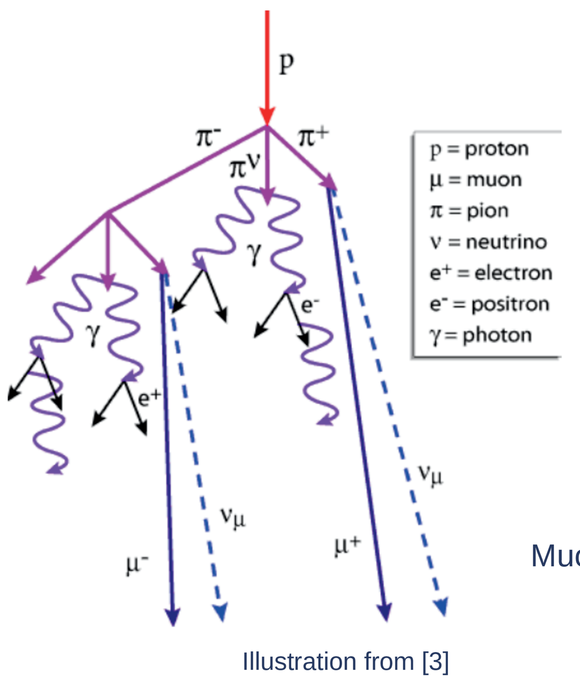
Machine learning in muography: Optimisation of muon detection systems for border control using TomOpt

Universidad de Oviedo

UCL Université catholique de Louvain

Authors: Samuel Álvarez Lueje, Zahraa Daher, Maxime Lagrange and Pietro Vischia

Introduction



- High energy cosmic particles impact with the Earth's atmosphere triggering large chain reactions.
- Great variety of particles, with muons being amongst them.
- ~1000 cosmic rays / m²s

Muons
- Mass: ~105 MeV
- Sea level flux: ~100 s⁻¹m⁻²
- Highly penetrating
- Very low ionization = safe
- Wide range of energy: GeV-TeV

Muons can be used to map the interior of objects based on the scattering with other particles in their path.

Muon + Tomography

Muography

With the scattering angles of the muons we can compute the radiation length X0 of the material.

(1) $$\frac{1}{X_0} \propto \frac{Z(Z+1)}{A}\, Ln\left(\frac{287}{\sqrt{Z}}\right)$$

Objective

Simulate and optimise muon detectors through differentiable programming with the TomOpt software.

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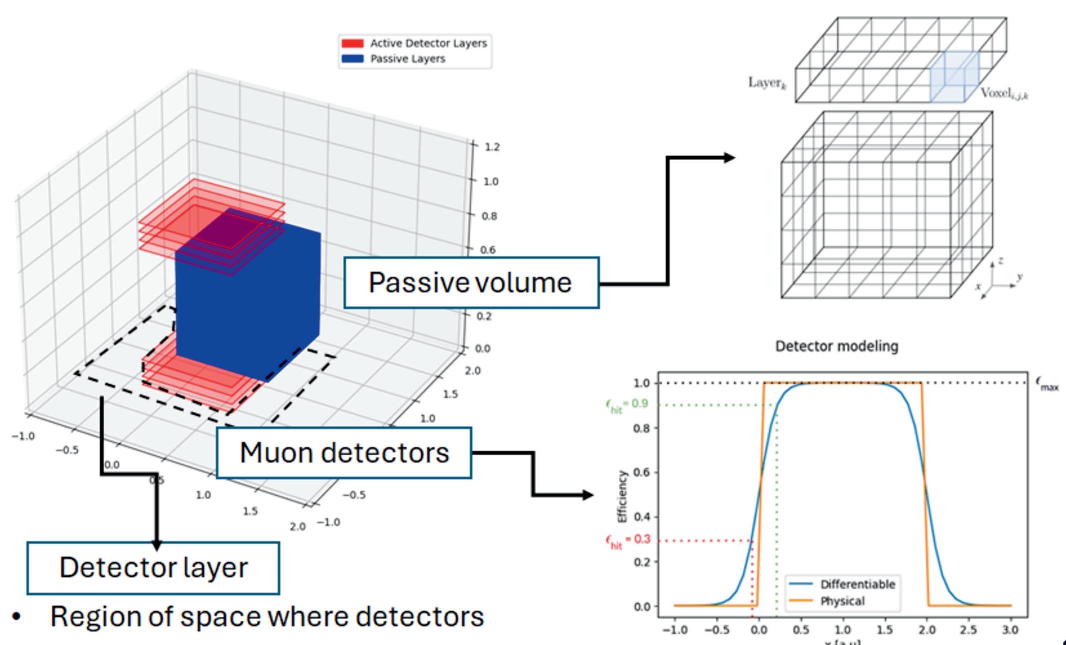
Explore other machine learning applications in this context.

