STAND-ALONE COSMIC-RAY TOMOGRAPHY WITH SECONDARY PARTICLES

Muographers2023, Naples

Maximilian Pérez Prada

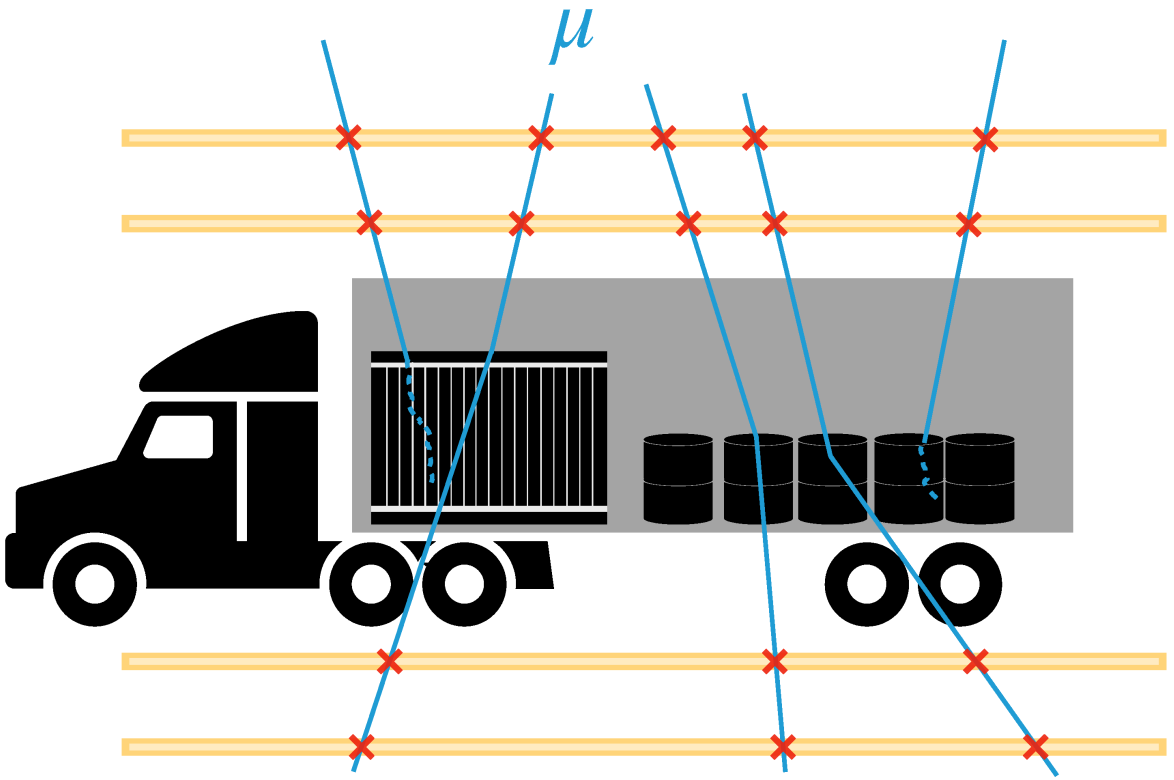
Institute for the Protection of Maritime Infrastructures

21.06.2023

DLR

The ‚classic‘ cosmic-ray tomography

The growing success of cosmic-ray tomography applications is based on two main measurement concepts: muon scattering and muon absorption



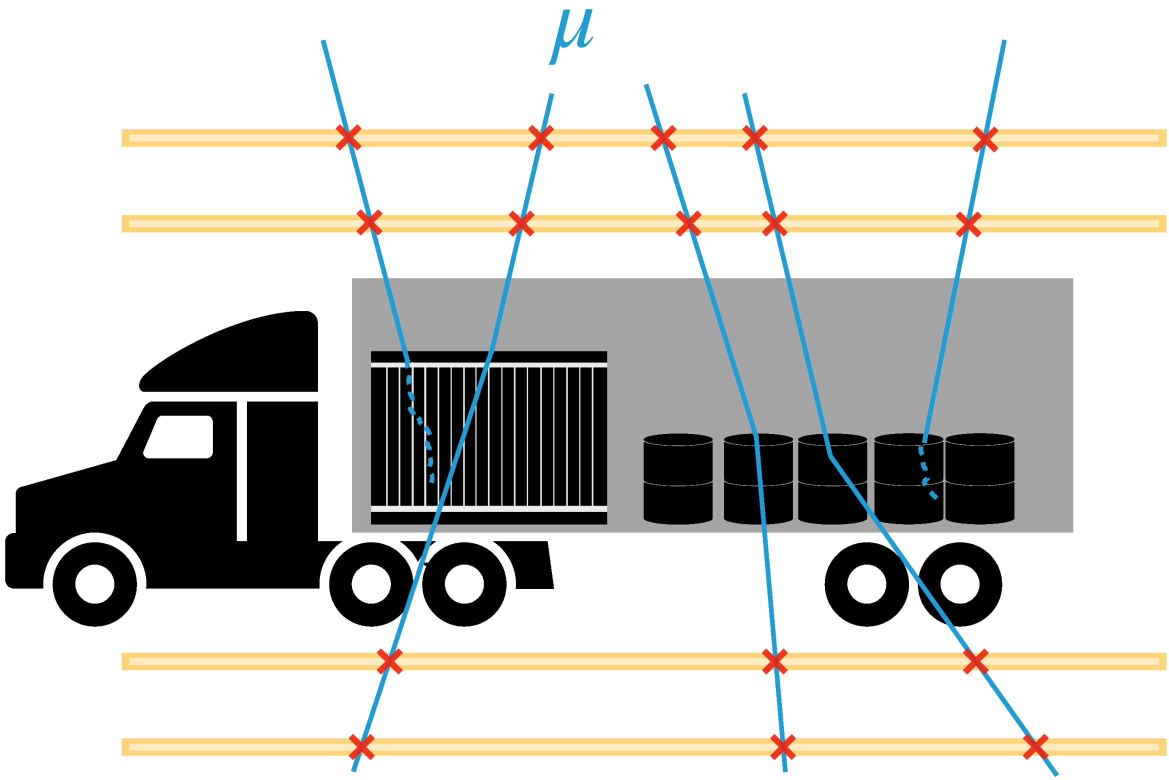
Source: MDPI

The ‚classic‘ cosmic-ray tomography

The growing success of cosmic-ray tomography applications is based on two main measurement concepts: muon scattering and muon absorption

- The scattering angle correlates with the density of the examined volume
- The absorption rate correlates with the density of the examined volume

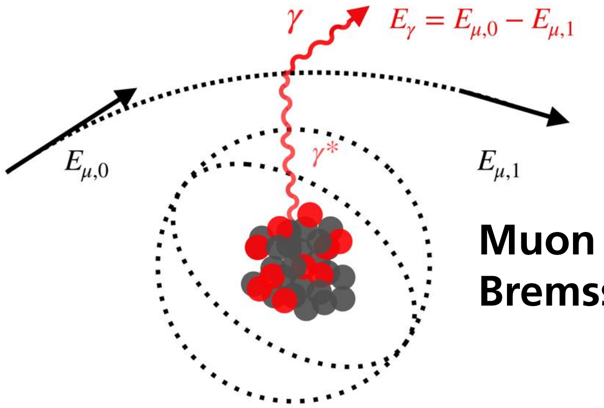
→ Both methods allow a detailed 3D volume reconstuction



