# Muon tomography of the University of Coimbra

Muographers 2023, 19th June 2023, Naples

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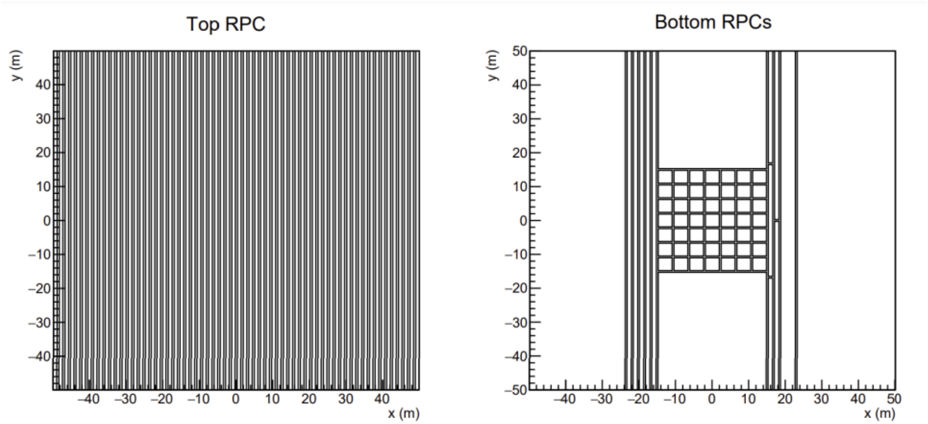
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
*partículas e tecnologia*

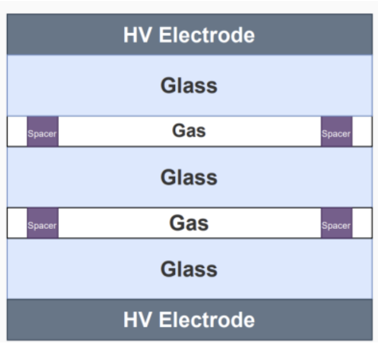
Universidade do Minho

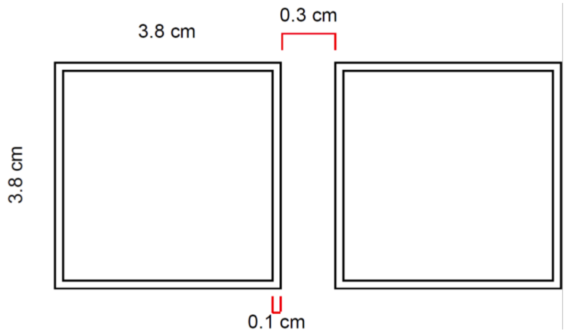
# Detector: 4 RPC planes

Aiming at a higher and more uniform efficiency:

- Modification of the pads' electronic gains
- Modelling of spacers, dead area and shifts for efficiency calculation



# Site: University of Coimbra

Acquisitions for 2 years:

- At 7 locations
- With different detector planes spacing
- With different detector inclinations

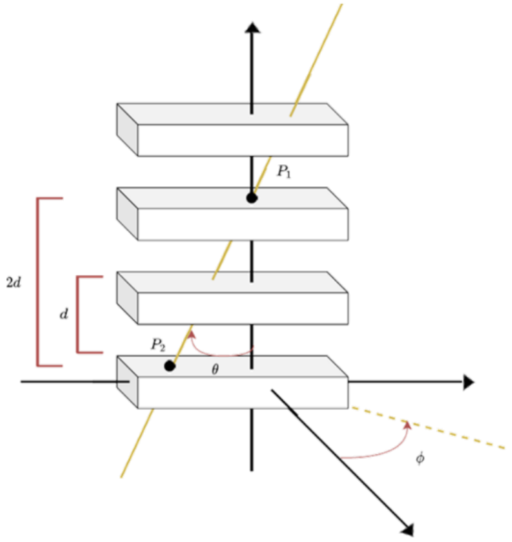
# Data analysis

Filtering:

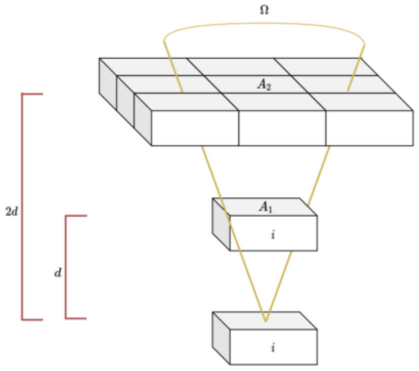
- Detection on top plane (strips)
- Correct straight-line reconstruction (if using 3 planes)

Treatment:

- Correction by the vertical efficiencies of each pad
- Calculation of muon transmission dividing experimental muon flux by an open sky muon flux simulation




$$\epsilon_k\left[i\right] = \frac{Nklm\left[i\right]}{G_k Nlm\left[i\right]}$$

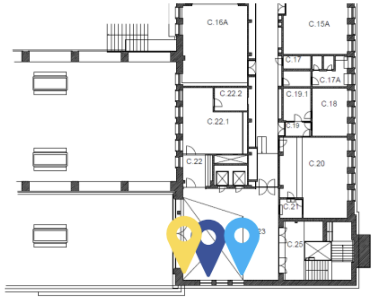


# Simulation

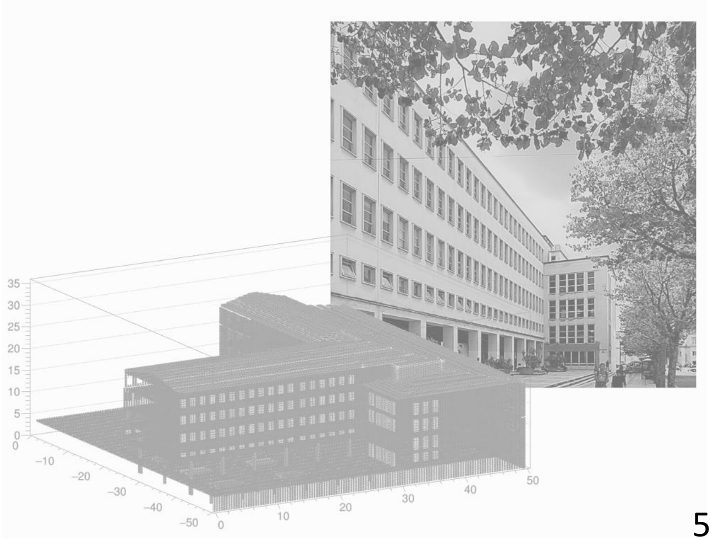
Muograph simulation based on:

- Monte Carlo methods
- The detector geometry
- The building’s plants
- An exponential model for transmission

