University of BRISTOL

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Development of muon scattering tomography for a detection of reinforcement in concrete

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Goal

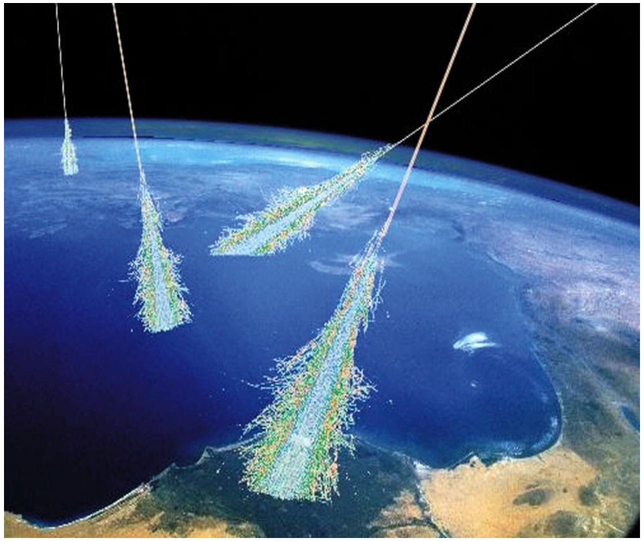
- Inspection of big, reinforced concrete structures is an on going problem;
- Existing non-destructive scanning techniques have many limitations to inspect thick items;
- Muon scattering tomography is a promising tool to address this challenge.

https://basiccivilengineering.com/2019/09/reinforced-concrete-and-importance-of-rebar.html

Why muons?

Muons:

- Large angular and energy spread.
- Flux and energy of muons depend on the zenith angle.
- naturally occur at decent rates (~100 Hz/m^2)
- They can penetrate several kilometers of rock!
- Charged particles – can be easily detected;
- All these combined make muons an excellent probe to study enclosed spaces from a safe distance.



https://www.space.com/32644-cosmic-rays.html

Secondary cosmic rays:

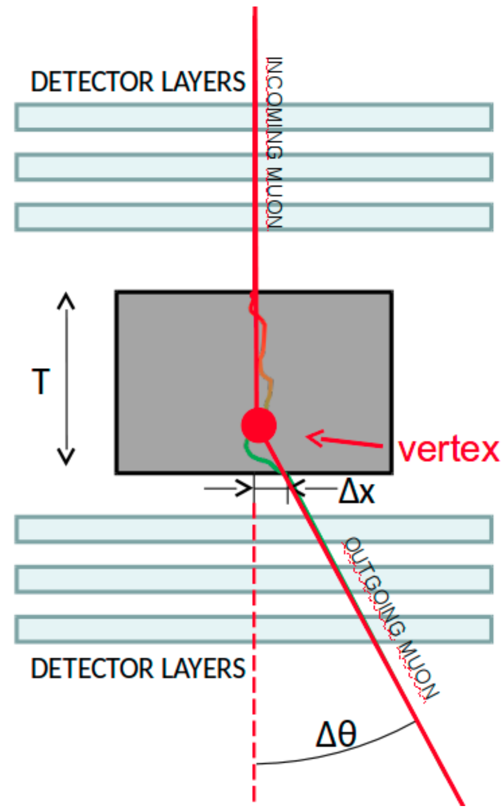
<u>Muon scattering depends on material it traverses!</u>

Muon scattering tomography

- It relies on multiple scattering of cosmic muons on the atoms in the traversed material;
- Measurement of the muon trajectory before and after leaving the tested volume – angle, θ, and vertex reconstruction;
- The angular distribution is Gaussian, with σ_0 depending on the radiation length X_0 and thus on Z (atomic number):

$$\sigma_\theta \approx \frac{13.6\,MeV}{\beta pc} z \sqrt{\frac{z}{X_0}} [1 + 0{,}038 \ln(\frac{xz^2}{X_0 \beta^2})]$$

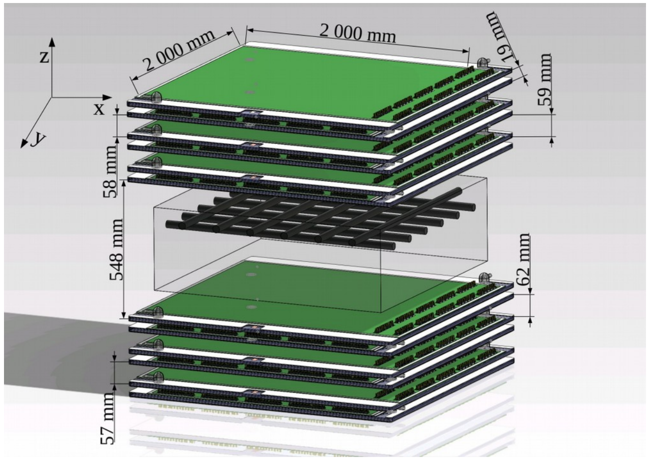
$$X_0 \approx \frac{716.4\,A}{Z(Z+1)\ln(\frac{287}{\sqrt{(Z)}})} [g \cdot cm^{-2}]$$

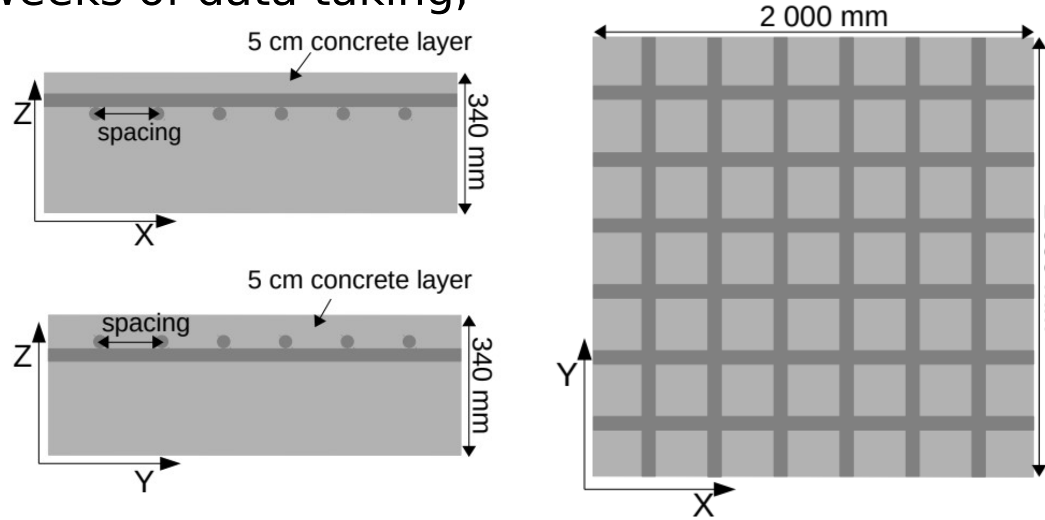


- The Z^2 means that the technique is very sensitive for high-Z materials a contrast of high-Z and low-Z material!

Simulations - Geant4

- Muon scattering tomography can be used to scan big concrete structures;
- Simulations of reinforced concrete block 200 cm × 200 cm × 34 cm;
- Mesh sizes are common in industry:
  - rebar diameters between 6 and 20mm;
  - mesh spacing 7.5, 10, 15 and 20 cm
- Simulation based on real system performance which resulted in a position resolution of approximately 450 μm;
- Simulation worth one or two weeks of data taking;

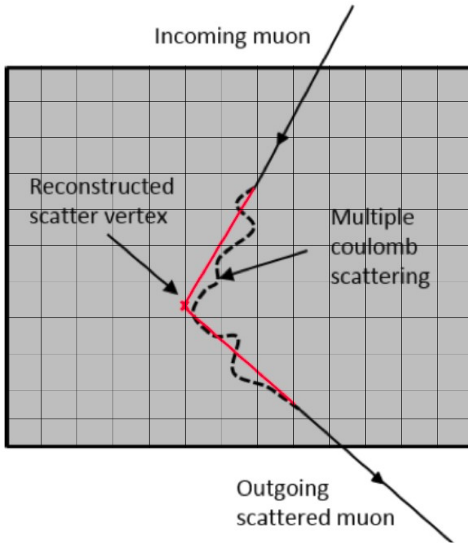




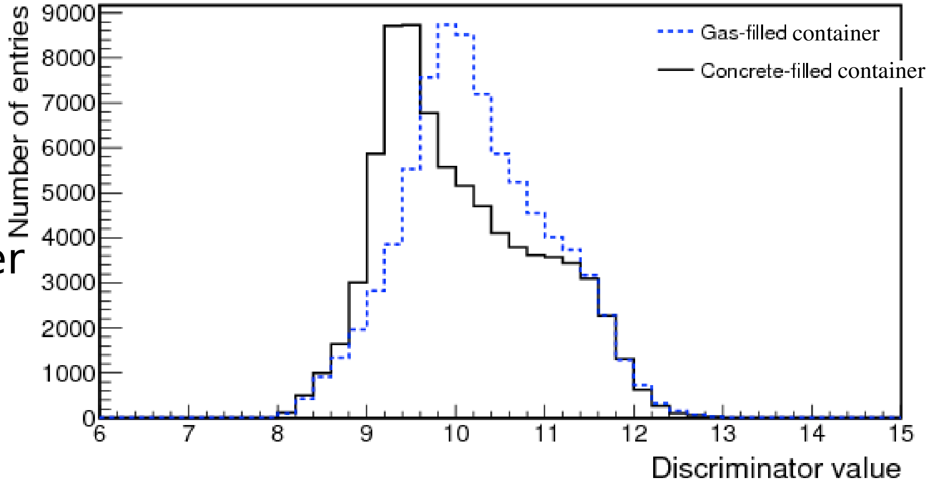
Our reconstruction method - metric method

- Divide scanned volume into voxels;
- Rely on ‘clusteredness’ of the high scattering vertices;
- Based on reconstructed vertex position ($V_{i,j}$), weighted metric for each pair of vertices in each voxel:

$$m_{ij} = \frac{||v_i - v_j||}{\theta_i \theta_j}$$

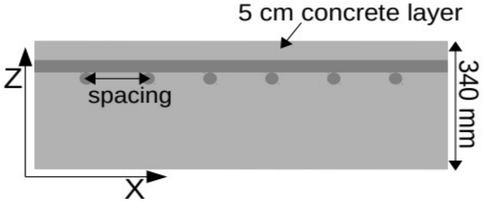


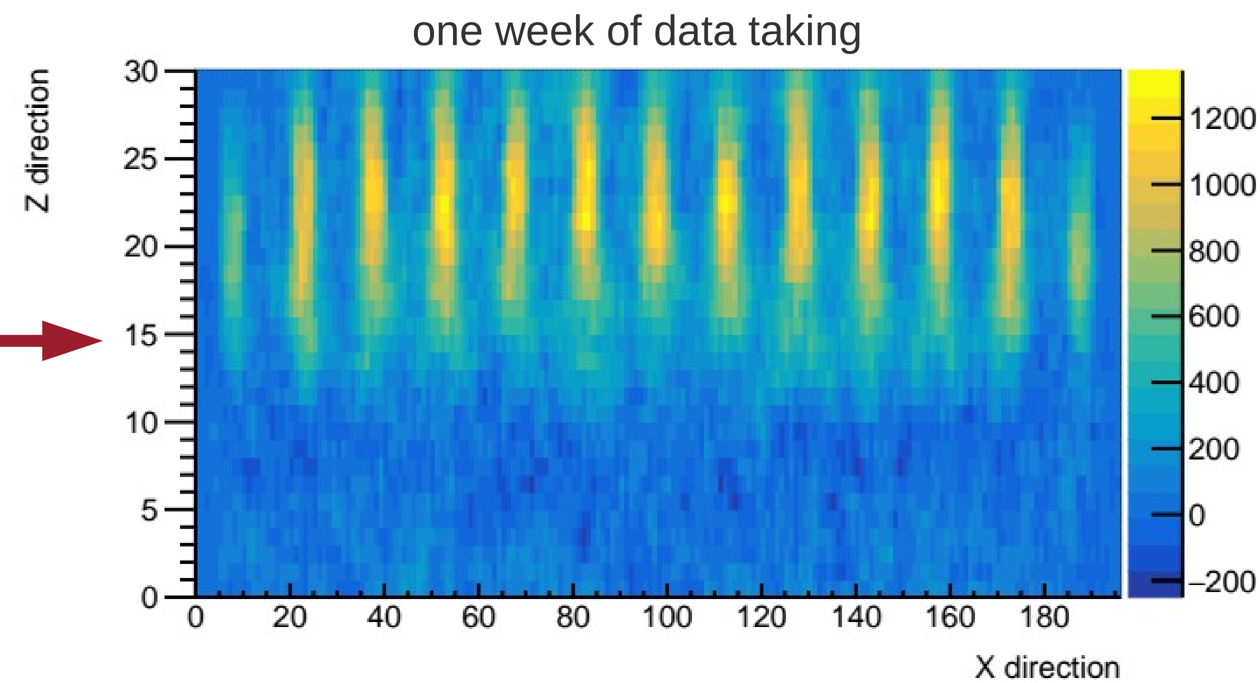
- Median of the metric distribution in a single cubic bin – **discriminator value;**
- **Discriminator distribution is different for every material;**
- Mean of discriminator distributions from analysed voxels are the basis of the further analysis;