Source: MDPI

A missing piece: secondary particles

The interaction of muons leave traces: secondary particles



Muon Bremsstrahlung

Muon capture

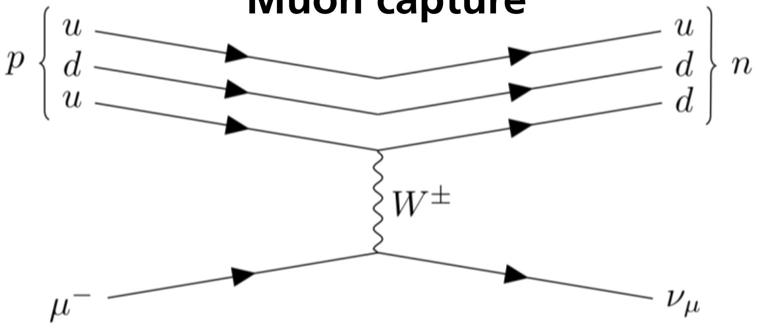
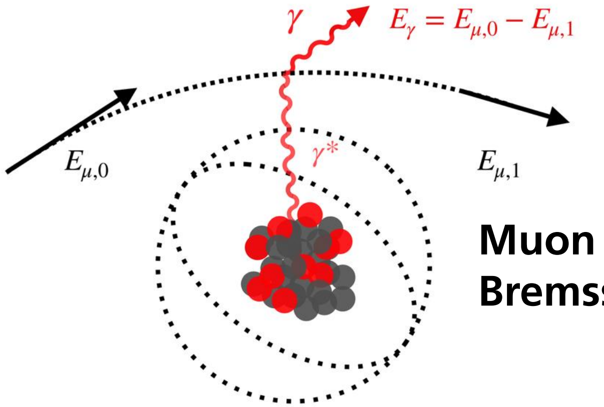


Image sources: Research Gate, Laboratory for Nuclear Technologies, ELENA

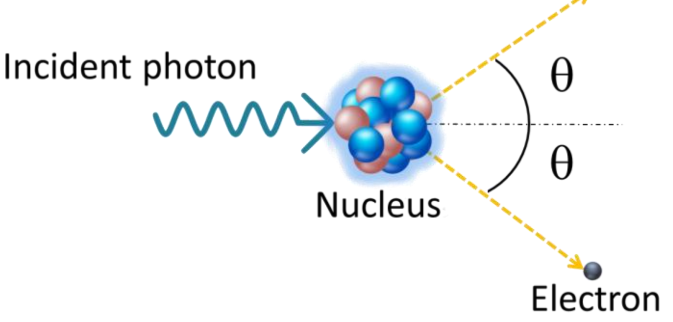
A missing piece: secondary particles

The interaction of muons and other cosmic-ray shower particles leave traces: secondary particles



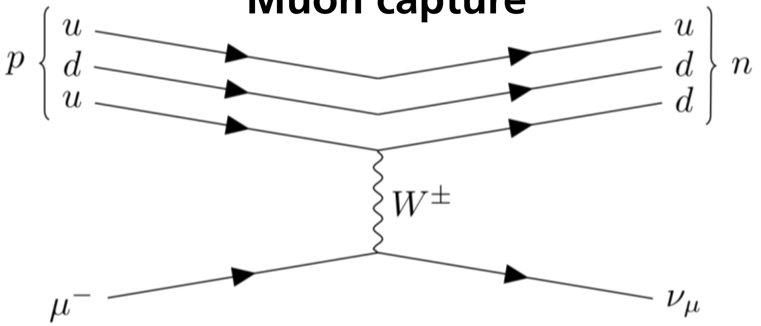
Muon Bremsstrahlung

Pair production



And many more …

Muon capture



Induced fission

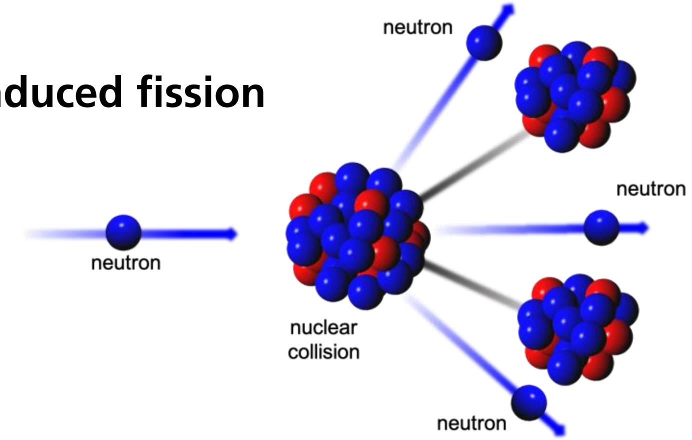
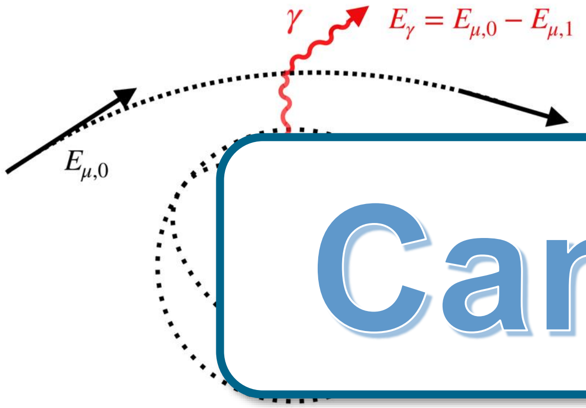


Image sources: Research Gate, Laboratory for Nuclear Technologies, ELENA

A missing piece: secondary particles

The interaction of muons and other cosmic-ray shower particles leave traces: secondary particles

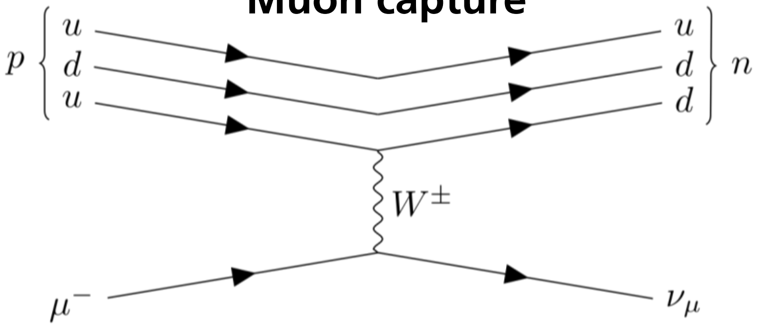


Pair production

…ny more …

Can we utilize this?