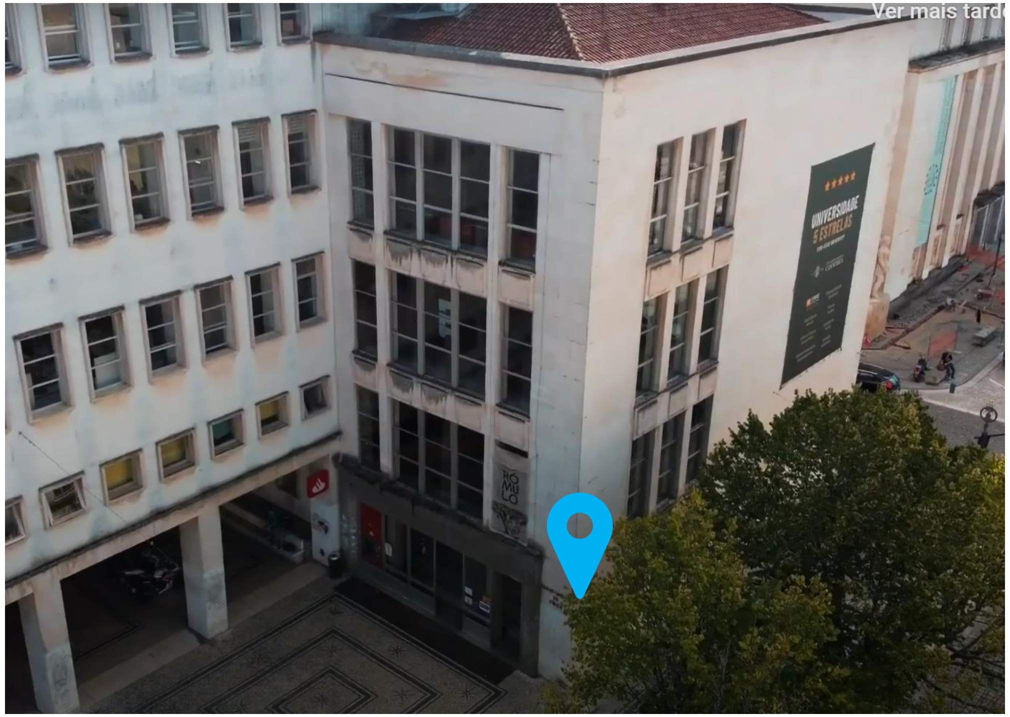
Basement

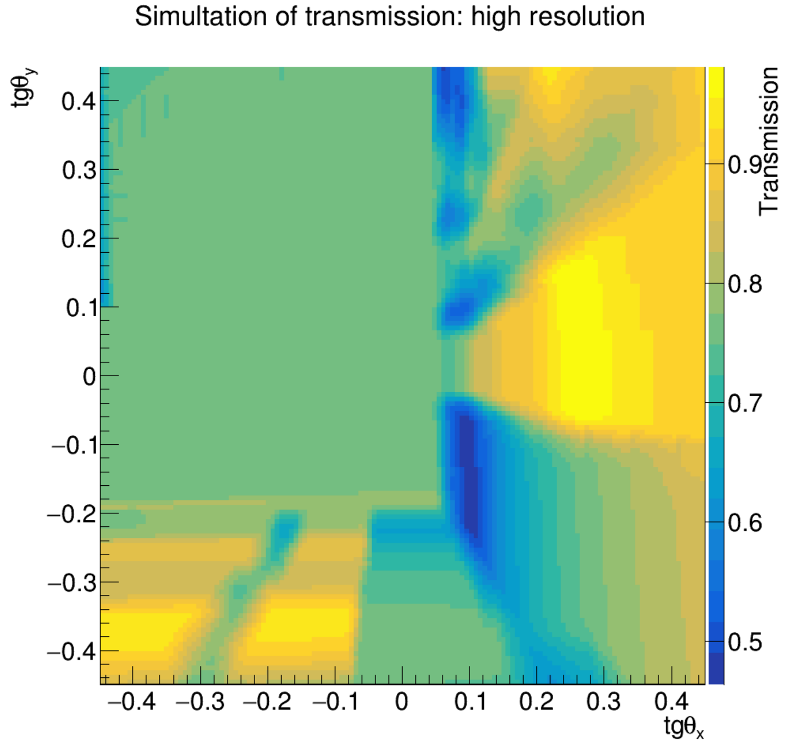


Ground floor

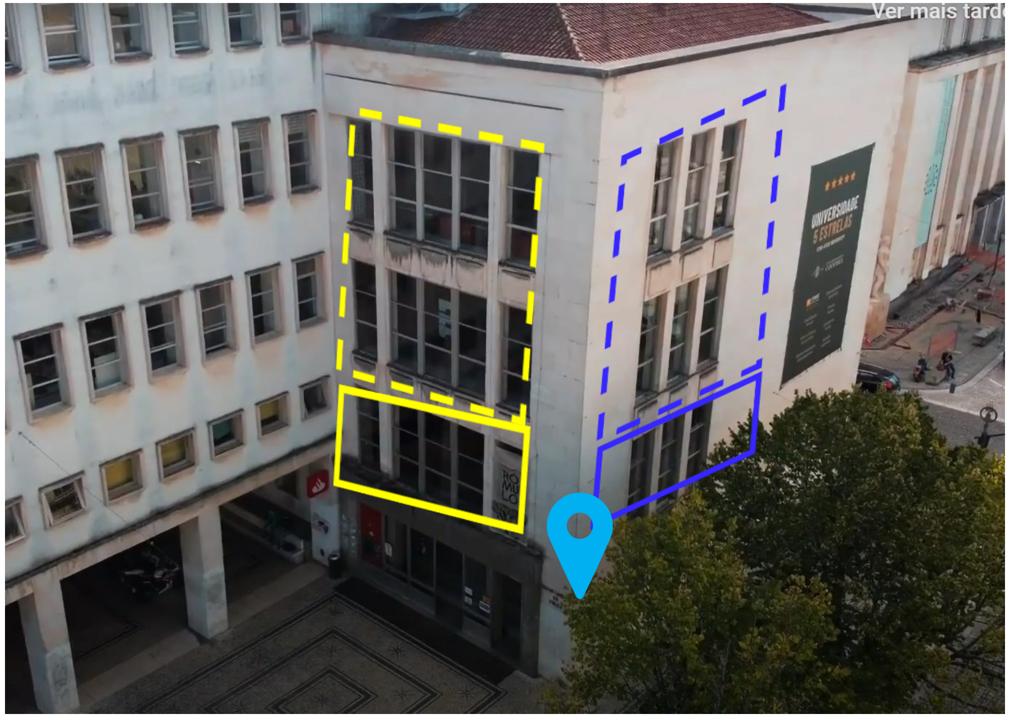


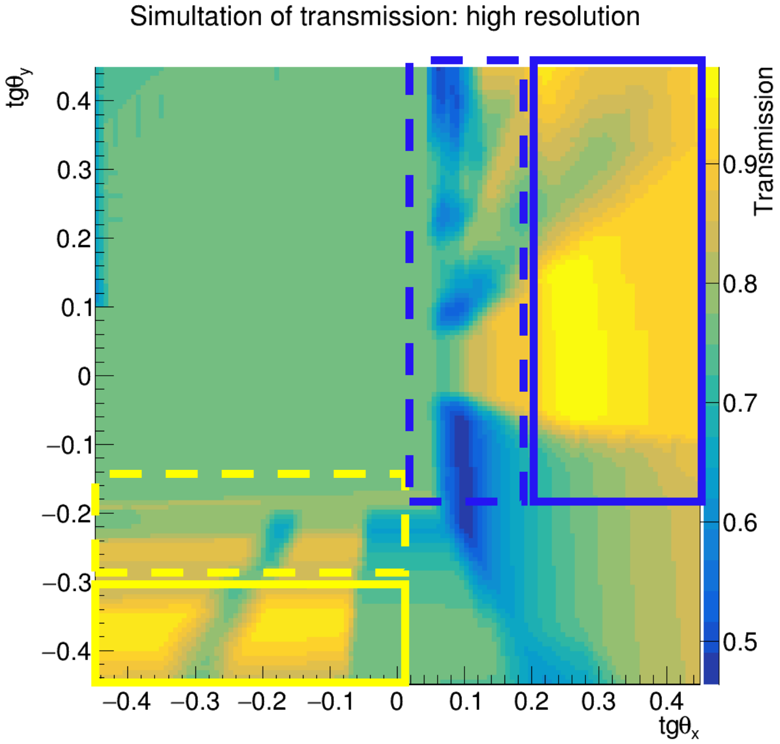
# Simulation: example



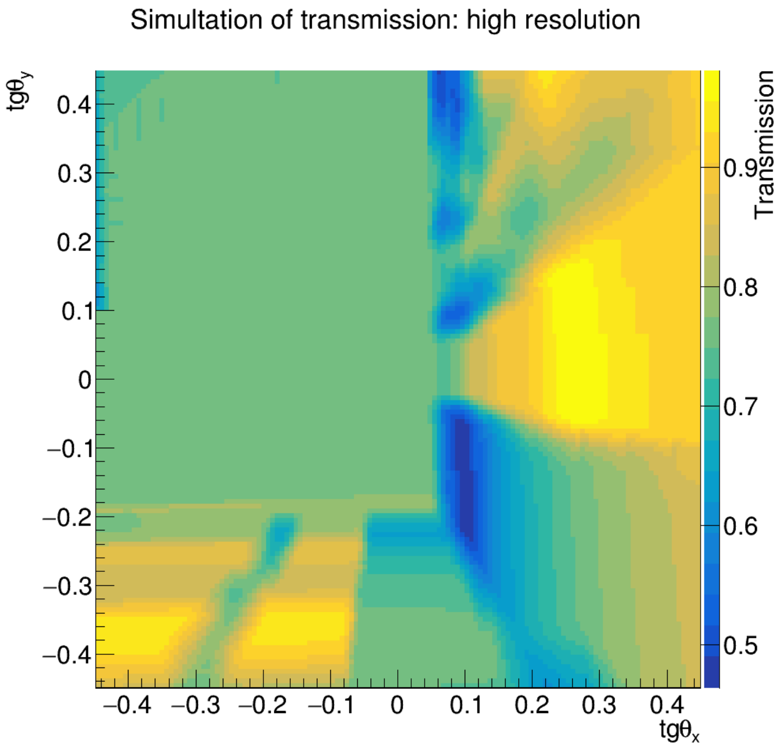



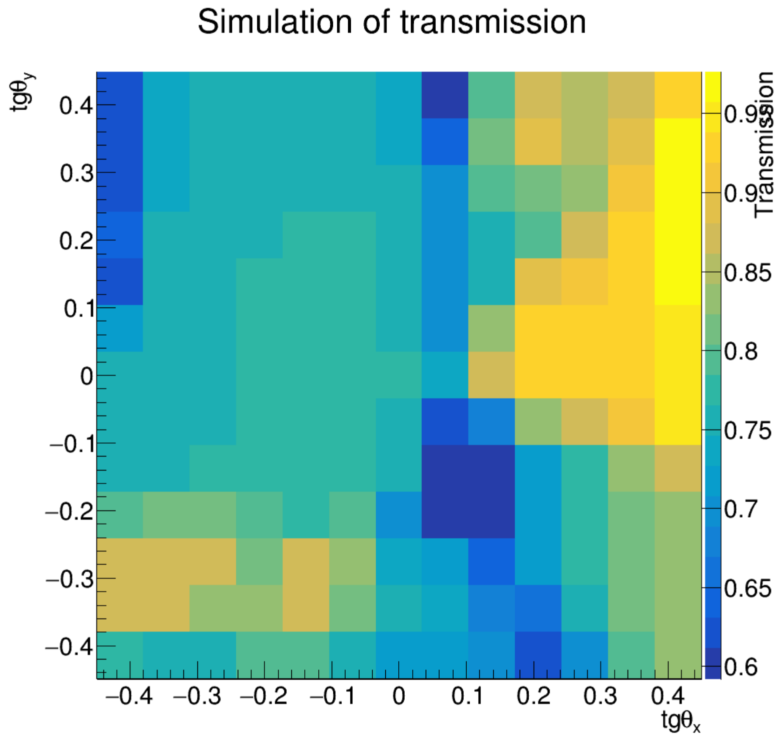
# Simulation: example



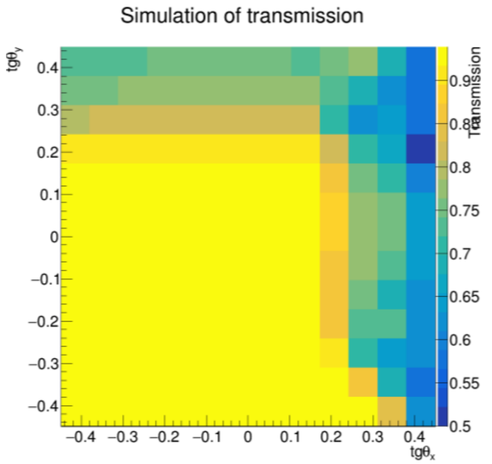



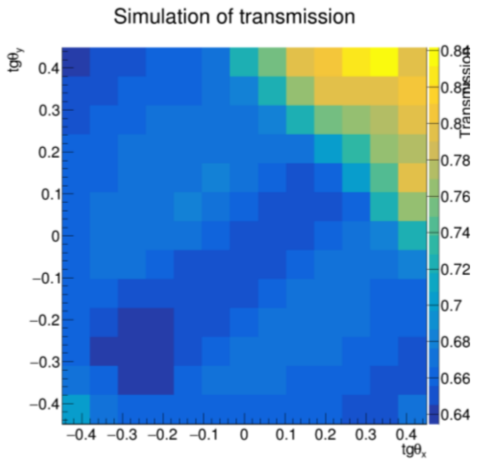
# Simulation: example

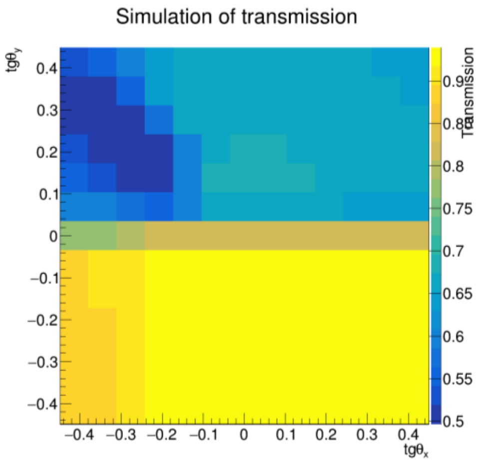


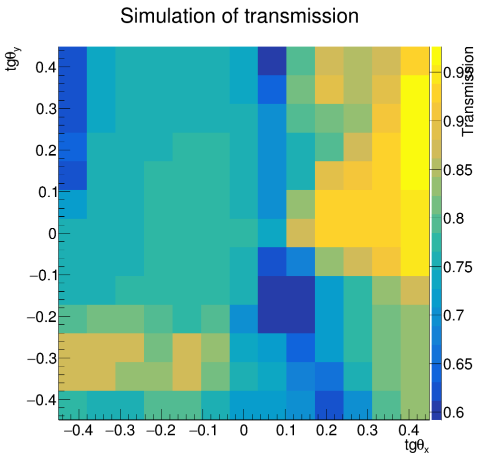



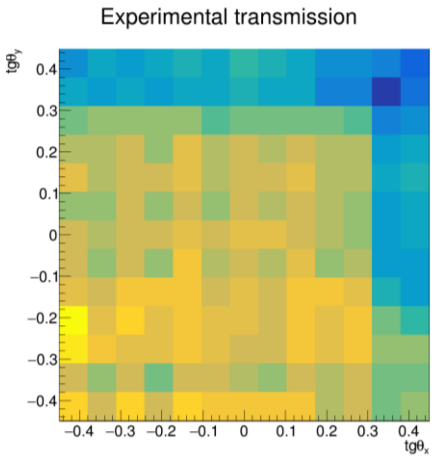
# 2D results

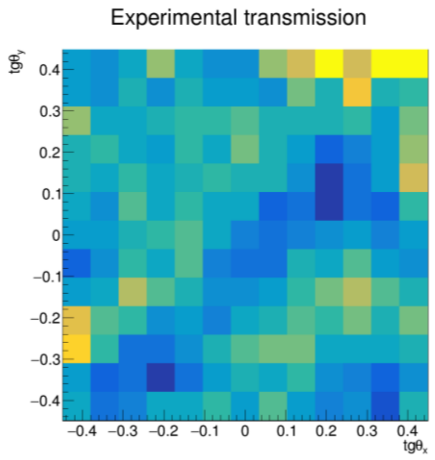

Simulation of transmission
tgθy
tgθx
Transmission

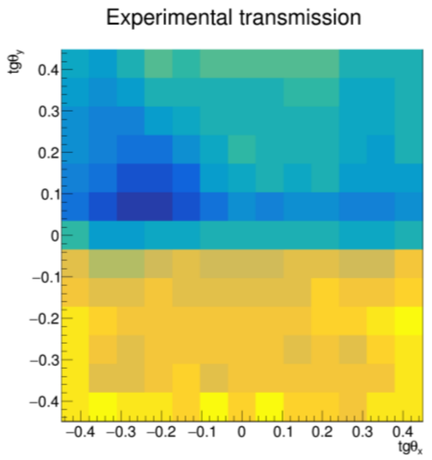

