Muography for the Colombian Volcanoes

R. de León-Barrios, J. Peña-Rodríguez, J.D. Sanabria-Gómez, A. Vásquez-Ramírez, R. Calderón-Ardila, C. Sarmiento-Cano, A. Vesga-Ramírez, D. Sierra-Porta, M. Suárez-Durán, H. Asorey and **L.A. Núñez**

Agenda of Colombian Muography

- Muography in a nutshell
- Preliminary ideas and prototypes
- Possible muography site for vulcanology
- Observation site at Cerro Machín
- The hybrid Muon Telescope: MuTe
- The MuTe digital twin
- MuTe electronics
- Particle discrimination
- First Muogram
- Simulated Annealing optimizing density distribution

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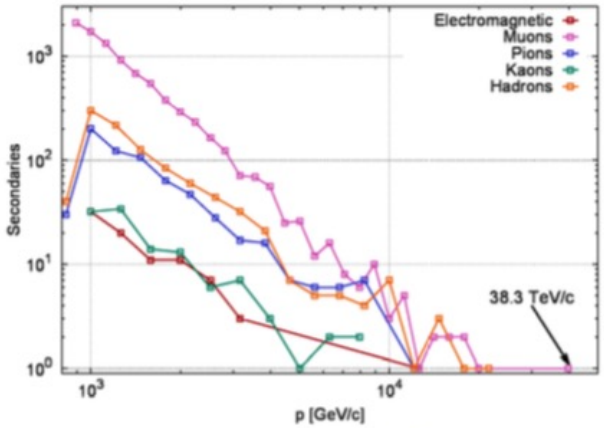
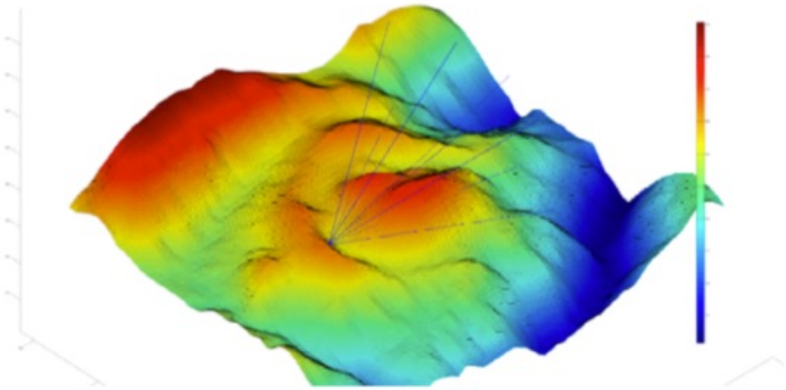
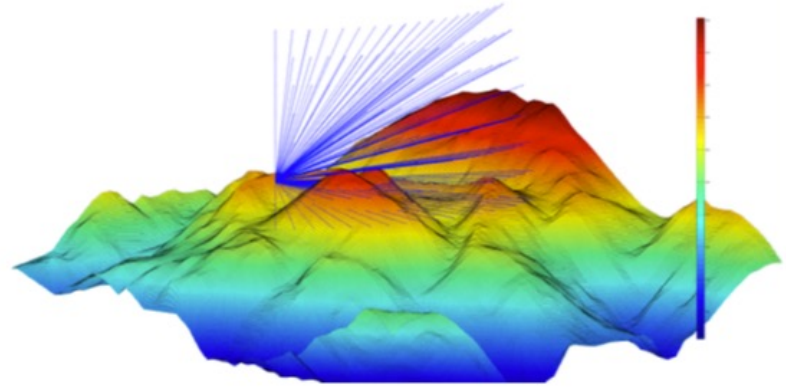
Volcanos Muongraphy







Muongraphy primer

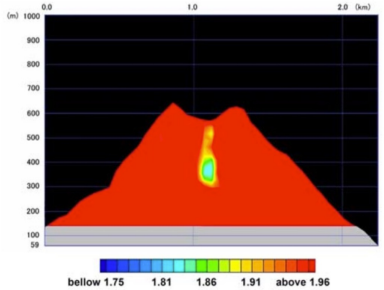
- Muons: Very low stopping power:

$$\left(\frac{dE_\mu}{dX_{\text{std rock}}}\right) \simeq 6\text{MeV cm}^{-1}$$

- High energy atmospheric muons can penetrate hundreds of meters of rock
- From the known atmospheric muon flux and measured directional flux across the volcano → rock opacity
- From rock opacity and volcano and detector geometry → internal density profile
- Internal density profile → deep volcanic structures

Volcanoes Muongraphy

Tanaka et al., Nature Comms 5 (2014) and refs



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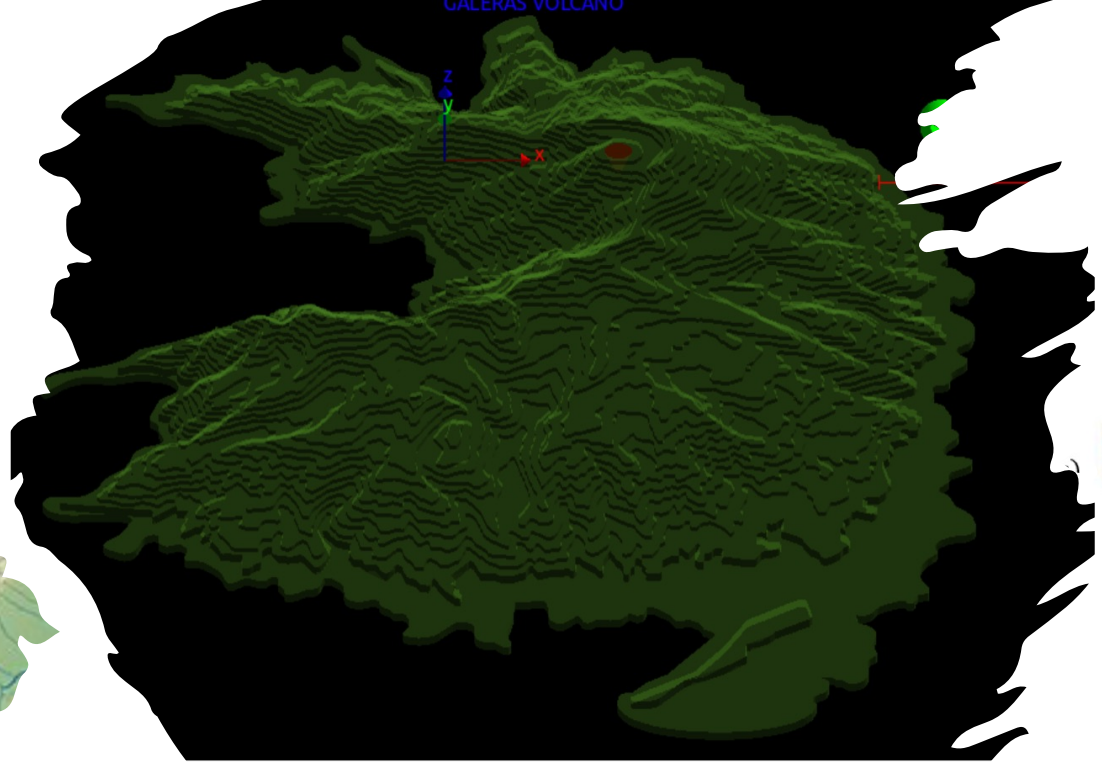

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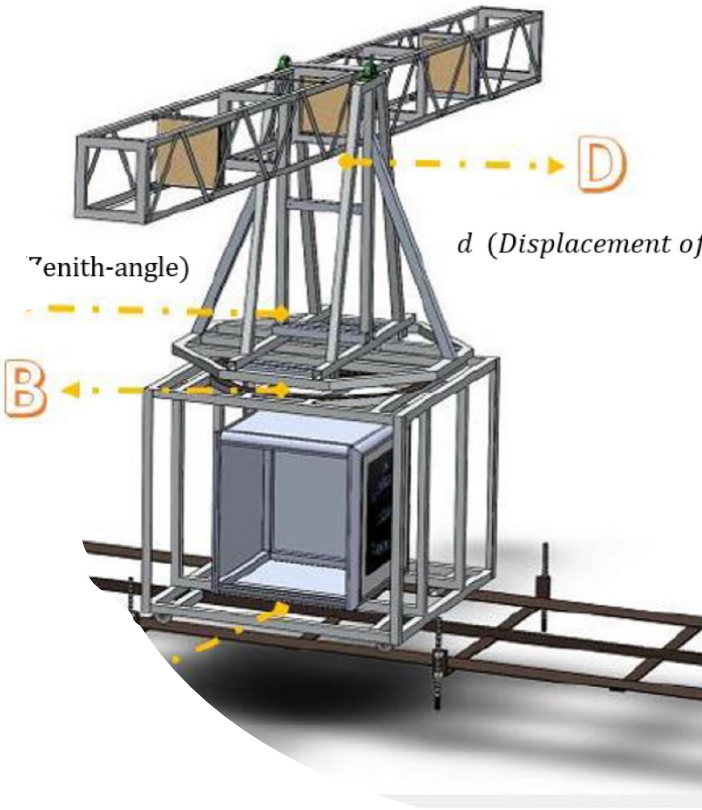
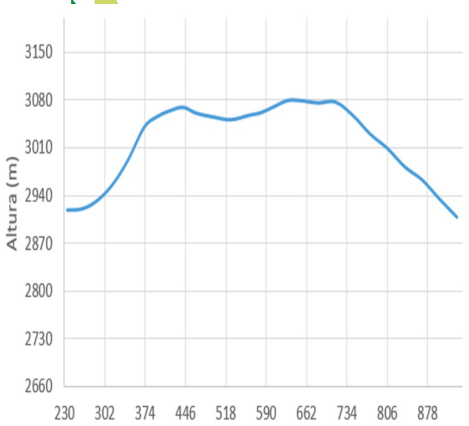
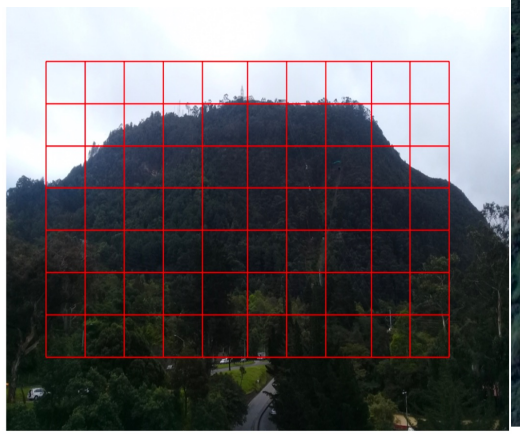