Muon capture



Induced fission

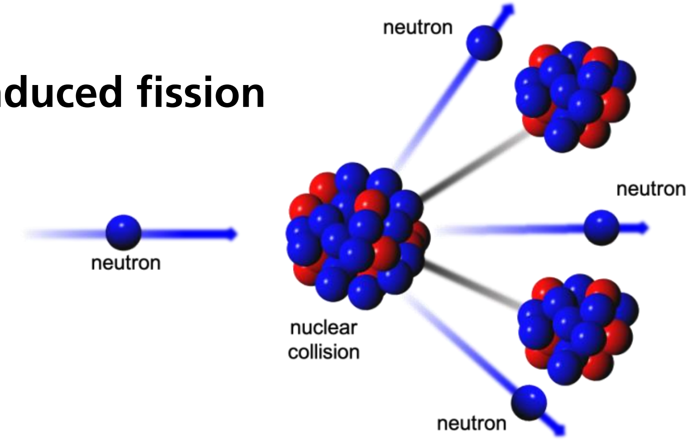


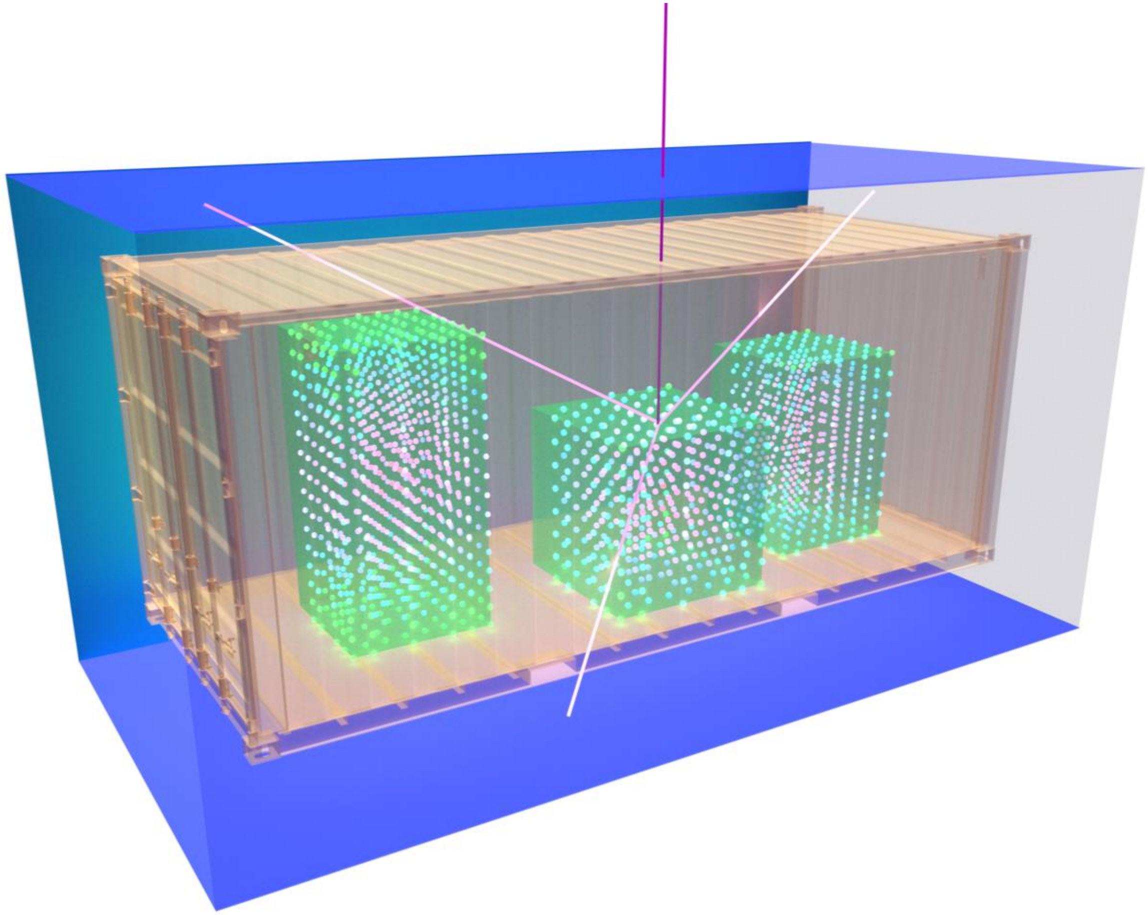
Image sources: Research Gate, Laboratory for Nuclear Technologies, ELENA

Let’s put it to a test

Previous publication: MDPI Instruments, DOI 10.3390/instruments6040066

Scenario:

- 4 detector layers with perfect acceptance & efficiency: above, below, left & right of container
- Container: steel box (4 mm thick walls) with 20 ft ISO dimensions



Reconstruction procedure

Step 1: Selection and combination of different secondary particles and detection layers

→ Possible discrimination between materials due to different secondary particle kinematics

	Photons	**Neutrons**	**Electrons**
Upper detector	$M1$	$M2$	–
Sidewise detectors	$M3$	$M4$	–
Lower detector—production	$M5$	$M6$	–
Lower detector—absorption	$M7$	$M8$	$M9$

Reconstruction procedure

Step 1: Selection and combination of different secondary particles and detection layers

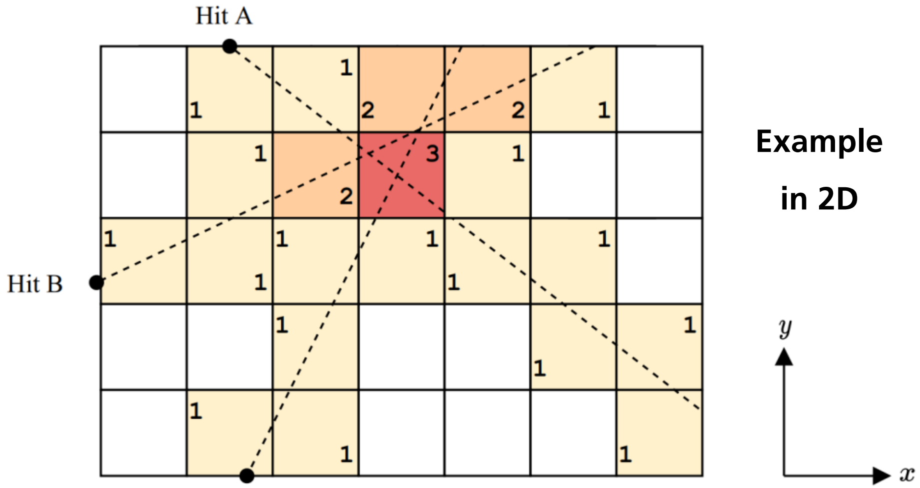
→ Possible discrimination between materials due to different secondary particle kinematics

	Photons	Neutrons	Electrons
Upper detector	$M1$	$M2$	–
Sidewise detectors	$M3$	$M4$	–
Lower detector—production	$M5$	$M6$	–
Lower detector—absorption	$M7$	$M8$	$M9$

Step 2: 3D voxel map creation

→ Ray-tracing: trace back the secondary particles from their point of detection through the whole voxelized volume

→ The more crossings (score) a voxel has, the higher its density or atomic number