Applying method to rebar grid in concrete

- Applying a mean of discriminator distribution method to sub-volumes;



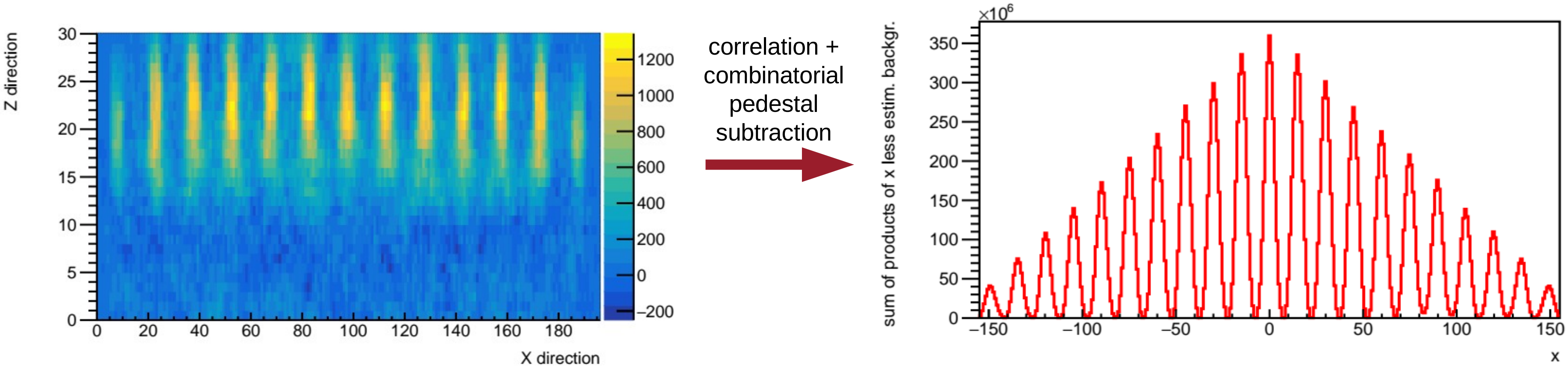


- Background was defined as a pure concrete block and subtracted from image plot of studied scenario;

Correlation

- Reinforcement is repetitive structure and provides a periodic signal which can be detected;
- This is done by calculating the correlation of the 2D histogram:

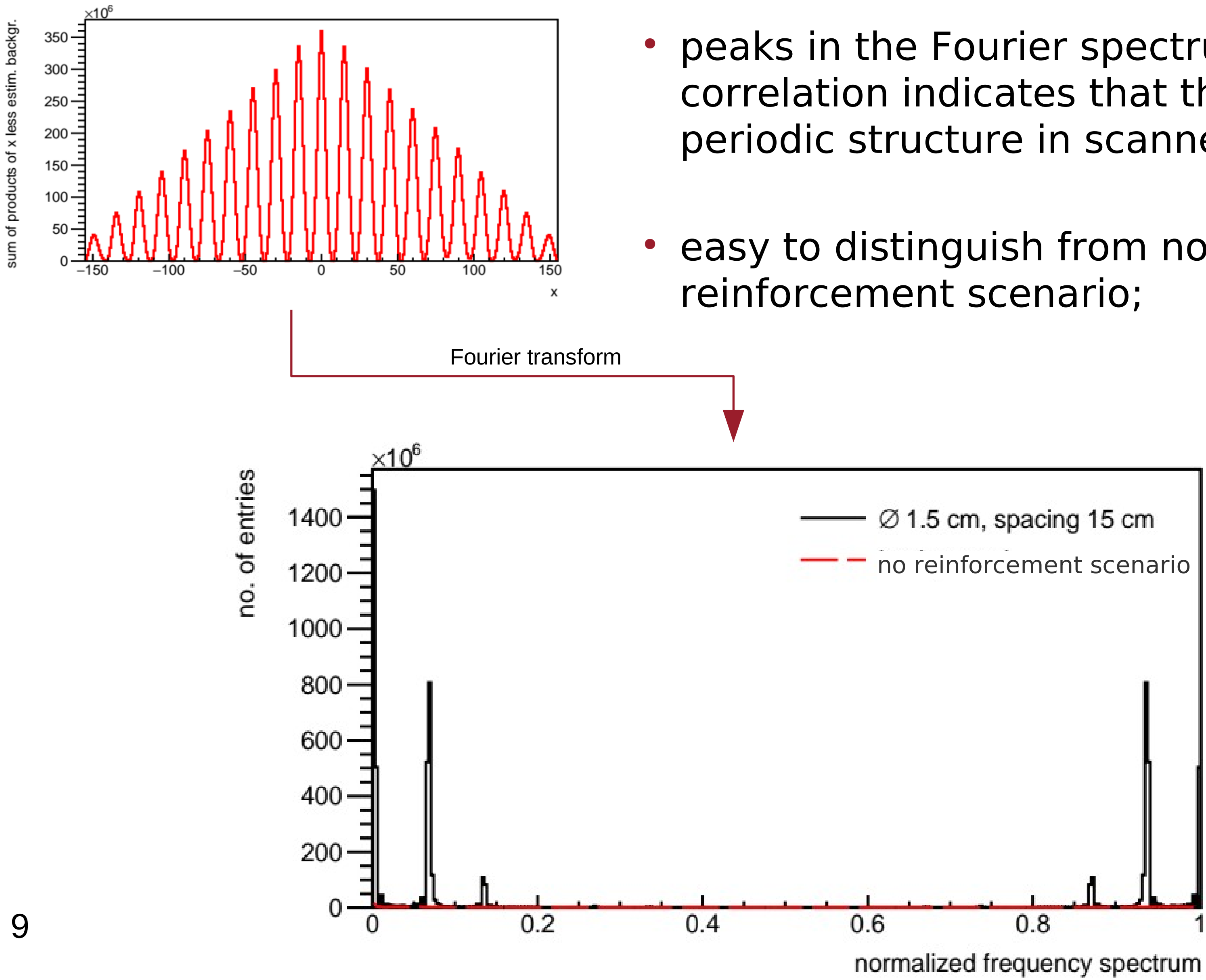
$$R_s(\tau)=\int_{y_{min}}^{y_{max}}\int_{x_{min}}^{x_{max}} f(x',y')f(x'+\tau,y')dx'dy'$$



- The triangular shape is due to the variation of the overlapping area. It is observed as the triangular dependence of the amplitude of the periodic structure;
- The periodic structure is due to the reinforcement spacing.

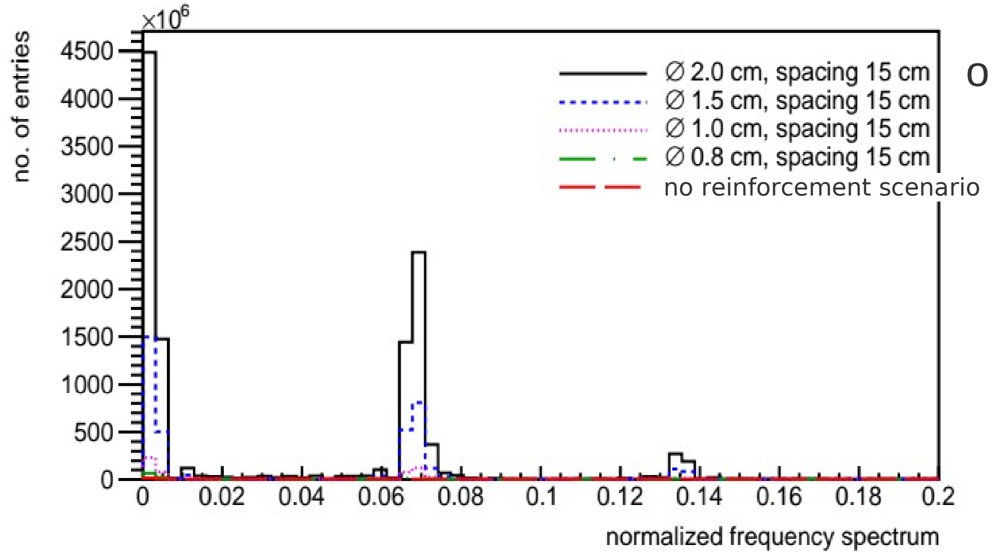
Fourier transform

- peaks in the Fourier spectrum of the correlation indicates that there is a periodic structure in scanned object;
- easy to distinguish from no reinforcement scenario;

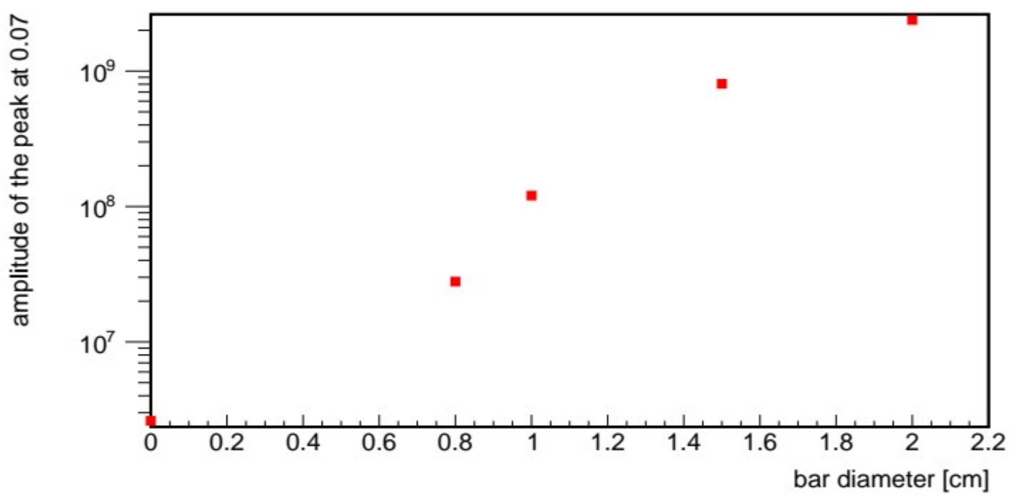


Measuring rebar diameter

- We can measure rebar diameter since peak amplitude depends on the diameter of the bar.