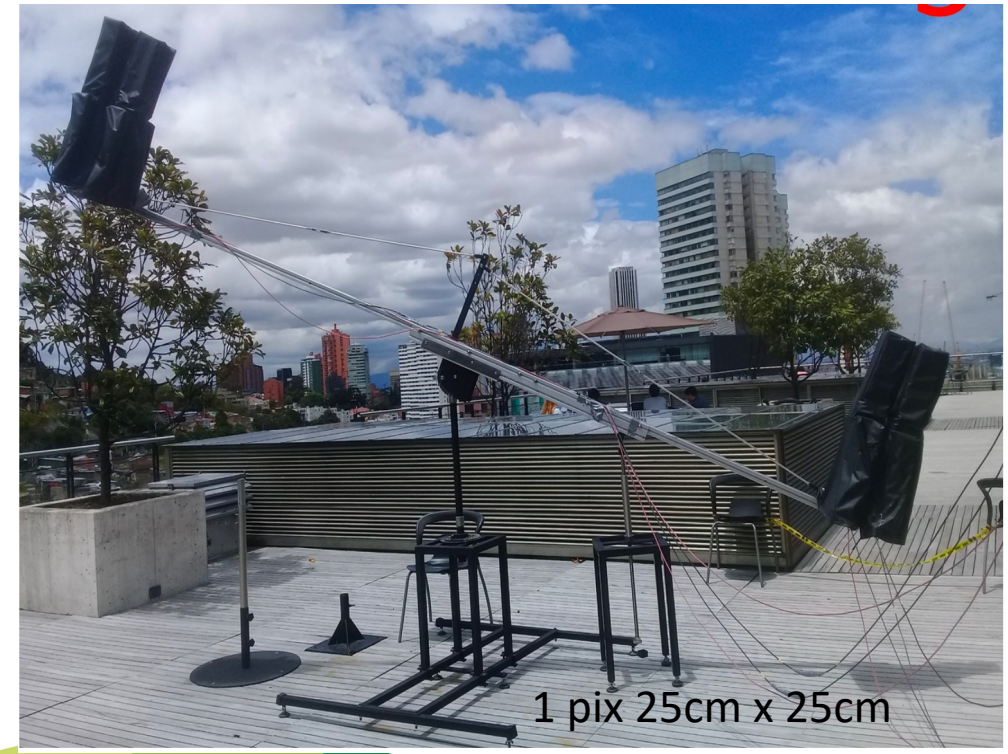
Preliminary ideas of Colombian Muography

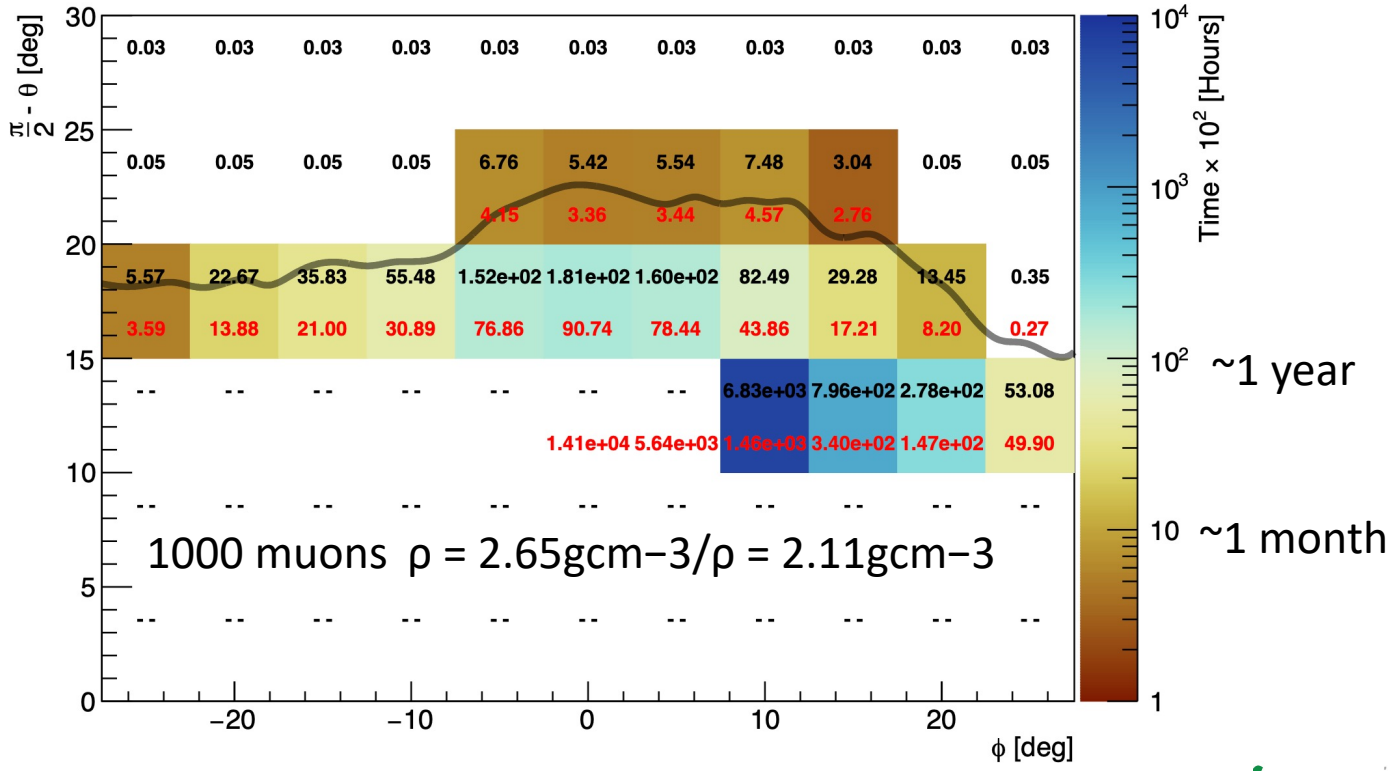
- **Guerrero, I. D., et al (2019).** Design and construction of a muon detector prototype for study the galeras volcano internal structure. In *Journal of Physics: Conference Series* (Vol. 1247, No. 1, p. 012020).

Preliminary hodoscope prototype



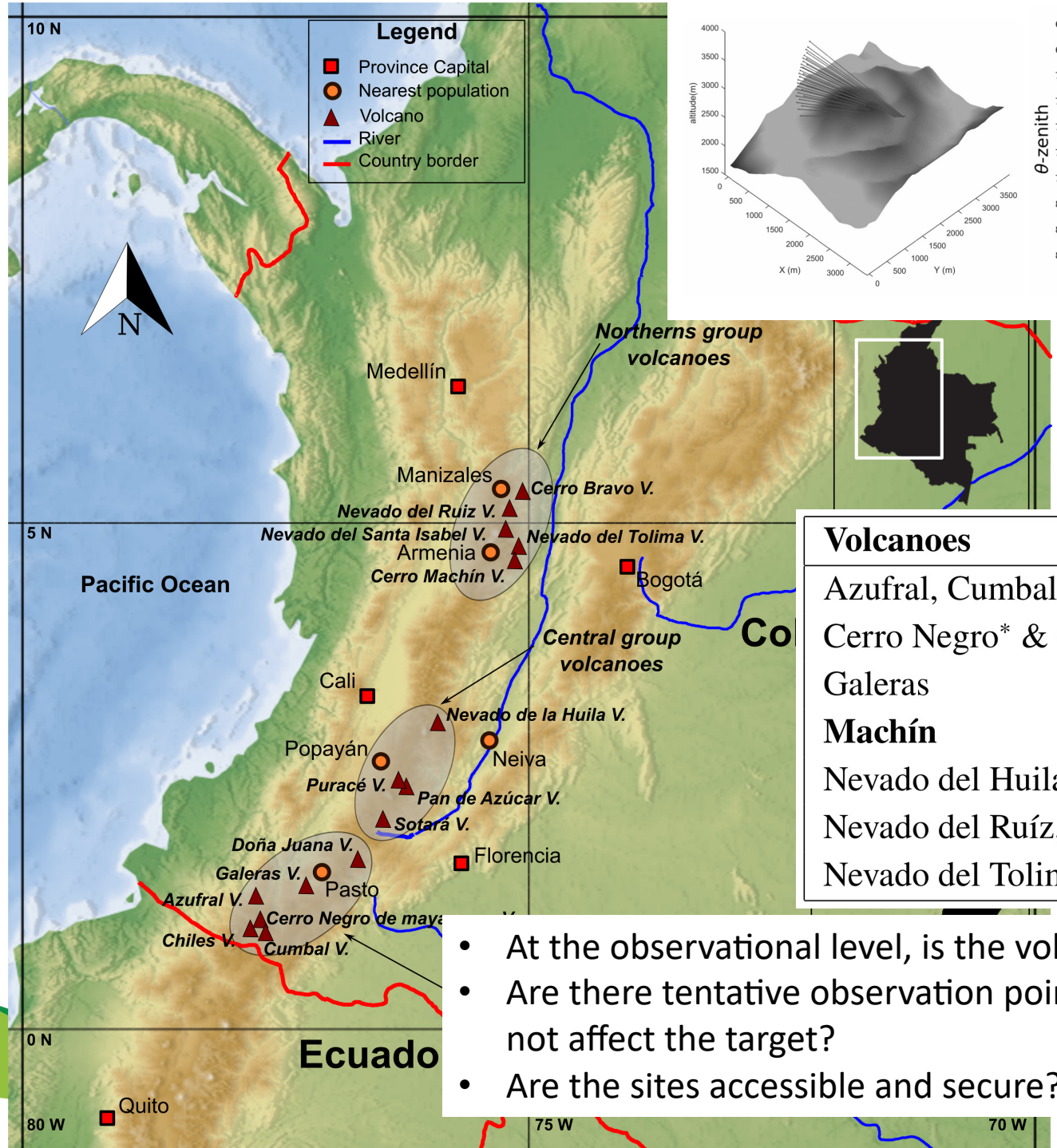


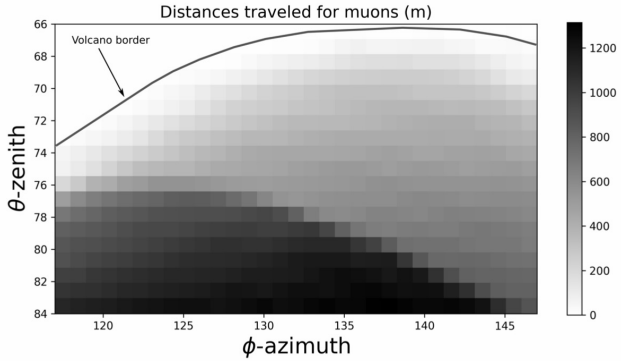




Useche-Parra, J. *et al* (2019). Estimation of cosmic-muon flux attenuation by Monserrate Hill in Bogota. *JINST*, *14*(02), P02015.

Vesga-Ramírez, A. *et al* (2020). Muon Tomography sites for Colombian volcanoes. *Annals of Geophysics*, *63*(6), 661.





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13 volcanoes analyzed
Only Cerro Machín complies

Volcanoes	Q 1	Q 2	Q 3
Azufral, Cumbal, Dona Juana & Sotará	N	Y	N
Cerro Negro* & Chiles*	Y	Y	N
Galeras	Y	N	Y
Machín	**Y**	**Y**	**Y**
Nevado del Huila	N	Y	N
Nevado del Ruíz, Nevado Santa Isabel & Puracé	N	Y	Y
Nevado del Tolima	N	N	Y

- At the observational level, is the volcano base width less than 1,500 m?
- Are there tentative observation points where the surrounding topography does not affect the target?
- Are the sites accessible and secure?

