Detector optimization in Muon Scattering Tomography

Maxime Lagrange on behalf of the **TomOpt authors***

Second MODE Workshop on Differentiable Programming for Experiment Design

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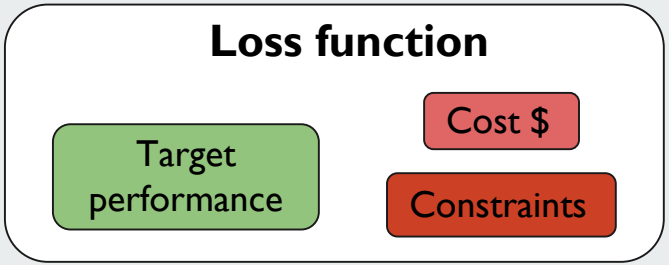
Previously…

“Gradient-based optimization”

$$x^{(k+1)} = x^{(k)} + \eta_k \cdot \nabla_x f(x^{(k)})$$

“Express the desired task as a loss function”



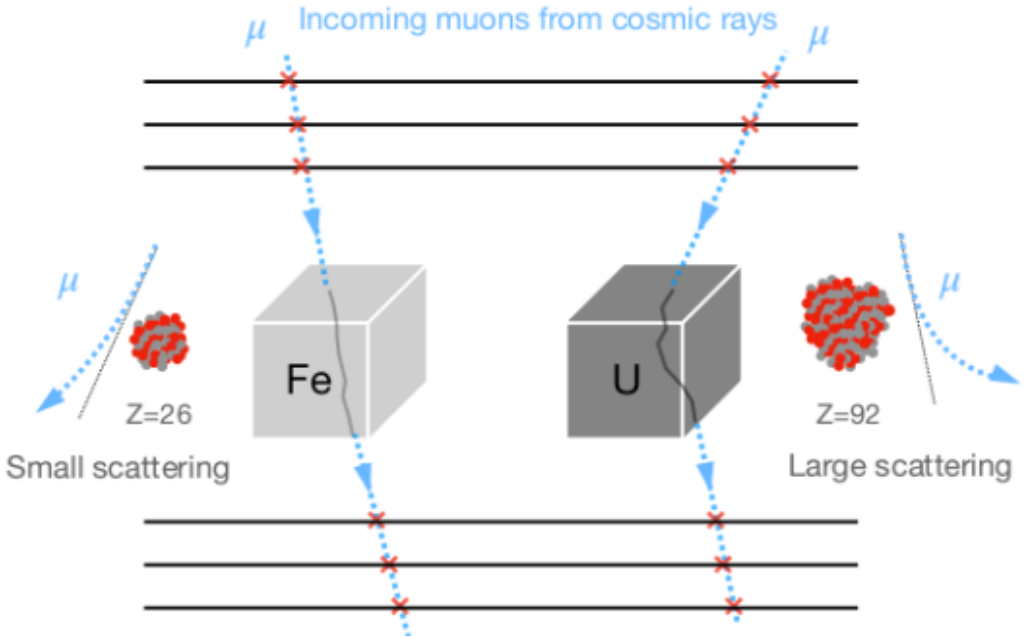
OUTLINE

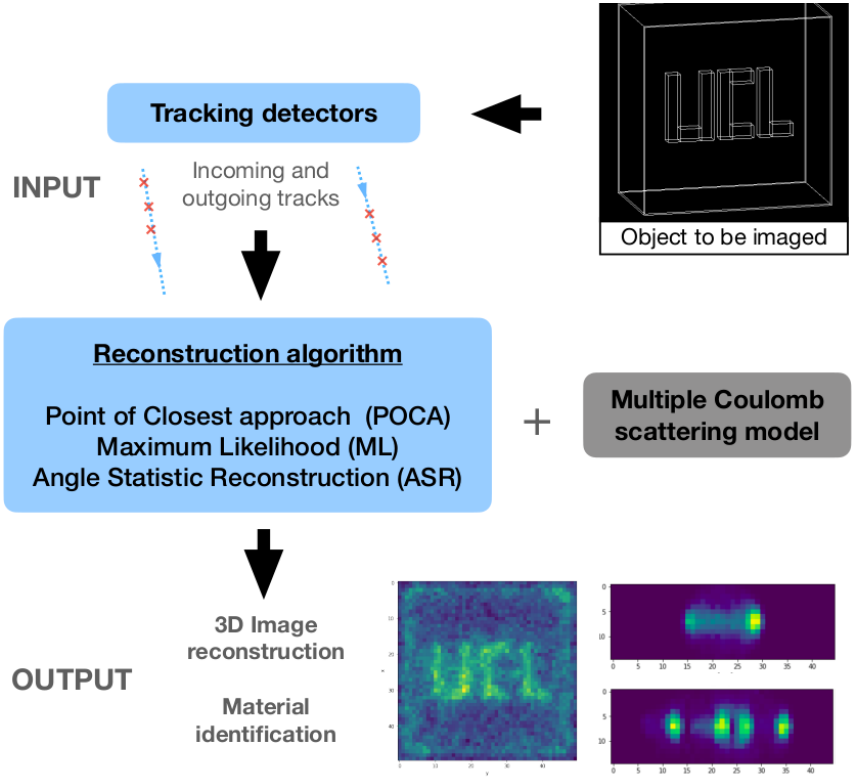
I - Muon Scattering Tomography applications

II - Parameter space in MST

III - TomOpt optimization example

Muon Scattering Tomography





I - Muon Scattering Tomography applications

Silent Border MST scanner for border guard

Cosmic Ray Tomograph for Identification of Hazardous and Illegal Goods hidden in Trucks and Sea Containers