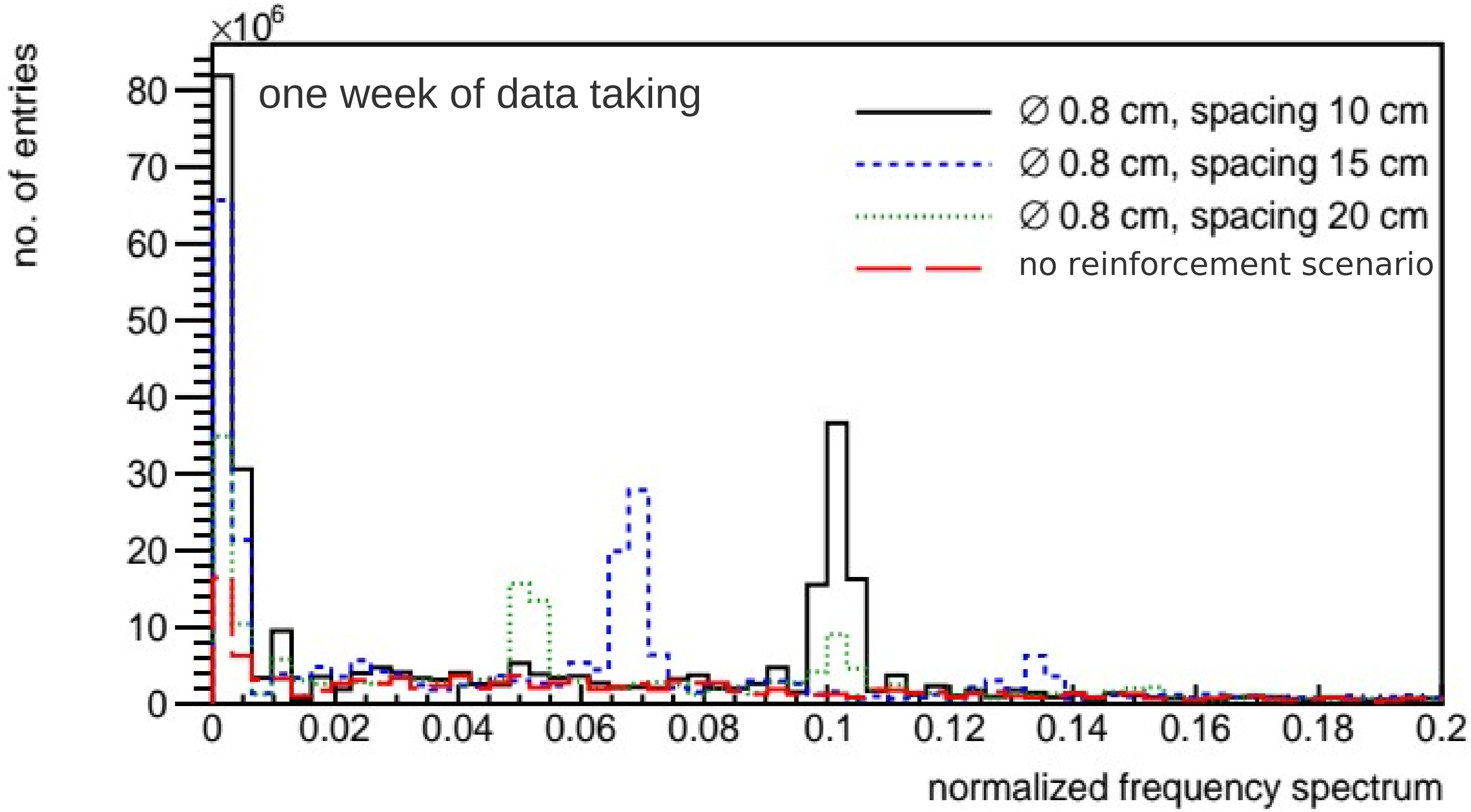


one week of data taking



Determination of the spacing

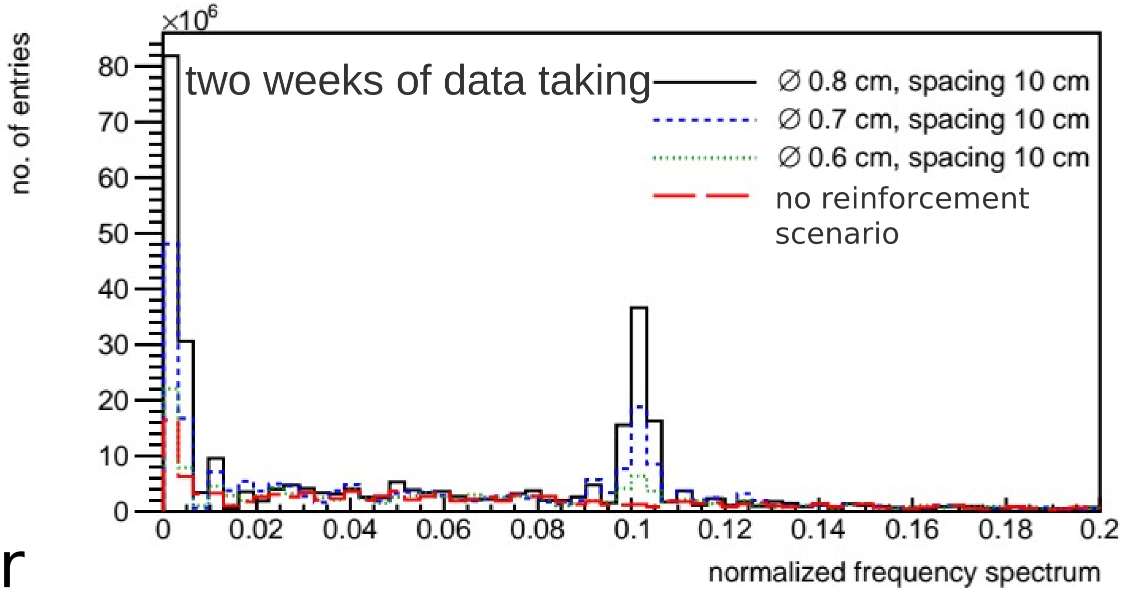
- The peak locations yield the reinforcement spacing;

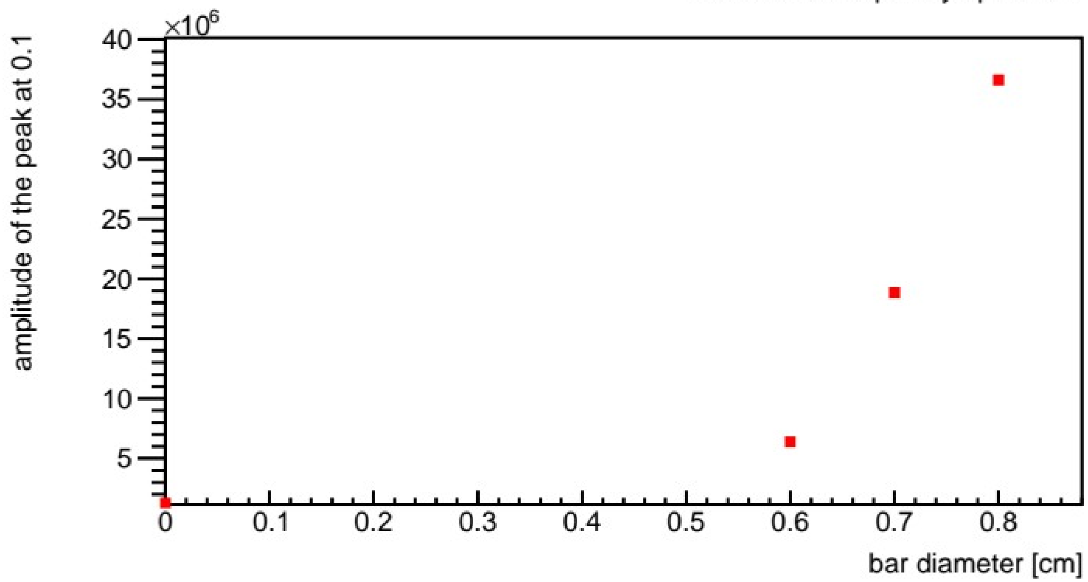


Limits of the method

- The smallest rebar currently used in industry is 6 mm;

- We can detect it after two weeks of data taking;



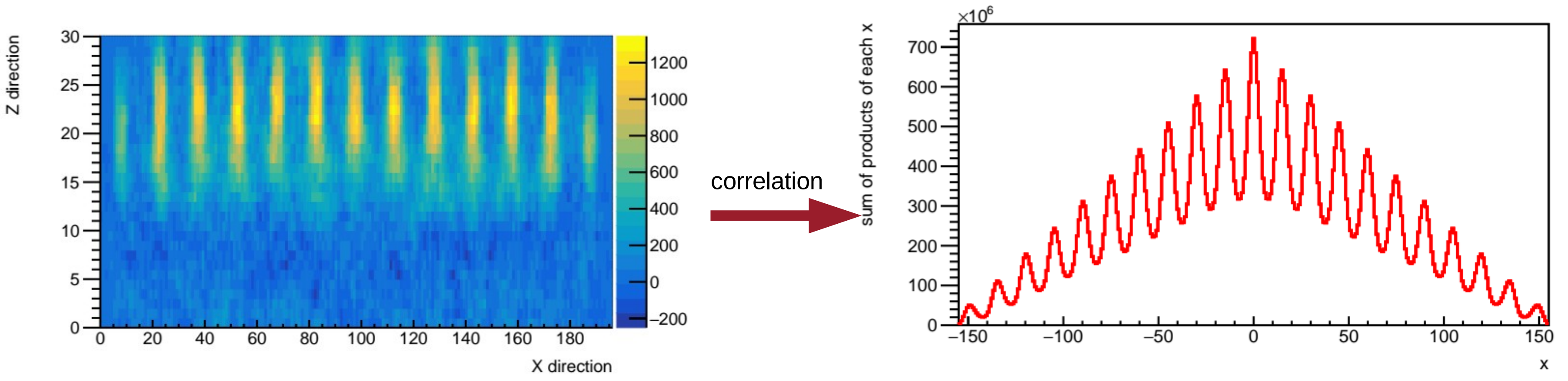


Summary

- Muon scattering tomography is a great technique to detect reinforcement in concrete structures: passive, uses naturally occurring radiation so no radiation introduced;
- The periodicity of the reinforcement results in peaks in Fourier spectrum;
- Peak location depends on the spacing of the rebars, while peak height depends on the rebar diameter;
- We can detect the smallest rebars used in industry, 6 mm diameter;
- Detailed description of the reinforcement studies can be found in:
  - Magdalena Dobrowolska *et al* 2020 *Smart Mater. Struct.* 29 055015
  - Magdalena Dobrowolska *et al* 2021 *Eng. Res. Express* 3 035037

Back up slides

Background subtraction

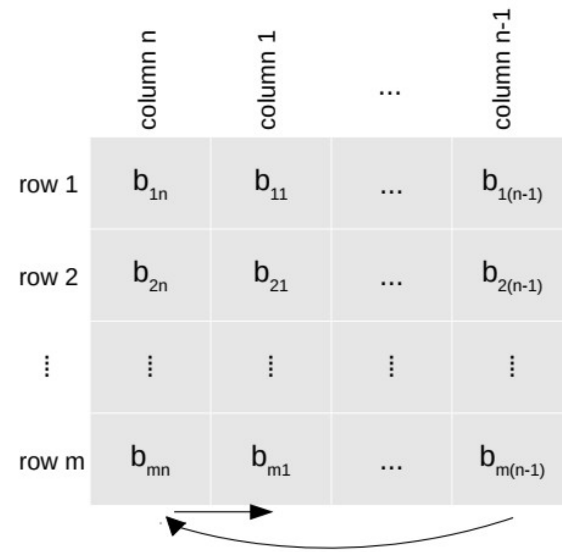


The triangular shape is due to the finite size of the mask. The autocorrelation of the background yields the triangular shape. The rebar mesh yields the peaks.

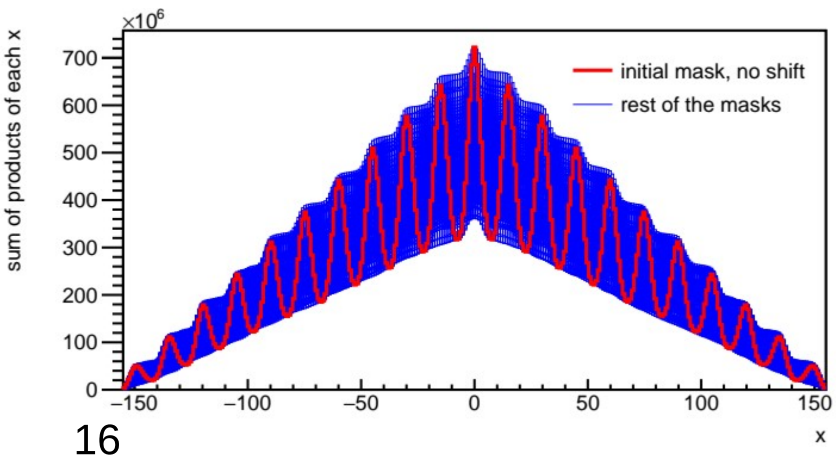
Background subtraction

- Before the Fourier transformation, that triangular background needs to be subtracted. To estimate it, the complete series of correlations, $R_{b,k}$ is calculated, where the mask is defined:

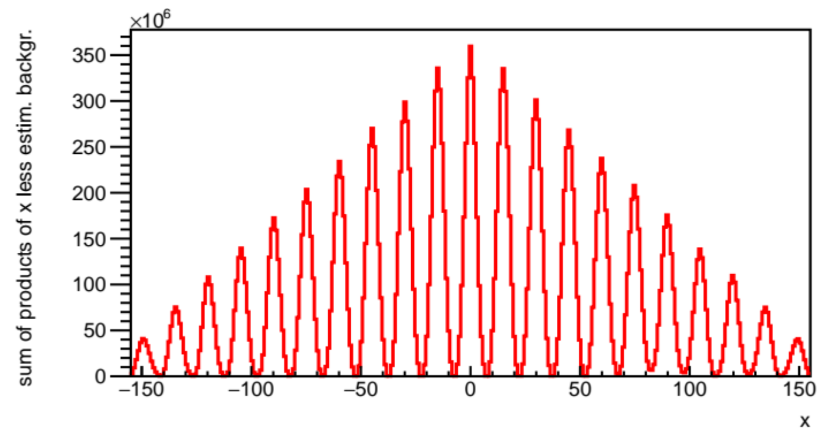
$$R_{b,k}(\tau)=\int_{y_{min}}^{y_{max}}\int_{x_{min}}^{x_{max}} f(x',y')f(x'+\Delta_k+\tau,y')\,dx'\,dy'$$



- For each bin in the signal correlation, the minimum value of $R_{b,k}$ is subtracted;



