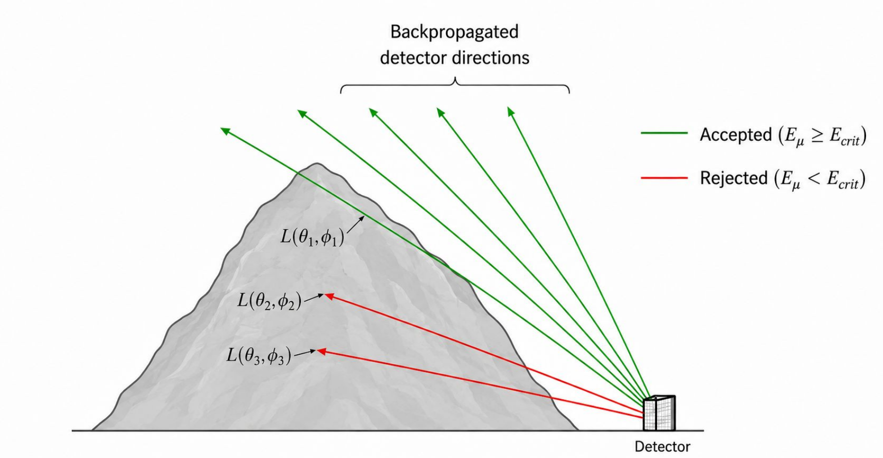
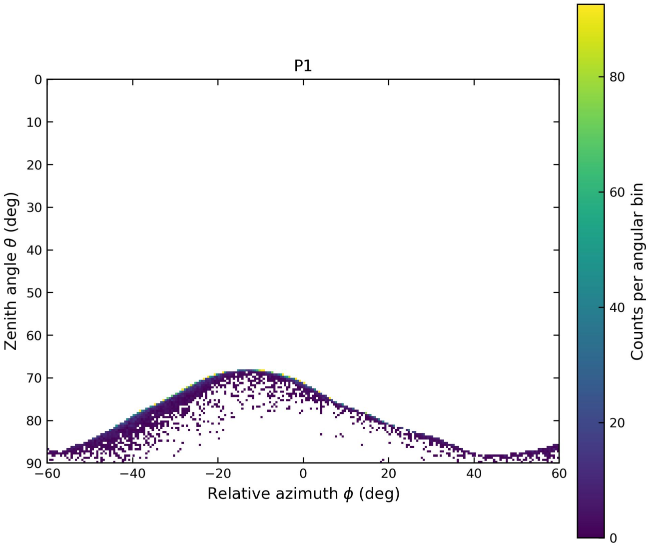
Geometry Filtering → Ray Back propagation → CSDA → Energy condition



Keep only energetically allowed directions ($E_\mu \geq E_{crit}$)



Now we know which muons survive. But they do not travel in perfect straight lines.

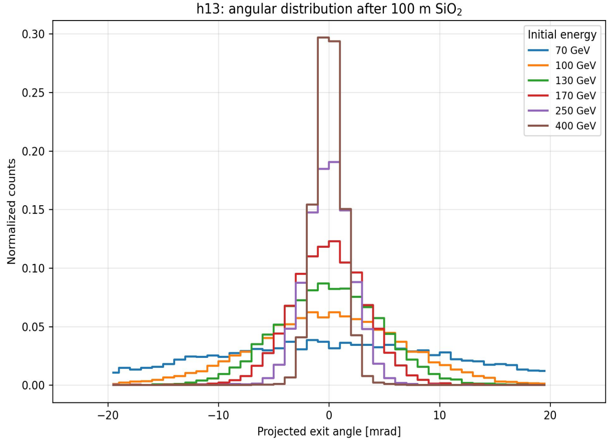
Why do we need a scattering kernel?

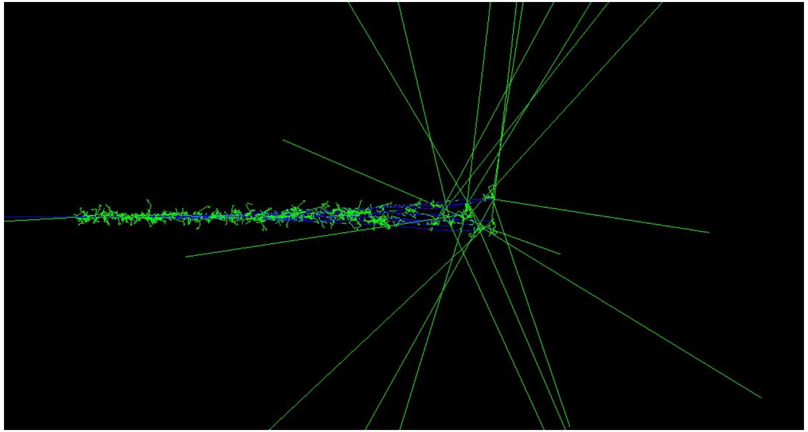
After the volcano filter, muons survive, but they do not travel in perfect straight lines.

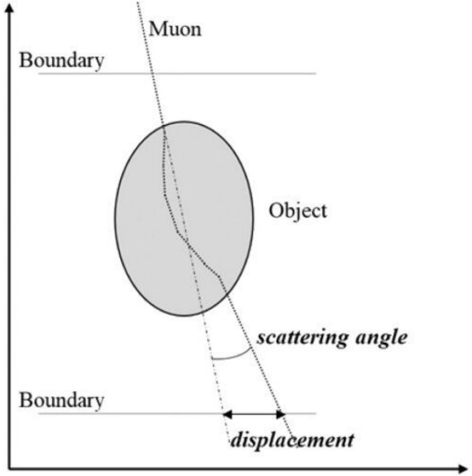
- Straight-line propagation ignores angular scattering.
- Lynch & Dahl gives a first scattering scale.

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

- But it does not describe the full migration pattern.
- Geant4 gives detailed exit-angle distributions.
- These distributions are stored in an empirical kernel.





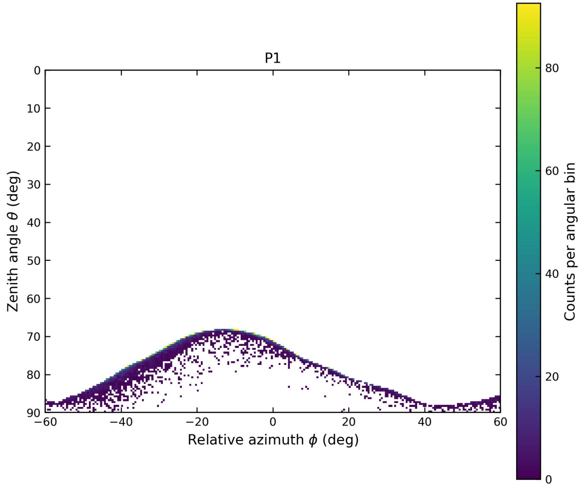


Highland, NIM 129, 497–499 (1975); Lynch & Dahl, NIM B 58, 6–10 (1991).

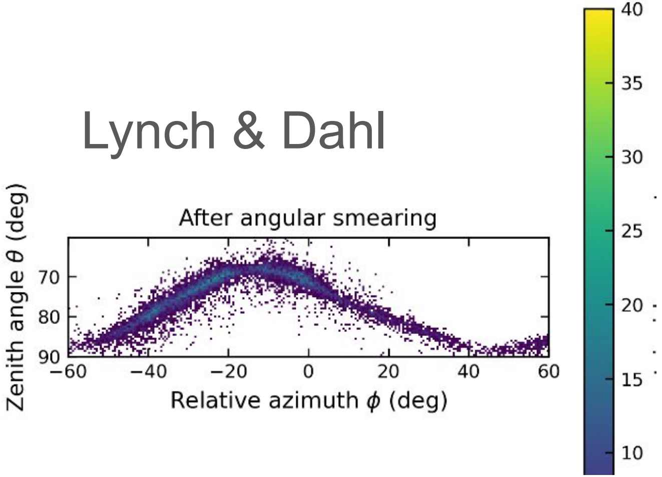
Scattering changes the final muogram

We run Geant4 once, and reuse the result many times.