Simulation of transmission
tgθy
tgθx
Transmission

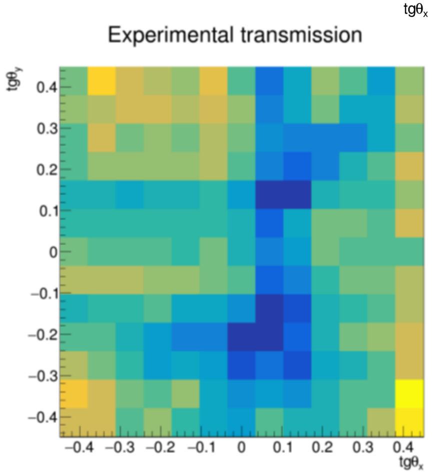

Simulation of transmission
tgθy
tgθx
Transmission


Simulation of transmission
tgθy
tgθx
Transmission


Experimental transmission
tgθy
tgθx


Experimental transmission
tgθy
tgθx


Experimental transmission
tgθy
tgθx


Experimental transmission
tgθy
tgθx

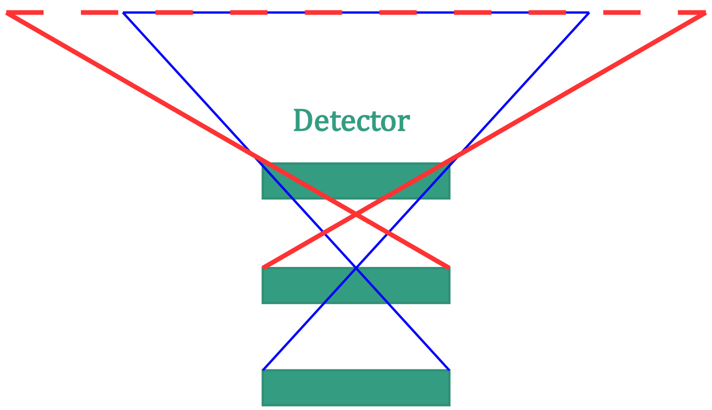
# Combining resolutions

Resorting to different plane combinations there are 3 muographs with different perspectives and resolutions looking at intersecting FOV.

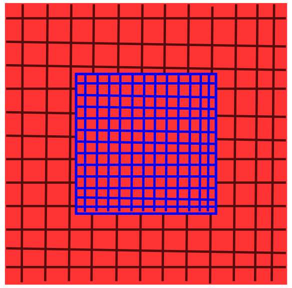
All the maps must be consistent. Iteratively, we try to construct a map with higher resolution (HR) based on this:

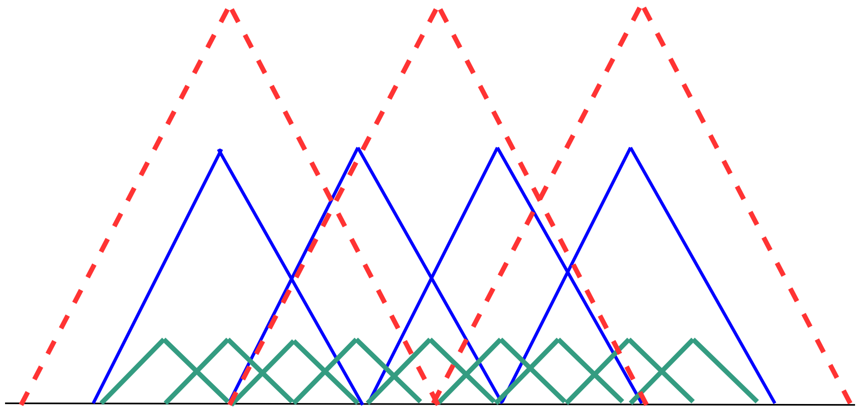
1. For each pixel of the HR, the entries of the LR and VLR maps that share FOV are added with a weight
2. The LR and VLR maps are reconstructed from the HR and compared with the experimental by calculating the residuals
3. Step 1-2 are repeated but with the residuals

FOV = Field Of View



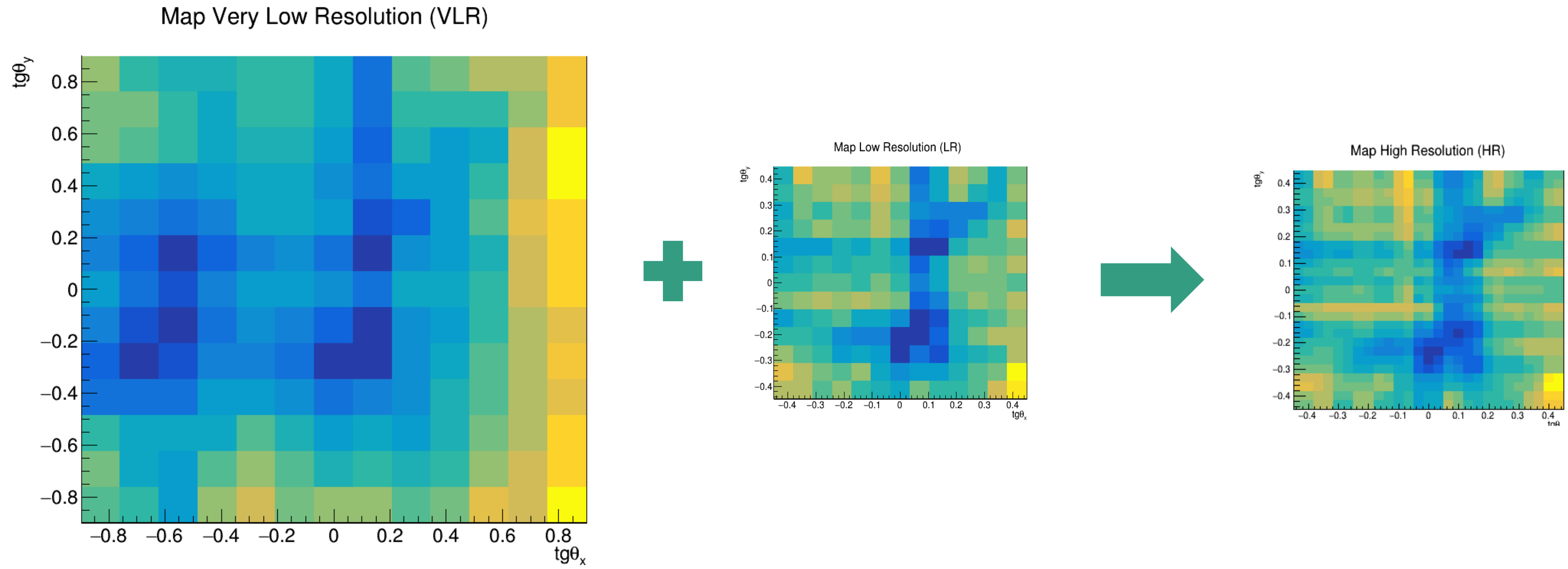

Map Low Resolution (LR)
+
Map Very Low Resolution (VLR)





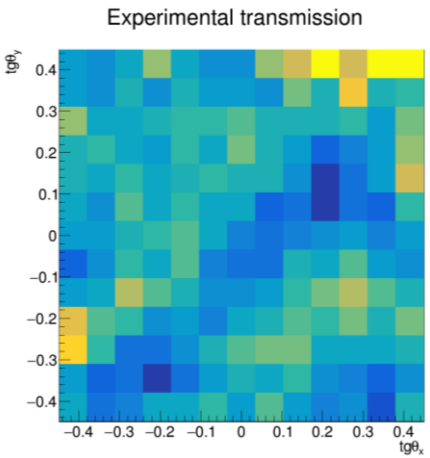
Map High Resolution (HR)

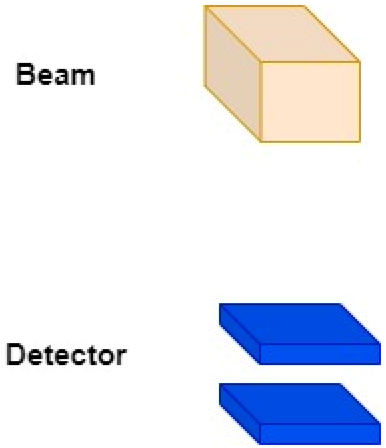
# Combining resolutions

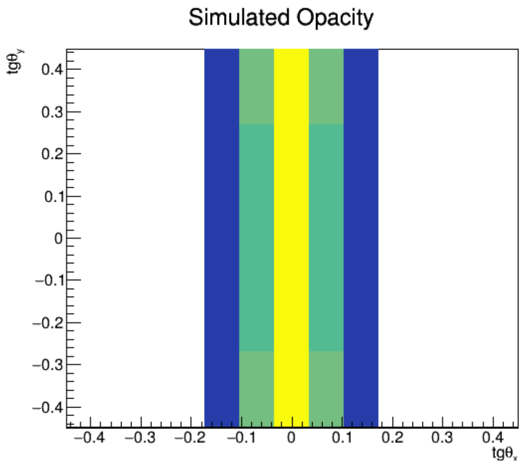


# 3D reconstruction: case study

In one muograph we have a simple object, a beam, oriented 45° to the detector.