Cerro Machín is one of the most dangerous active volcanoes in Colombia

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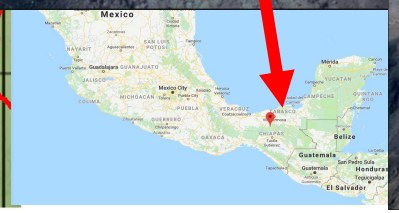
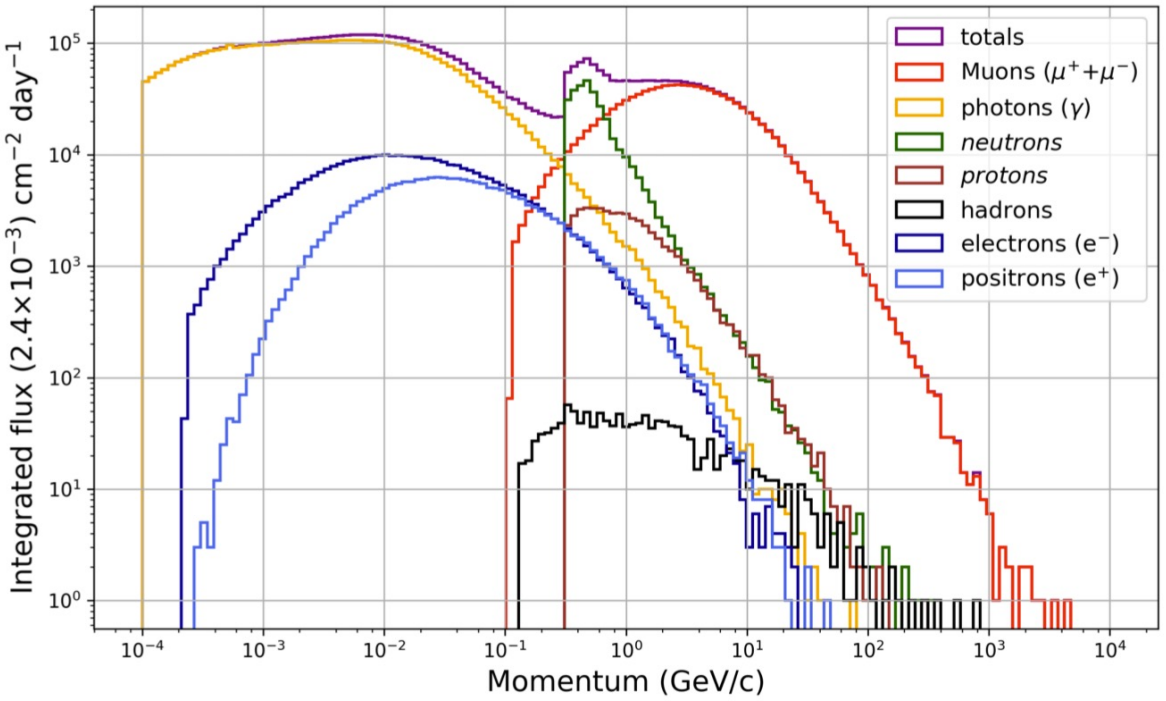
Colombian Volcanoes

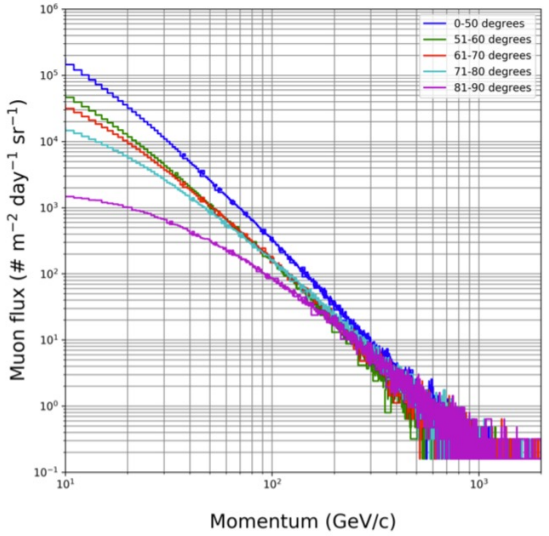
Cerro Machin Volcano

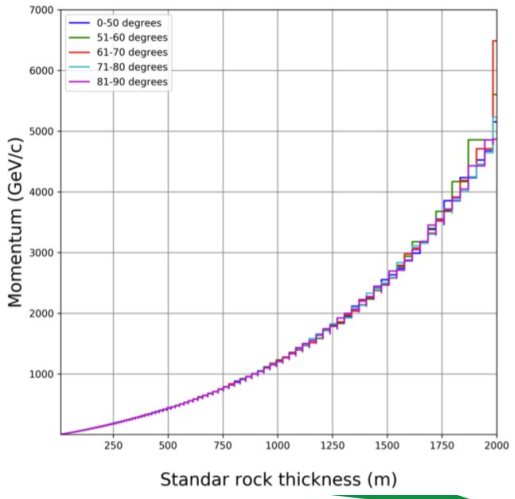


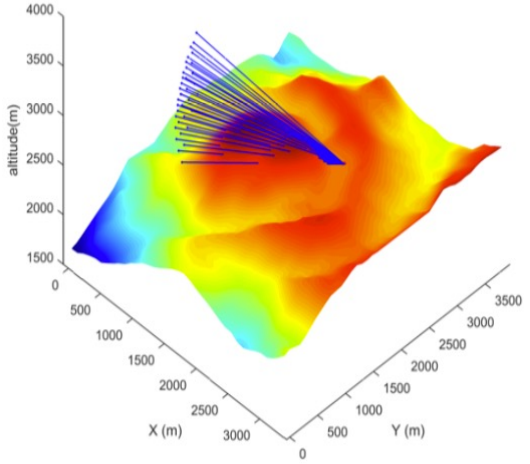
Chichonal or Chichón (Mx) The most deadly eruption of the century (1982)

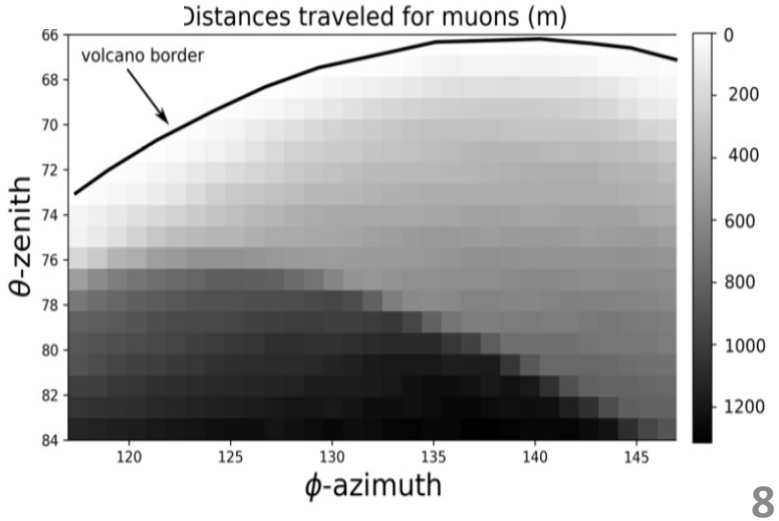
Particle/Muon flux at Cerro Machín











Ray tracing in muon trajectories

Sarmiento-Cano, C., et al (2020). Performance of the LAGO water Cherenkov detectors to cosmic ray flux. *arXiv preprint arXiv:2010.14591*.

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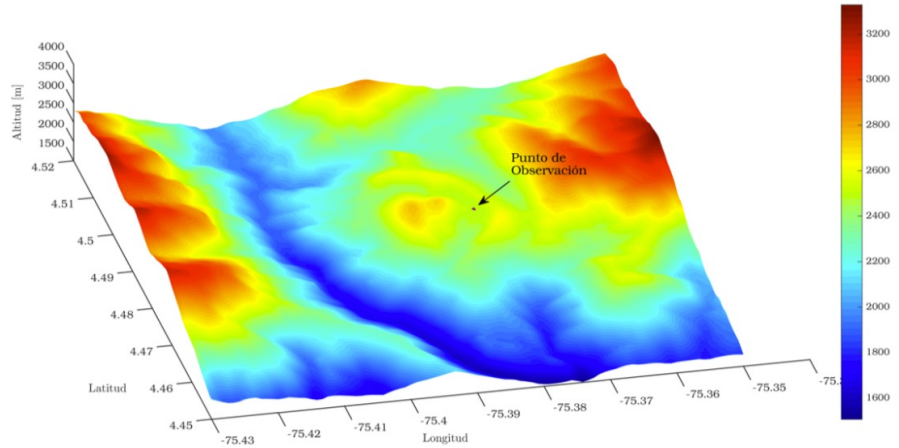
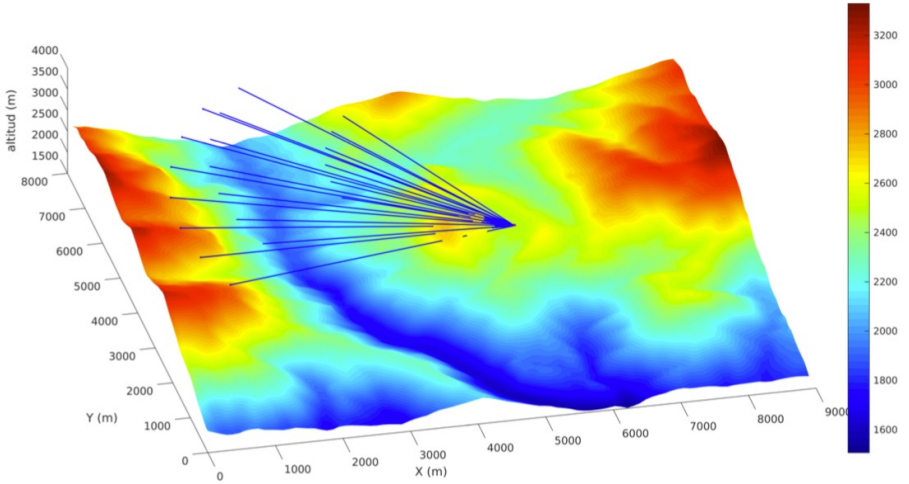
Observation points at Cerro Machín

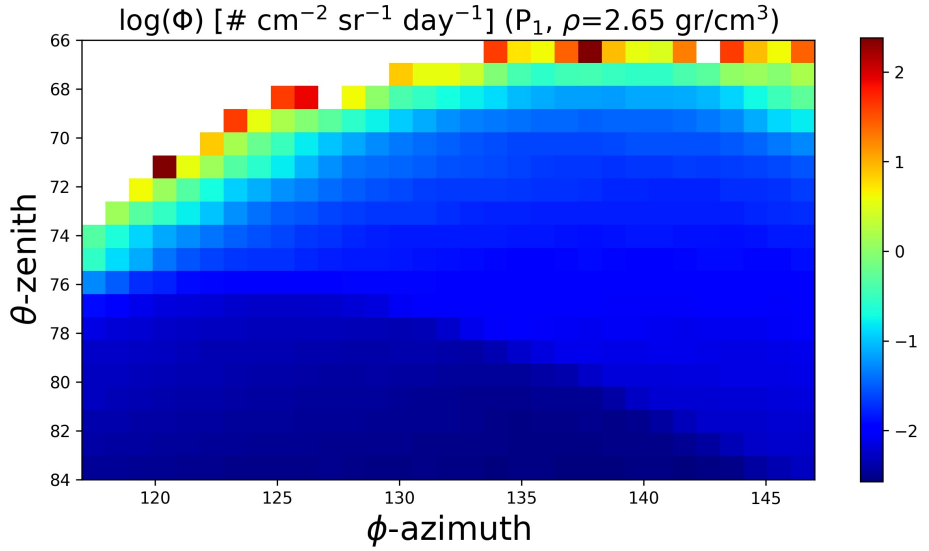


Cerro Machín points	P_1	P_2	P_3	P_4
Latitude (°N)	4.492	4.491	4.493	4.494
Longitude (°W)	75.381	75.380	75.392	75.388
Distance to center of the edifice (m)	836	946	762	730
Maximum observed depth (m)	208	228	250	190

Table 2: Feasible observation points at Cerro Machín volcano (4°29'23.08"N, 75°23'15.39"W) complying with the "thumb criteria" described in section 5.2. The maximum observed depth are those points where the emerging muon flux is less than 10^{-2} muons per cm^2 per day, corresponding to zenith angles $\theta \approx 82°$.



Simulated flux at observation points



Vesga-Ramírez, A. *et al* (2020). Muon Tomography sites for Colombian volcanoes. *Annals of Geophysics*, *63*(6), 661.