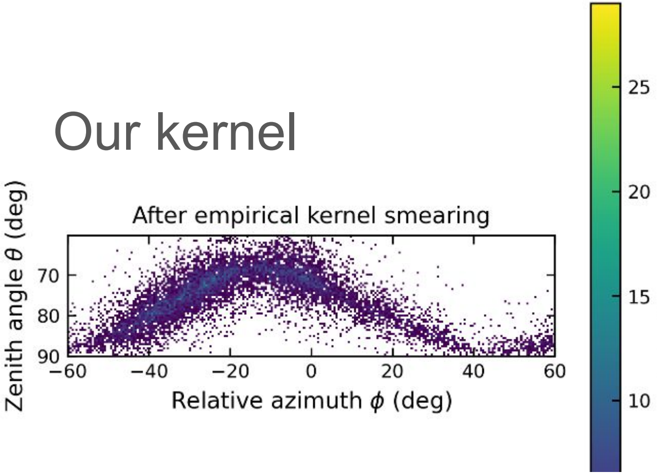
- Run Geant4 for many thickness–energy cases.
- Store the exit-angle distributions.
- Convert them into probability kernels.
- Apply the kernel to surviving muons.
- Obtain the scattered muogram.



Lynch & Dahl



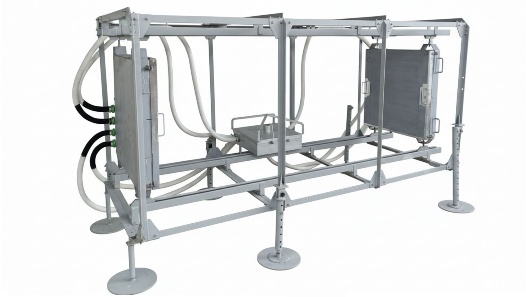
Our kernel

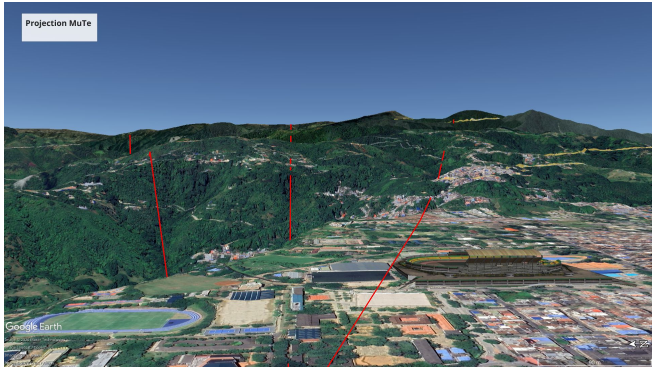


Next step: apply the model and compare it with real measurements.

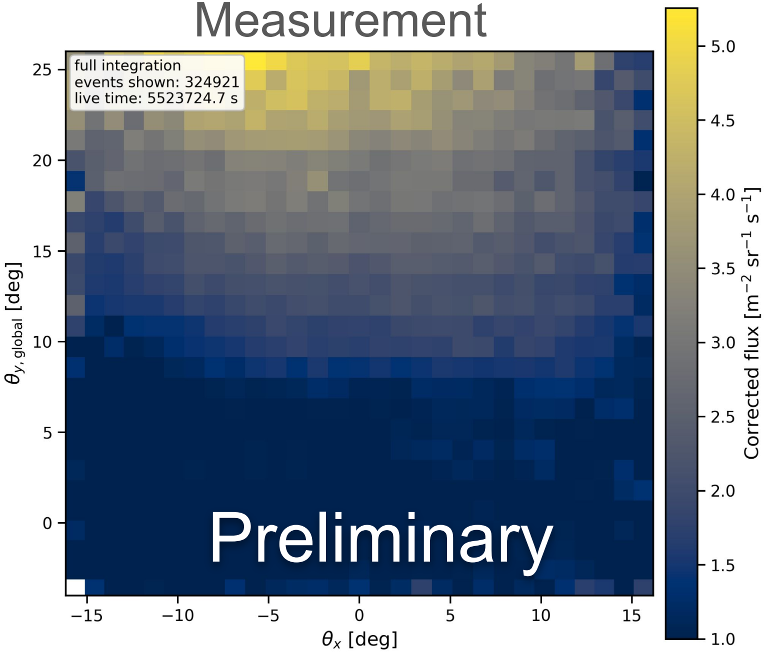
Muon shadow from the Andes: measurement and simulation

The measured mountain shadow is compared with the simulated muogram.

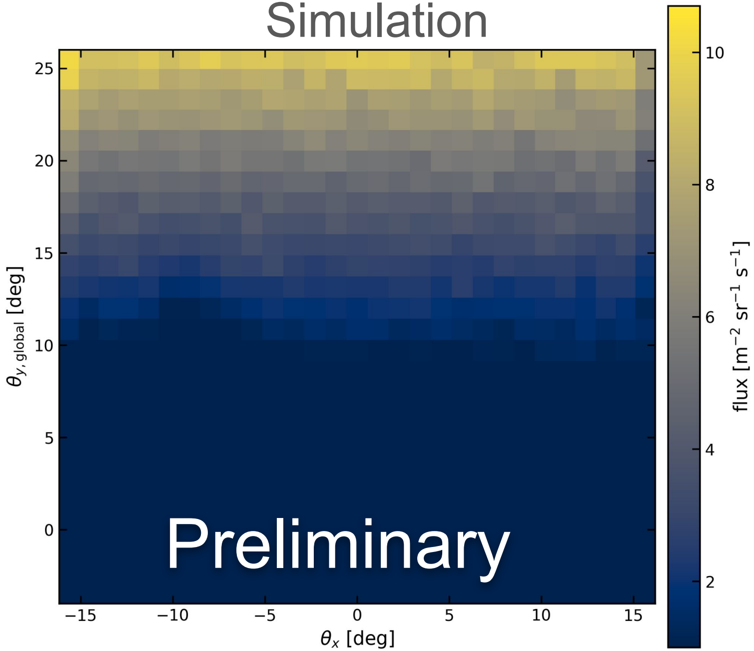




Measurement



Simulation

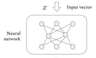


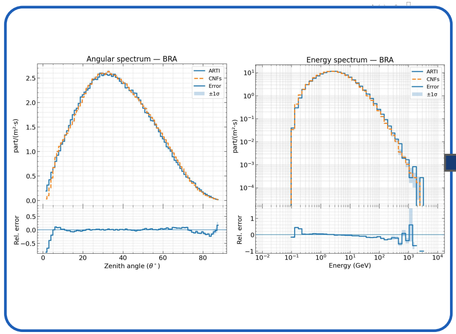
Final remarks

A fast modular model can keep the main physics of full Monte Carlo, but with lower computational cost.

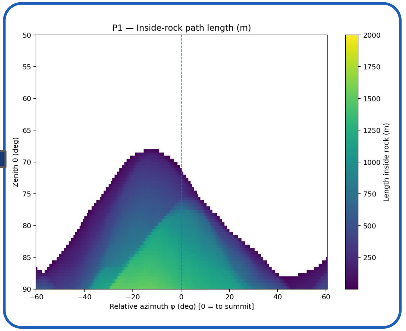
- The model combines AI flux generation, backpropagation, and angular scattering.
- Geant4 information is reused through an empirical scattering kernel.
- The first comparison with MuTe data shows the expected mountain shadow.
- Next step: quantitative comparison including detector response, acceptance, and uncertainties.