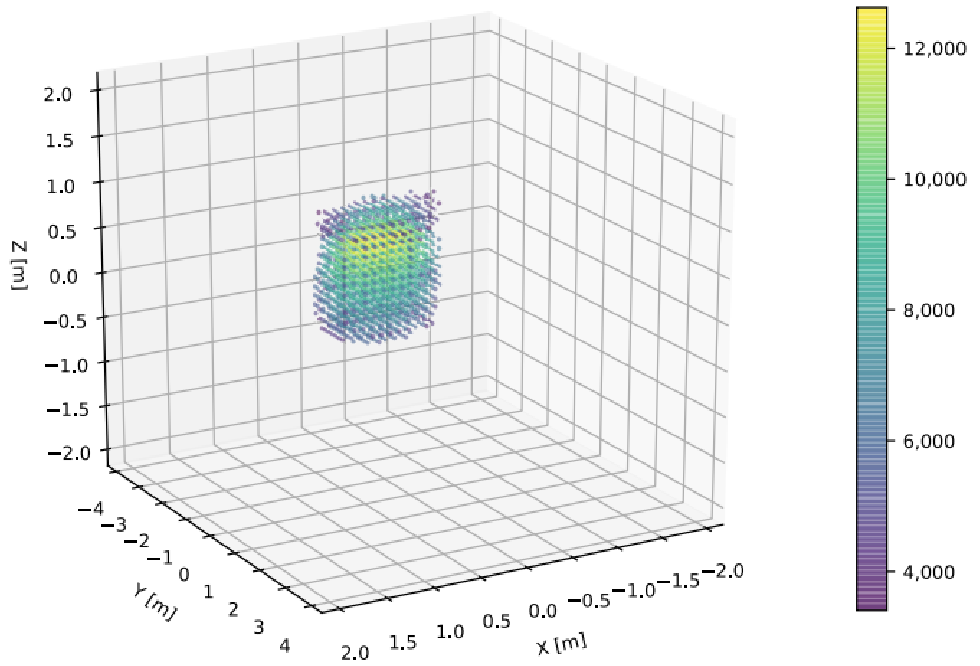
Example in 2D

Source: MDPI

Example 3D maps

One lead and one water block – empty container subtracted

Lead optimized combination



Water optimized combination

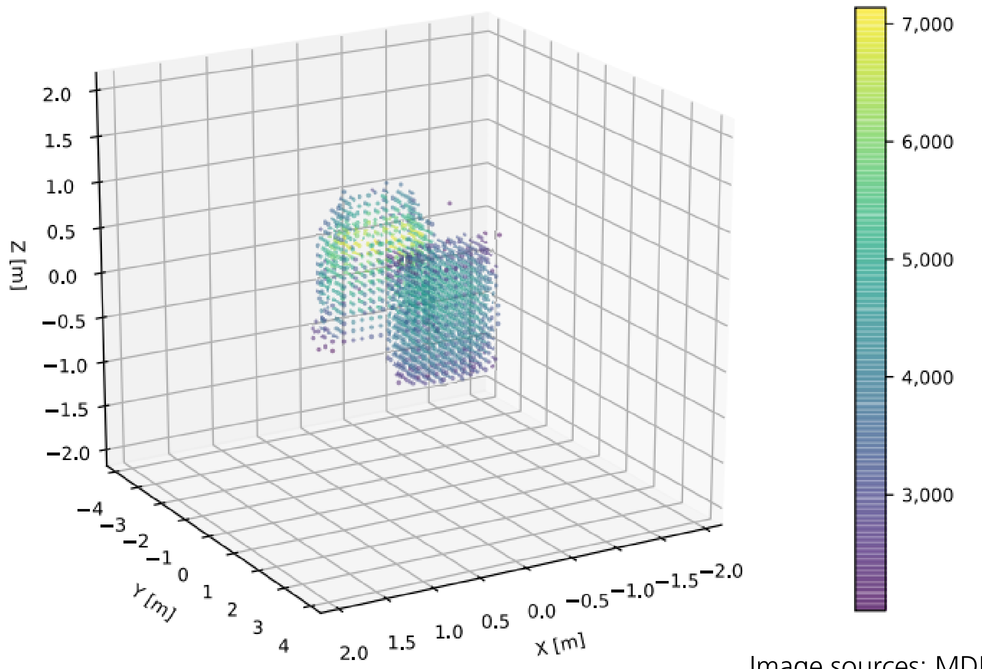


Image sources: MDPI

More Details:

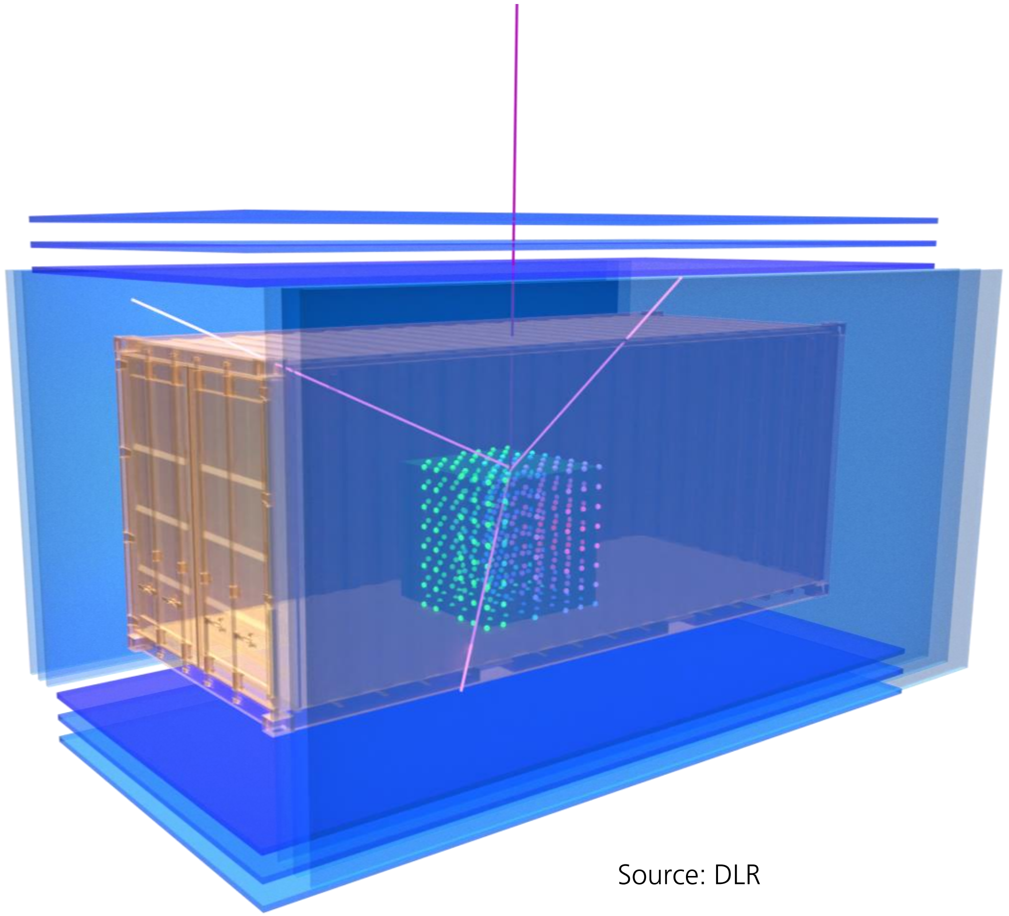
Pérez Prada, M.; Barnes, S.; Stephan, M. Analysis of Secondary Particles as a Complement to Muon Scattering Measurements. *Instruments* 2022, *6*, 66. https://doi.org/10.3390/instruments6040066

Getting more realistic

- Previous work was based on the assumption of perfect detection resolution and efficiency