Triangular background subtraction

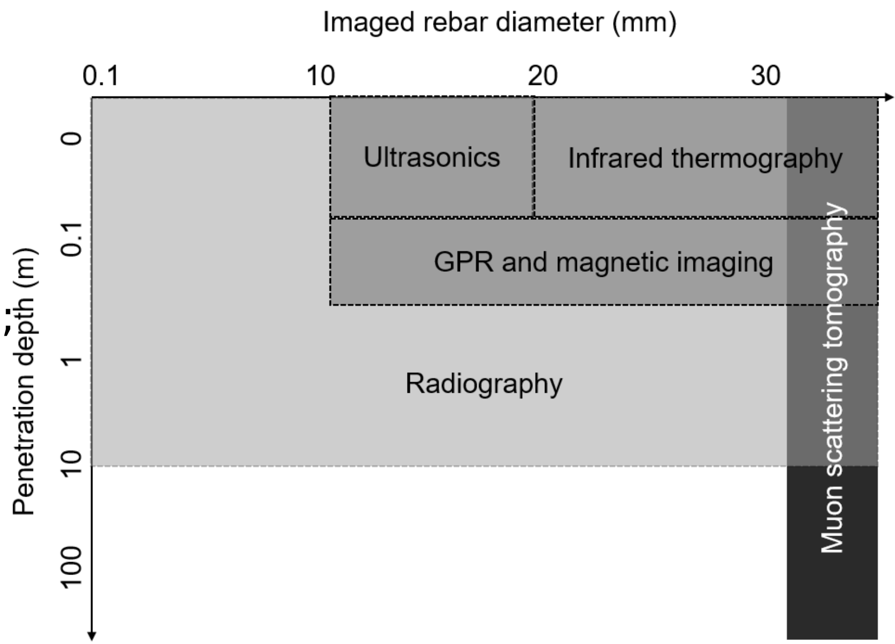


Critical comparison with existing imaging methods

- Magnetic imaging and ground penetrating radar:
  - 10–20 mm diameter rebars at depths of 10–50 cm;
  - GPR is affected by ground moist fine silts;
- infrared thermographics and ultrasonics:
  - can fill any low-depth imaging at < 20 cm;

  All of these techniques excel in quantifying rebar thickness and location, but precise rebar size estimation is still an ongoing challenge;

  Errors dramatically increasing with penetration depth and rebar congestion;
- High resolution and high depth imaging can be realised using x-ray and neutron radiography. However, as the use of active sources of radiation presents an acute risk to human health, it is rare to see these techniques applied outside of laboratory post-mortem testing.



Magdalena Dobrowolska *et al* 2020 *Smart Mater. Struct.* 29 055015

Introduction

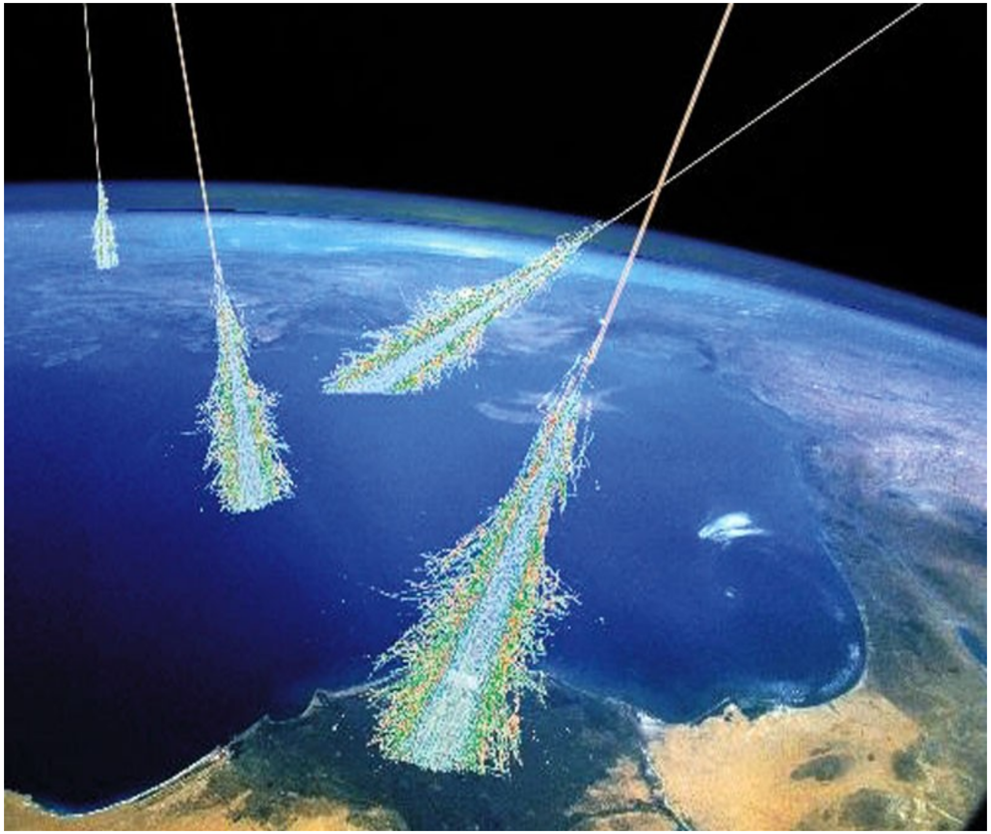
- There has been a real surge in cosmic ray tomography over the last 10 years.
- Muon imaging is a technique to explore closed volumes from a safe distance.
- Muon imaging was first pioneered/ reinvented by Hiroyuki Tanaka
  - Prof Tanaka is measuring the 3D density structure of volcanoes.
- Now people are working on
  - homeland security
  - legacy nuclear waste
  - volcano imaging
  - carbon capture and storage monitoring
  - mining
  - …

https://royalsociety.org/science-events-and-lectures/2018/05/cosmic-ray-muography/

What are cosmic rays?

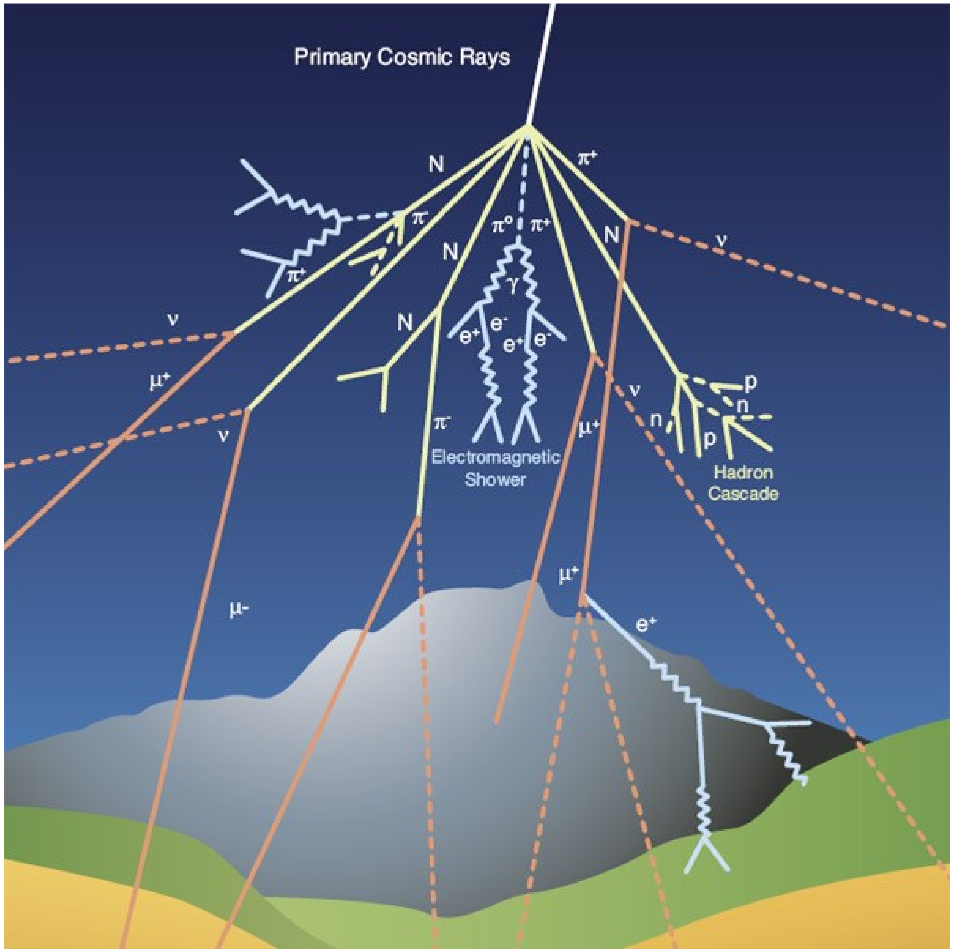
Cosmic rays:

- are high energy, charged particles,
- are background radiation,
- have velocities near the speed of light;



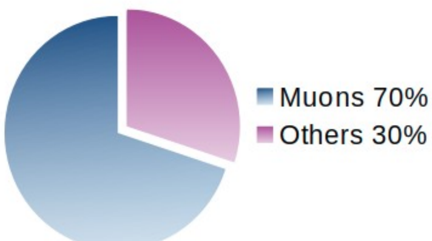
https://www.space.com/32644-cosmic-rays.html

How do cosmic rays interact?



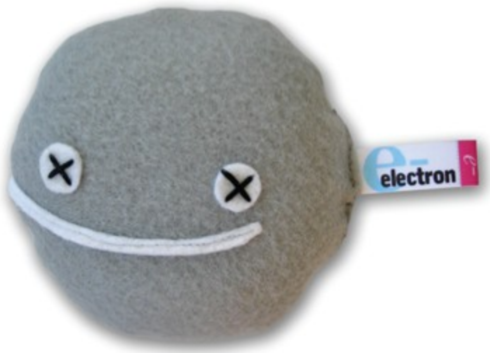
https://cds.cern.ch/images/CMS-PHO-GEN-2017-008-1

Primary cosmic rays (protons and light nuclei) interact in the atmosphere and decay into showers of secondary cosmic rays. Most of them are pions which swiftly decay to muons.



On Earth, we are constantly bathed in (secondary) fundamental particles from cosmic rays.

Muons

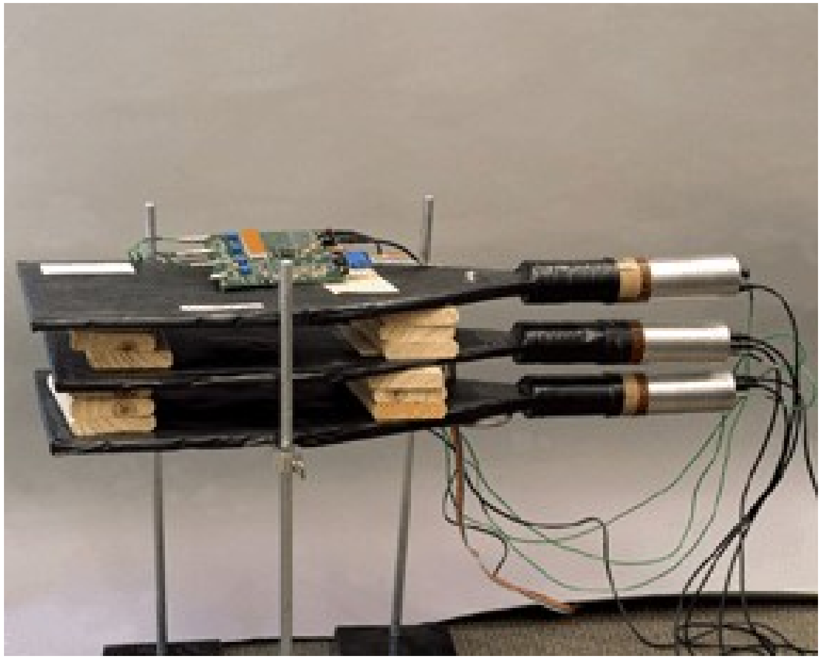


- $M = 105.66\ MeV/c^2 = 1.88 \times 10^{-28}$ kg
- Same charge as electrons
- Large angular and energy spread.
- Flux and energy of muons depend on the zenith angle.
- naturally occur at decent rates (~100 Hz/m^2)
- They can penetrate several kilometers of rock!
- All these combined make muons an excellent probe to study enclosed spaces from a safe distance.

https://www.particlezoo.net/products/muon, https://www.particlezoo.net/products/electron