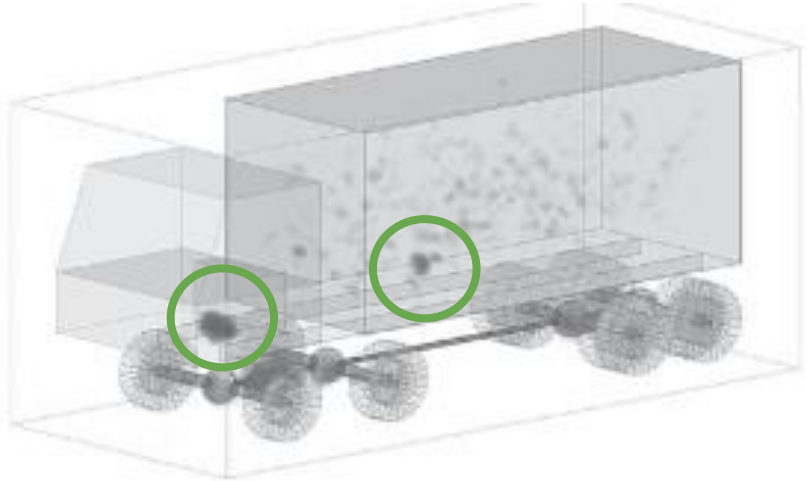
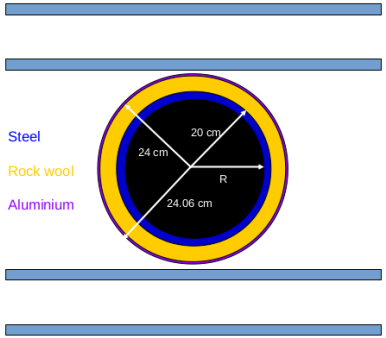


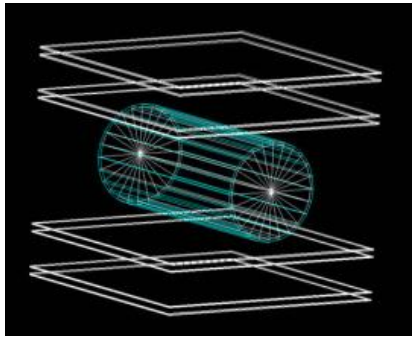
Illustration from "Muography of different structures using muon scattering and absorption algorithms"

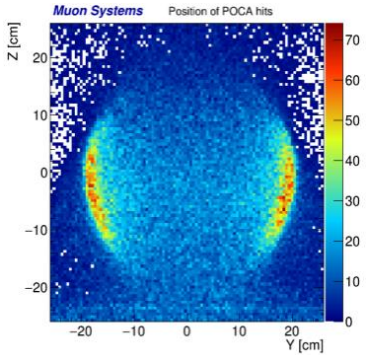
Constraints	Target performance
Short **acquisition time**	**Anomaly detection**

Industrial scanning solutions

1 - Measurement of the width of an insulated pipe



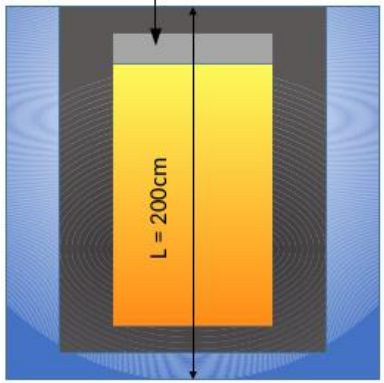


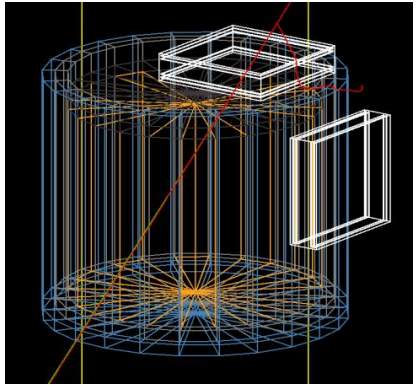


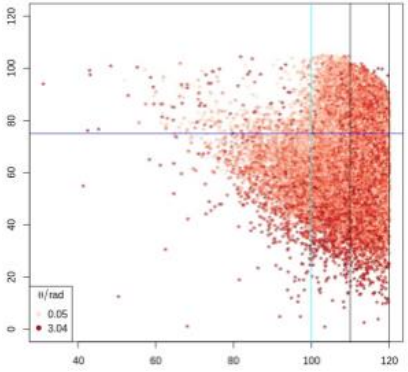
Illustrations from "Non-destructive testing of industrial equipment using muon radiography"