Getting more realistic

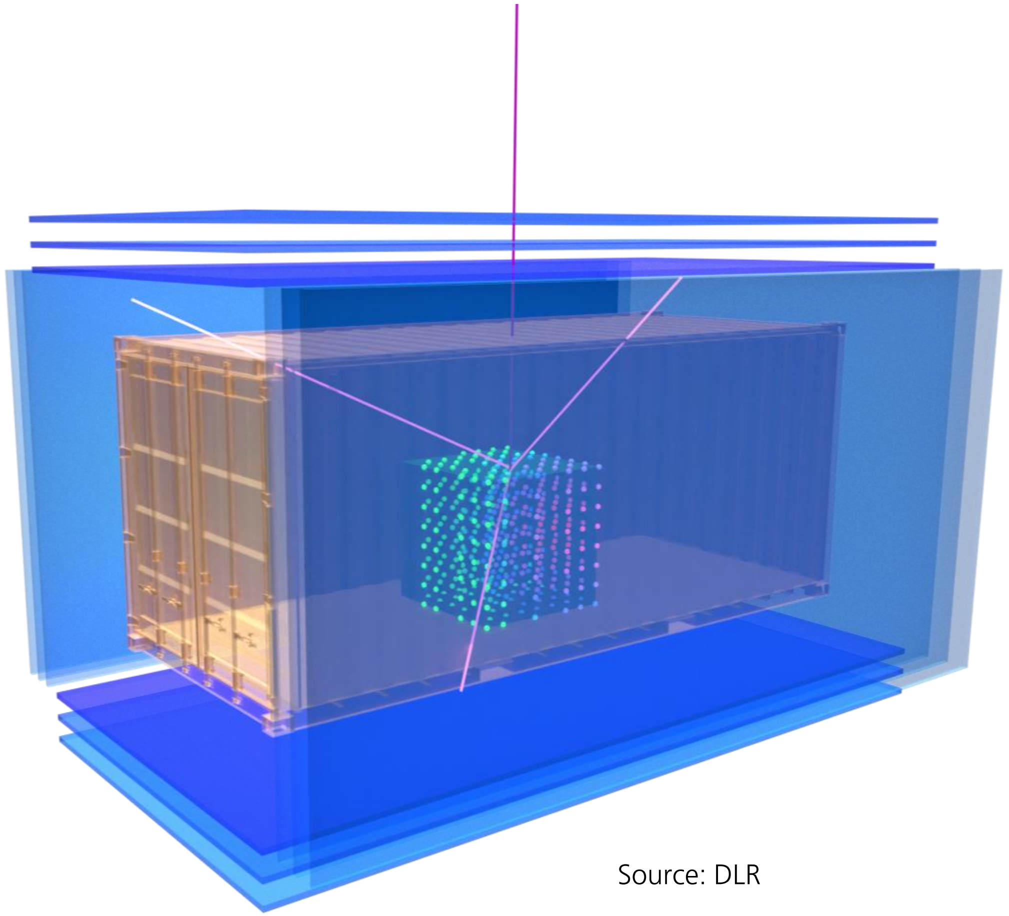
- Previous work was based on the assumption of perfect detection resolution and efficiency
- More realistic scenario includes:
  - Possible detector setup
    → Inclusion of realistic material thickness
    to simulate impact on secondary particles



Source: DLR

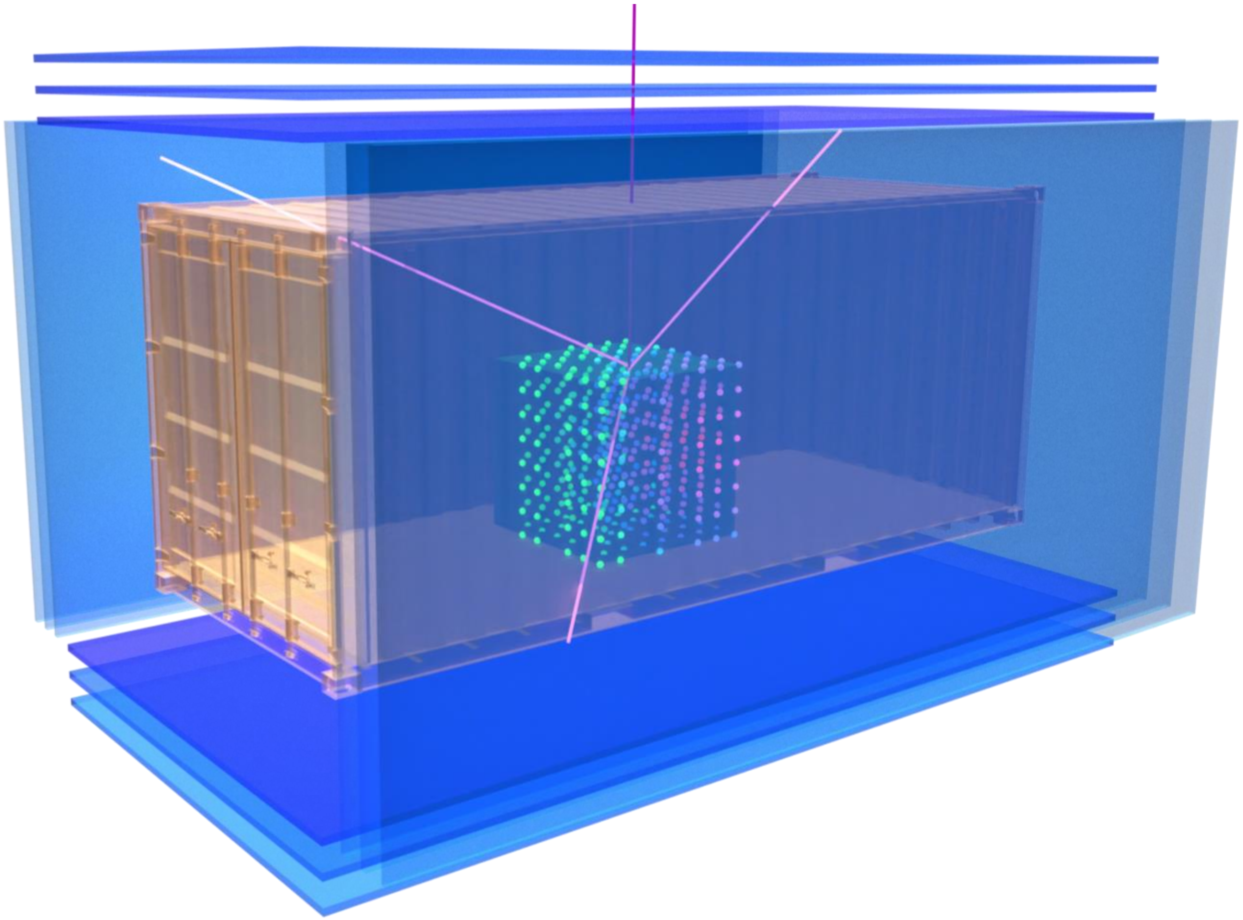
Getting more realistic

- Previous work was based on the assumption of perfect detection resolution and efficiency
- More realistic scenario includes:
  - Possible detector setup
    → Inclusion of realistic material thickness to simulate impact on secondary particles
  - Implementation of spatial resolution and detection efficiency
    → Only offline, no readout from the scintillator material is simulated
    → No particle ID simulated, but using GEN-truth information instead