Methodology: TomOpt

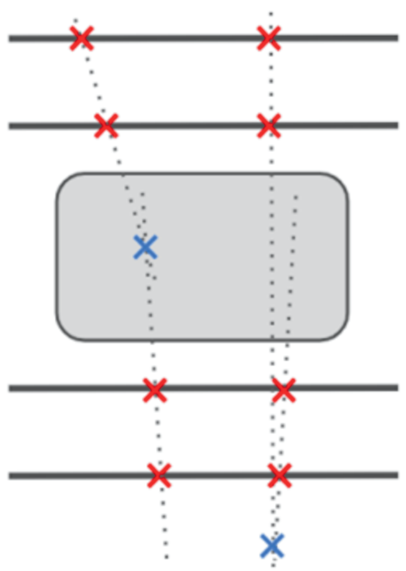
Volume modelling



- Region of space where detectors can move

Muon propagation

- Muons: (p,x,y,z,θ,φ)
- Hits are generated in the detector panels.
- Trajectories reconstructed
- The scattering points are found using the POCA (Point of Closest Approach) method.

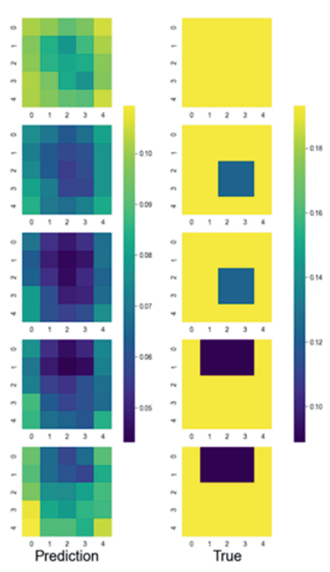


Passive volume mapping

POCA points let us pinpoint the area of the volume in which the muon has scattered.

Averaging the scattering angles and momenta of the muons one can estimate the value of the radiation length in that area.

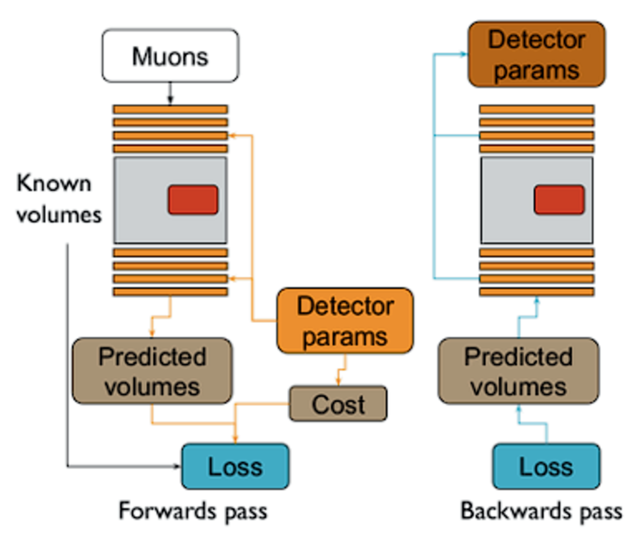
The precision of this computation is subject to the spatial resolution of the detectors and the number of voxels of the passive volume.