Deep learning muon flux

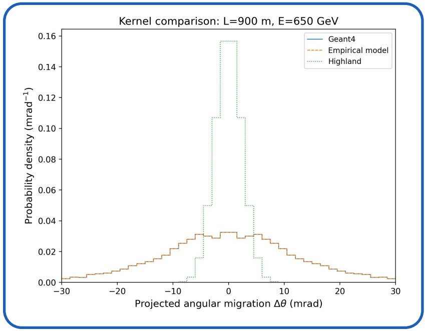




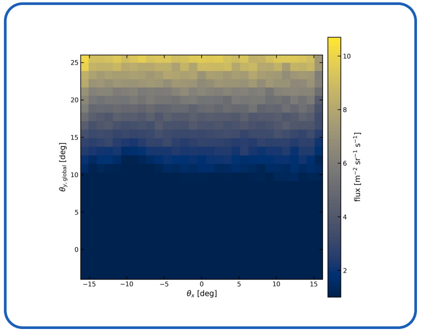
Backpropagation



Angular Dispersion



muogram



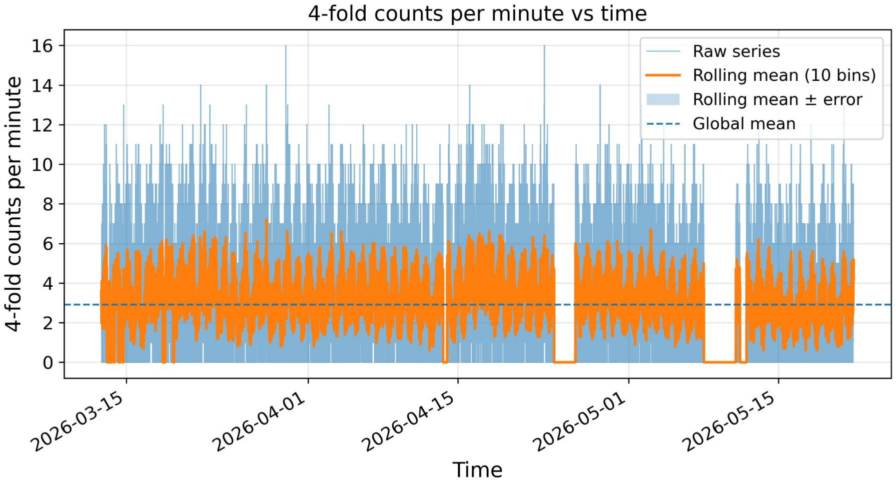
Thanks

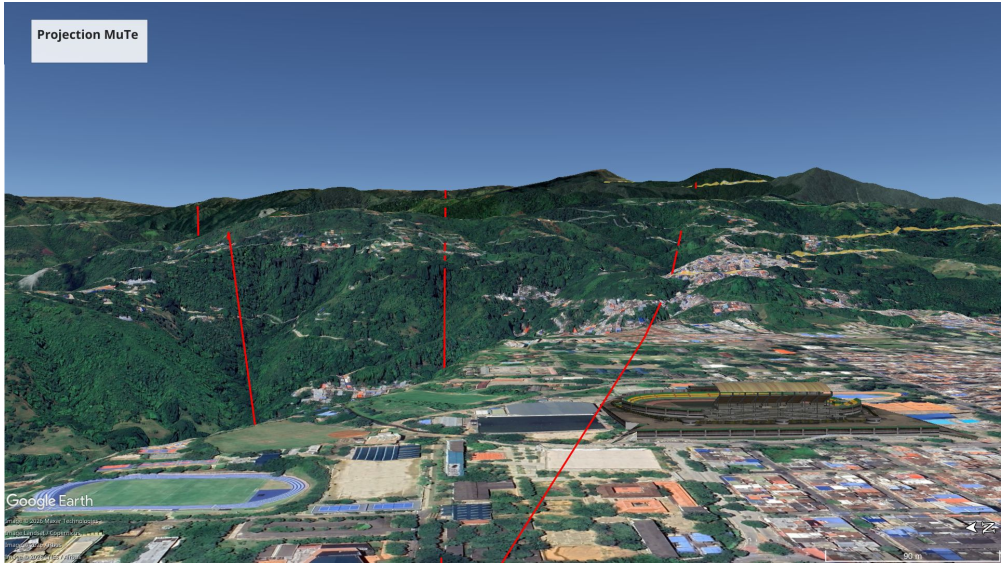
Rafael A. Martínez Rivero.
rafael2248058@correo.uis.edu.co

Real MuTe data for model comparison

We use the current mountain-facing campaign to compare the simulated shadow with measured muon data.

- Mountain-facing MuTe campaign from the laboratory building.
- More than 100 days of accumulated muon data.
- 4-fold coincidence events are used for the measured flux.
- Large rock thickness produces a strong open-sky flux suppression.





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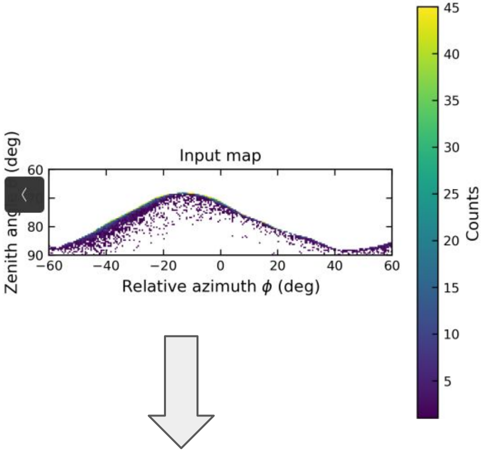
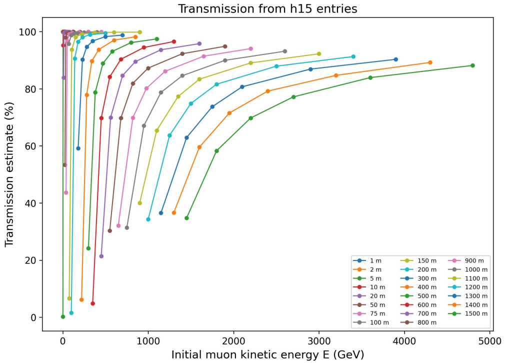
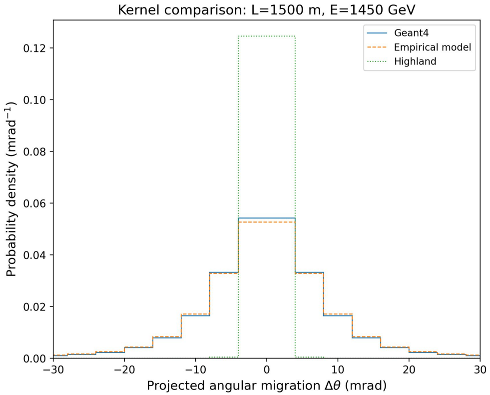
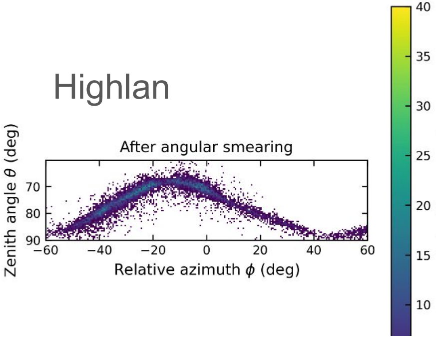


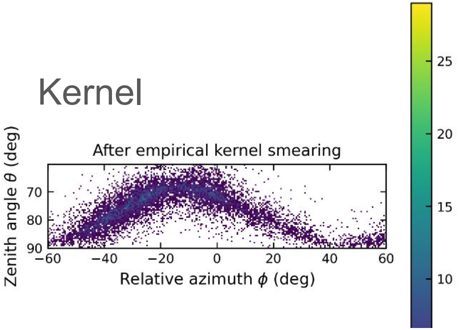




Highlan



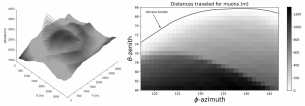
Kernel



Next step: apply the model and compare it with real measurements.

Flux Estimation: ARTI framework Monte Carlo based.

Provides the reference site-dependent muon flux. The generative model learns to reproduce it quickly.



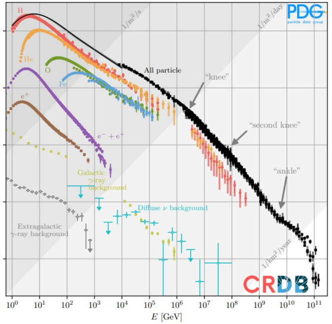
Volcano	Criterion 1:	Criterion 2:	Criterion 3:
Azufral	N	Y	N
Cerro Negro*	Y	Y	N
Chiles*	Y	Y	N
Cumbal	N	Y	N
Dona Juana	N	Y	N
Galeras	Y	N	Y
Machín	**Y**	**Y**	**Y**
Nevado del Huila	N	Y	N
Nevado del Ruíz	N	Y	Y
Nevado Santa Isabel	N	Y	Y
Nevado del Tolima	N	N	Y
Puracé	N	Y	Y
Sotará	N	Y	N

Vesga-Ramírez, A., et al (2020). **Muon**

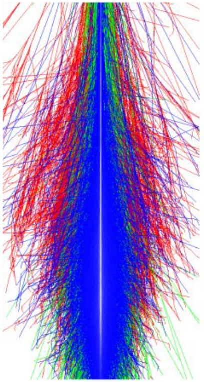
es.