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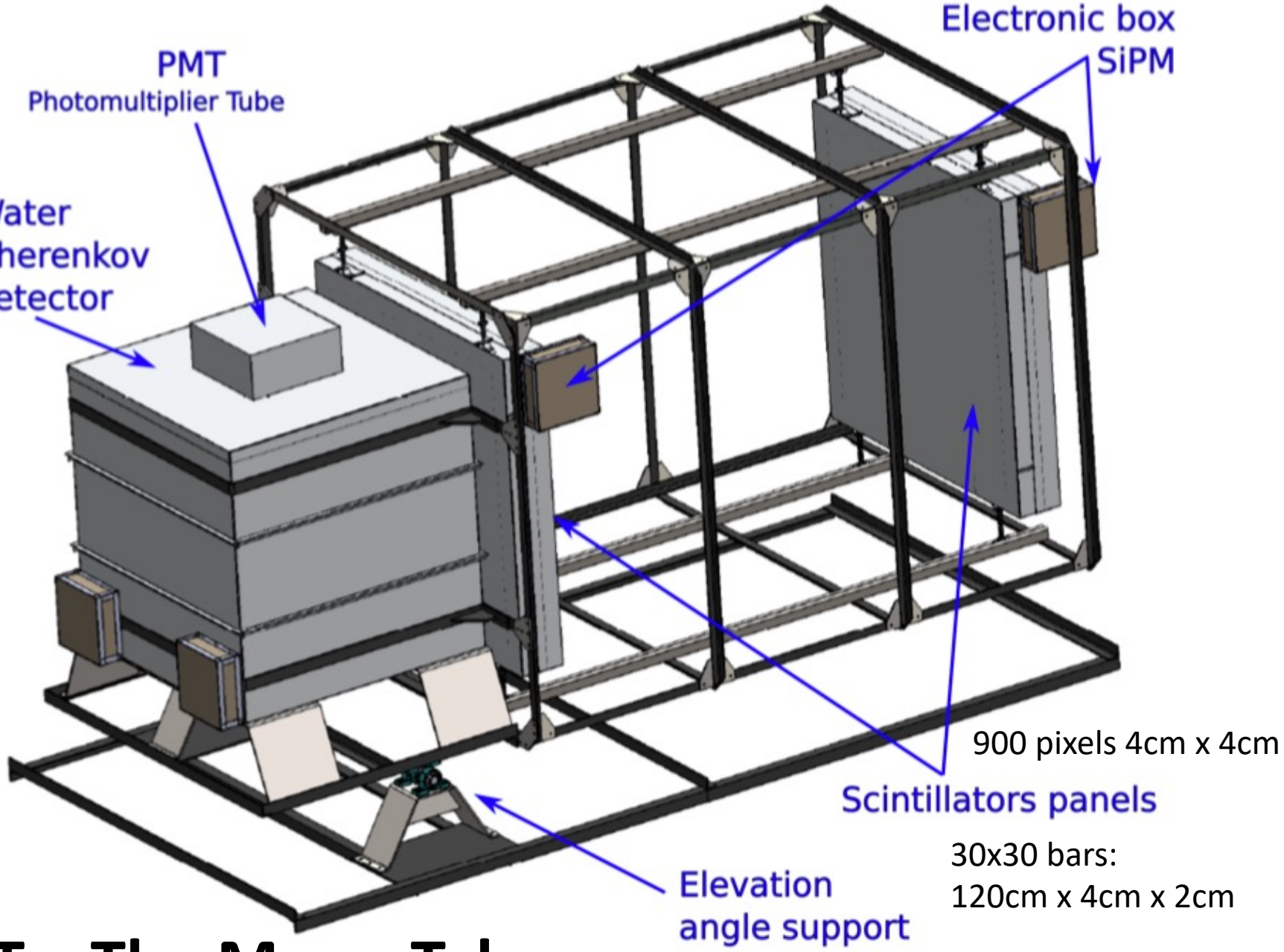
Peña-Rodríguez, J. et al (2020).
Design and construction of MuTe: a hybrid muon telescope to study colombian volcanoes. *JINST*, *15*(09), P09006.



MuTe: The Muon Telescope

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MuTe digital twin

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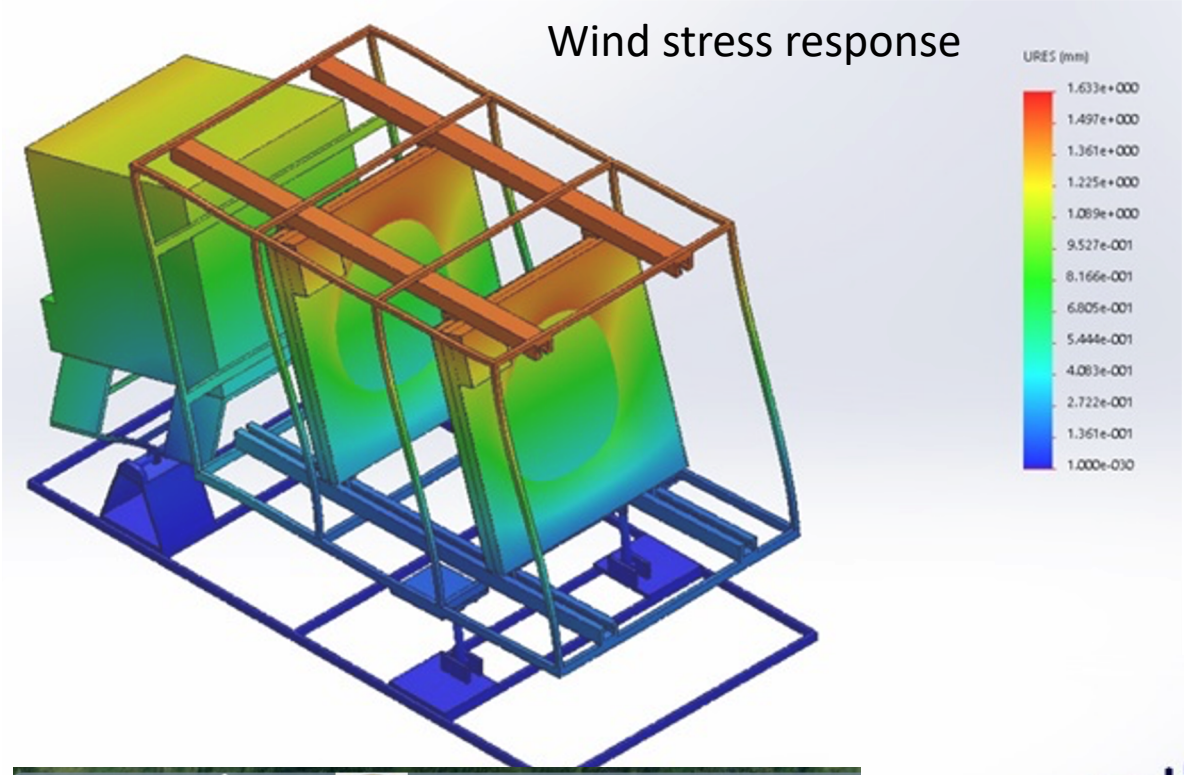
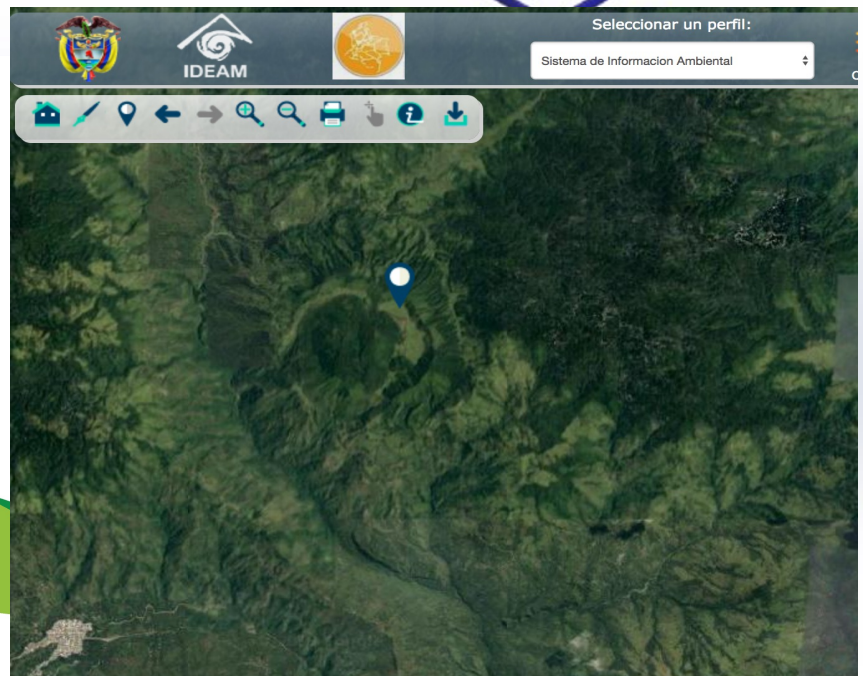
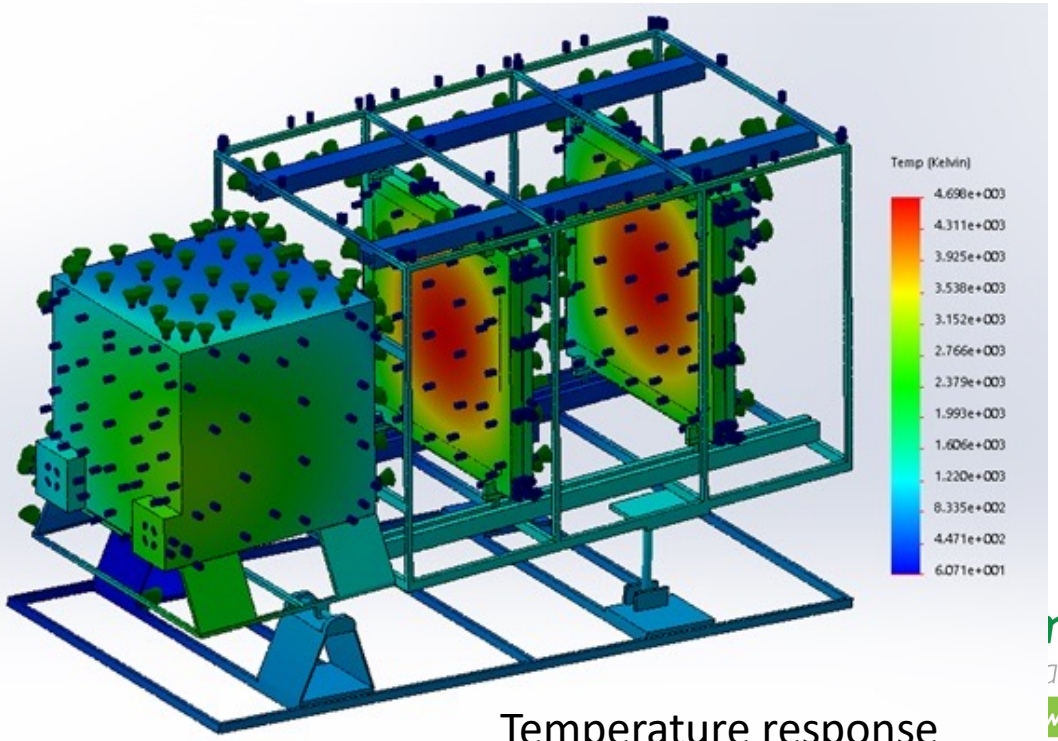
Peña-Rodríguez, J. et al (2020).
Design and construction of MuTe: a hybrid muon telescope to study colombian volcanoes. *JINST*, *15*(09), P09006.