(2) $$X_0 = \left(\frac{0.0136\, GeV}{p^{rms}}\right)^2 \frac{\delta z}{\cos(\bar{\theta}^{rms})} \frac{2}{\theta_{tot}^{rms}}$$

Detector optimisation

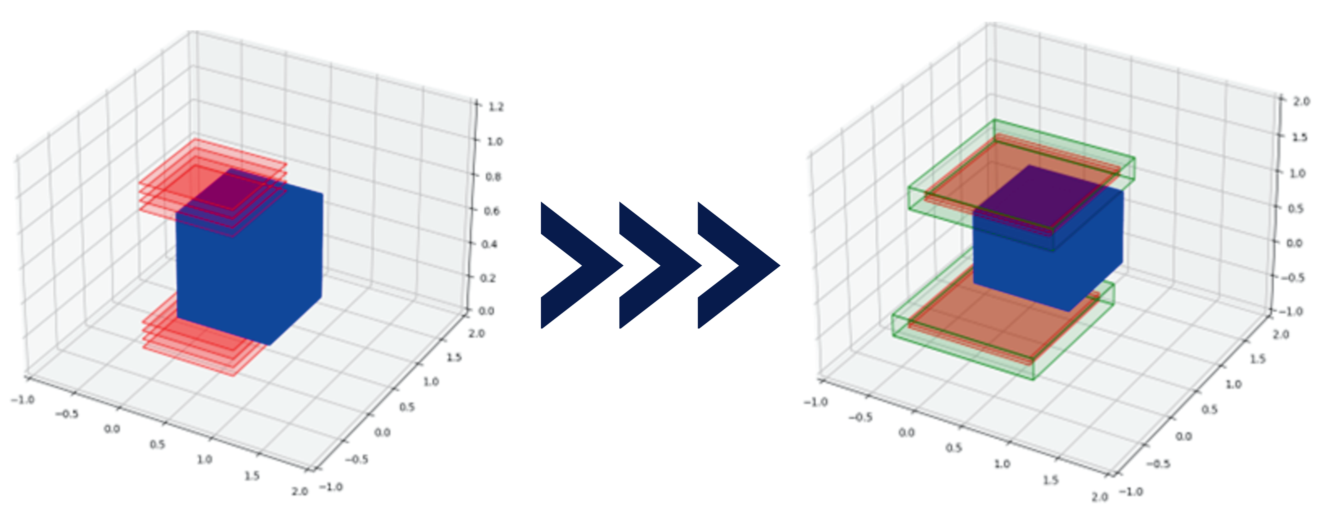
Learnable parameters (x, y, z, dx, dy)



Reproduced from [1]

Results

Hodoscope, a composite detector



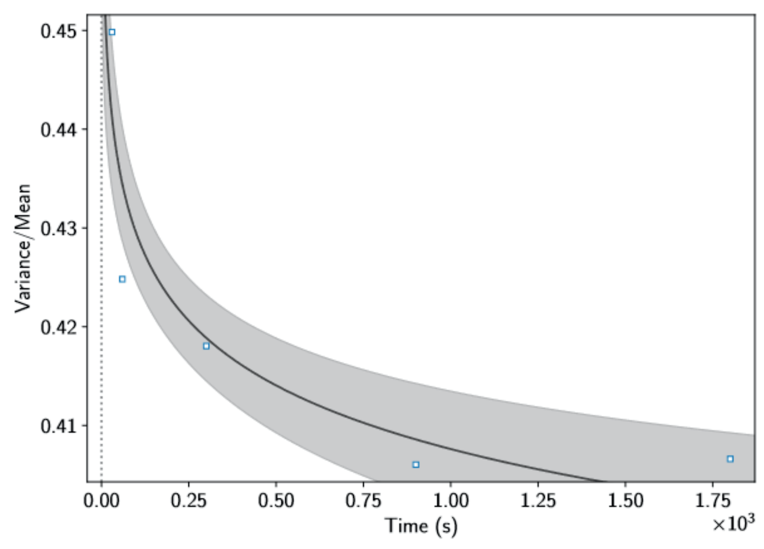
- New add-on class in TomOpt
- Detector panels fixed inside a casing
- The whole detector is free to move
- Optimisable (x, y, z)
- Fixed surface area