2 - Estimation of slag on a furnace laddle

unknown amount of waste





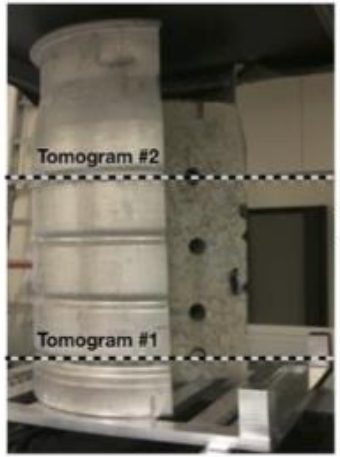


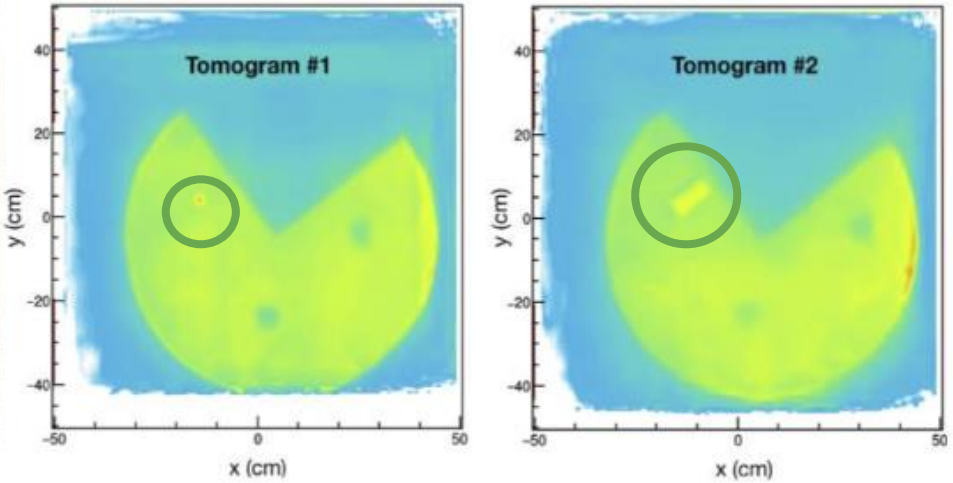
Target performance
Anomaly detection

Constraints
Portability, logistic

Nuclear Industry

Nuclear waste characterization





Illustrations from: "Muon Imaging Applications for Nuclear Waste Management and Decommissioning"

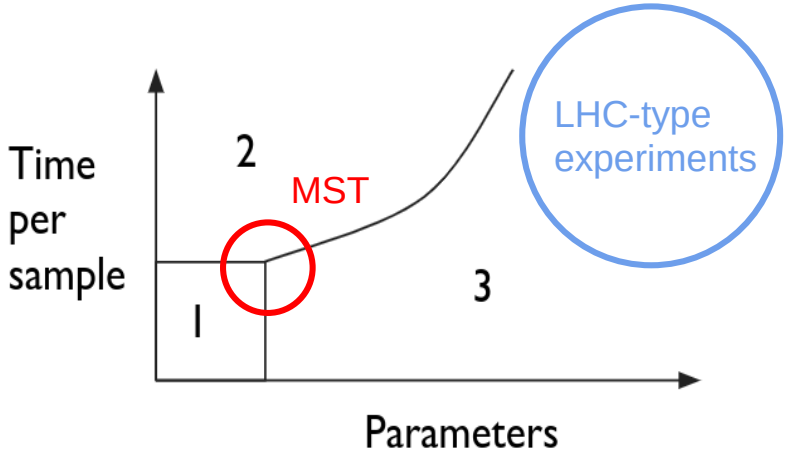
(University of Glasgow)

Constraints
Logistic

Target performance
Accurate material identification

II - Parameter space in Muon Scattering Tomography

Parameter space in MST



1. Grid/random search
2. Bayesian optimisation, Simulated annealing, genetic algorithm, particle swap optimisation, …
3. Gradient-based optimisation: Newtonian, gradient descent, BFGS, …

Hardware

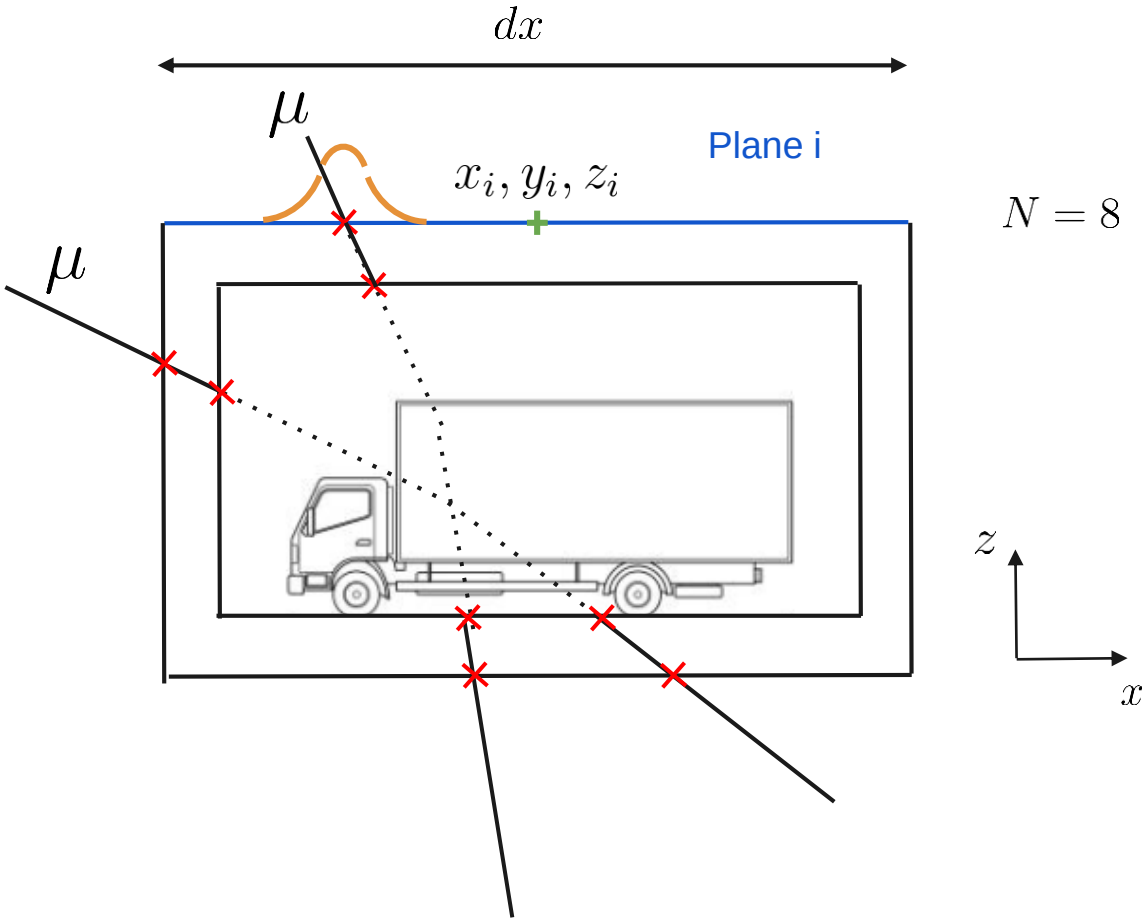
- Tracking system **technology** (RPC's, scintillators, micromegas, drift tubes, etc..)
- **Spatial resolution**
- **Efficiency**
- **Tracking system** (# planes, dimensions, geometry)