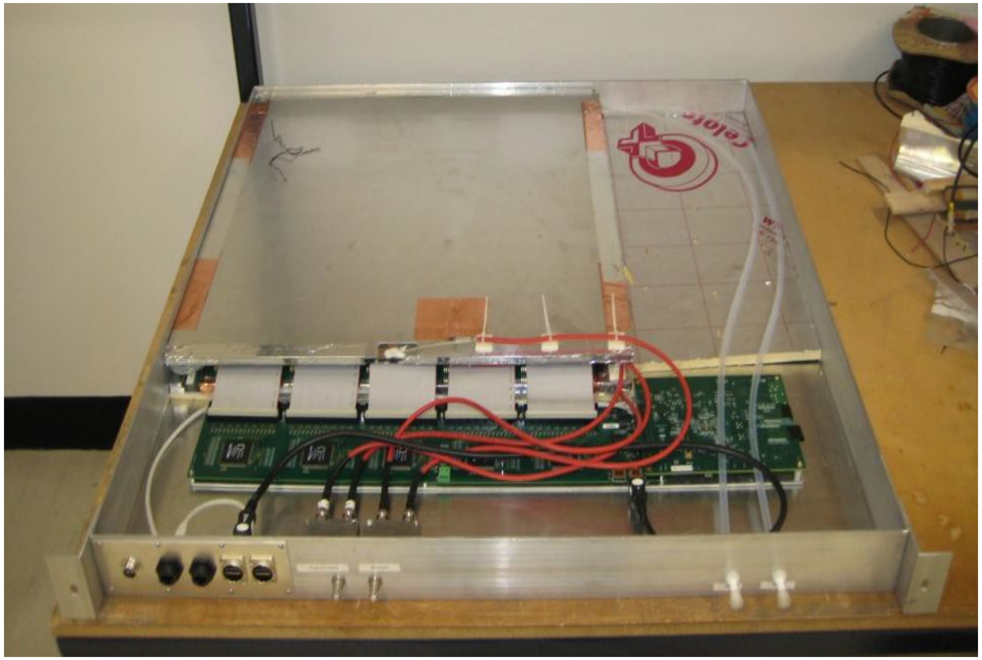
How can we detect muons?

scintillators



- A scintillator is a material that emits light under the influence of an ionizing radiation.
- If the particle has enough energy to excite the material, a signal is produced and measured.

gas detector



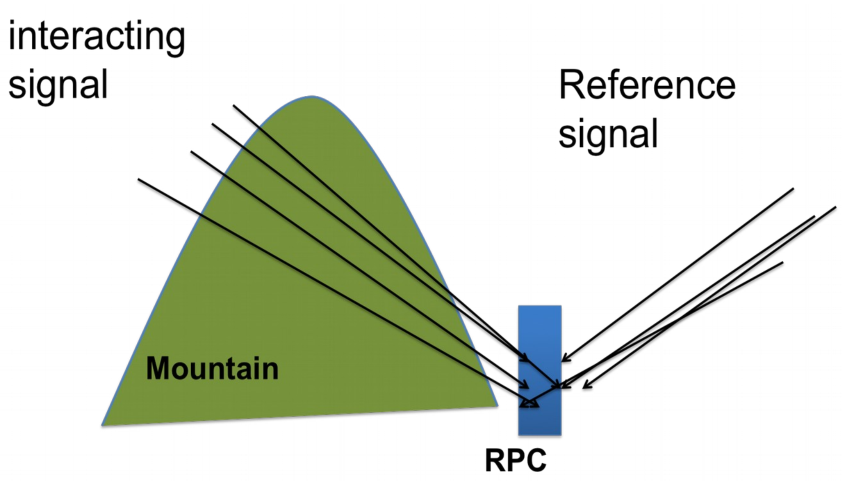
- Gas detectors use the ionising effect of radiation.
- If a particle (muon) has enough energy to ionize atoms or molecules of gas, a signal is produced and measured.

Applications of muon tomography

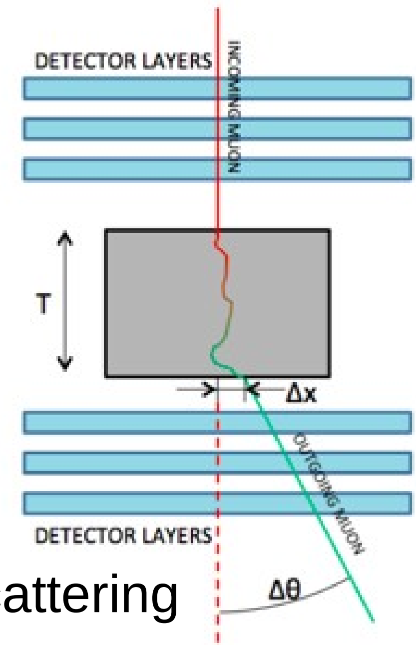
- imaging of hidden, unknown objects
- different types of detectors are used
- two techniques:

radiography

scattering tomography



muon absorption



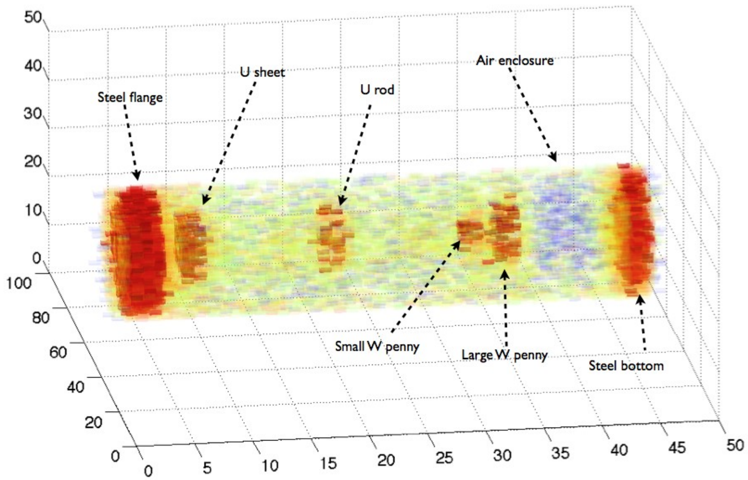
muon scattering

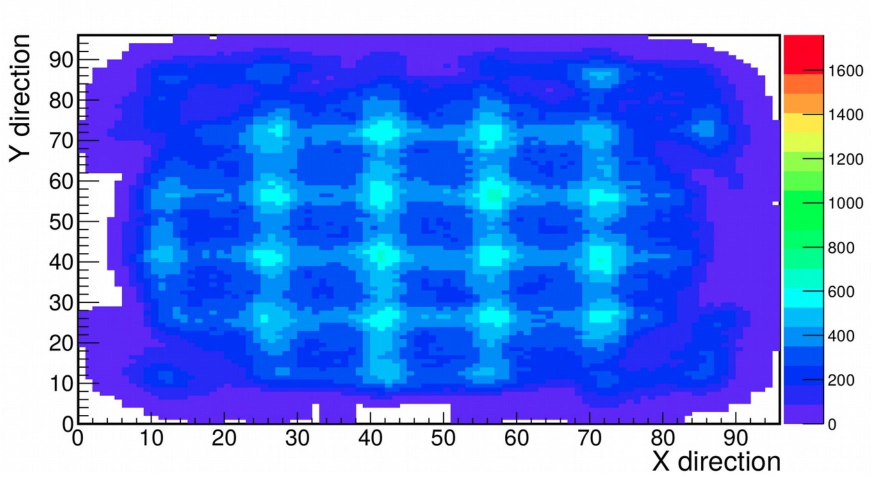
What is muon imaging and what is not?

- It provides lot of information about the material studied:
  - local density
  - presence and location of air bubbles and rebars in concrete
  - measurement of thickness of embedded objects
  - information of the corrosion of embedded iron
- What it does not do:
  - “traditional” imaging in terms of pretty pictures
- Major advantages:
  - does not require additional radiation sources
  - can stand quite far away;
  - does not interfere with anything else that goes on site
- Disadvantage:
  - it is not quick
  - need to ask the right questions

Muon scattering tomography in Bristol

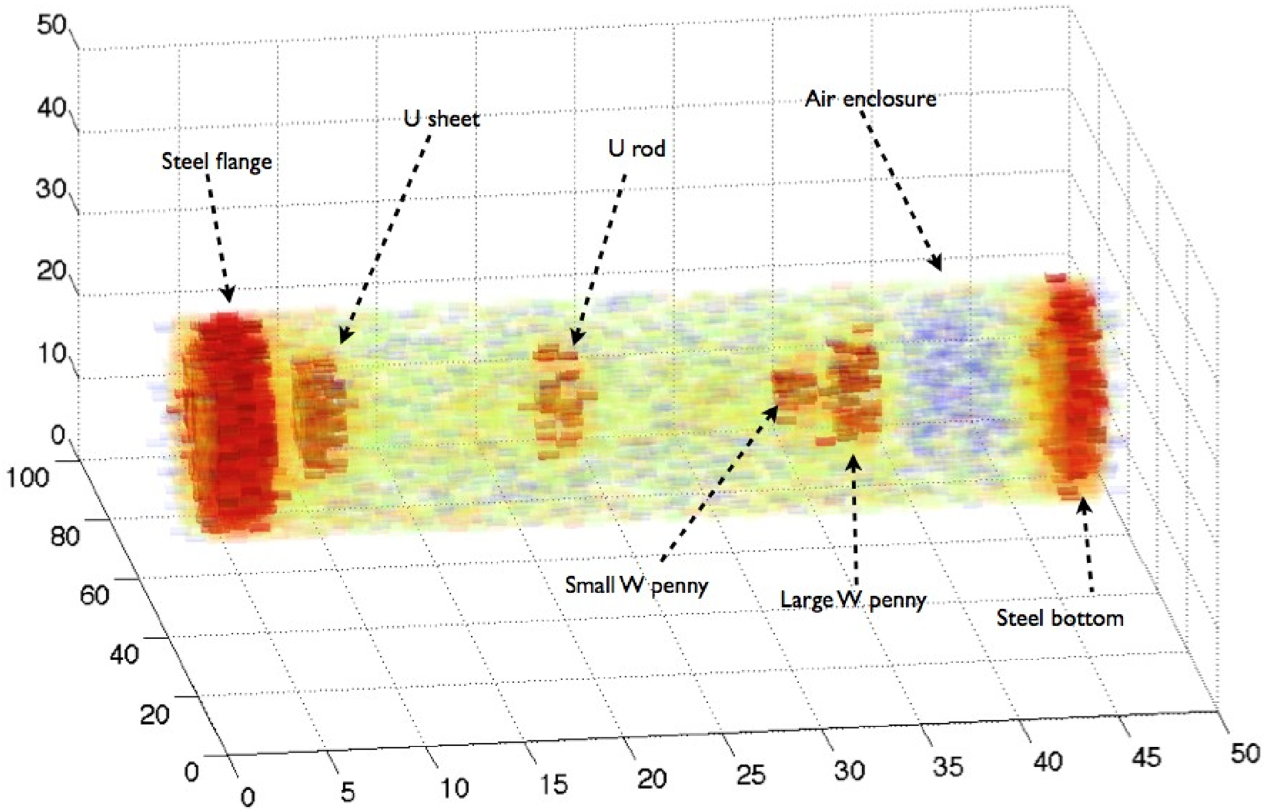
- Looking for nuclear bombs hidden in cargo containers.
- Monitoring on nuclear waste:
  - localising objects in concrete
  - gas bubbles in concrete
  - material identification
- Civil (nuclear) inspections:
  - localising reinforcement





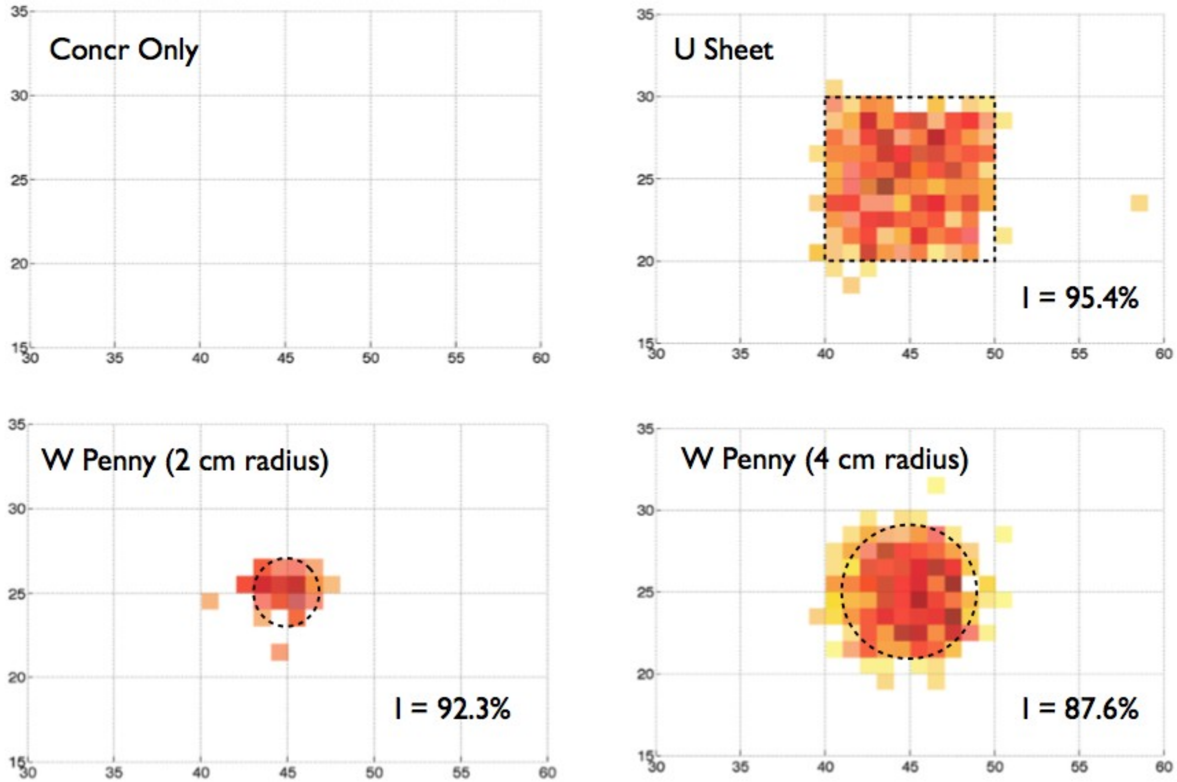
Waste drum monitoring

- Monte Carlo simulation of a small drum.
  - Top hat scans, 2 weeks of data, 50% momentum uncertainty