Source: DLR

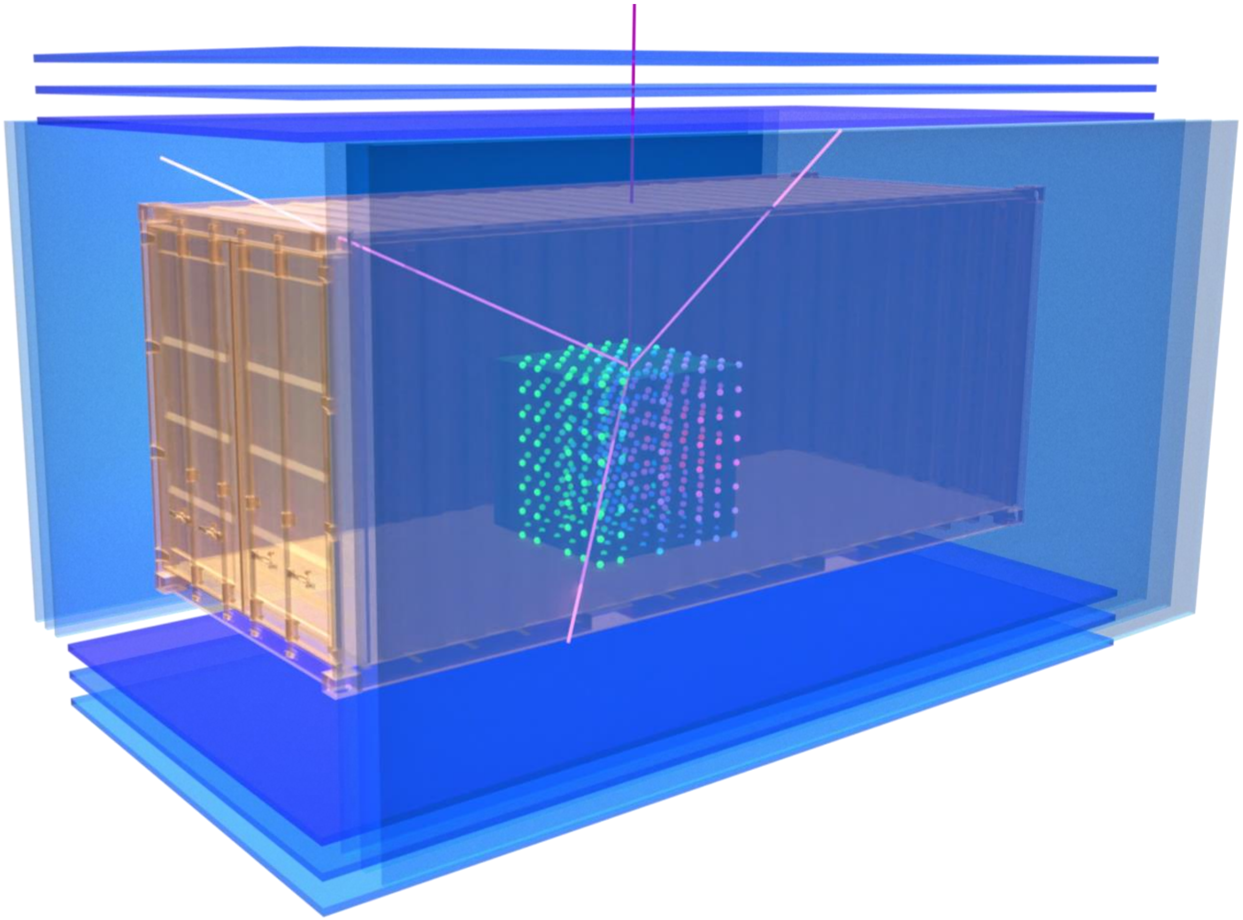
Secondary particle detector setup



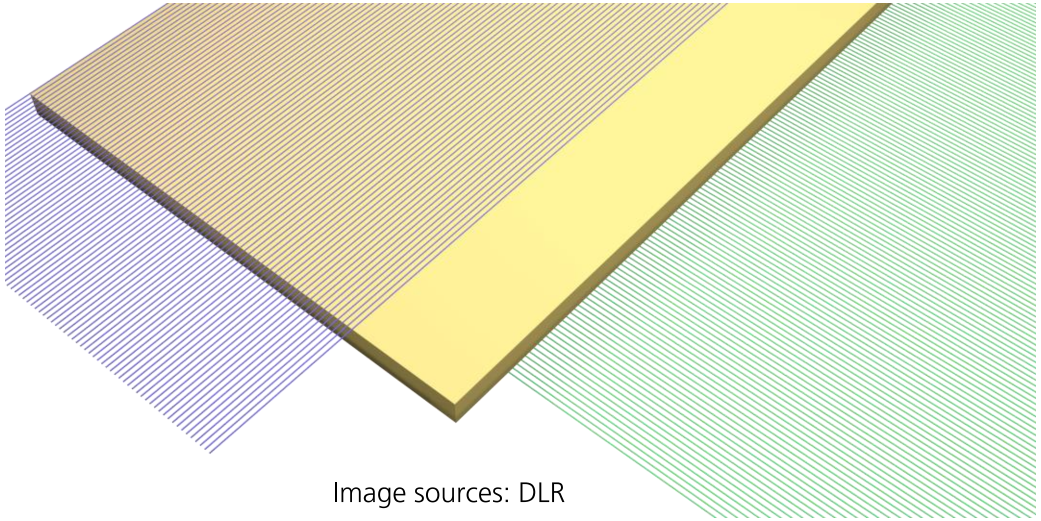
- 3 layers of plastic scintillator
- Plastic scintillator layer thickness: 50 mm
- Spacing between layers: 10 cm, 20 cm
- Detection efficiency per layer: 80%, 60%, 40%

Image sources: DLR

Secondary particle detector setup



- 3 layers of plastic scintillator
- Plastic scintillator layer thickness: 50 mm
- Spacing between layers: 10 cm, 20 cm
- Detection efficiency per layer: 80%, 60%, 40%

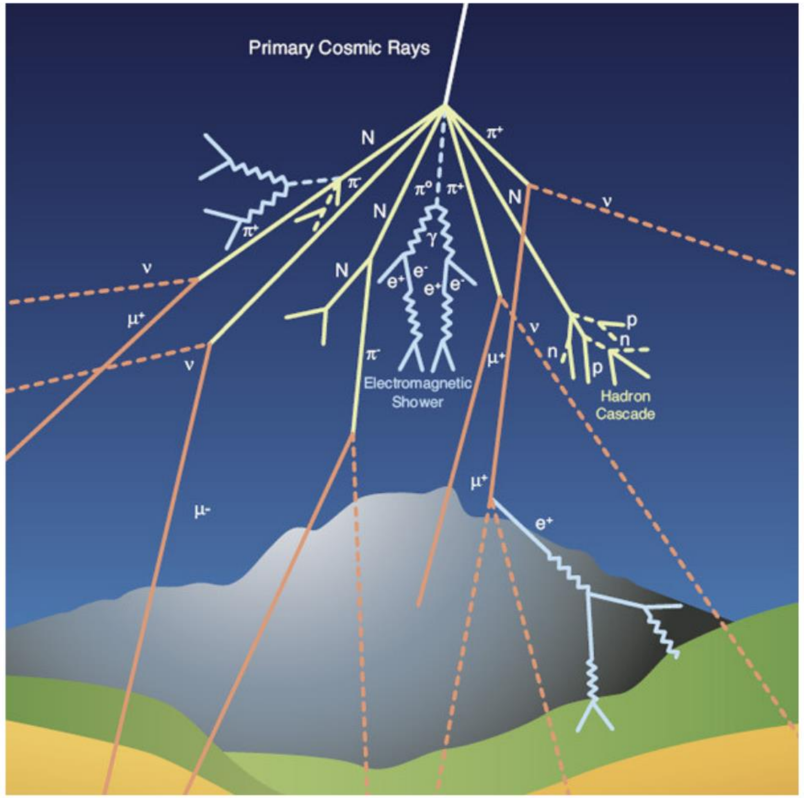


- Distance between wavelength shifting (WLS) fibers: 10 mm, 20 mm, 30 mm

Image sources: DLR

Test setup & scenarios

- Cosmic-ray shower generation:
  - CRY library with all particles enabled and max. shower size of 30
  - 100M cosmic-ray shower from 10 m × 10 m plane (equivalent to ~30 min of scan time)