Software

- **Reconstruction algorithms**
- **Material classifiers**
- **Image recognition, clustering**

Hardware parameters

Number of detection planes	N
Placement	x_i, y_i, z_i
Dimension	dx, dy
Spatial resolution	$\sigma_{x,y}$
Efficiency	ϵ
Technology	RPC's Scintillators MicroMegas



Detector parameters and performance

How does detector parameters affect performance?

Number of detection planes

Placement

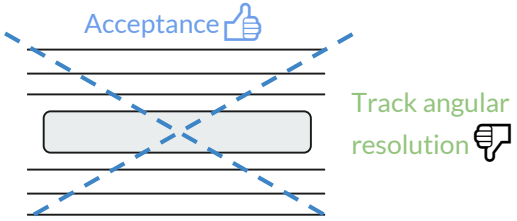
Dimension

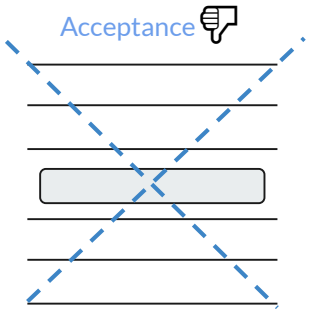
Spatial resolution

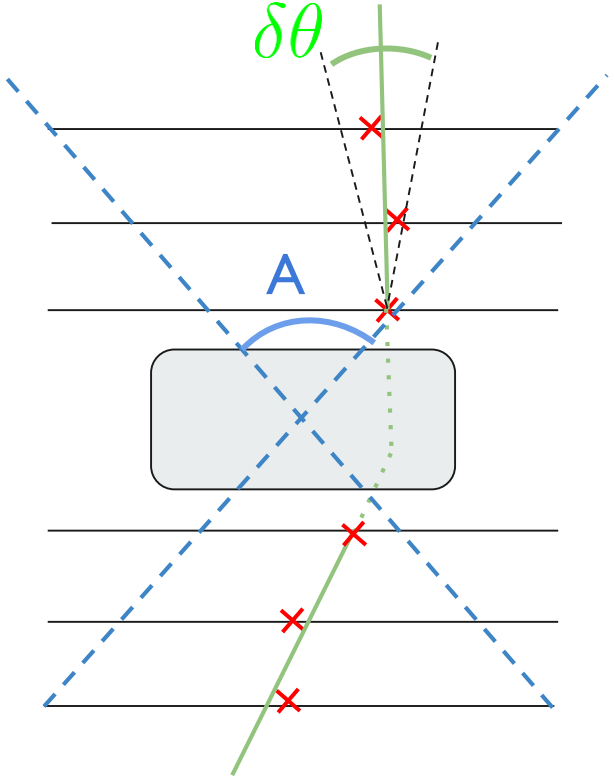
Efficiency

Track angular resolution

Acceptance

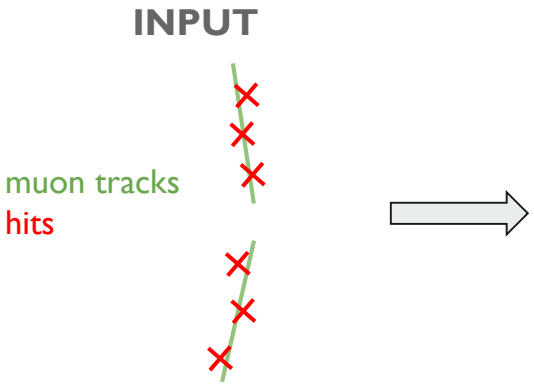




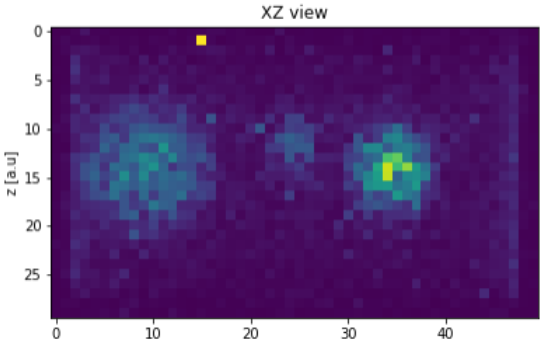


Software parameters

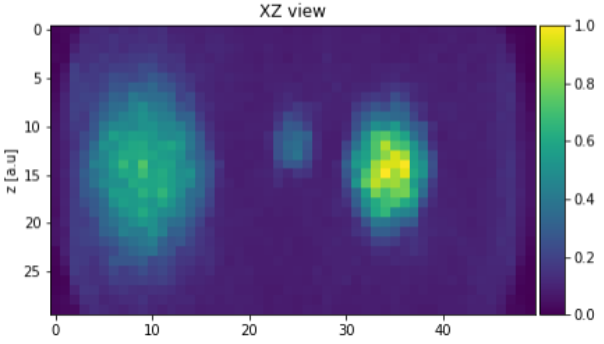
I - Reconstruction algorithm (POCA, ASR, Maximum Likelihood, Binned Clustered Algorithm, etc..)