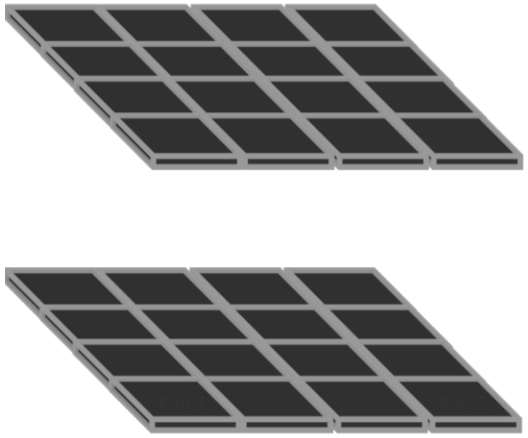



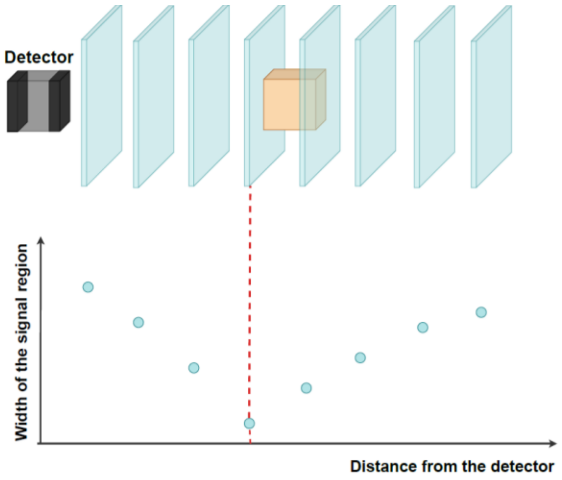

Opacity = Density x Distance

# 3D reconstruction: methods

## Backprojection



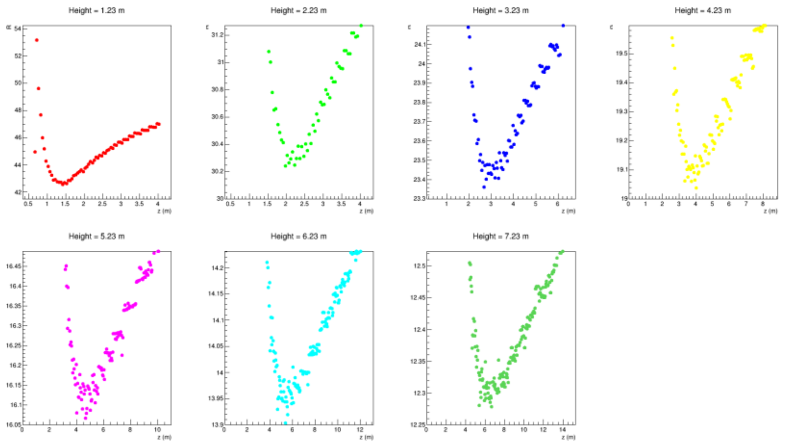
Detector



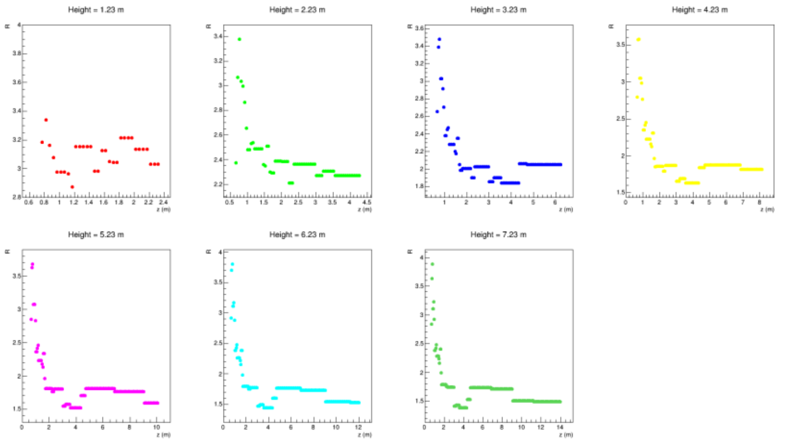

Phil. Trans. R. Soc. A 377: 20180063

Simulation

10x our resolution




Our resolution



# 3D reconstruction: methods

## Analytical inversion

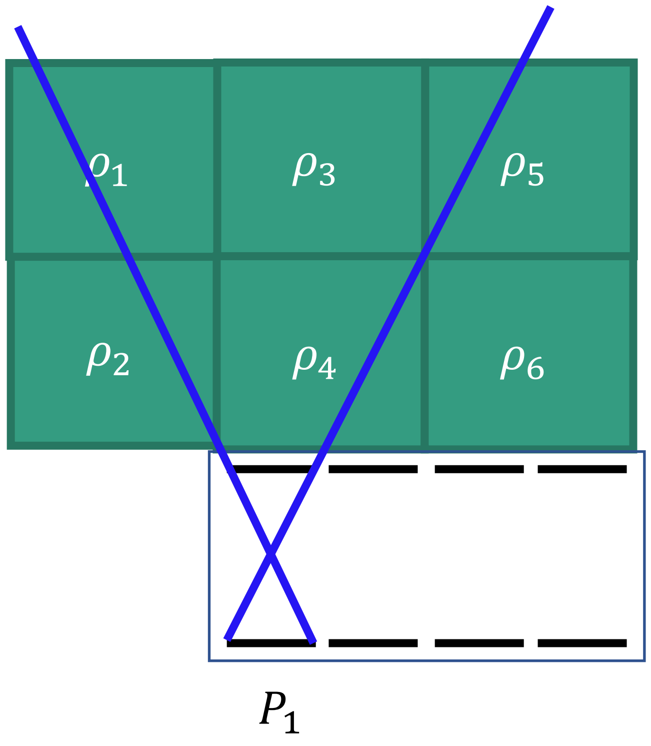
Our problem is given by the following equation

$$\boldsymbol{O^{meas}} = \boldsymbol{AP}$$

Where

- $\boldsymbol{O^{meas}}$ are the measured opacities
- $\boldsymbol{A}$ is the distances matrix
- $\boldsymbol{P}$ is the real world densities vector

$$\vec{O} = \begin{pmatrix} d_{1,1} & \cdots & d_{1,V} \\ \vdots & & \vdots \\ d_{i,1} & \ddots & d_{i,V} \\ \vdots & & \vdots \\ d_{49x49,\,1} & \cdots & d_{49x49,V} \end{pmatrix} \begin{matrix} \rho_1 \\ \vdots \\ \rho_V \end{matrix}$$



# 3D reconstruction: methods

## Analytical inversion

Possible inversions :