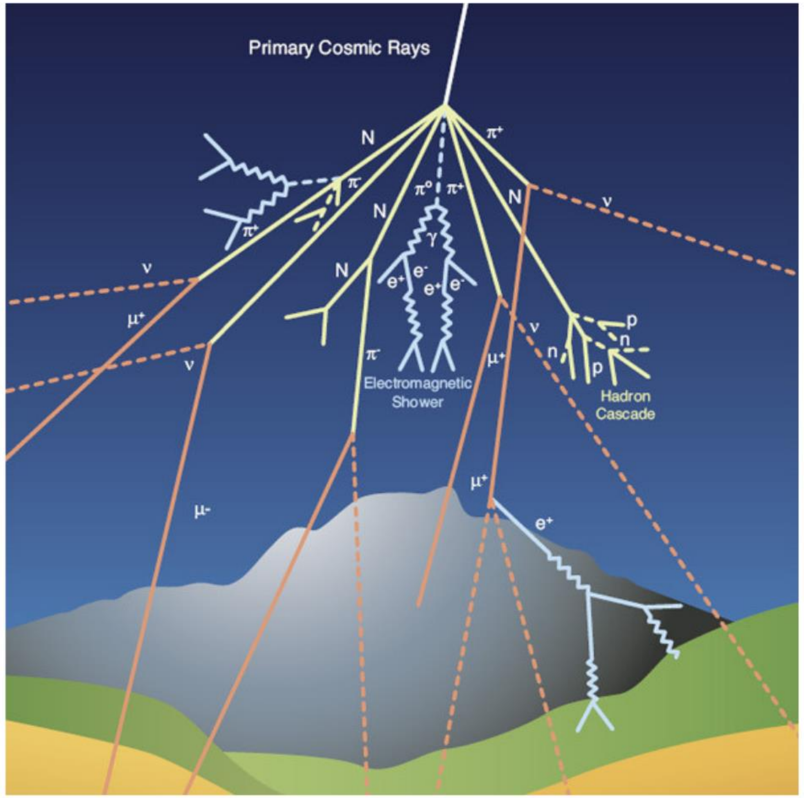


Source: CMS

A graphic representation of cosmic rays producing showers of particles

Test setup & scenarios

- Cosmic-ray shower generation:
  - CRY library with all particles enabled and max. shower size of 30
  - 100M cosmic-ray shower from 10 m × 10 m plane (equivalent to ~30 min of scan time)
- Test object:
  - Cube with volume of 1 m³ in the center of a simplified container
  - Material: water or lead
- Reconstruction:
  - Retuned the selection and combination of particle and detection layer for new setup
  - Voxel size in 3D map: 1 dm³



Source: CMS

A graphic representation of cosmic rays producing showers of particles

Performance metrics

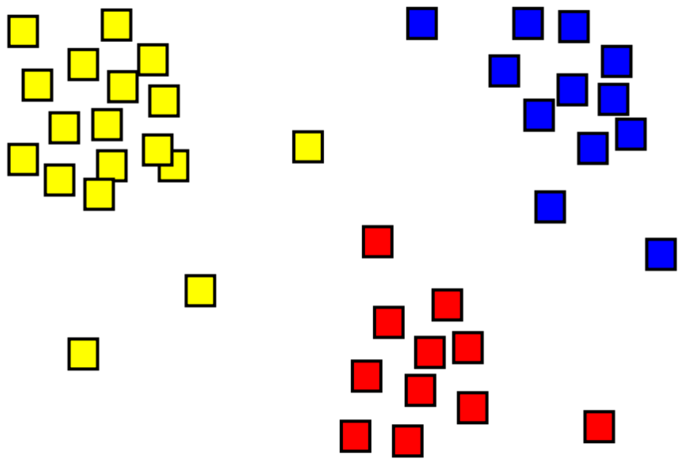
- To ensure a consistent measurement of the performance metrics, clustering is performed using the reconstructed density map as input
- Clustering method: set voxel with highest score as seed, loop over surrounding voxel and add them to the cluster, if its density score is at least 80% of the average score of the cluster

Performance metrics

- To ensure a consistent measurement of the performance metrics, clustering is performed using the reconstructed density map as input
- Clustering method: set voxel with highest score as seed, loop over surrounding voxel and add them to the cluster, if its density score is at least 80% of the average score of the cluster

Cluster metrics:

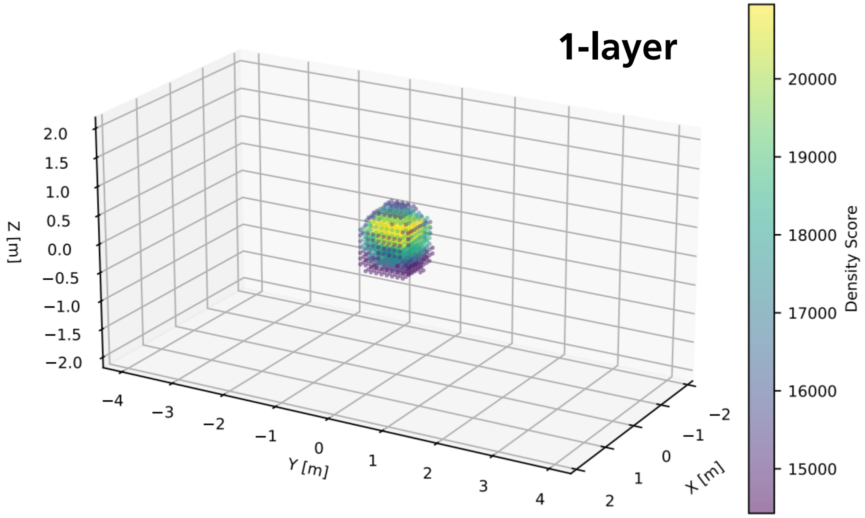
- Reconstructed object density score (average)
- Reconstructed object size: volume, side lengths
- Reconstructed object shape: Chamfer distance* between reconstructed and GEN-truth object

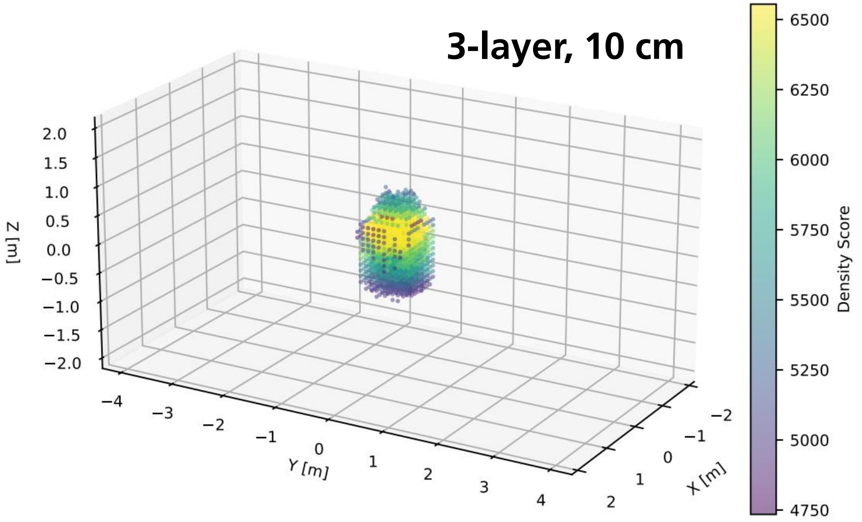


Source: Wikimedia

** Chamfer distance: sum of the squared distances between nearest neighbor correspondences of two point clouds (X, Y) centered at origin*