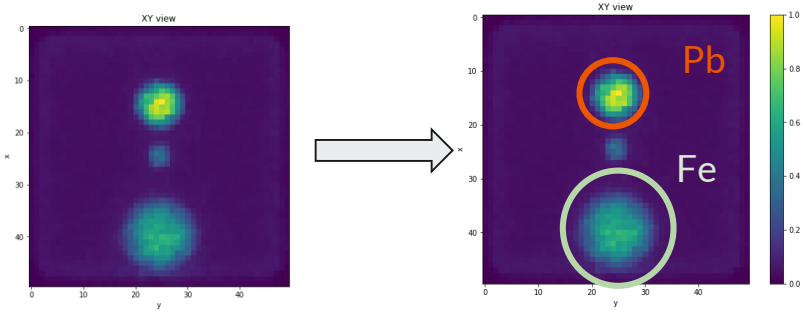
a - Point Of Closest Approach (POCA)



b - Angle Statistic Reconstruction algorithm (ASR)



II - Material classifiers



Typical MST reconstruction parameters

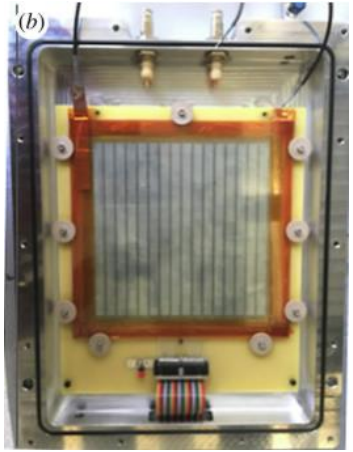
- Cuts on scattering angles
- Noise reduction
  sensitivity

Detector parameters and cost

Given its design and technology choices, how to estimate detector cost?

Local cost γ

Cost specific to the technology used



Sealed RPC prototype in development at UCLouvain

Local cost γ

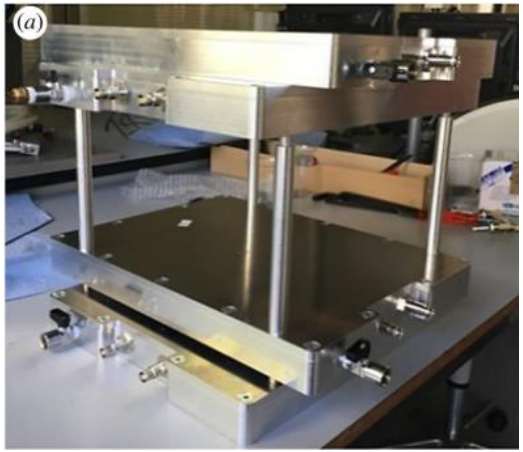
$$\gamma_{technology} = \gamma(x)$$

with x the performance properties of the given technology e.g time, spatial resolution, efficiency

$$\gamma \left[m^{-2}.readout^{-1} \right]$$

Global cost C(γ,φ)

Describe overall detector conception



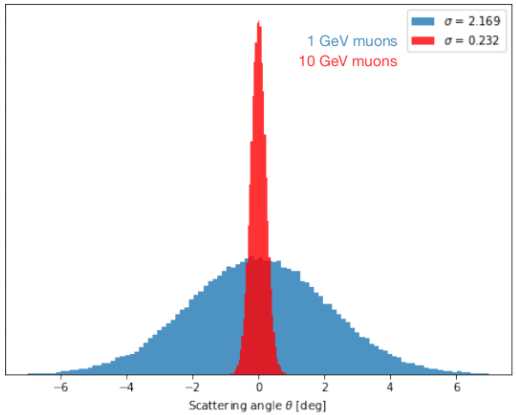
Portable muoscope in development at UCLouvain

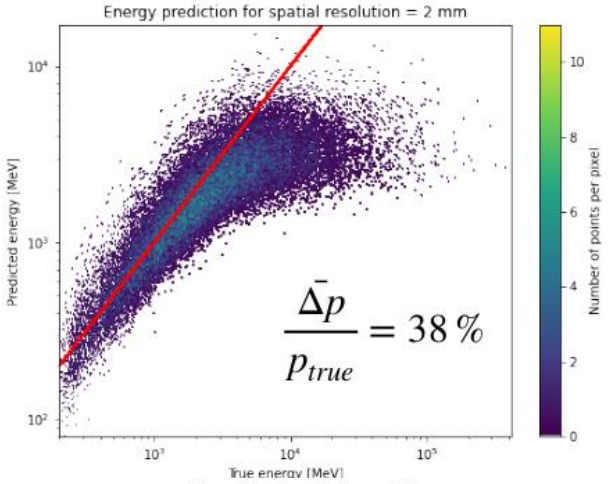
III - TomOpt optimization: Example border guard Use-case