Primary flux integration from observations at 112 km.

$$\Phi(E_p,Z,A,\Omega)=j_0(Z,A)\left(\frac{E_p}{E_0}\right)^{\alpha(E_p,Z,A)}$$

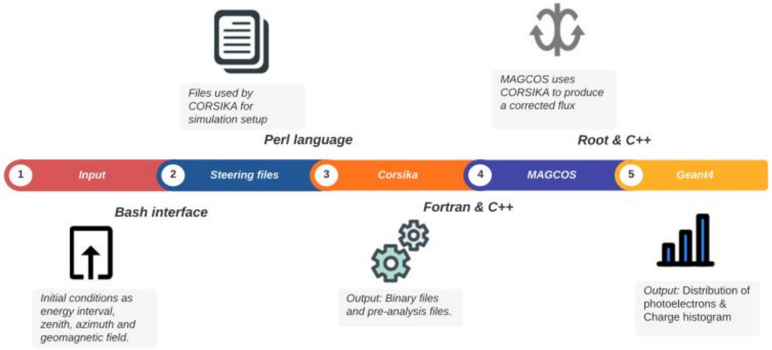


Spectrum (CRs). [Navas et al.(2024)] PDG



CORSIKA simulation for all the primaries particles with site depend condition

Recording of the secondary particles generated



Files used by CORSIKA for simulation setup

Perl language

MAGCOS uses CORSIKA to produce a corrected flux

Root & C++

1 Input — 2 Steering files — 3 Corsika — 4 MAGCOS — 5 Geant4

Bash interface

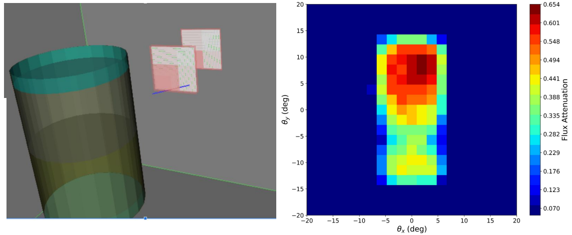
Fortran & C++

Initial conditions as energy interval, zenith, azimuth and geomagnetic field.

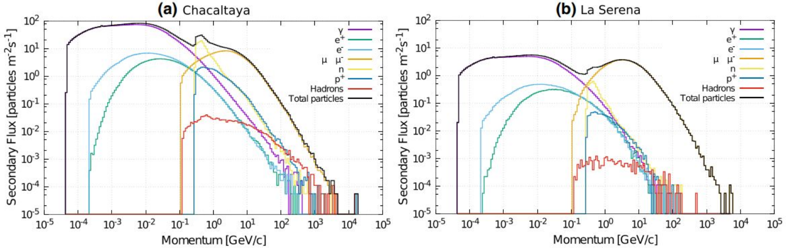
Output: Binary files and pre-analysis files.

Output: Distribution of photoelectrons & Charge histogram

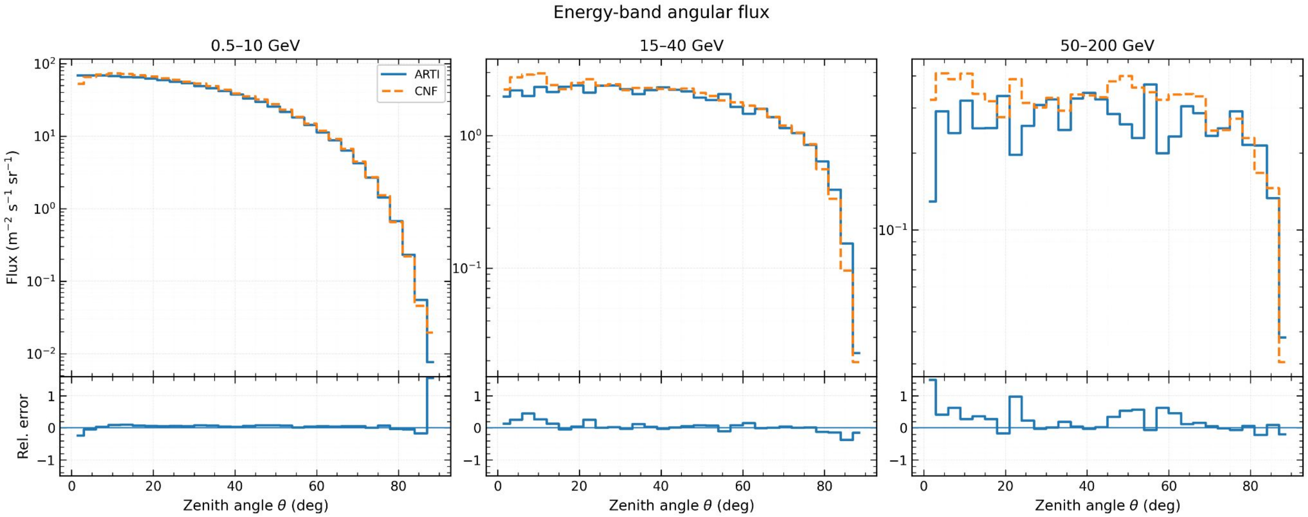
Sarmiento-Cano, & LAGO Collaboration. (2022). **The ARTI framework: cosmic rays atmospheric background simulations**. *The European Physical Journal C*, *82*(11), 1019.