Acquisition time

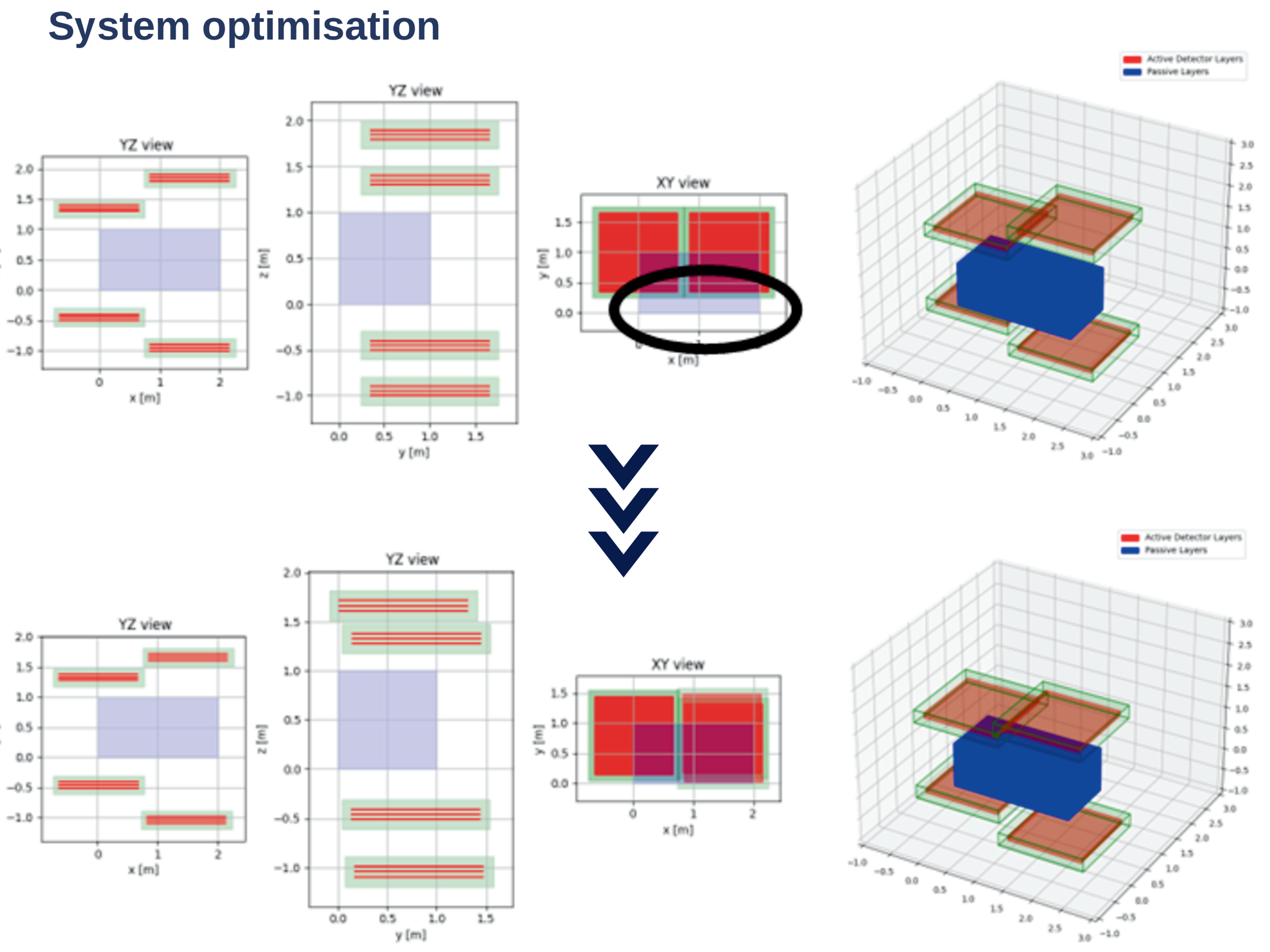
In muography we can't adjust the particle flux, therefore we must account for the acquisition time.

When using muography to scan cargo its necessary to bargain between performance and precision of the measurements, since the transporters may work on a tight schedule.