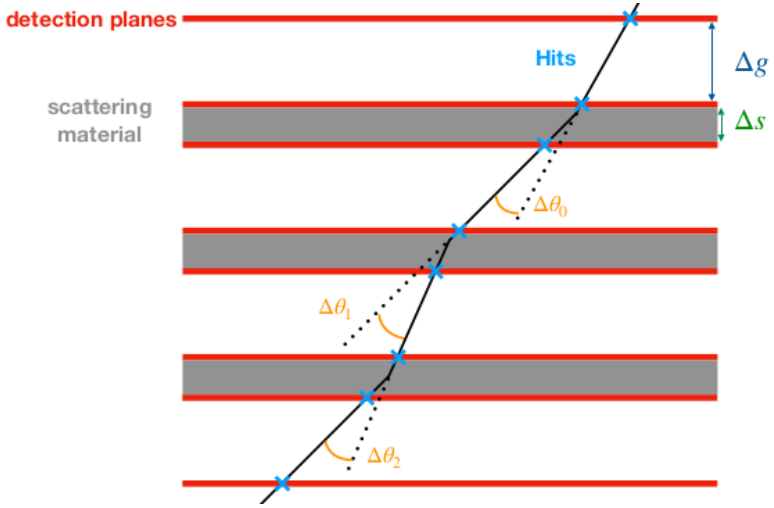
Muon momentum measurement

Muon **scattering amplitude**

$$\propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$





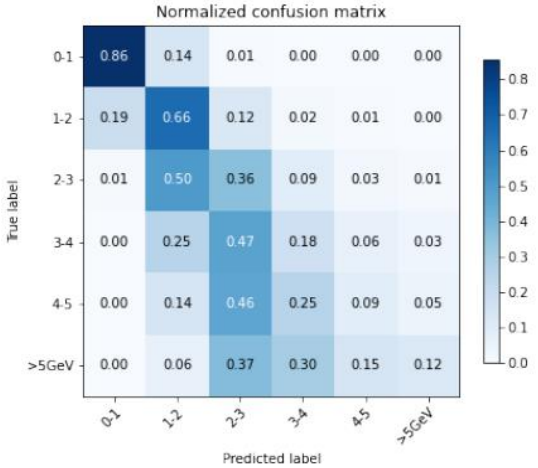


Scattering angle measurement

$$\theta_{RMS} = \frac{1}{3}(\theta_1^2 + \theta_2^2 + \theta_3^2)$$

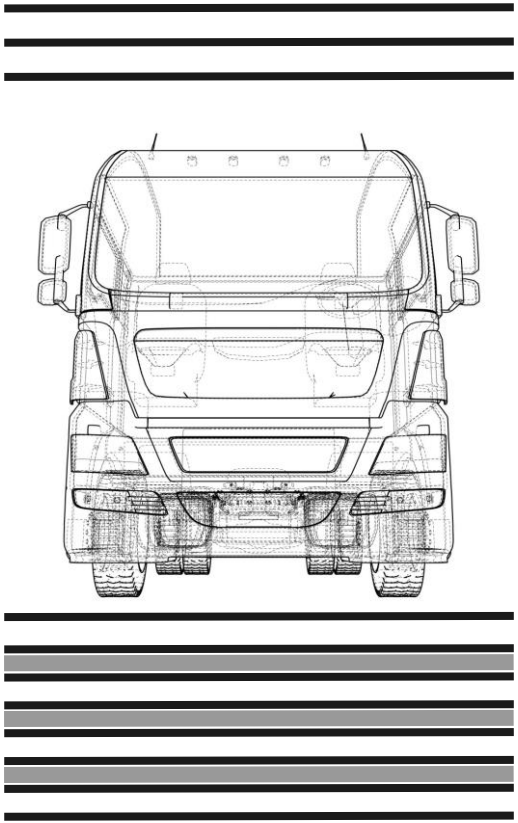
Multiple Coulomb scattering model

$$p = \frac{13.6MeV}{\theta_{RMS}}\sqrt{\frac{x}{X_0}}$$



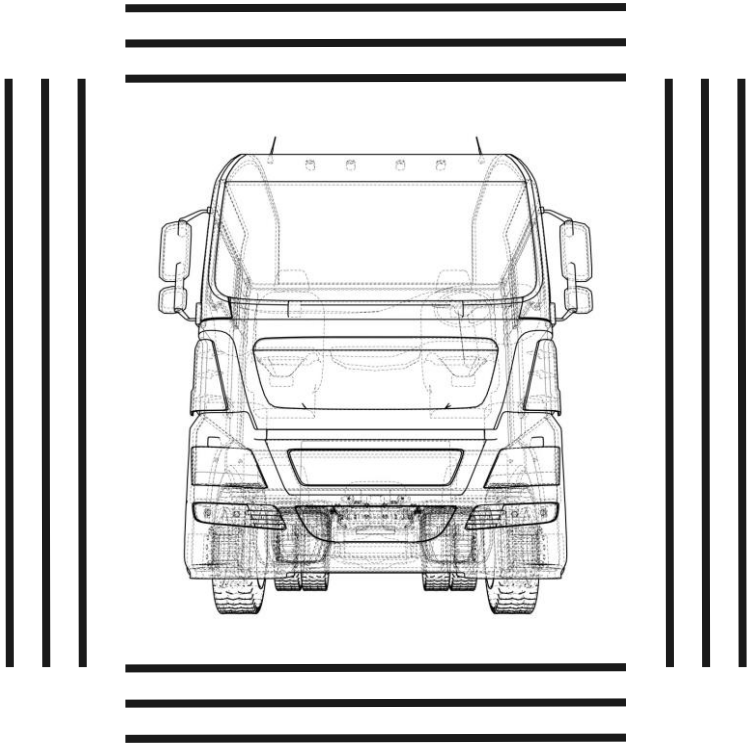
Question TomOpt will answer

Is it worth it to add a muon energy spectrometer to the detector?