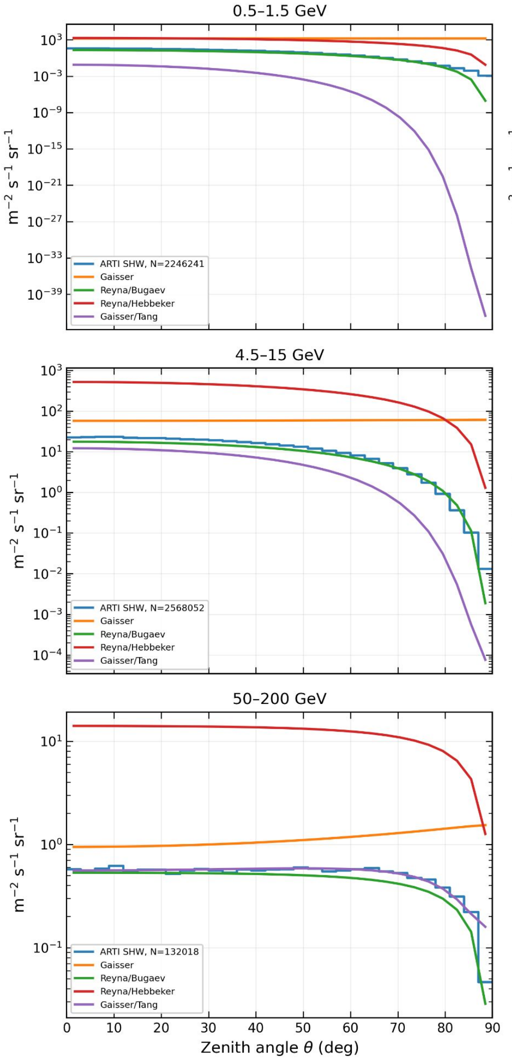


R. A. Martínez-Rivero, et al. (2025); **Muon imaging of hydrotreatment reactors.** *J. Appl. Phys.*

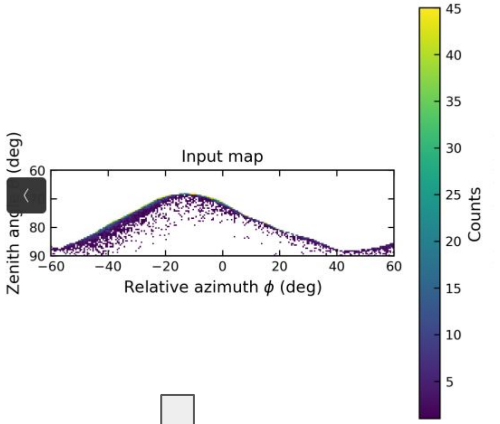


ARTI-Model in energy bands



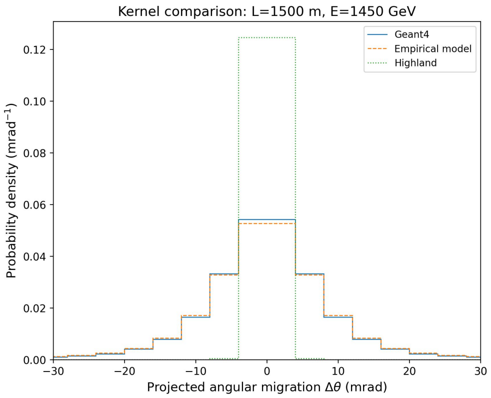


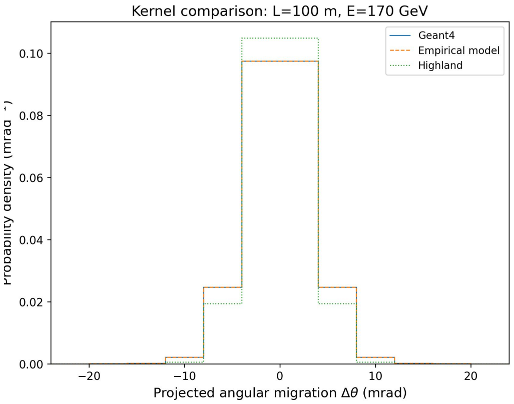
From Full MC to fast kernel of MCS: Muogram impact



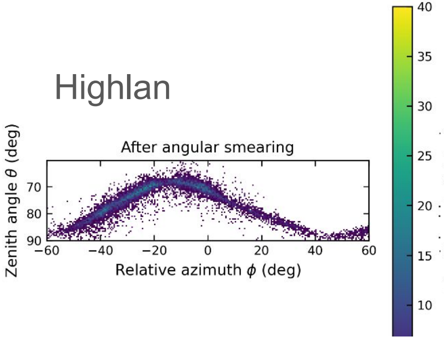
$$K(\Delta\Omega|E_\mu,L,\rho)=p(\Omega_{\rm out}-\Omega_{\rm in}|E_\mu,L,\rho),\ \int K(\Delta\Omega|E_\mu,L,\rho)\,d(\Delta\Omega)=1.$$

$$N_{\rm scat}(\Omega_{\rm rec})=\int dE_\mu\,d\Omega\,N_{\rm surv}(E_\mu,\Omega)\,K(\Omega_{\rm rec}-\Omega|E_\mu,L(\Omega),\rho).$$

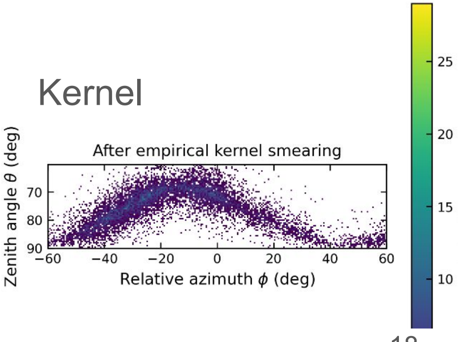




Highlan



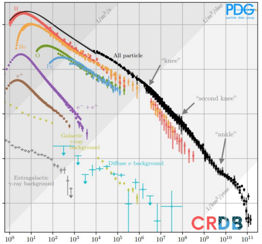
Kernel



Flux Estimation: ARTI framework Monte Carlo based.

Primary flux integration from observations at 112 km.

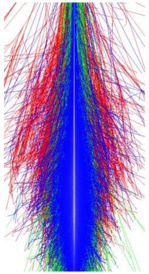
$$\Phi(E_p,Z,A,\Omega)=j_0(Z,A)\left(\frac{E_p}{E_0}\right)^{\alpha(E_p,Z,A)}$$



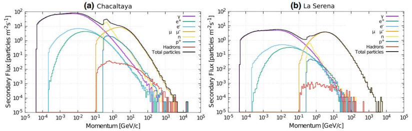
Spectrum (CRs). [Navas et al.(2024)] PDG

CORSIKA simulation for all the primaries particles with site depend condition

$$\mathbf{c}_{\text{site}} = (\text{latitude},\ \text{longitude},\ h,\ B_t,\ B_z)$$

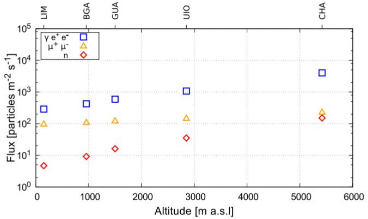


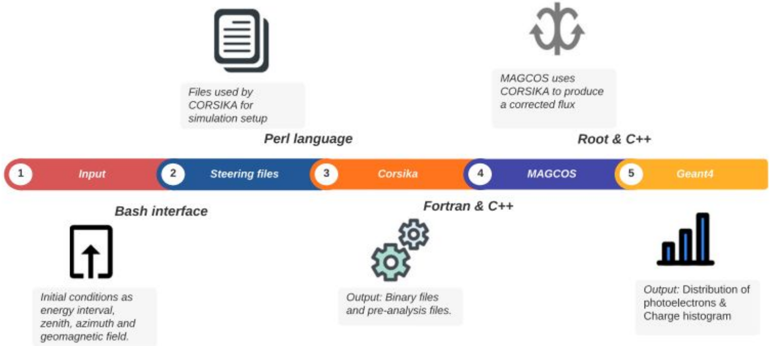
Recording of the secondary particles generated



Vestibulum congue tempus

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor. Donec facilisis lacus eget mauris.





Files used by CORSIKA for simulation setup

MAGCOS uses CORSIKA to produce a corrected flux

Perl language

Root & C++

1 Input

2 Steering files

3 Corsika

4 MAGCOS

5 Geant4

Bash interface

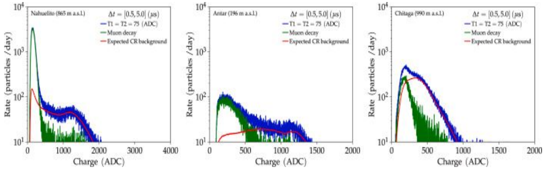
Fortran & C++

Initial conditions as energy interval, zenith, azimuth and geomagnetic field.

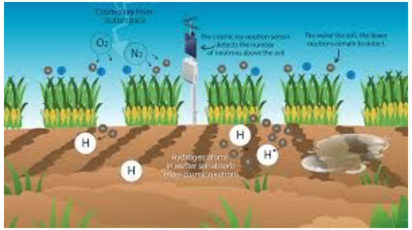
Output: Binary files and pre-analysis files.

Output: Distribution of photoelectrons & Charge histogram

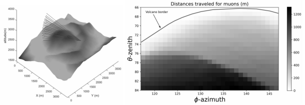
Sarmiento-Cano, & LAGO Collaboration. (2022). **The ARTI framework: cosmic rays atmospheric background simulations**. *The European Physical Journal C*, *82*(11), 1019.