Instrument response To climate variables

Wind stress response







Temperature response

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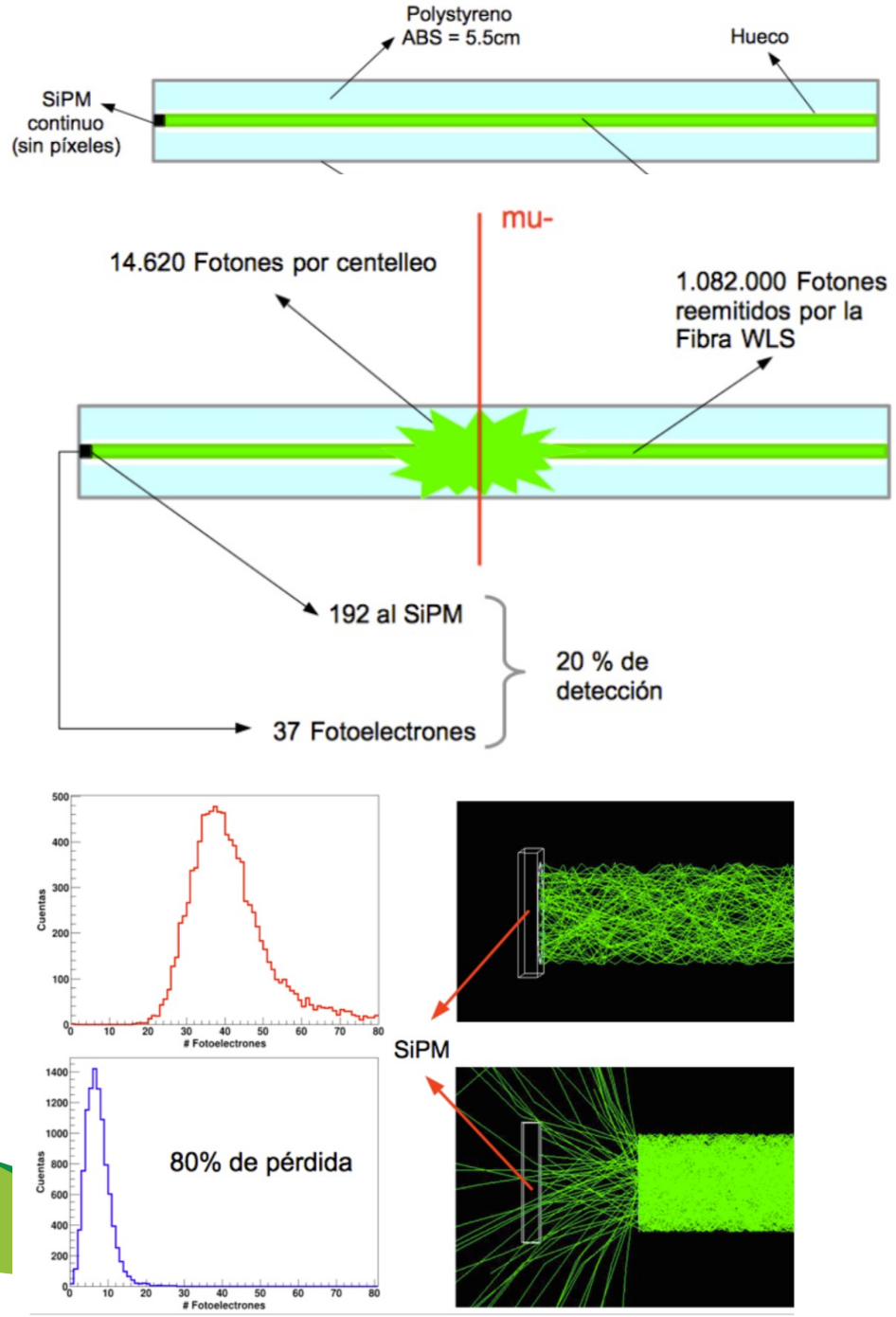
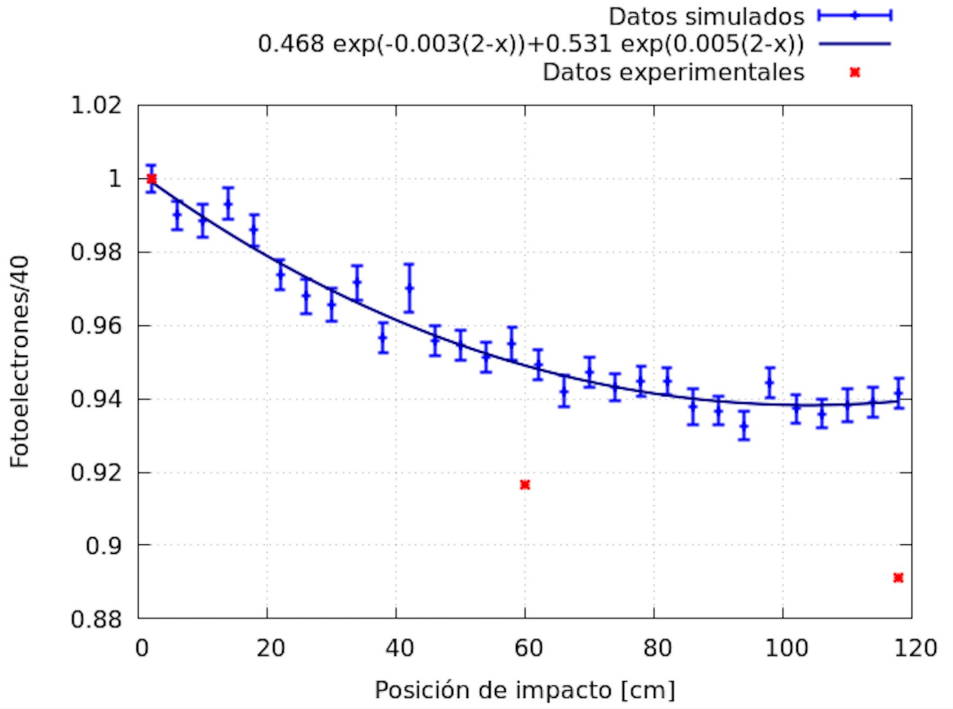
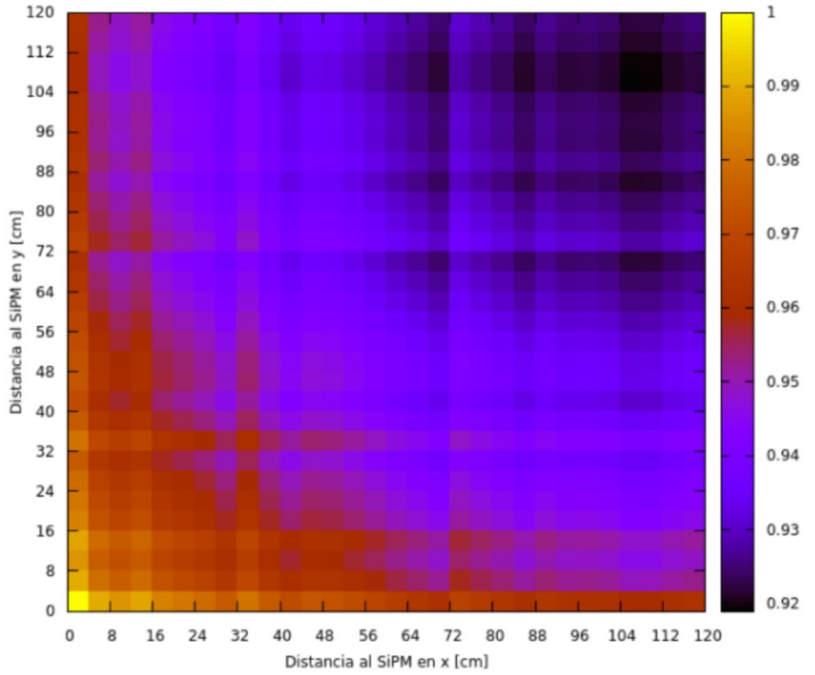
Vásquez-Ramírez, A., et al (2020). Simulated response of mute, a hybrid muon telescope. *JINST*, *15*(08), P08004.





Geant4 Simulations



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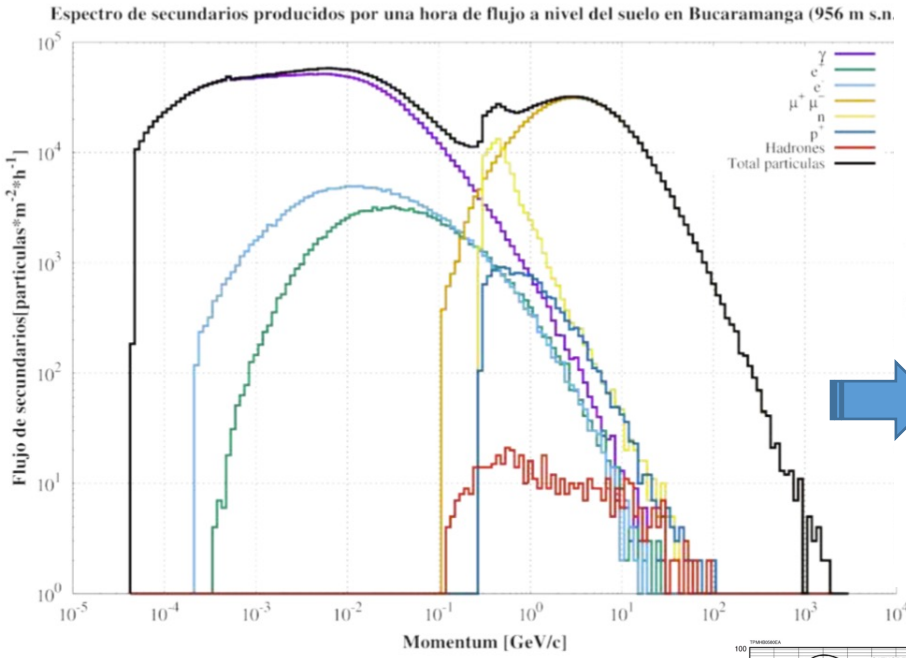
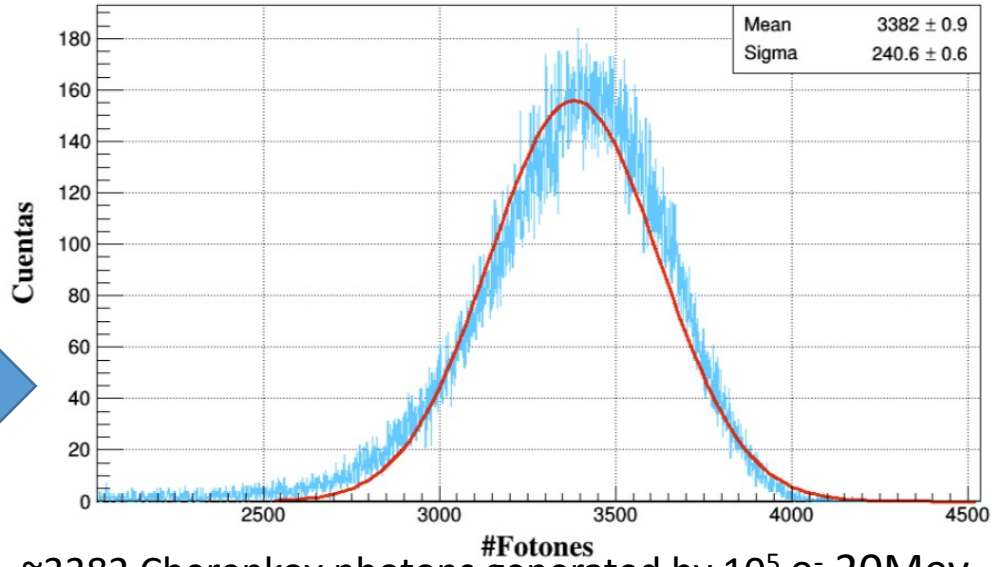
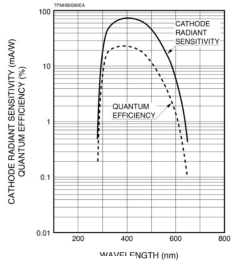
Vásquez-Ramírez, A., et al (2020). Simulated response of mute, a hybrid muon telescope. *JINST*, *15*(08), P08004.