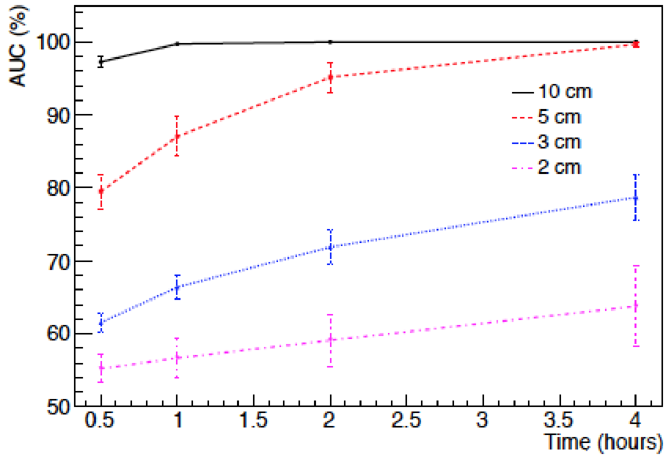


Waste drum monitoring

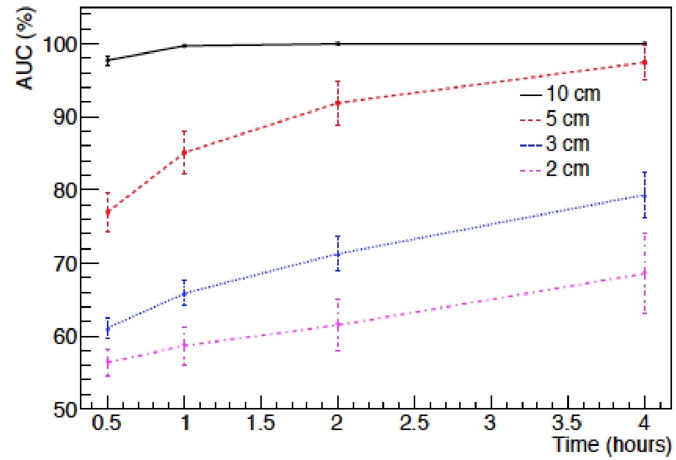
- Can even see shapes of objects
  - cylindrical U rod (1 cm radius, 10 cm height)
  - thin quadratic U sheet (0.5 x 10 x 10 cm^3)
  - two W pennies of 1 cm thickness (2 cm and 4 cm radius).
- Technique clearly works well for examining waste drum contents.
- How precise can we measure the outlines?
  - For edge finding another algorithm was successfully developed with the obtained resolution of $\sigma = 2.9 \pm 0.5$ mm.



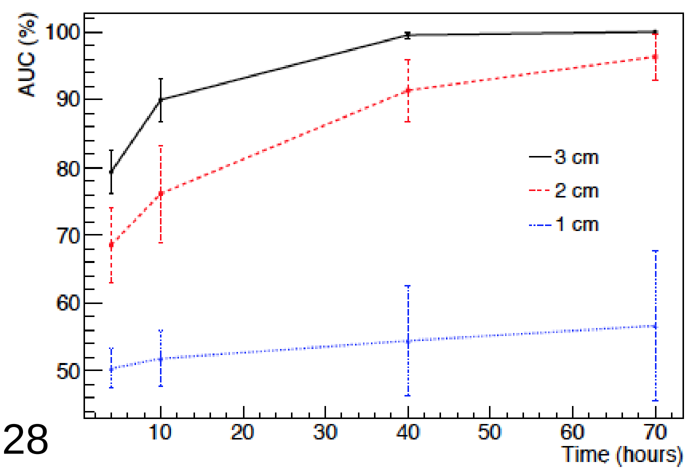
Material identification



- Separation U and Pb almost perfect for 10x10x10cm^3 after 1 hour. It takes longer for smaller blocks. Still, it works down to 2x2x2cm^3.



- Separation U and W almost perfect for 10x10x10cm^3 after 1 hour. It takes longer for smaller blocks. Still, again it works down to 2x2x2cm^3.



- Can even discriminate U and Pu for 3x3x3cm^3 blocks.

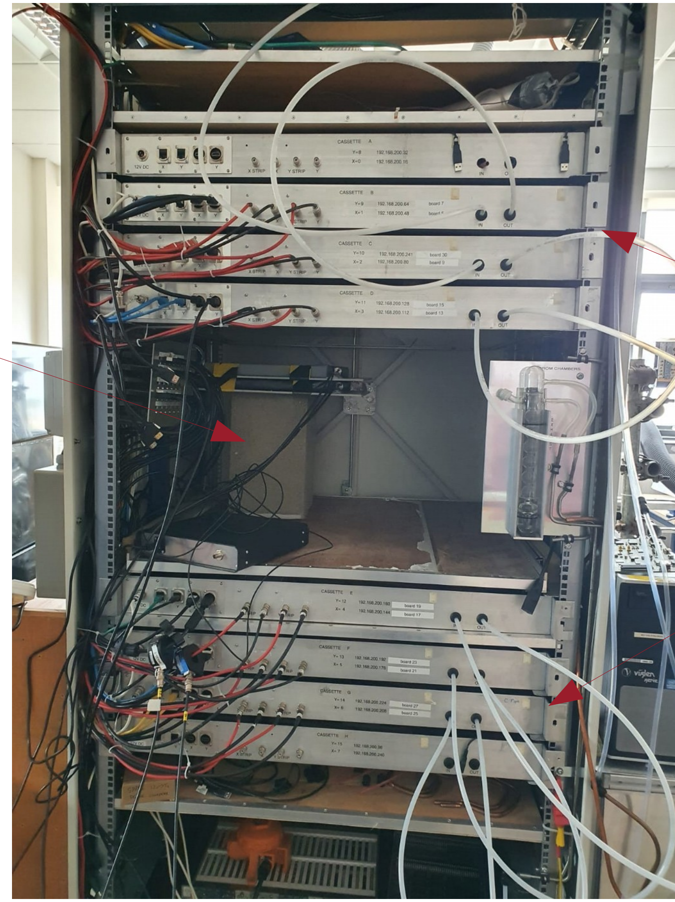
Experimental data study - Fenswood Farm

a barrel is currently being scanned

detectors

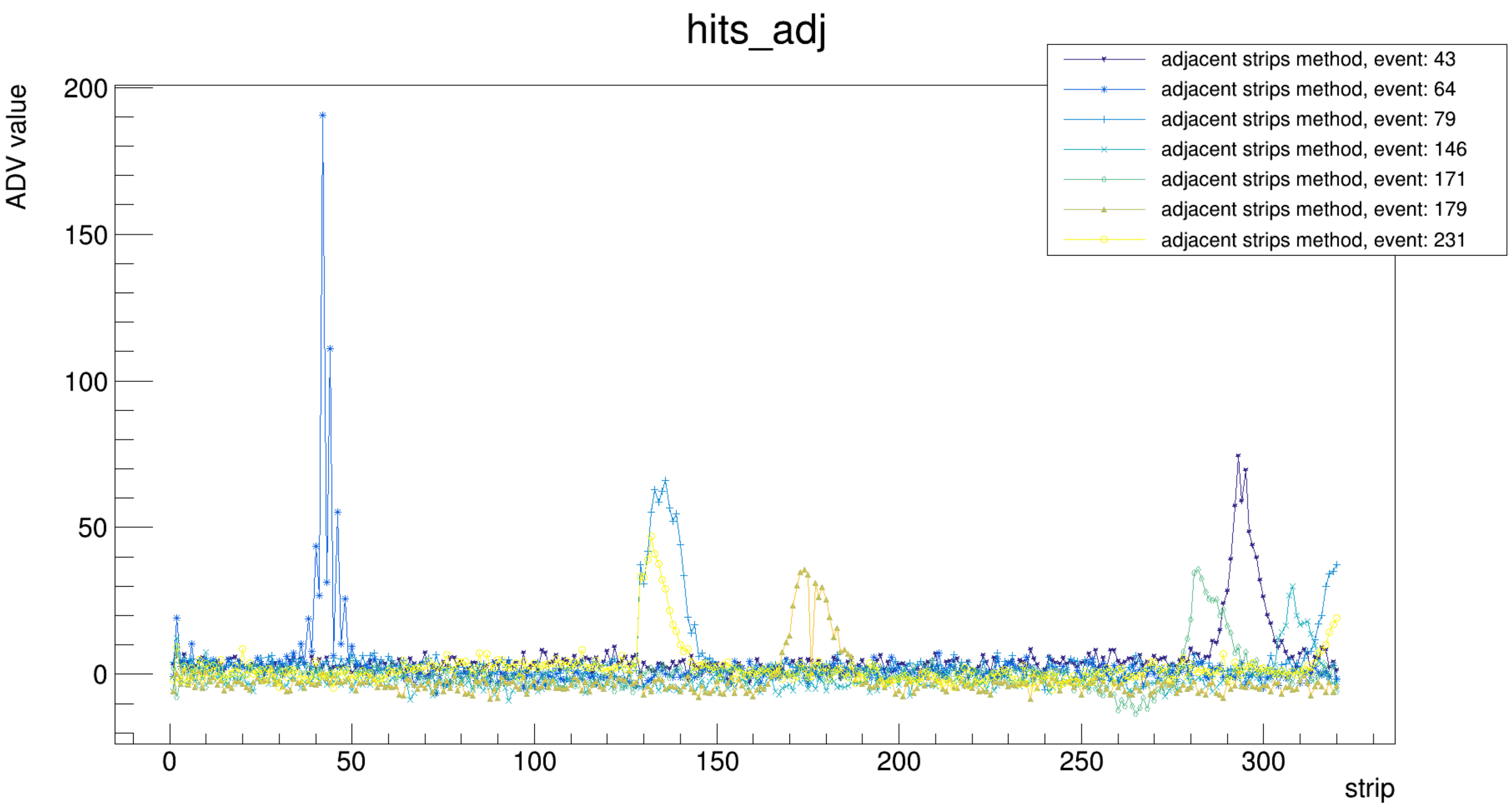
Experimental data study – university lab

Concrete block with unknown content is being scanned now



detectors

Experimental data – muon hit signal



- Currently, we are taking experimantal data in both systems.
- Above, strips with higher signal indicate that there was muon hit.