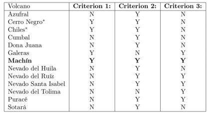


Otiniano, L.,& LAGO Collaboration. (2023). **Measurement of the muon lifetime and the Michel spectrum in the LAGO water Cherenkov detectors as a tool to enhance the signal-to-noise ratio.** *Nuclear Instruments and Methods in Physics Research*



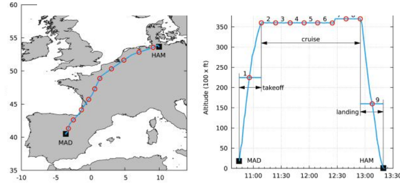
J. Betancourt, et al. (2025) **Enhanced water Cherenkov detector for soil moisture detection.**



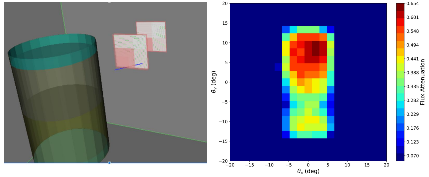


Volcano	Criterion 1:	Criterion 2:	Criterion 3:
Azufral	N	Y	N
Cerro Negro*	Y	Y	N
Chiles*	Y	Y	N
Cumbal	N	Y	N
Dona Juana	N	Y	N
Galeras	Y	N	Y
Machín	**Y**	**Y**	**Y**
Nevado del Huila	N	Y	N
Nevado del Ruíz	N	Y	Y
Nevado Santa Isabel	N	Y	Y
Nevado del Tolima	N	N	Y
Puracé	N	Y	Y
Sotará	N	Y	N

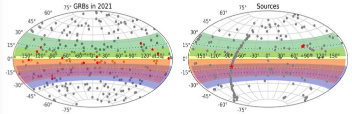
Vesga-Ramírez, A., et al (2020). **Muon Tomography sites for Colombian volcanoes.** *ANNALS OF GEOPHYSICS*, *63*(6).



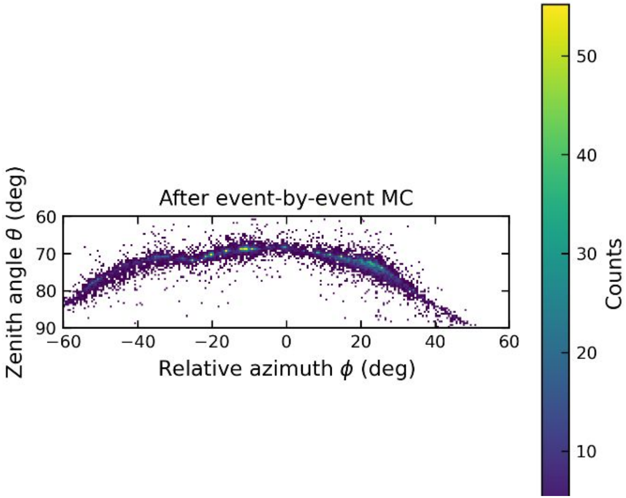
Asorey, H.,et al;. (2023). **ACORDE: A new application for estimating the dose absorbed by passengers and crews in commercial flights.** *Applied Radiation and Isotopes.*

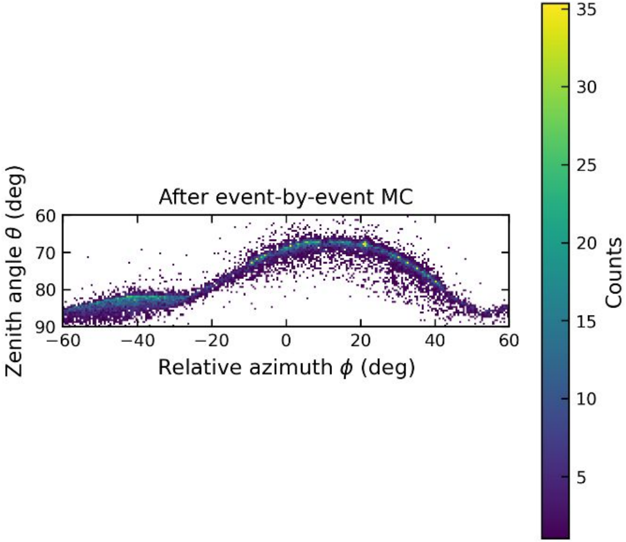


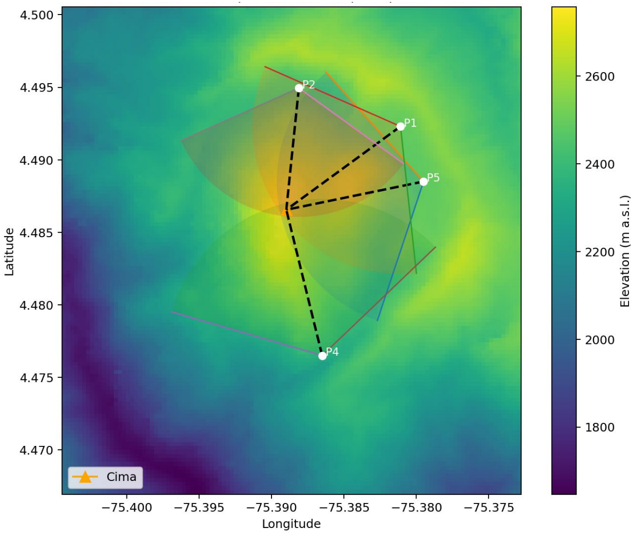
R. A. Martínez-Rivero, et al. (2025); **Muon imaging of hydrotreatment reactors.** *J. Appl. Phys.*

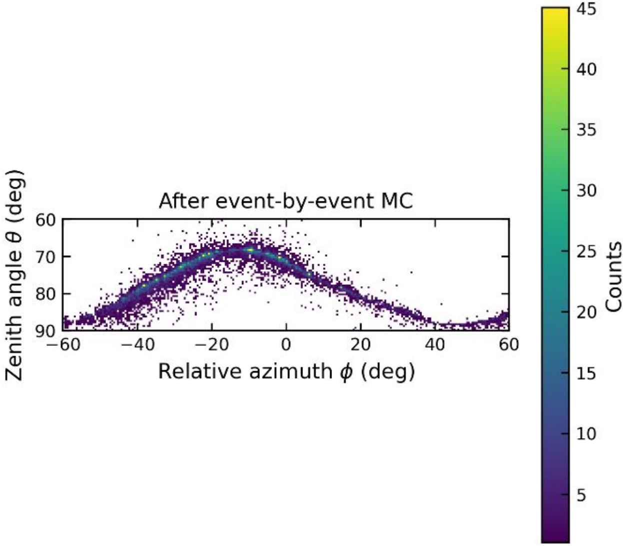


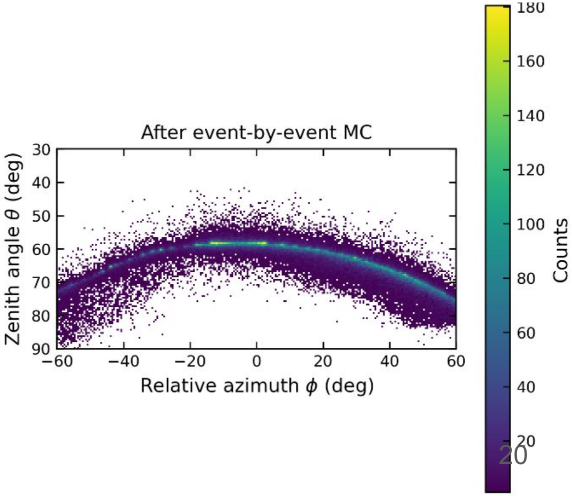
Sidelnik, I.,& LAGO Collaboration. (2023). **The capability of water Cherenkov detectors arrays of the LAGO project to detect Gamma-Ray Burst and high energy astrophysics sources.** *Nuclear Instruments and Methods in Physics Research*


After event-by-event MC
Zenith angle θ (deg)
60
70
80
90
Relative azimuth ϕ (deg)
−60
−40
−20
0
20
40
60
Counts
50
40
30
20
10

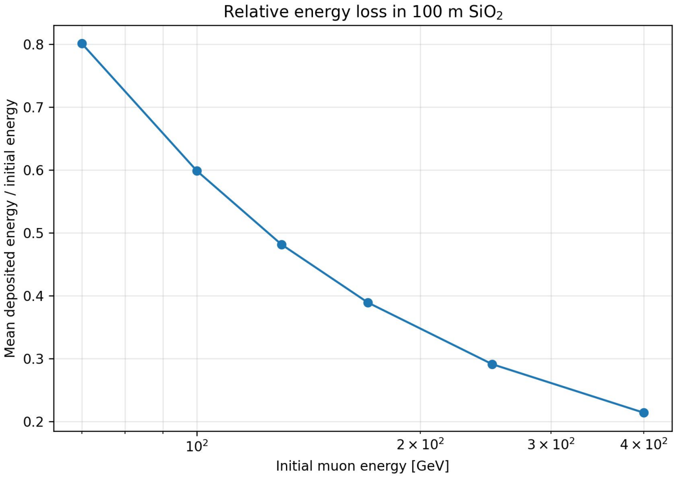

After event-by-event MC
Zenith angle θ (deg)
60
70
80
90
Relative azimuth ϕ (deg)
−60
−40
−20
0
20
40
60
Counts
35
30
25
20
15
10
5