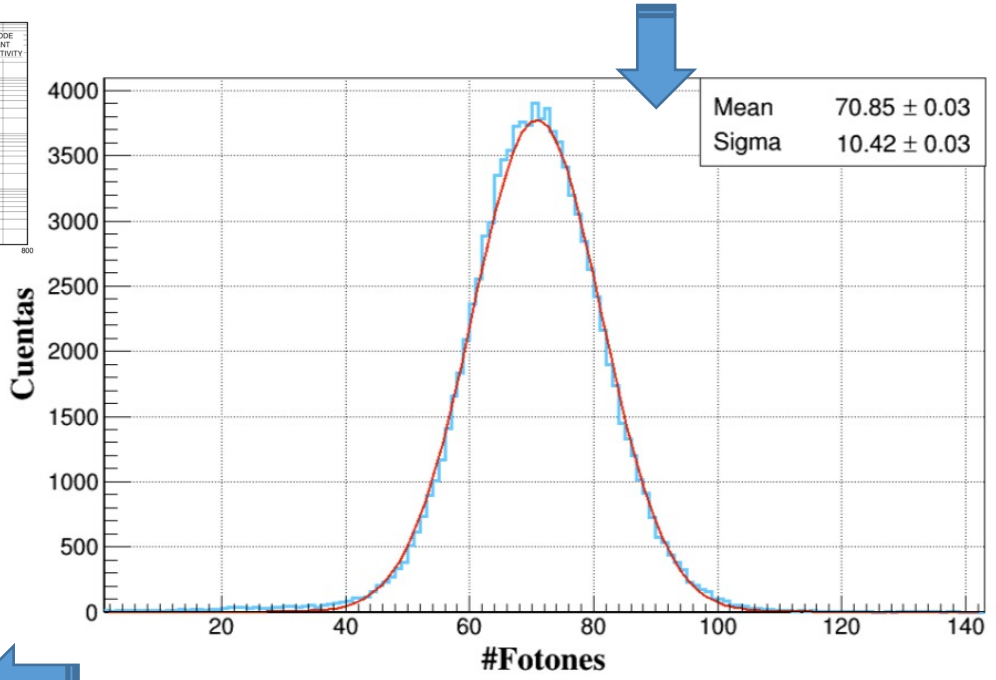




~3382 Cherenkov photons generated by 10^5 e^- 20Mev

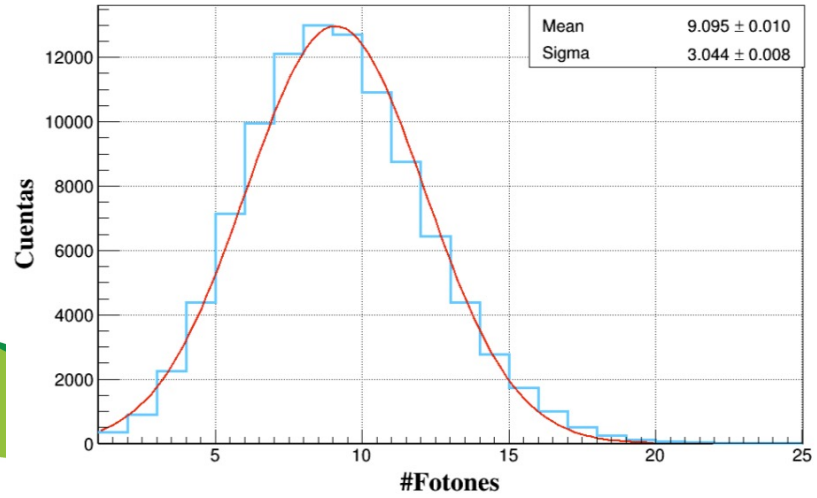
Simulations chain for the efficiency of WCD





~70 Cherenkov photons impacting PMT

~6 photo-electrons detected @PMT



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MuTe electronics

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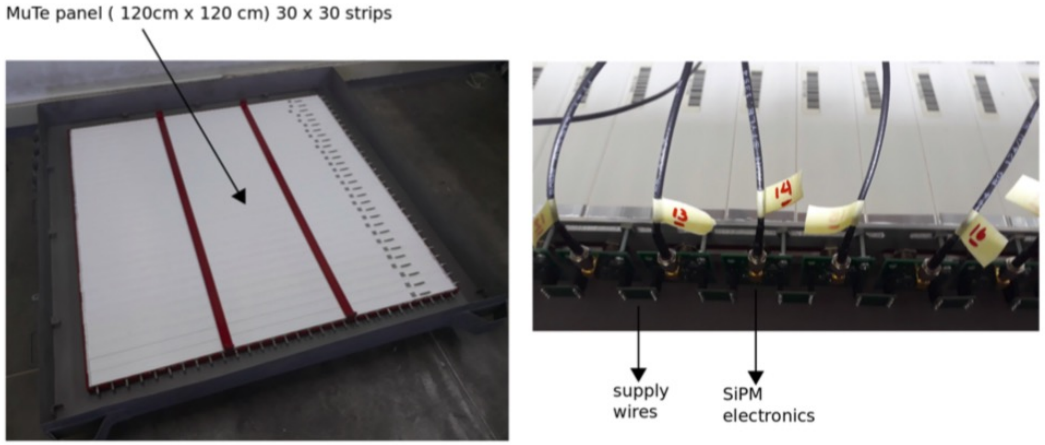

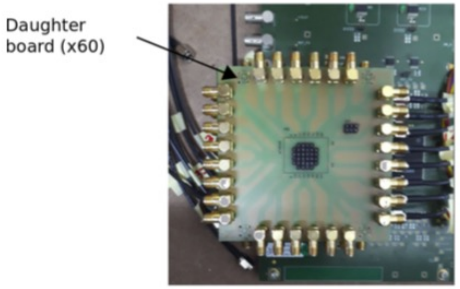

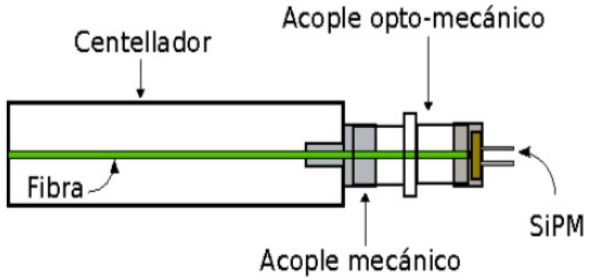

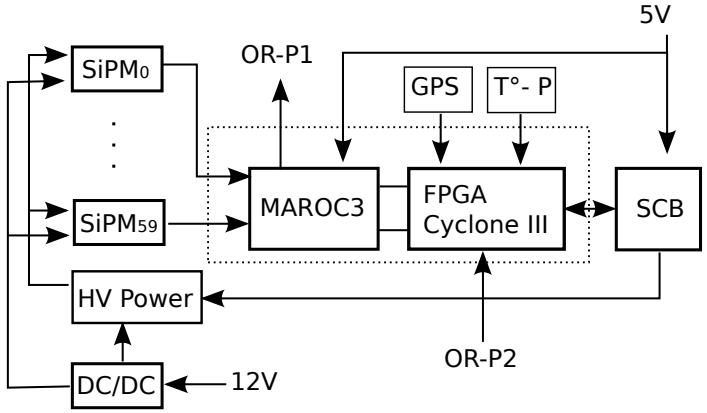

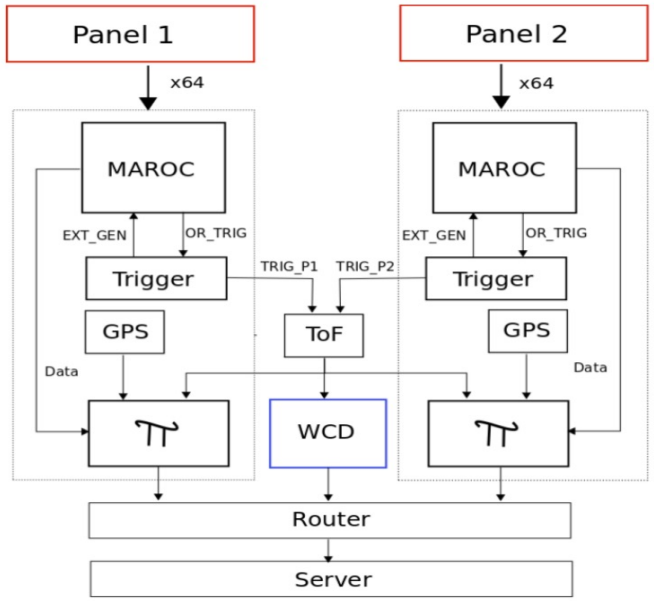

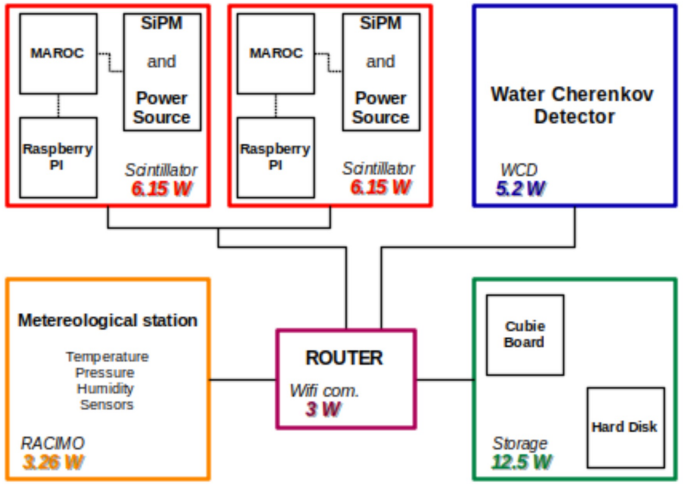

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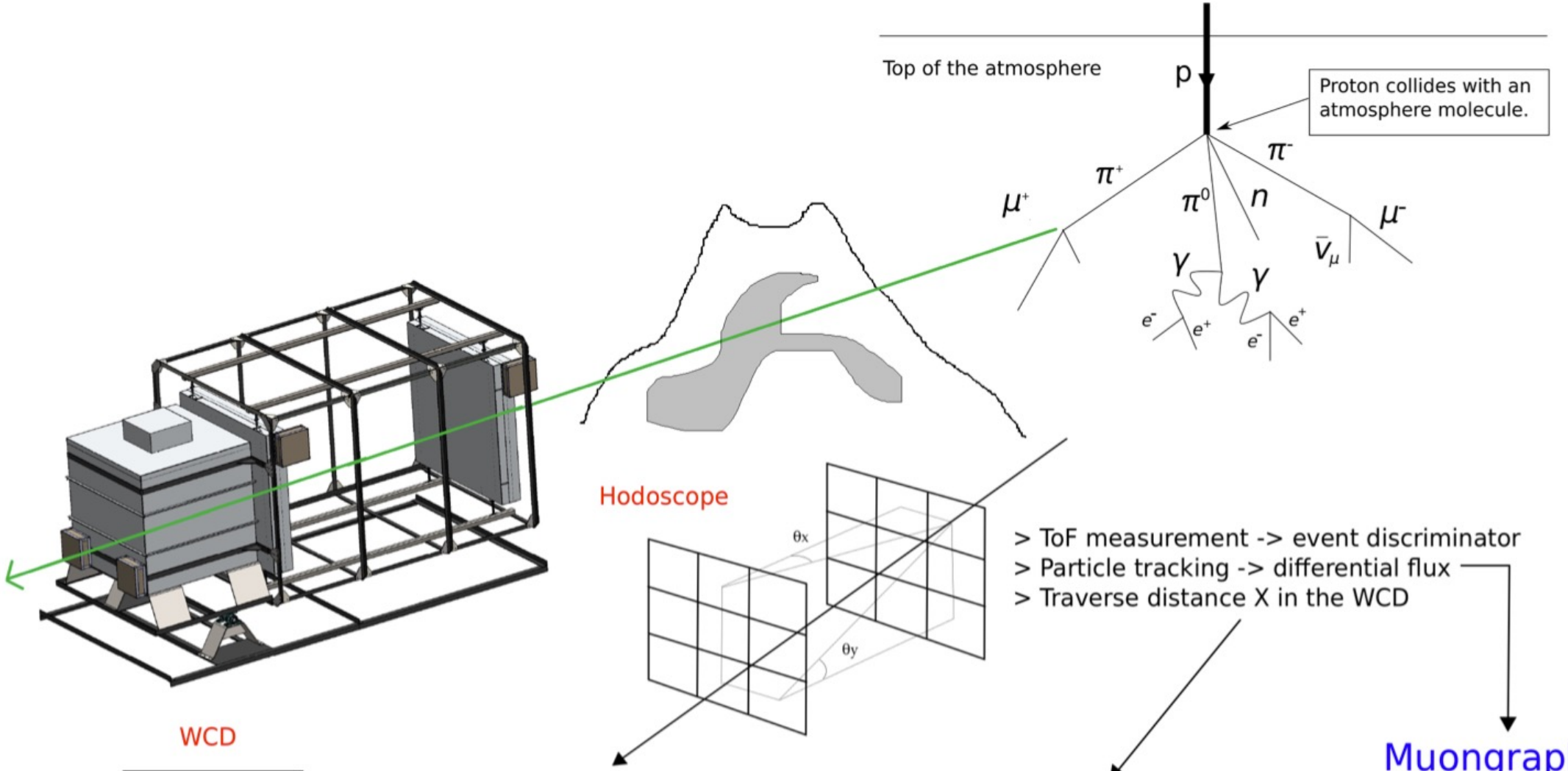