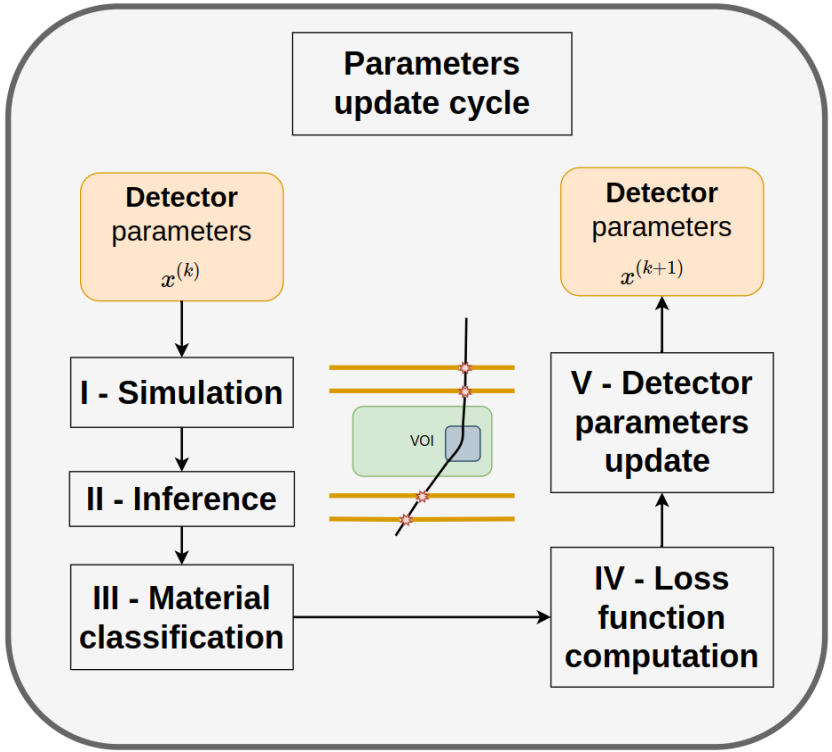
momentum measurement module

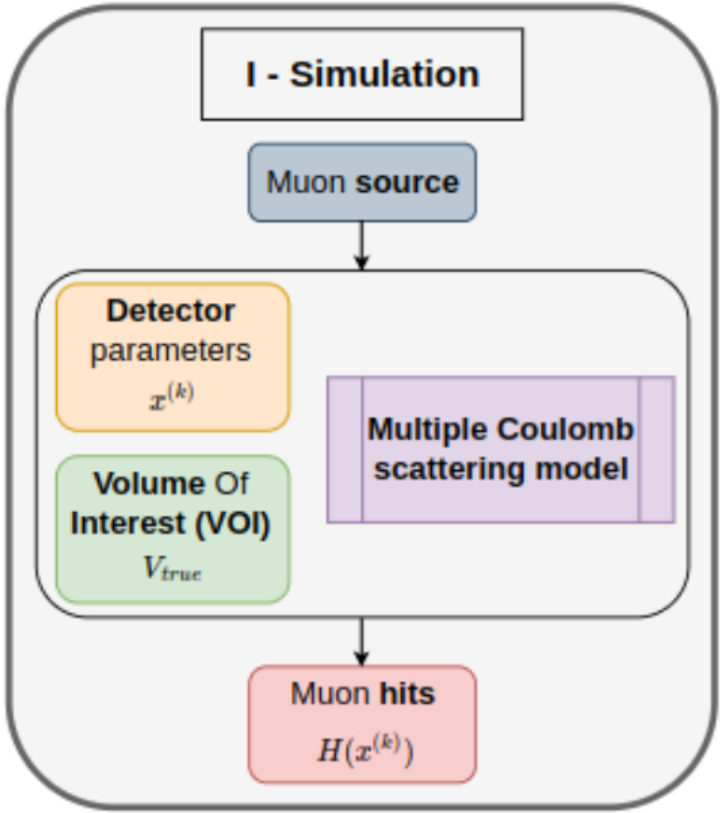
OR



BACKUP SLIDES

TomOpt


Parameters update cycle
Detector parameters $x^{(k)}$
I - Simulation
II - Inference
III - Material classification
VOI
Detector parameters $x^{(k+1)}$
V - Detector parameters update
IV - Loss function computation


I - Simulation
Muon source
Detector parameters $x^{(k)}$
Volume Of Interest (VOI) V_{true}
Multiple Coulomb scattering model
Muon hits $H(x^{(k)})$

TomOpt

II - Inference

Tracking

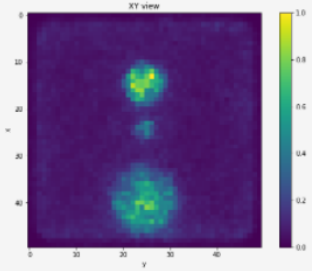
Muon **hits**
$H(x^{(k)})$

Scattering **angles**
$\Delta\theta(x^{(k)})$

Momentum prediction
$E : \Delta\theta \longrightarrow \mathbb{R}$

Reconstruction algorithms
$R : \Delta\theta, H, p_{pred} \longrightarrow \mathbb{R}$