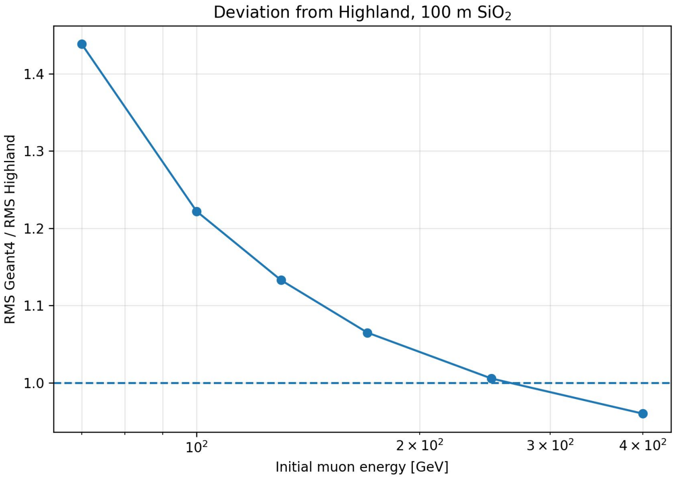

P1
P2
P4
P5
Cima
Latitude
4.500
4.495
4.490
4.485
4.480
4.475
4.470
Longitude
−75.400
−75.395
−75.390
−75.385
−75.380
−75.375
Elevation (m a.s.l.)
2600
2400
2200
2000
1800

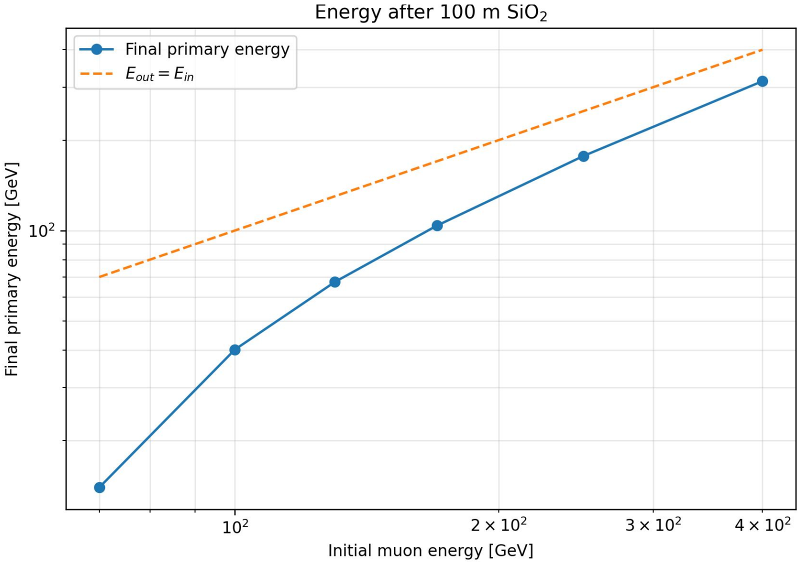

After event-by-event MC
Zenith angle θ (deg)
60
70
80
90
Relative azimuth ϕ (deg)
−60
−40
−20
0
20
40
60
Counts
45
40
35
30
25
20
15
10
5

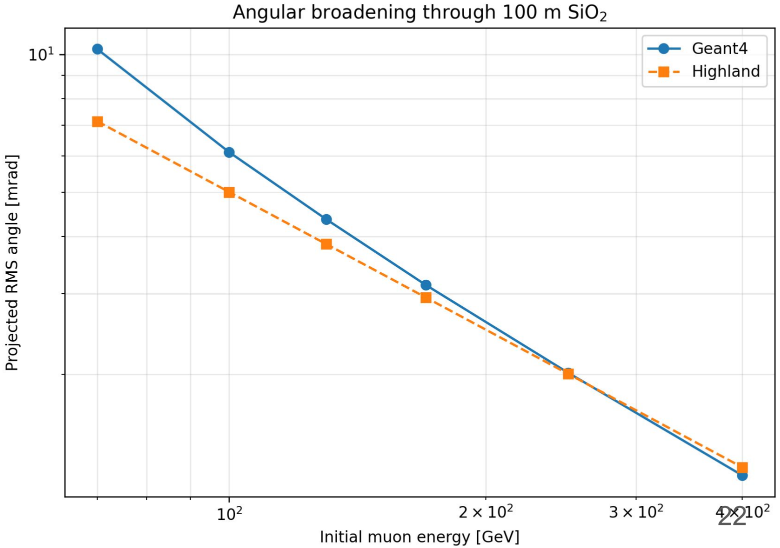

After event-by-event MC
Zenith angle θ (deg)
30
40
50
60
70
80
90
Relative azimuth ϕ (deg)
−60
−40
−20
0
20
40
60
Counts
180
160
140
120
100
80
60
40
20

Geant4 Simulation

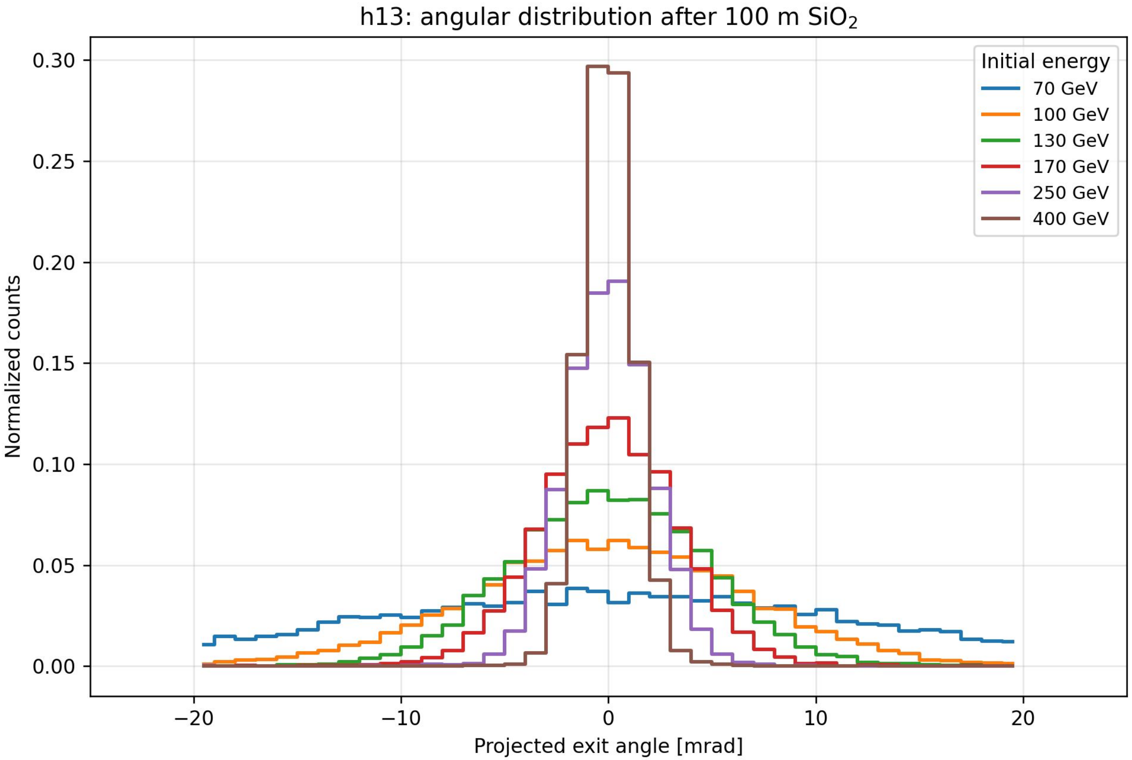

Relative energy loss in 100 m SiO_2
Mean deposited energy / initial energy
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10^2
2×10^2
3×10^2
4×10^2
Initial muon energy [GeV]