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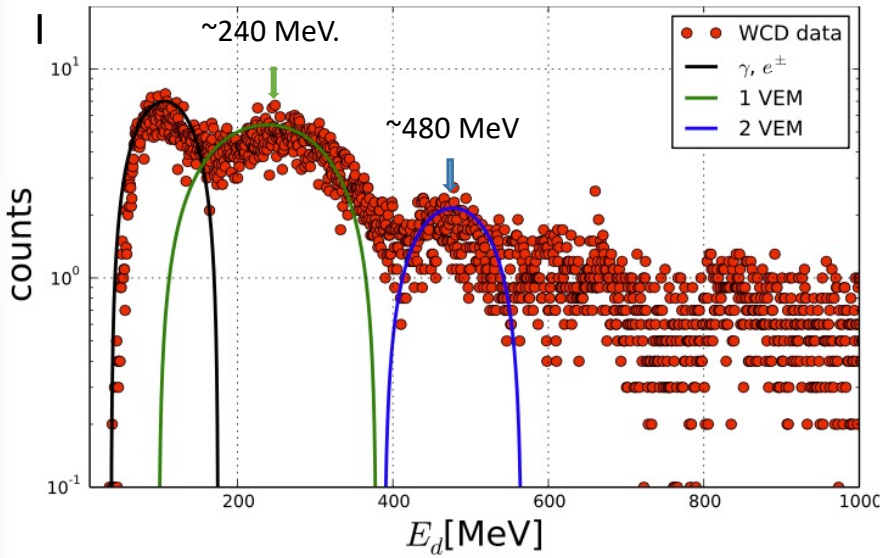

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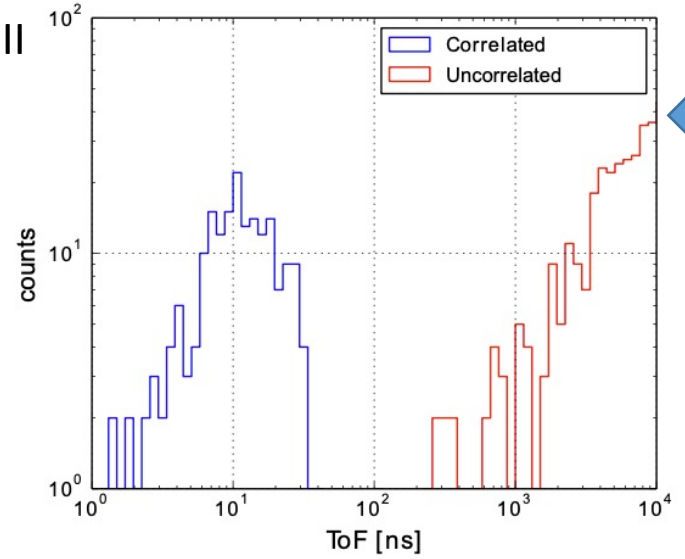

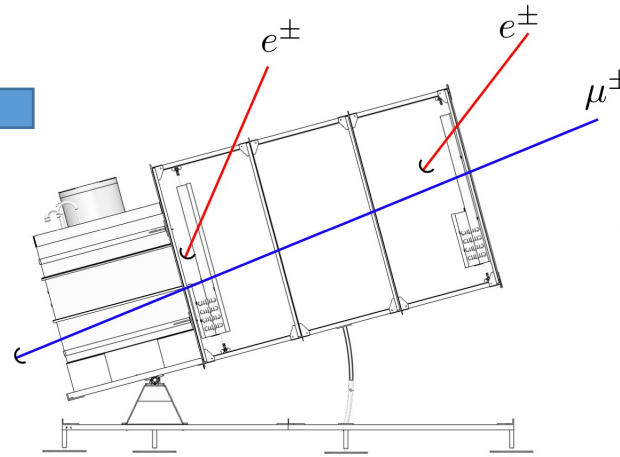

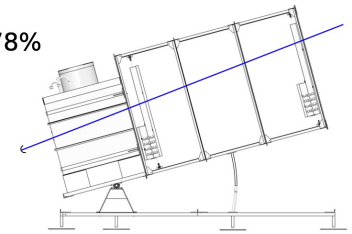

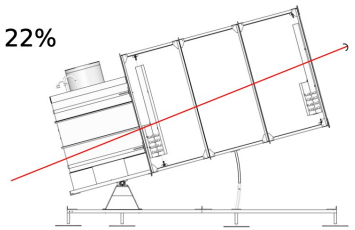

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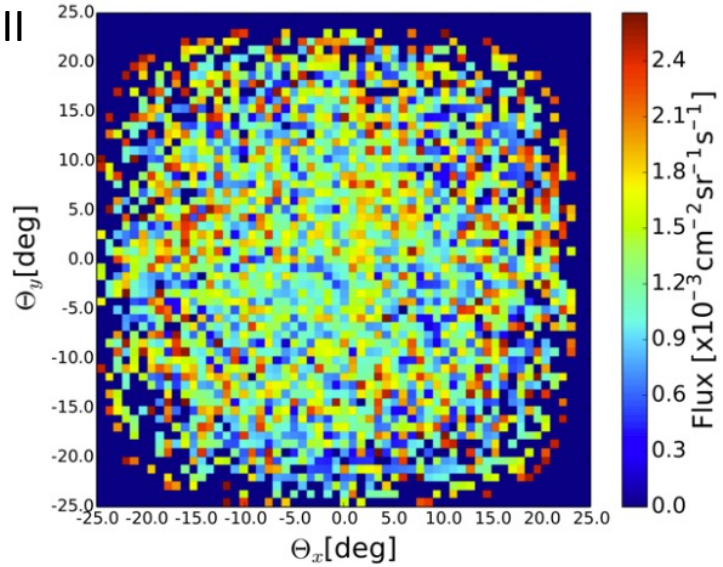
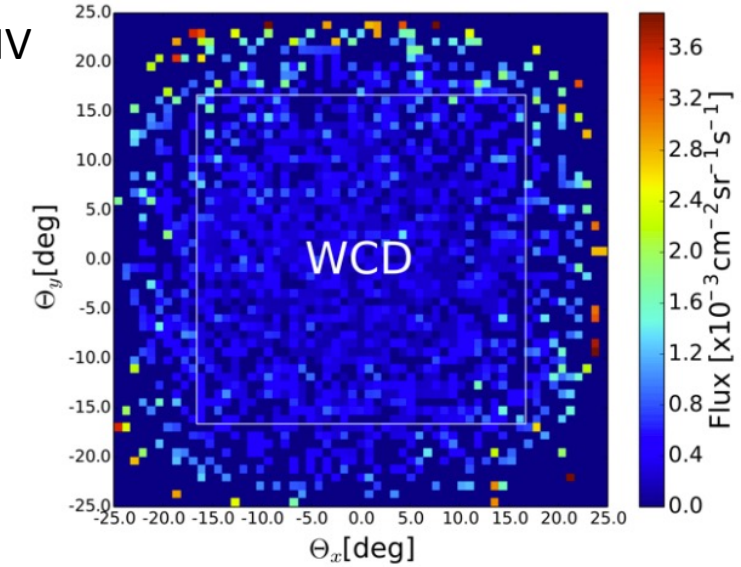