Predicted 3D **scattering density** map
$M(x^{(k)})$

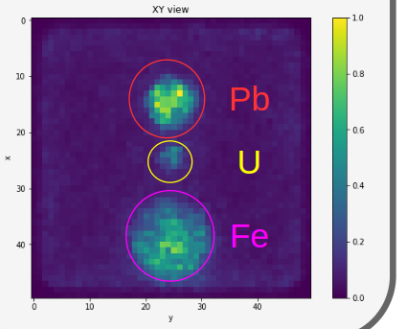


III - Material classification

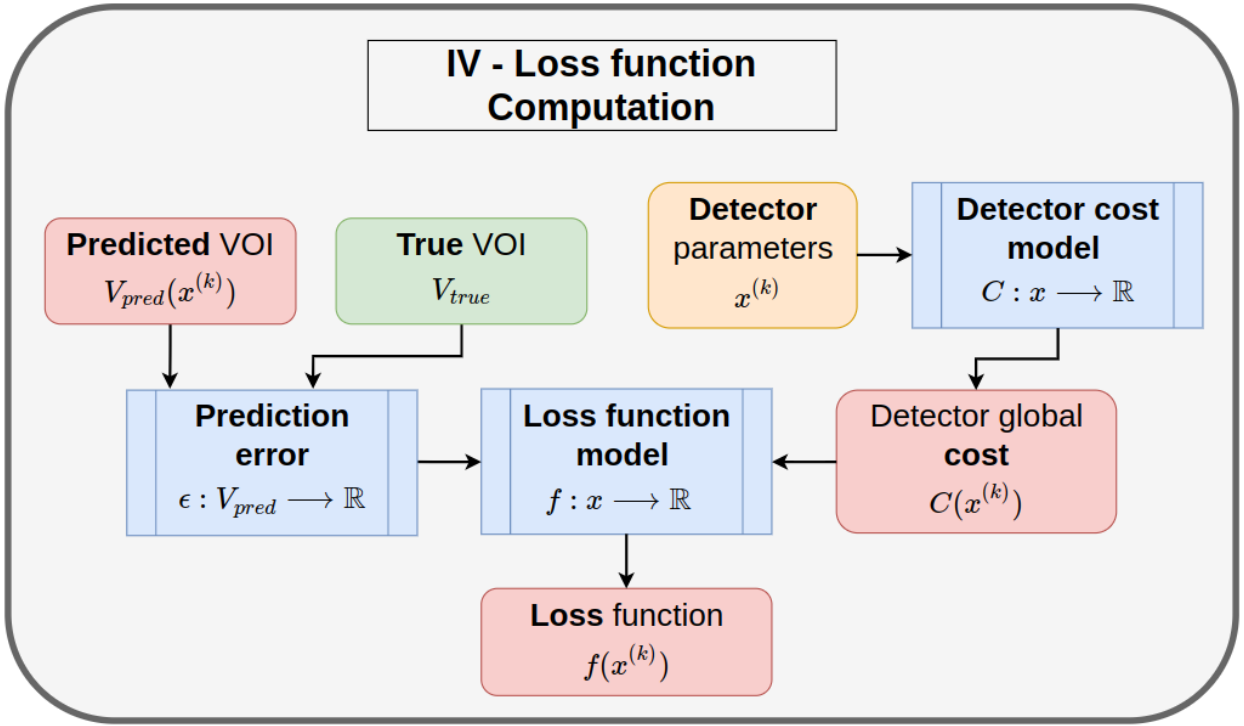
Predicted 3D **scattering density** map
$M(x^{(k)})$

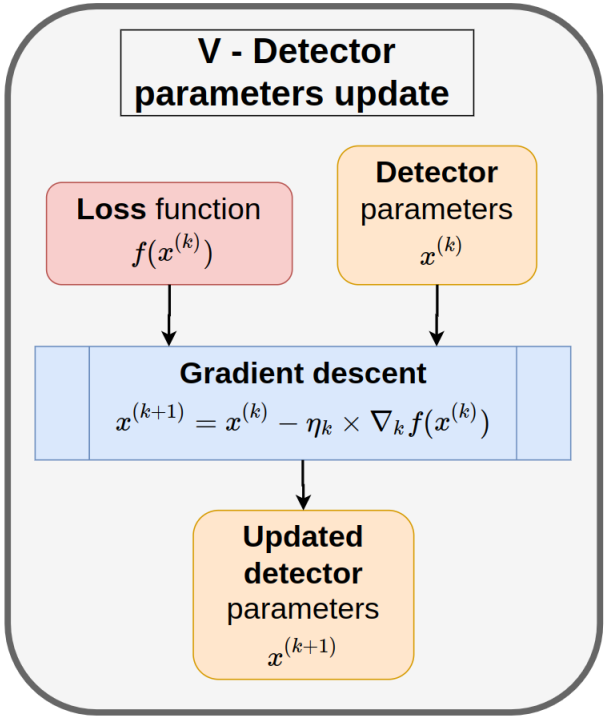
MVA classifiers

Predicted VOI
$V_{pred}(x^{(k)})$



TomOpt


IV - Loss function Computation
Predicted VOI
$V_{pred}(x^{(k)})$
True VOI
V_{true}
Detector parameters
$x^{(k)}$
Detector cost model
$C : x \longrightarrow \mathbb{R}$
Prediction error
$\epsilon : V_{pred} \longrightarrow \mathbb{R}$
Loss function model
$f : x \longrightarrow \mathbb{R}$
Detector global cost
$C(x^{(k)})$
Loss function
$f(x^{(k)})$


V - Detector parameters update
Loss function
$f(x^{(k)})$
Detector parameters
$x^{(k)}$
Gradient descent
$x^{(k+1)} = x^{(k)} - \eta_k \times \nabla_k f(x^{(k)})$
Updated detector parameters
$x^{(k+1)}$