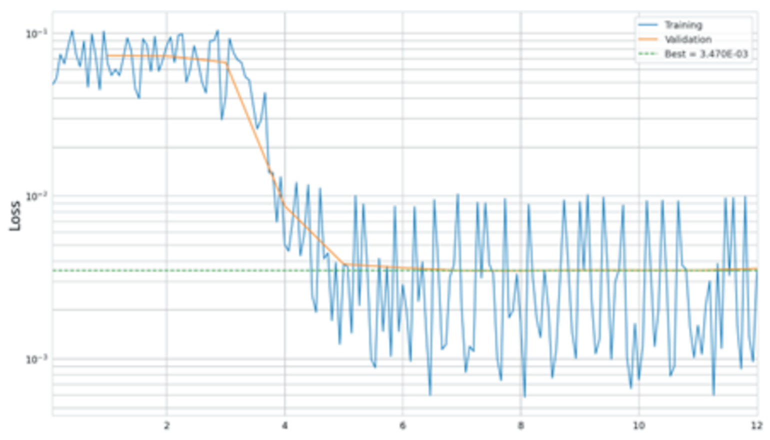
$$n_{muons}(t) = A * \phi * t$$



System optimisation



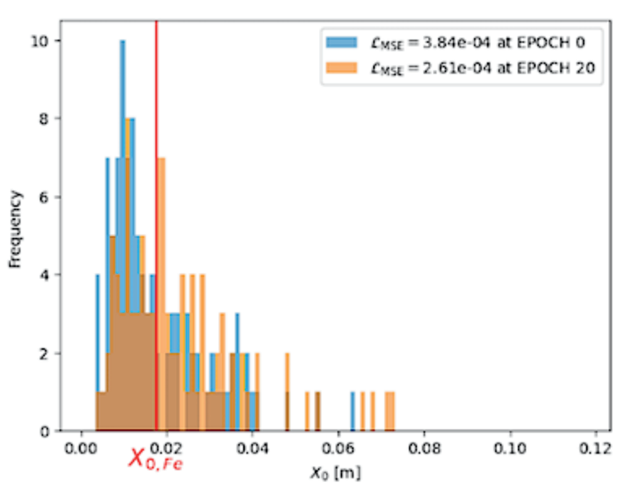
- Suboptimal initial volume coverage solved.
- Loss function decreases more than an order of magnitude.
- Loss fluctuations caused by the stochastic nature of muon generation and scattering.



The algorythm works as intended with systems of low/medium complexity but ocasionally stalls when trying to optimise more complex detector or material configurations.

Current limitations

- Prioritize performance over precision: only one scattering per muon.
- Results bias: overall underestimation of radiation lengths.



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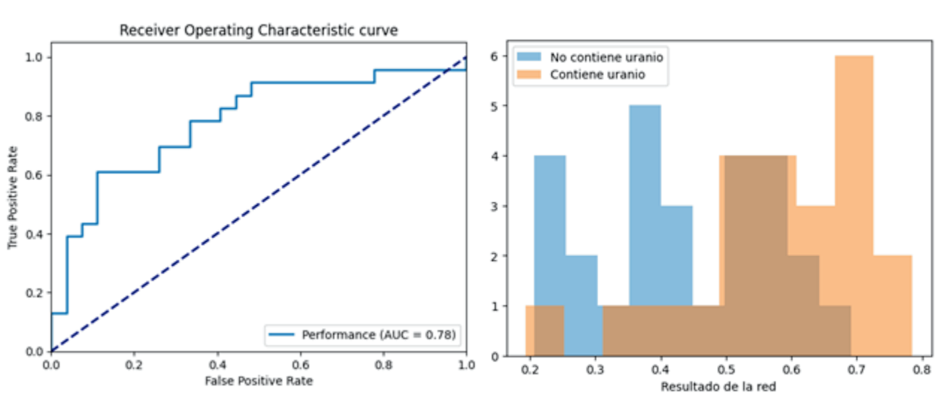
ML for muography data analysis

After optimising the system the data might not be clear enough to conclude if a volume contains an illegal material just by looking at it.



Conclusion

Mugography is a field of expertise that's hard to access since it requires a lot of time and very sensitive detectors. Designing experiments for it happens to be very hard and expensive.

Through simulations we can save us all this trouble plus we can adapt the algorythms to work with AI and explore further into more complex configurations.

In the context of cargo scanning software like TomOpt becomes crucial to develop experiments and properly implement this technology, greatly reducing the cost and the potential damage of the classic method (X-ray).

Bibliography

1. Giles C. Strong et al., TomOpt: Differential optimisation for task- and constraint- aware design of particle detectors in the context of muon tomography, Sep., 2023, arXiv:2309.14027v2 [physics.ins-det].
2. Zahraa Zaher et al., Optimisation of muon portals for border controls using TomOpt. MARESEC 2024 proceeding.
3. Justin Mule et al., Measuring Cosmic Ray Muon Showers at Suffolk County Community College