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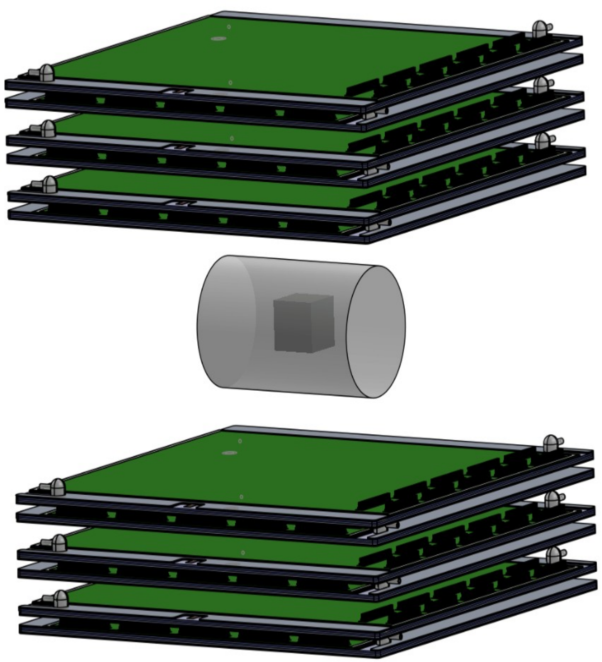
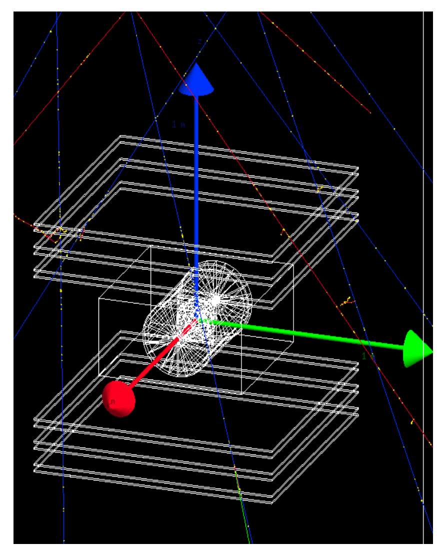
Gas bubbles study

Simulations - Geant4

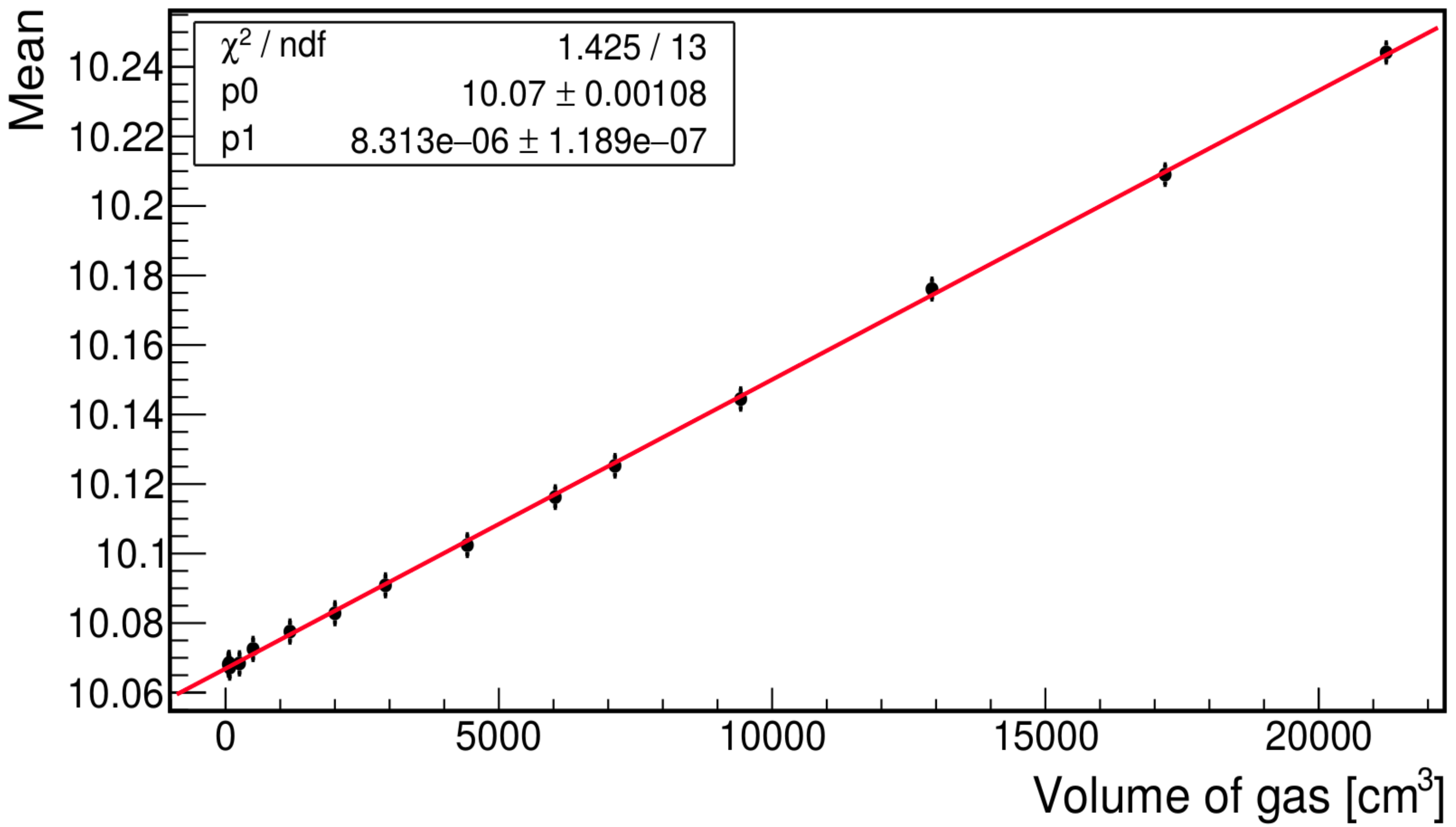
- Cylinder with base radius 20 cm and height 40 cm;
- Tube filled with a material with concrete density;
- The simulated volume of gas ranged from 32 cm^3 to 21 liters;
- Simulation based on real system performance
- CRY - a cosmic ray database;





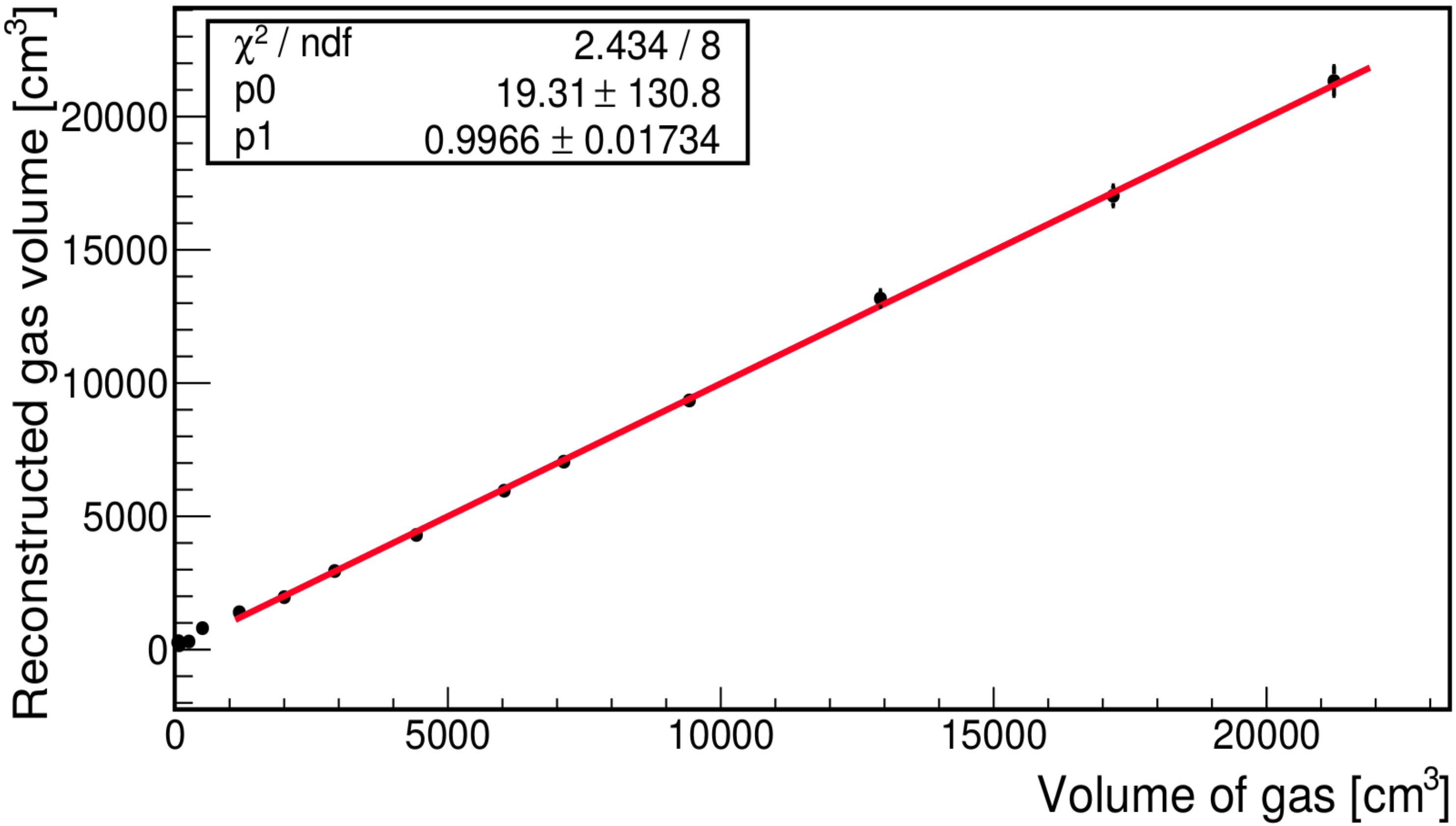
Variable with monotonic dependence on the volume of gas

From the distribution of the discriminator, the volume of gas can be reconstructed using the determined linear dependence of the mean of the distribution.



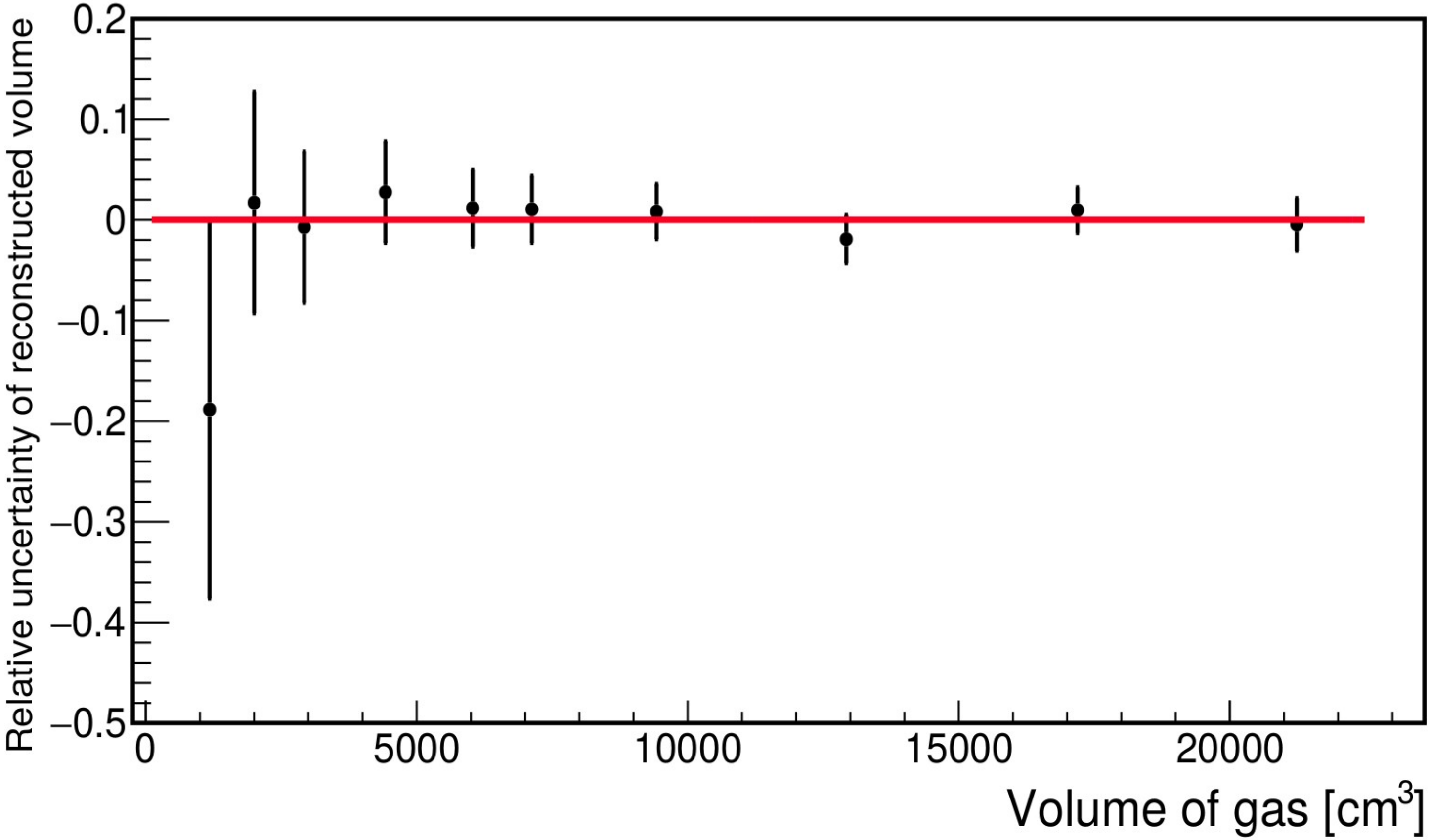
Reconstructed amount of gas

$$V_{rec} = \frac{\mu_{discr} - (10{,}066 \pm 0{,}002)}{(8{,}356 \pm 0{,}149) \times 10^{-6}}$$