1. The Least Squares: $\boldsymbol{P^{rec}} = [\boldsymbol{A^T A}]^{-1}\boldsymbol{A^T O^{meas}}$
2. The Weighted Least Squares: $\boldsymbol{P^{rec}} = [\boldsymbol{A^T W_e A}]^{-1}\boldsymbol{A^T W_e O^{meas}}$
3. The Minimum Length: $\boldsymbol{P^{rec}} = \boldsymbol{A^T}[\boldsymbol{A A^T}]^{-1}\boldsymbol{O^{meas}}$
4. The Weighted Minimum Length: $\boldsymbol{P^{rec}} = \langle \boldsymbol{P} \rangle + \boldsymbol{W_m A^T}[\boldsymbol{A\, W_m A^T}]^{-1}[\boldsymbol{O^{meas}} - \boldsymbol{A}\langle \boldsymbol{P} \rangle]$
5. The Damped Least Squares: $\boldsymbol{P^{rec}} = [\boldsymbol{A^T A} + \boldsymbol{\epsilon I}]^{-1}\boldsymbol{A^T O^{meas}}$
6. The Weighted Damped Least Squares: $\boldsymbol{P^{rec}} = \langle \boldsymbol{P} \rangle + \boldsymbol{W_m^{-1}}\, \boldsymbol{A^T}[\boldsymbol{A W_m^{-1} A^T} + \boldsymbol{\epsilon W_e^{-1}}]^{-1}[\boldsymbol{O^{meas}} - \boldsymbol{A}\langle \boldsymbol{P} \rangle]$
7. …

William Menke, “Geophysical Data Analysis: Discrete Inverse Theory” 1989

# 3D reconstruction: methods

## Iterative reconstruction

1. World initialization
2. Back-projection of experimental muographs (EM)
3. Forward-projection of the world generating reconstructed muographs (RM)
4. Comparison of the EM and RM by calculating the residuals: EM - RM
5. Back-projection of the residuals
6. Truncation of the voxels' densities at a wise interval [0, 3000] kg/m^3
7. Steps 3-5 again until a predefined number of iterations or until residuals are  under predefined threshold

$$\rho_v^j = \rho_v^{j-1} + \Delta\rho_v^j$$

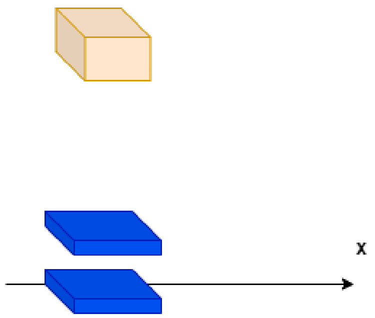
$$\Delta\rho_v^j = \frac{1}{\sum_{m=1}^{N_m} w_m H(A_{m,v})} \sum_{m=1}^{N_m} w_m \frac{O_m - O_m^{j-1}}{\left|\overrightarrow{A_m}\right|^2} A_{m,v}$$

NIM A 1013 (2021) 165665

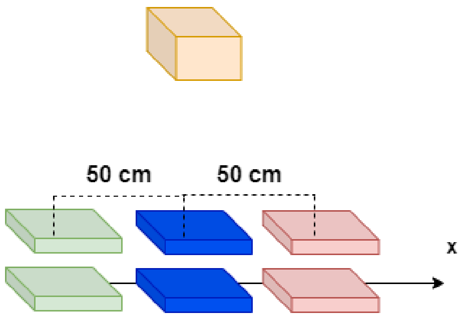
# 3D reconstruction: methods

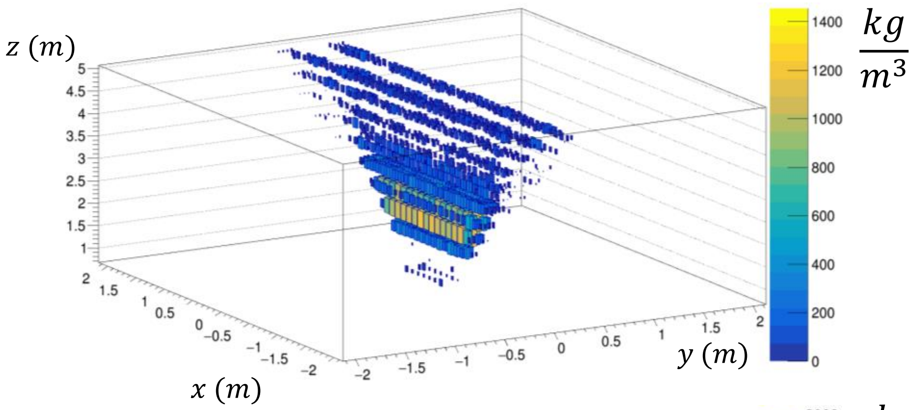
## Iterative reconstruction: simulation

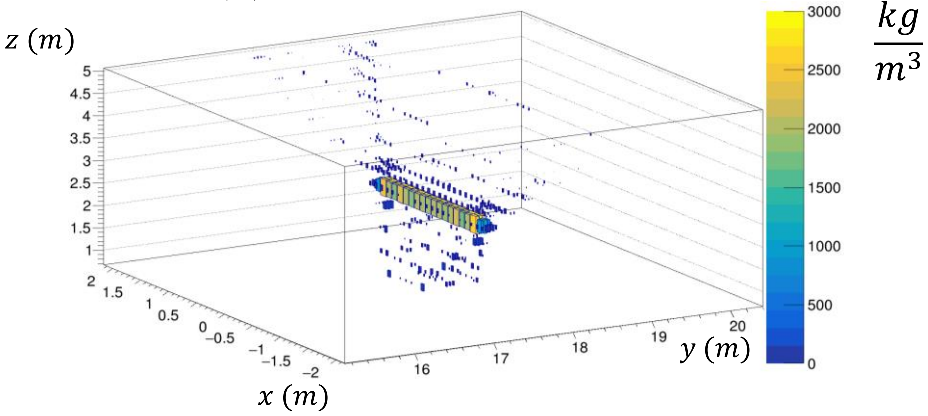
1 Muograph




3 Muographs

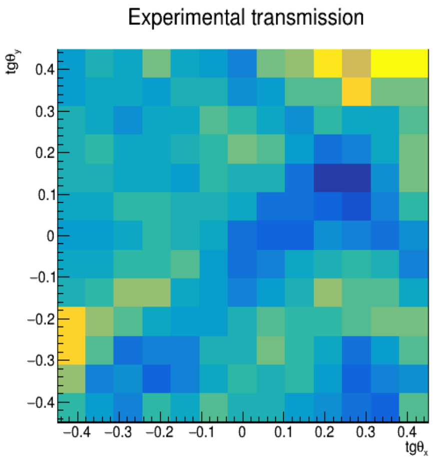


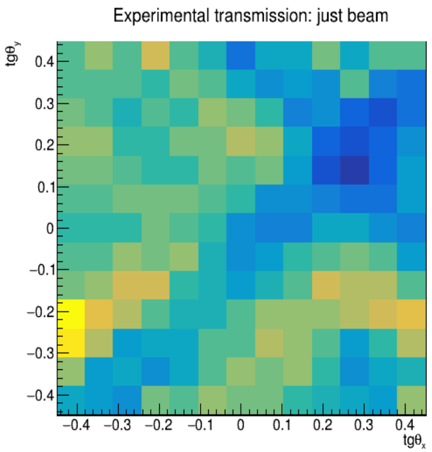



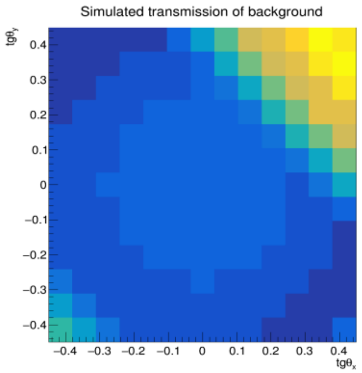
# 3D reconstruction: methods

## Iterative reconstruction: data



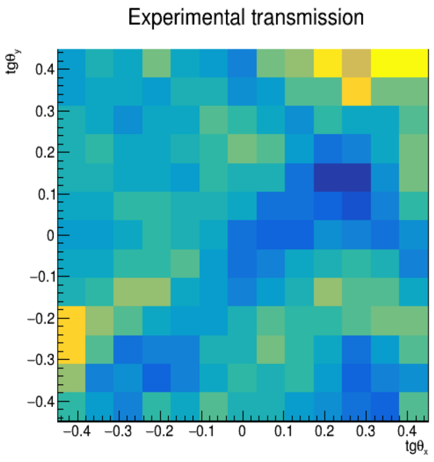



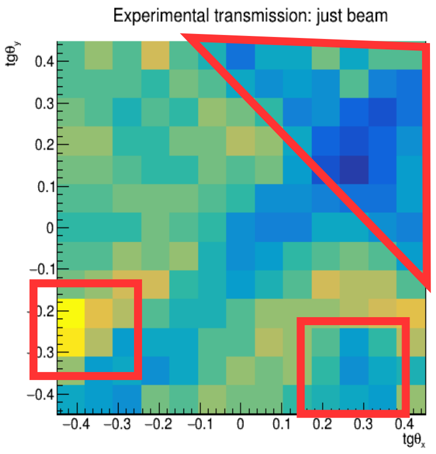

Divide by:

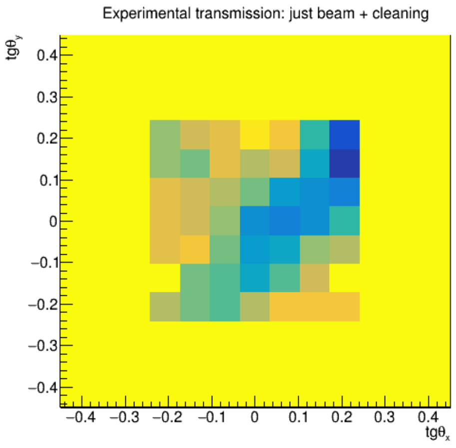


# 3D reconstruction: methods

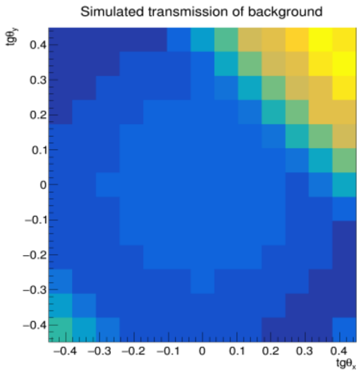
## Iterative reconstruction: data



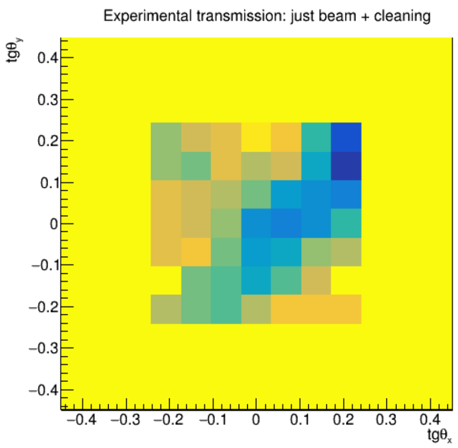

Divide by:

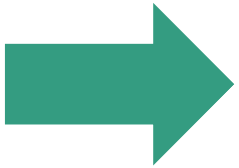



Windowing of region of interest

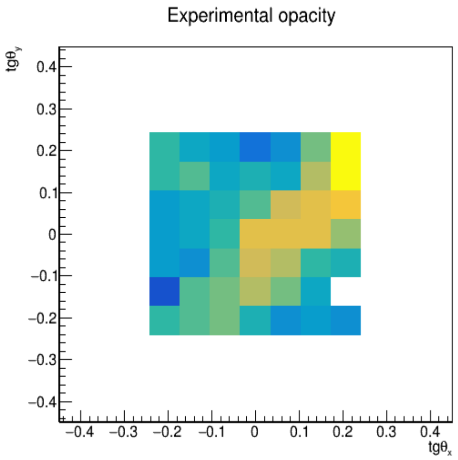
# 3D reconstruction: methods

## Iterative reconstruction: data



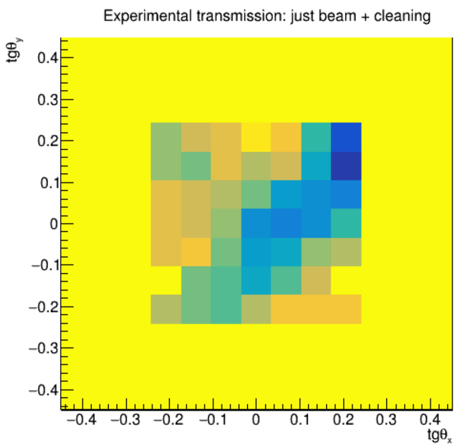



Transformation
to opacity

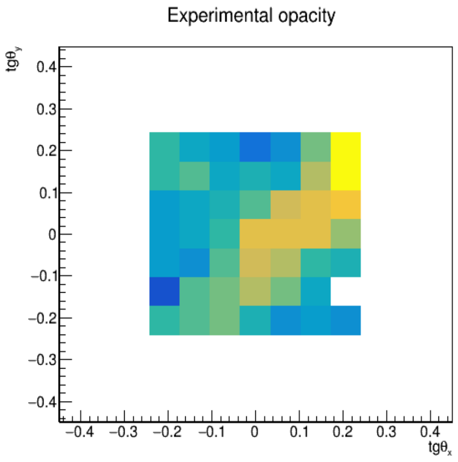


# 3D reconstruction: methods

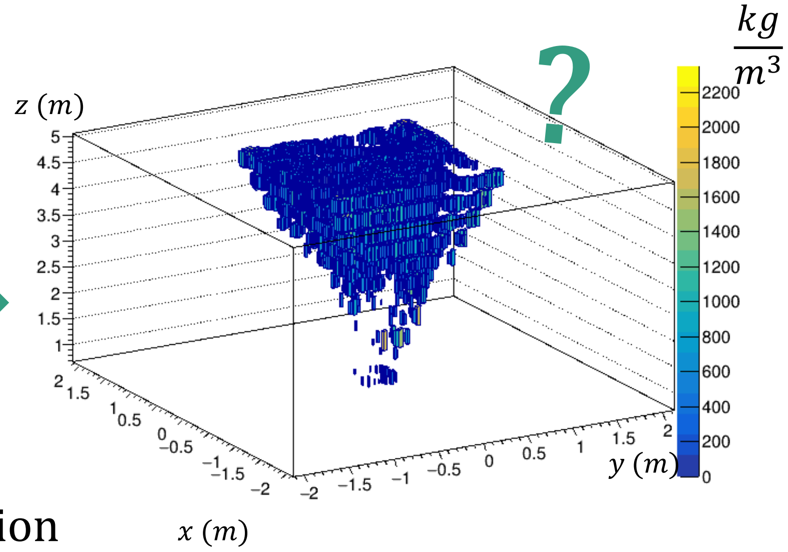
## Iterative reconstruction: data




Transformation to opacity

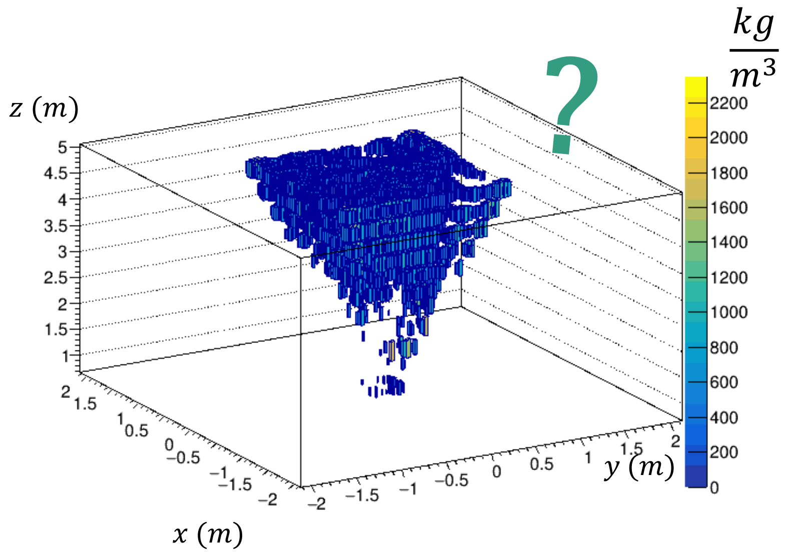



Reconstruction



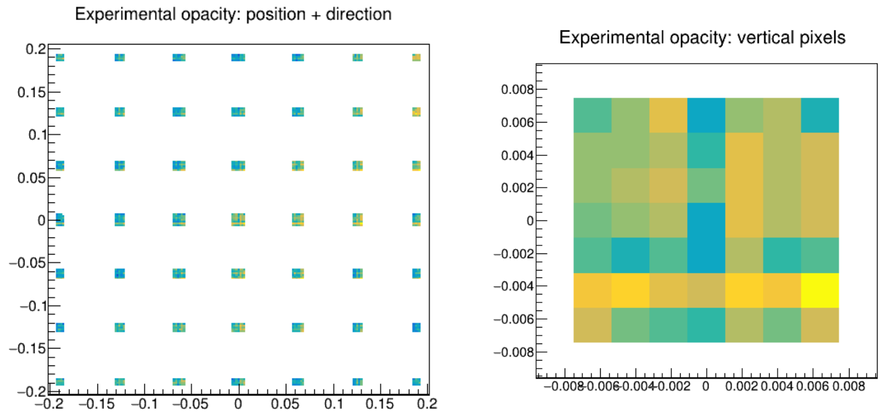
# 3D reconstruction: methods

## Iterative reconstruction: data

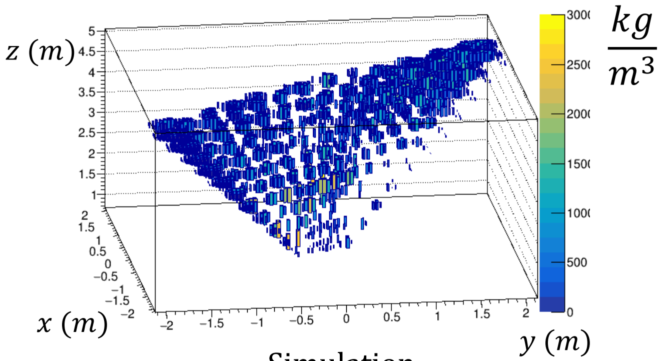



Troubleshooting

Incoherent pixel opacities




Beam and detector not oriented




Simulation

# Future work

**Data analysis**

- Improve the detector model: more accurate characterization of the spacers and dead area
- Study the open-sky muon flux at Coimbra through indirect measurements

**Reconstruction methods**

- Continue the development of the analytical inversion
- Introduce more structures into the simulation and reconstruct them with the iterative method
- Continue to apply the developed reconstruction algorithms to the data
- Propagate uncertainties through the reconstruction algorithms

# Thank you for your attention

## Any questions?

Partners:

Funding:

Team:

**Instrumentation and Particle Physics Team (LIP)**

Lisbon Pole:

Bernardo Tomé, Isabel Alexandre, Lorenzo Cazon, Marco Pinto, Mário Pimenta, Luis Afonso, Pedro Assis, Sofia Andringa

Coimbra Pole:

Alberto Blanco, João Saraiva, Jorge Francisco Silva, Luís Lopes, Paolo Dobrilla

Minho Pole:

Magda Duarte, Raul Sarmento

**Geophysics Team**

ICT – UÉvora:

Bento Caldeira, Ines Hamak, José Borges, Josué Figueira, Mourad Bezzeghoud, Pedro Teixeira, Rui Oliveira

LNEG:

João Matos

**Outreach Team**

CCV do Lousal:

João Costa, Vanessa Pais

# Simulation: transmission model

Exponential model for transmission: being $t$ the transmission of a single ceiling of density $\rho_{ceil}$ and width $D_{ceil}$

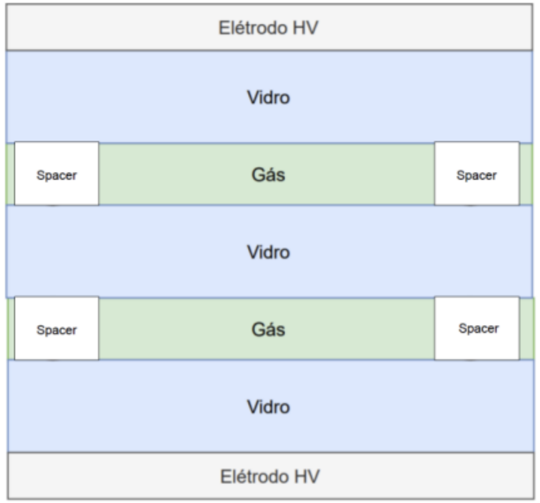
| Acquisition | # ceilings above the detector | Transmission | t |
|---|---|---|---|
| August 2020 | 7 | $t_A = t^7$ | $t = \sqrt[5]{\frac{t_A}{t_S}} \approx 0.94$ |
| September 2020 | 2 | $t_S = t^2$ | |

So, for the passage of the muon on an object of density $\rho$ by a distance $D$, the equivalent number of unit ceilings is calculated:

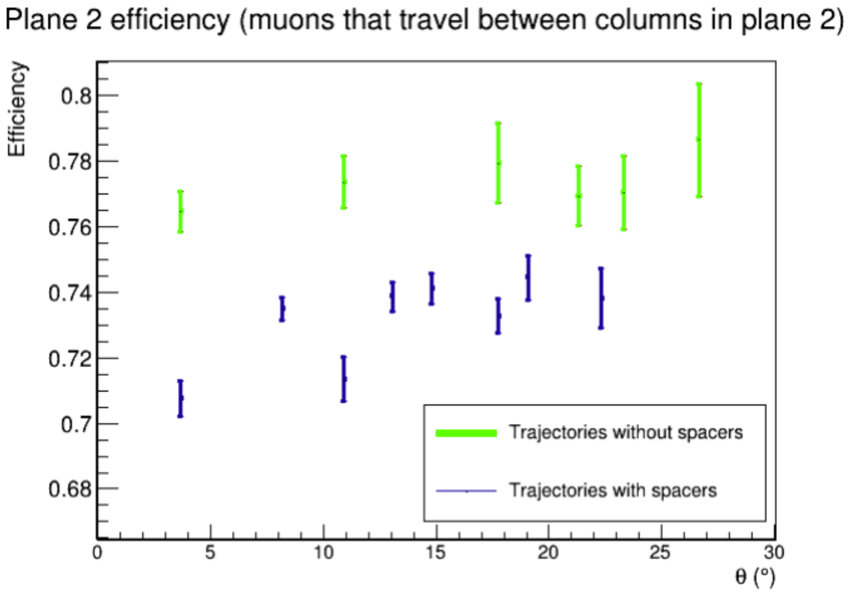
$$\#\, unit\ ceilings = \frac{D}{D_{ceil}} \times \frac{\rho}{\rho_{ceil}}$$

$$T = t^{\#\, unit\ ceilings}$$

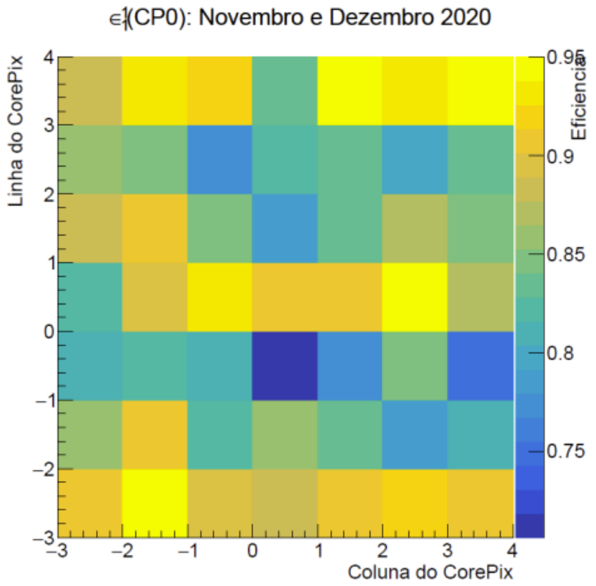
# Efficiency



Elétrodo HV
Vidro
Spacer
Gás
Spacer
Vidro
Spacer
Gás
Spacer
Vidro
Elétrodo HV

Plane 2 efficiency (muons that travel between columns in plane 2)
Efficiency
θ (°)
Trajectories without spacers
Trajectories with spacers

∈(CP0): Novembro e Dezembro 2020
Linha do CorePix
Coluna do CorePix
Eficiencia

# Using the extension of the detector