Statistical approach to muography as a non-destructive testing technique for industry problem solving

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Muons systems

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Outline

- Introduction
- Muons and muography
- Statistical basis of the algorithm
  - Probability density functions
  - Kernel density estimation
  - Monte-Carlo simulations
  - Likelihood minimization
- The algorithm
- Results obtained
- Conclusions

Section I
General introduction

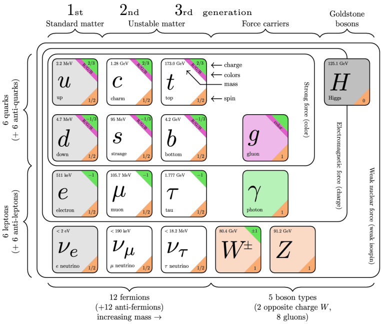
Main goal of this work

Develop a new framework allowing to perform a muography experiment to characterize the inner properties of physical objects using data science and advanced statistical models.

Particle physics and muons

The Standard Model **describes the fundamental particles** existing and their interactions:

- Introduced in the 1970s and still considered to be valid, but probably incomplete
- Simple in concept but extremely precise
- Lots of successful predictions made over the years, such as the existence of the top quark and the Higgs boson



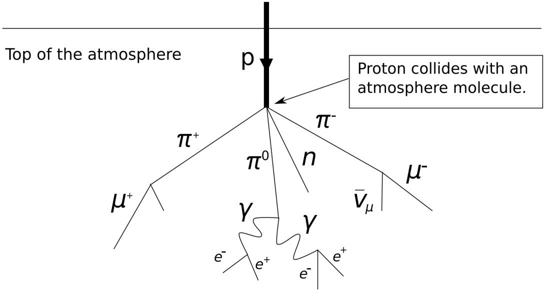
Muons

- Muons μ^- are one of the 12 fundamental particles existing
- They have a relatively small interaction cross-section with ordinary matter, allowing them to cross material without being stopped, making them interesting.

Cosmic rays

Comic rays are a **constant flux of high energy particles** reaching the Earth:

- Mostly made out of protons and atomic nuclei
- Trigger a decay chain by interacting with the atmosphere, producing muons
- Muons are not stable ($\tau \simeq 2.2\mu$s) but relativity can make them live long enough to reach the ground $\rightarrow$ 10.000 cosmic muons are observed per m^2 and per minute at sea level.



Interaction with matter

Muons interact with matter through two main processes:

Ionization

Ionization, when the incident muon gives some of its energy to the electrons of the absorber, but quite small for MIPs such as cosmic muons.

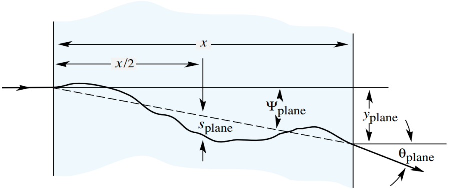
Multiple scattering

Multiple Coulomb scattering inducing a stochatic deviation whose central angular deviation can be described by a Gaussian of width θ_0.

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \left(\frac{x}{X_0 \beta^2} \right) \right]$$

This deviation depends on the number of radiation lengths X_0 and therefore on the medium crossed.

$\rightarrow$ Basis of the muography principle.



Muon tomography

Instead of *calculating* the deviation expected for a cosmic muon, we can *measure* the positional and angular deviation suffered **to estimate the properties of the medium crossed**.
$\rightarrow$ Main idea behind the principle of **muon tomography**, or **muography**.

This method prevents several advantages over other imaging techniques:

- Non-destructive

Experimental setup

Statistical basis

Probability density functions

Kernel density estimation

Monte-Carlo simulations

Maximum likelihood estimation

General idea

MuonState

Surfaces and Volumes

Cylinders and pipes

Propagator

Likelihood

Generator validation

Pipes geometries

Kernel density functions

Likelihood curves

Conclusion

Future improvements

Thank you
for your attention!

Any questions?

Ionization

Ionization happens when the incident muon gives some of its energy to the electrons of the absorber, as described by the Bethe-bloch formula.

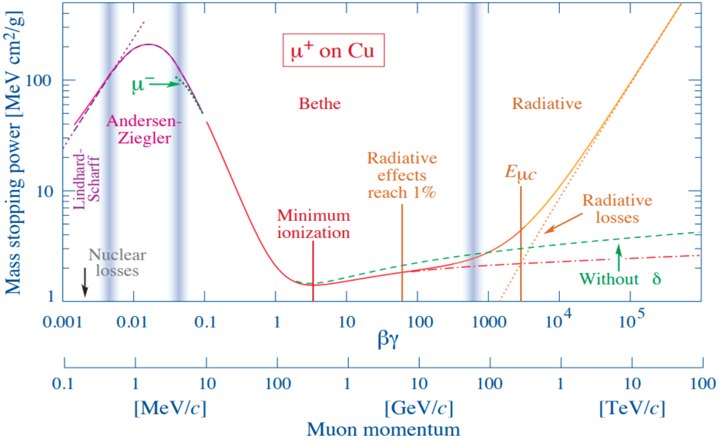
$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right) \right]$$

The **mass stopping power** of material depends on:

- The charge number of incident particle z
- The atomic mass and charge of absorber A and Z
- The relativistic factors β and γ
- The maximum possible energy transfer to an electron in a single collision W_{max}
- And the mean excitation energy I.

Ionization

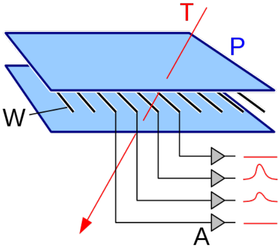
Cosmic muons have an energy of the order of the GeV and are therefore referred to as minimum ionizing particles, so ionization is not considered in this work.



Muon detectors

Multiwire proportional chambers use an array of high-voltage wires, placed within a chamber filled with a gas, in which an electric field is created.

A muon crosses the detector leaves small electric charges behind, collected by the wires while leaving a signal. The combination of the signals on the different wires give us information regarding the muon.



Most important parameters of a muon detector:

- The **spatial resolution**, ideally as small as possible
- The **acceptance**, related to the size of the detector
- And the **efficiency**, which should be as high as possible to make the measurement reliable and fast.