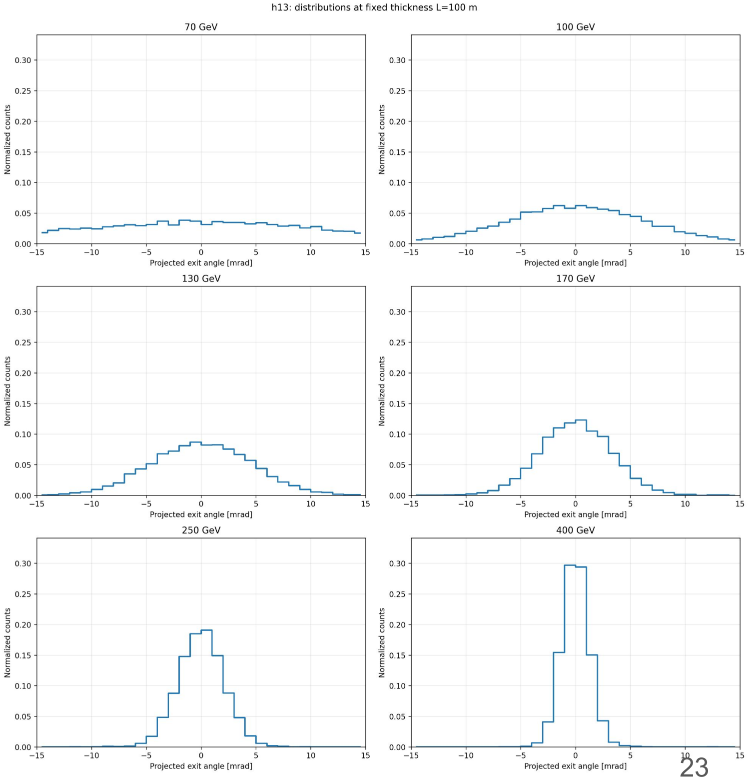

Deviation from Highland, 100 m SiO_2
RMS Geant4 / RMS Highland
1.4
1.3
1.2
1.1
1.0
10^2
2×10^2
3×10^2
4×10^2
Initial muon energy [GeV]

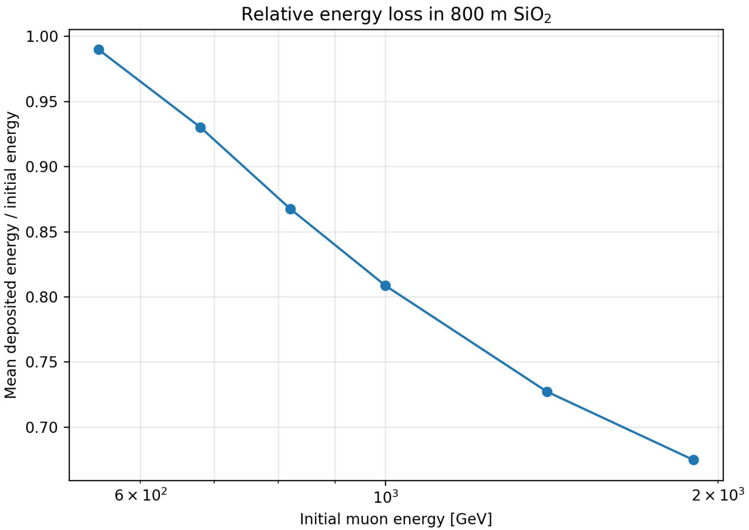

Energy after 100 m SiO_2
Final primary energy
$E_{out} = E_{in}$
Final primary energy [GeV]
10^2
10^2
2×10^2
3×10^2
4×10^2
Initial muon energy [GeV]

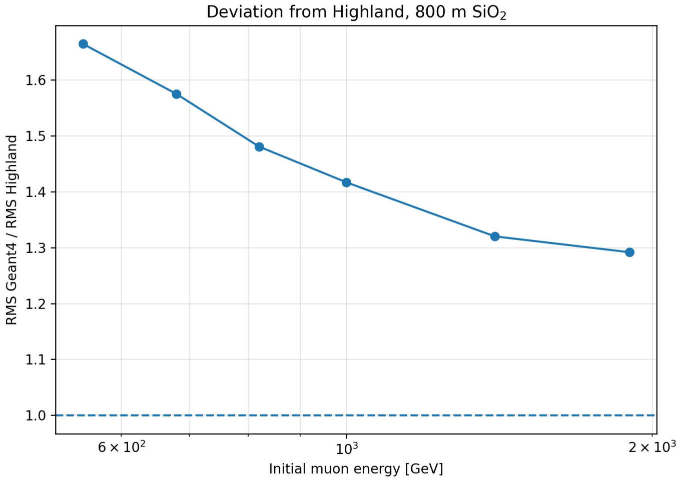

Angular broadening through 100 m SiO_2
Geant4
Highland
Projected RMS angle [mrad]
10^1
10^2
2×10^2
3×10^2
4×10^2
Initial muon energy [GeV]

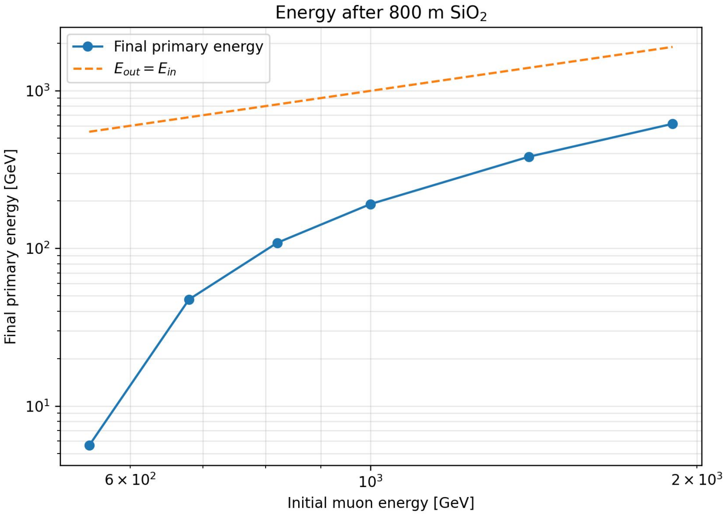
Exit-angle distribution

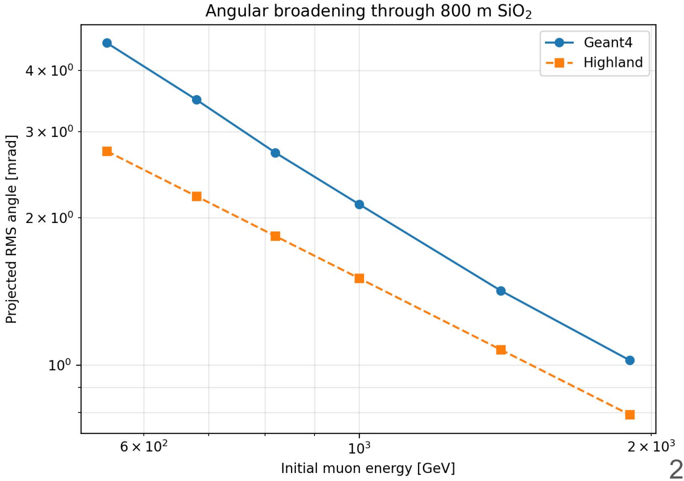





Relative energy loss in 800 m SiO_2
Mean deposited energy / initial energy
1.00
0.95
0.90
0.85
0.80
0.75
0.70
6×10^2
10^3
2×10^3
Initial muon energy [GeV]


Deviation from Highland, 800 m SiO_2
RMS Geant4 / RMS Highland
1.6
1.5
1.4
1.3
1.2
1.1
1.0
6×10^2
10^3
2×10^3
Initial muon energy [GeV]


Energy after 800 m SiO_2
Final primary energy
$E_{out} = E_{in}$
Final primary energy [GeV]
10^3
10^2
10^1
6×10^2
10^3
2×10^3
Initial muon energy [GeV]


Angular broadening through 800 m SiO_2
Geant4
Highland
Projected RMS angle [mrad]
4×10^0
3×10^0
2×10^0
10^0
6×10^2
10^3
2×10^3
Initial muon energy [GeV]