IV



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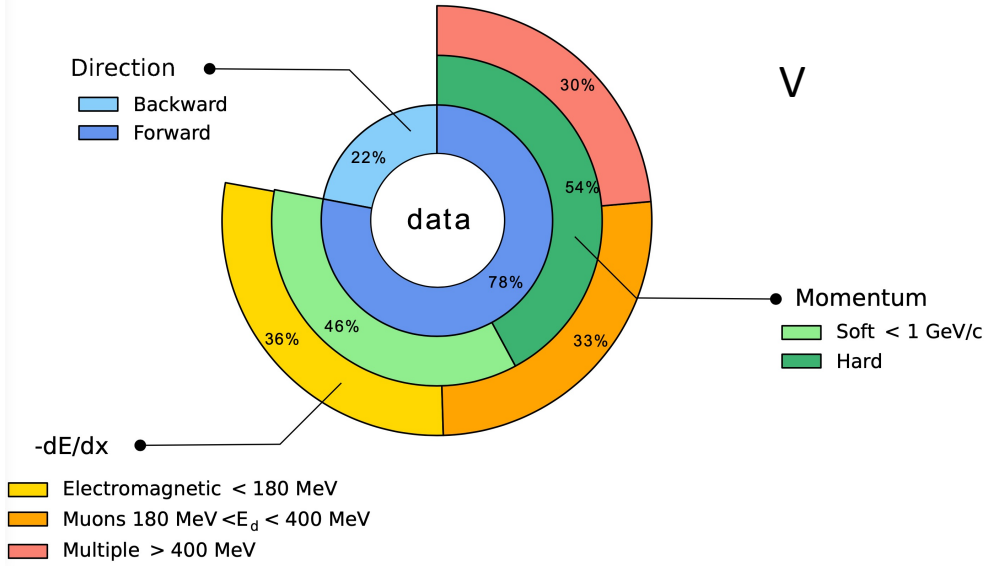
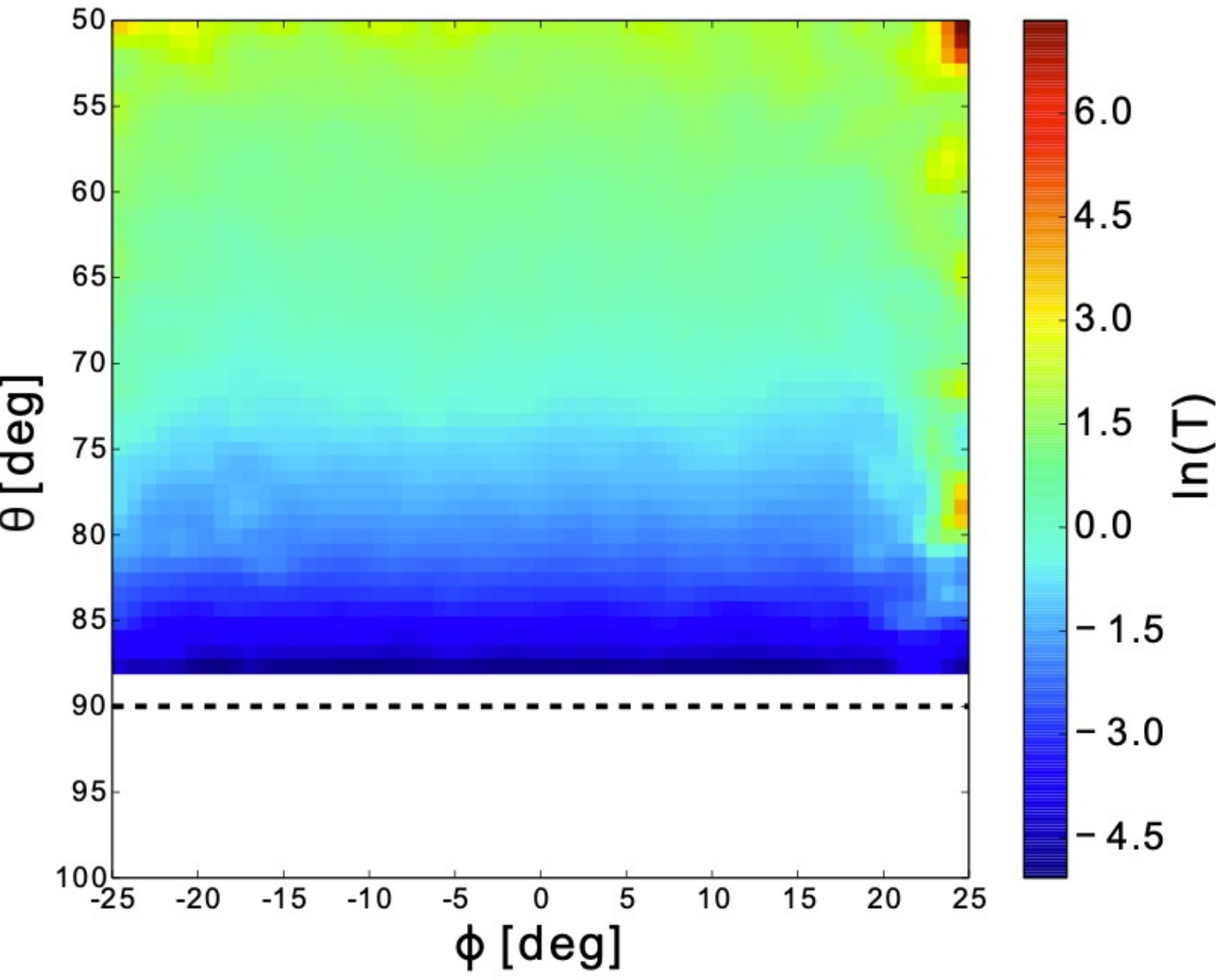
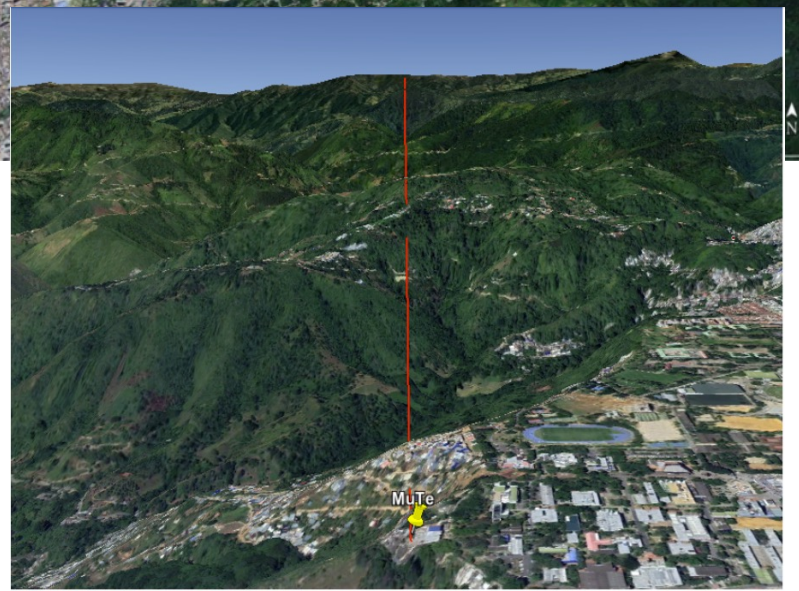


MuTe particle discrimination

MuTe first muography





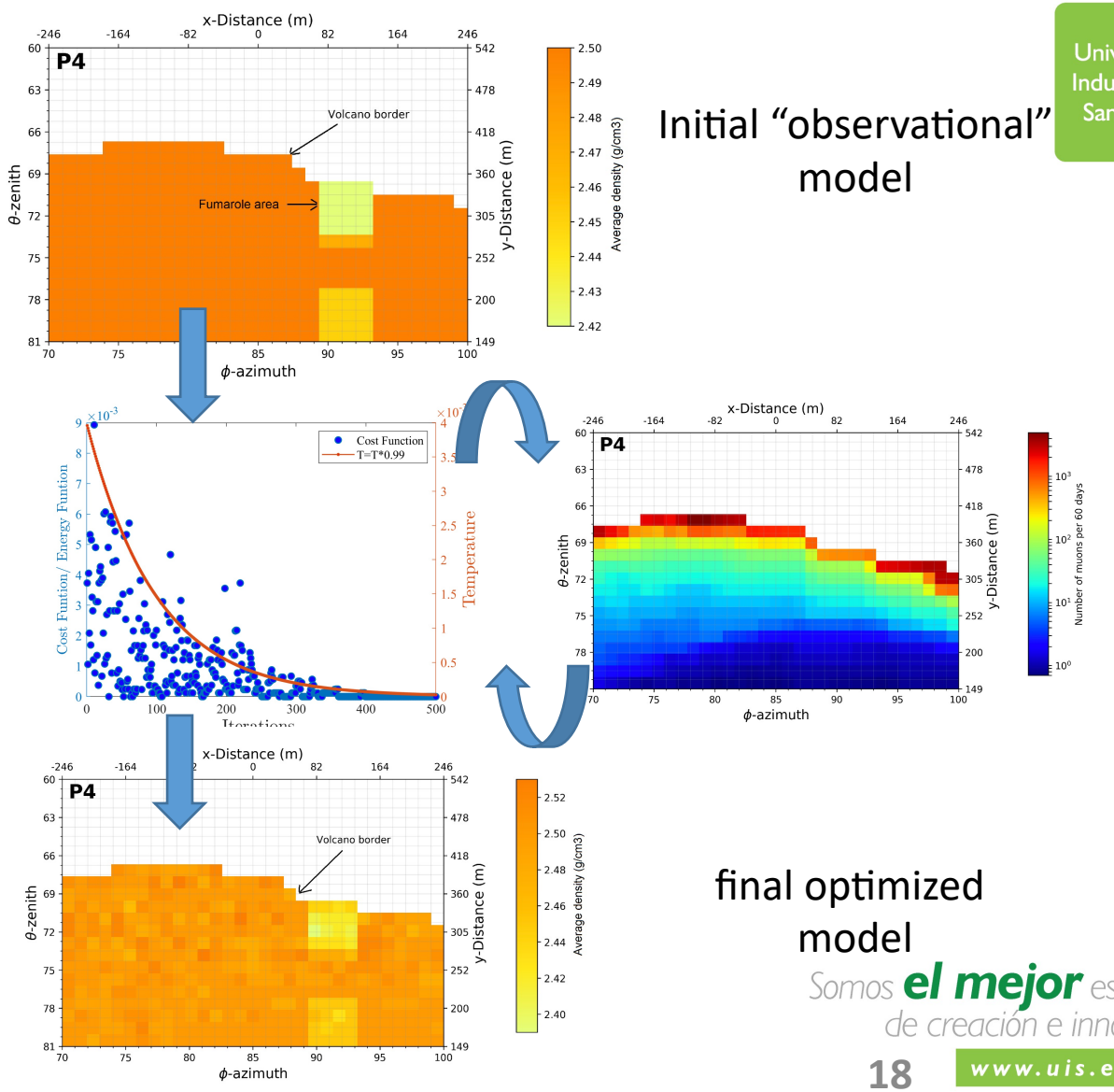
Optimization of density distribution

Table .4: **Inverse problem pseudo-code**

Input from forward modelling
N_{obs} number of observed muons

Begin
$T \leftarrow T_{initial}$; Set the initial evolution parameter T
$r \leftarrow RAM[0,1]$; Generate random number
$\bar{\rho}$; Select the initial simulated density model
$N_{sim}(\bar{\rho})$; Estimate the initial number of muons
$E(\bar{\rho}) = \|N_{obs} - N_{sim}(\bar{\rho})\|$; Calculate the initial cost function
LOOP for T from $T_{initial}$ to T_{final} with and step ΔT_k ; The ''cooling'' process
 LOOP for I from $I_{initial}$ to I_{final} with step ΔI ; The refinement proces
  $r \leftarrow RAM[0,1]$; Generate a random number
  $\bar{\rho}_r(T)$; Select a neighbour simulated density model
  $N_{sim}(\bar{\rho}_r, T)$; Estimate the number of muons for a random neighbour model
  $E(\bar{\rho}_r, T) = \|N_{obs} - N_{sim}(\bar{\rho}_r, T)\|$; Calculate the cost of a random neighbour model
  $\Delta E(\bar{\rho}_r, T) = E(\bar{\rho}, T) - E(\bar{\rho}_r, T)$; Calculate the random model energy difference
  If $\Delta E(\bar{\rho}_r, T) \leq 0$
  then
    $\bar{\rho}(T) \leftarrow \bar{\rho}_r(T)$; Set as a better density value
    $N_{sim}(\bar{\rho}, T) \leftarrow N_{sim}(\bar{\rho}_r, T)$; Set as better number of muons value
    $E(\bar{\rho}, T) \leftarrow E(\bar{\rho}_r, T)$; Set the better cost function value
  else
    Calculate $P = \exp\left(-\frac{\Delta E(\bar{\rho}_r, T)}{T}\right)$ the probability for the model admission
    Generate $r_{discrim} \leftarrow RAM[0,1]$ random number
    If $P > r_{discrim}$
    then
      $\bar{\rho}(T) \leftarrow \bar{\rho}_r(T)$
      $N_{sim}(\bar{\rho}, T) \leftarrow N_{sim}(\bar{\rho}_r, T)$
      $E(\bar{\rho}, T) \leftarrow E(\bar{\rho}_r, T)$
    EndIf
  EndIf
 $I \leftarrow I - \Delta I$
 EndLOOP I
$T \leftarrow T + \Delta T_k$ decrease temperature after several iterations
EndLOOP T
End

Simulated Annealing Algorithm



Initial "observational" model

final optimized model

Vesga-Ramírez, A. *et al* (2021). Simulated annealing for volcano muography. *J South Am Earth Sci*, *109*, 103248.

Colombian Muography

- Several Col research groups started with muography ideas & prototypes
- Possible volcano muography site: Cerro Machín & observation points
- Designg & built hybrid Muon Telescope: Hodoscope + WCD
- Detailed Telescope digital twin (Thermal, vibrations + Geant4 Det Models)
- Realible 64 channels electronics calibrated from the digital twin
- Hodoscope for trajectories and WCD as a calorimeters
- Particle discrimination based on energy deposited WCD + Machine Learning
- Discrimination of correlated from uncorrelated events
- Backward noise reduction based on precise ToF electronics
- Density optimization implementing Simulated Annealing algorithm.

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Thanks !