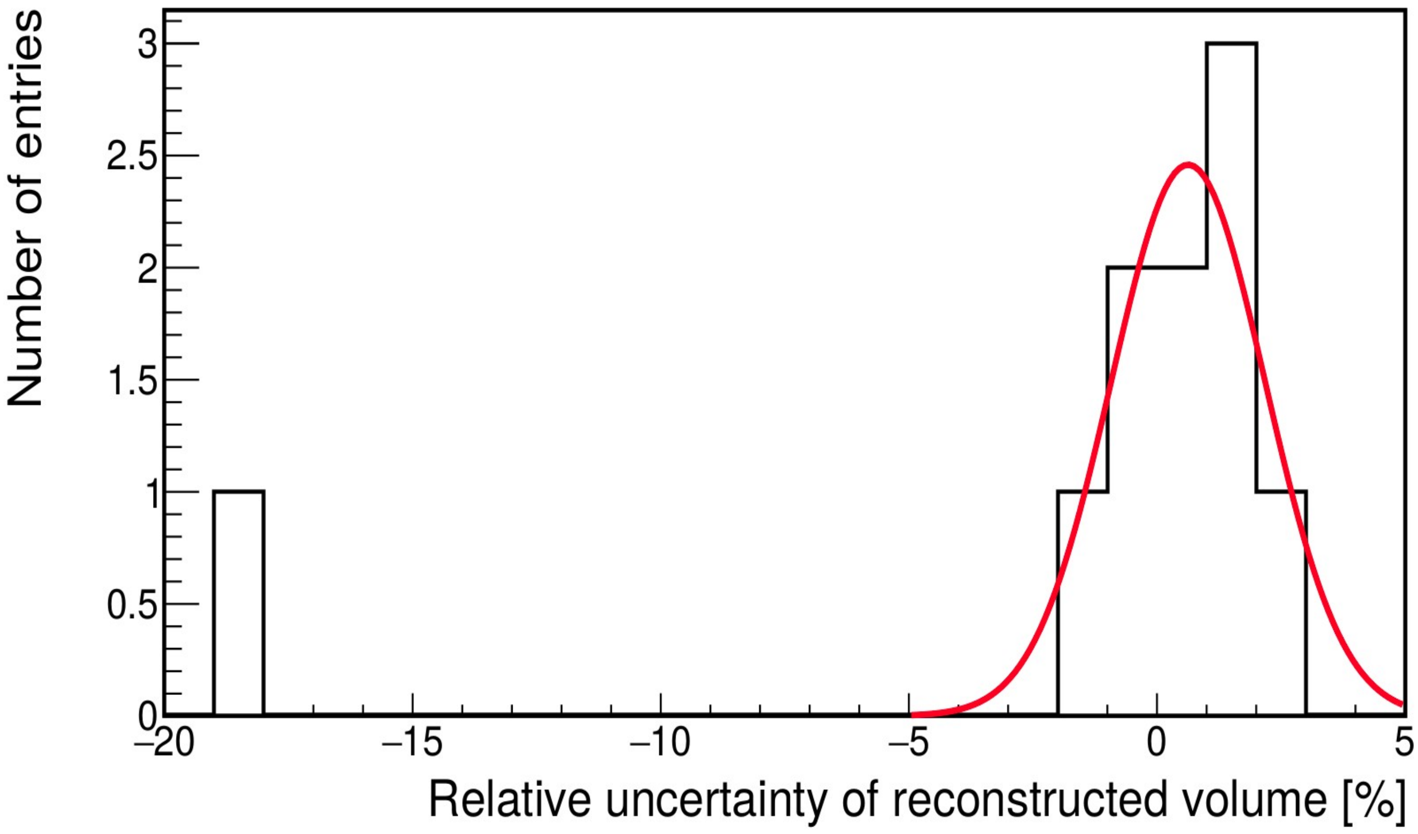
Relative uncertainty of reconstructed volume

Relative uncertainty of reconstructed volume: $\delta = \frac{V - V_{rec}}{V}$

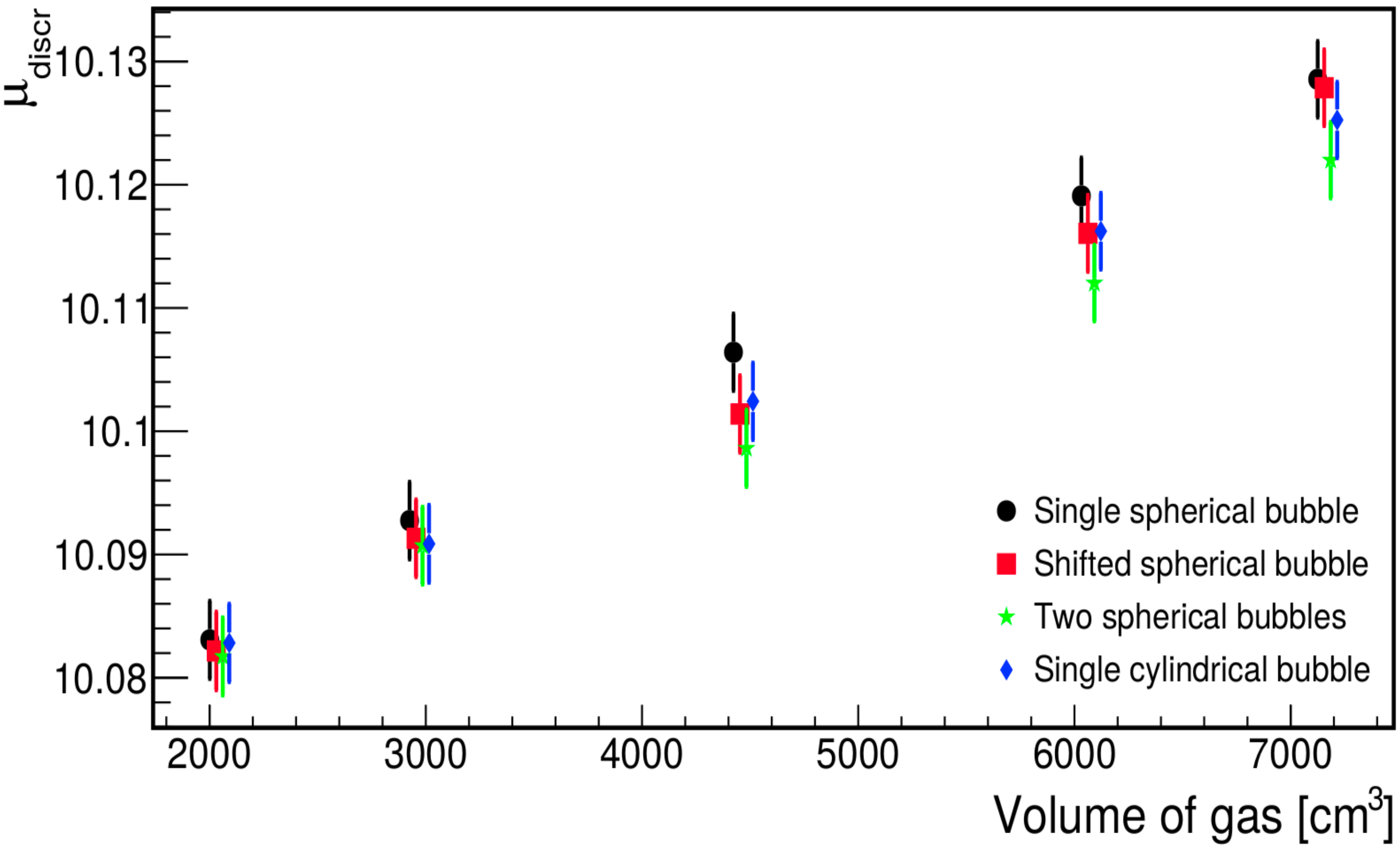


Resolution of the reconstructed volume

The resolution of the reconstructed volume for gas volumes larger than 2 liters was: 1,55 ± 0,77 %

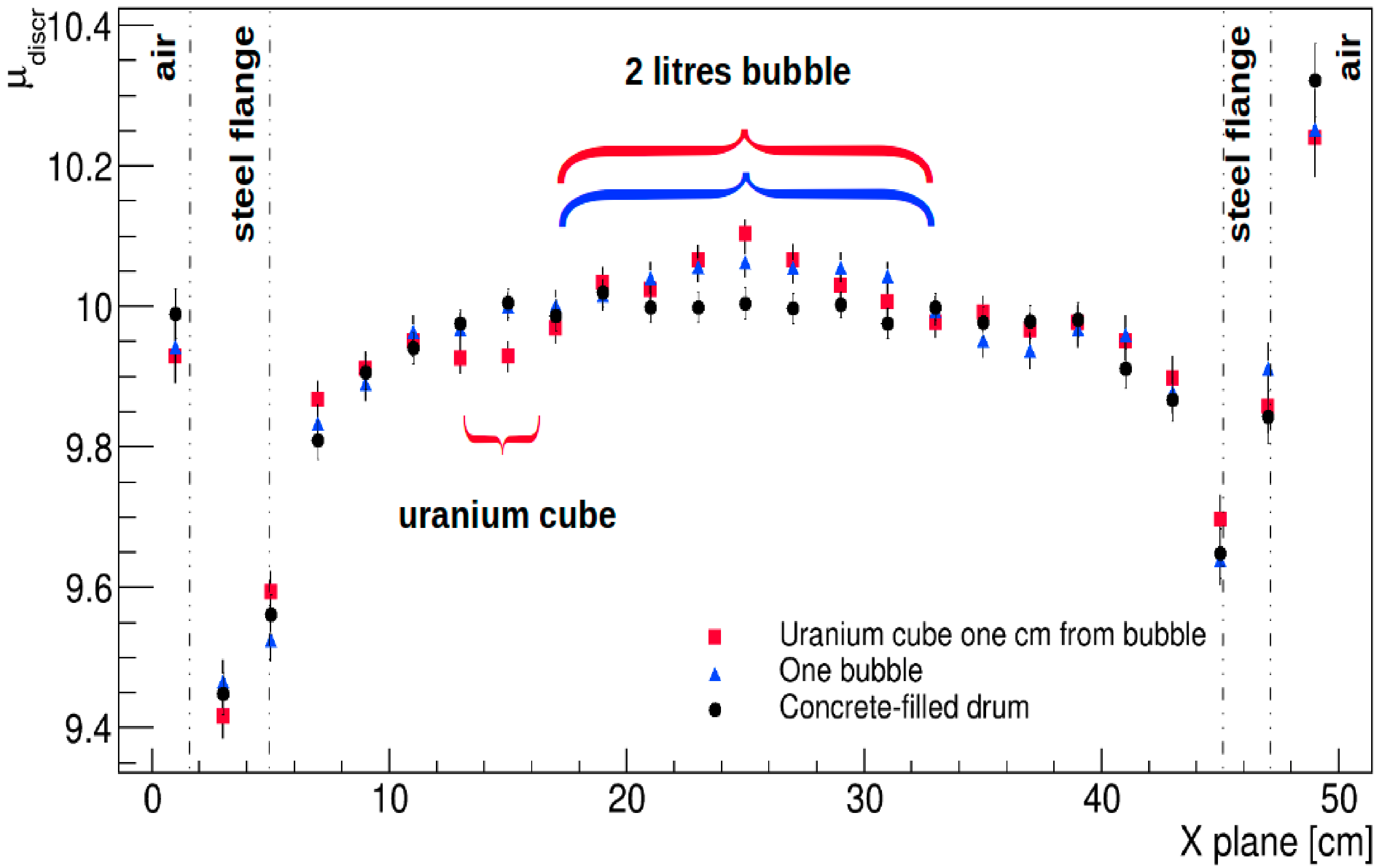


Sensitivity of the method to the location and shapes of gas volumes



The obtained result is **<u>independent</u>** on the shape of the gas area or its location

Sensitivity of the method to the location and shapes of gas volumes



By applying the method to small part of the tube, areas with different densities can be distinguished

Summary on gas bubbles study

- A variable was found that gives monotonic dependence on the gas volume in the radioactive waste container;
- The volume of gas was reconstructed with a resolution of 1.55 ± 0.77%;
- The results presented in the work do not depend on the geometry of the gas, however, by using the algorithm for individual slices, it is possible to distinguish the elements;
- Selected results of the master's thesis were presented at international conferences: Nuclear Science Symposium and Medical Imaging Conference in Atlanta, USA in October 2017 and Waste Management in March 2018;
- Publication in a peer-reviewed journal.

Journal of Instrumentation

A novel technique for finding gas bubbles in the nuclear waste containers using Muon Scattering Tomography

M. Dobrowolska[a], J. Velthuis[b], L. Frazão[b] and D. Kikoła[a]

Published 11 May 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab

Journal of Instrumentation, Volume 13, May 2018

Article PDF

Deployment

- field trials with our detector system we started
- detectors are placed either side of the wall or floor
- the detectors should be placed as close as possible to the object to be scanned and each other to maximize acceptance;