1-layer vs. 3-layer detection: lead block



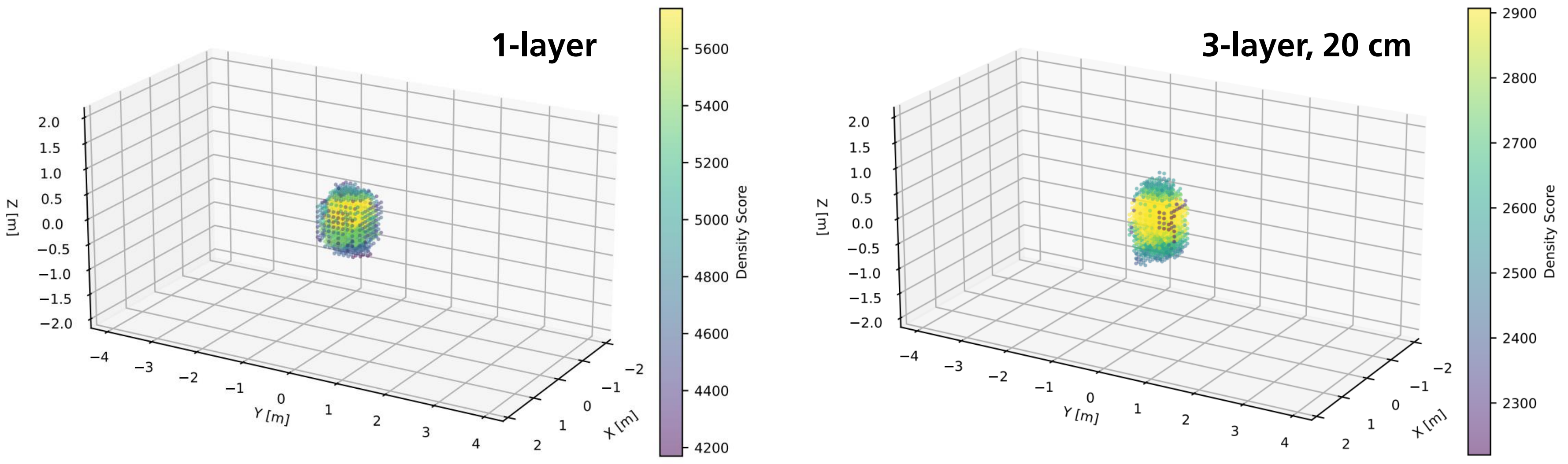


- 100% eff., perfect res.
- **1-layer:**
  Particle is detected and perfectly reconstructed from 1st layer only
- **3-layer:**
  Particle is detected only if it hits all layers and reconstructed by fitting the layer hits

	GEN-truth	1-layer	3-layer, 10 cm spacing	3-layer, 20 cm spacing
Score	---	17829	5896	5668
Size [m³]	1,210	0,942	1,388	1,332
dx [m]	1,1	1,1	1,1	1,1
dy [m]	1,0	1,0	1,0	1,0
dz [m]	1,1	1,2	1,9	1,8
Chamfer	– – –	4,8	12,1	11,2

- Setup has an acceptance of ~33%
- Significant size increase in z-direction
- Slight increase in Chamfer distance

1-layer vs. 3-layer detection: water block

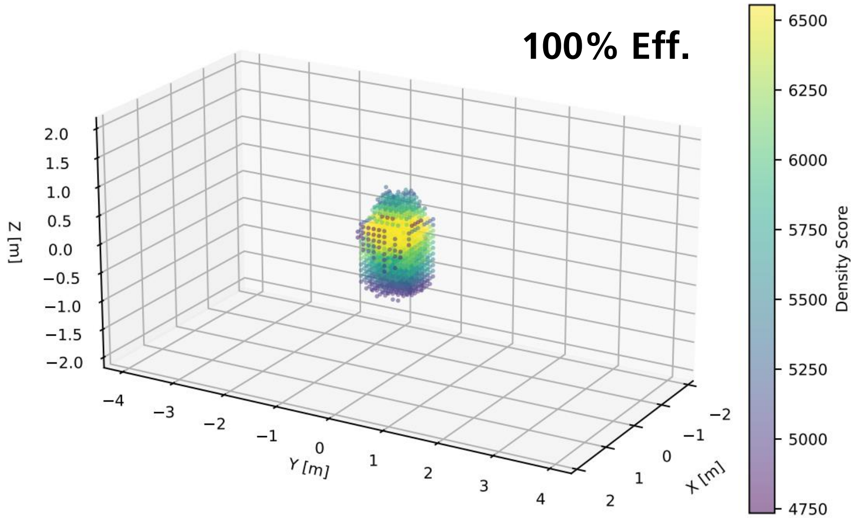


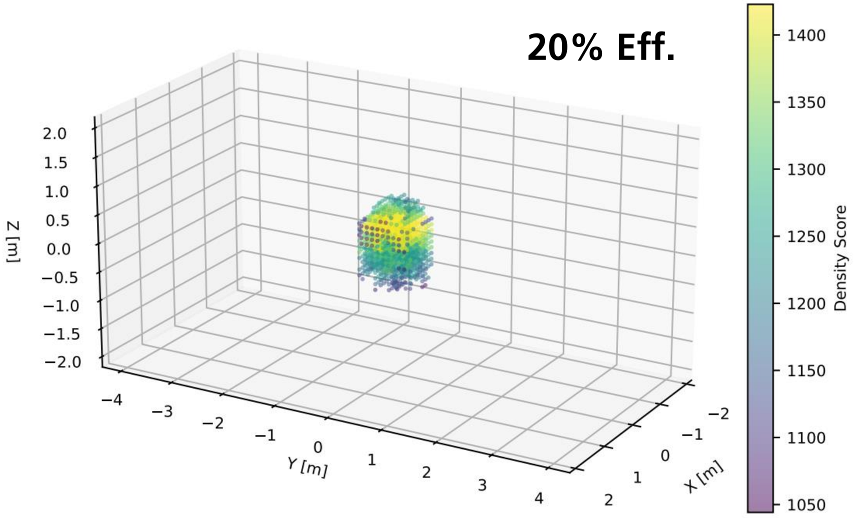
- 100% eff., perfect res.
- **1-layer:**
  Particle is detected and perfectly reconstructed from 1st layer only
- **3-layer:**
  Particle is detected only if it hits all layers and reconstructed by fitting the layer hits

	GEN-truth	1-layer	3-layer, 10 cm spacing	3-layer, 20 cm spacing
Score	---	5182	2762	2755
Size [m³]	1,210	1,050	1,078	1,066
dx [m]	1,1	1,1	1,0	1,0
dy [m]	1,0	1,0	1,0	1,0
dz [m]	1,1	1,4	1,7	1,7
Chamfer	– – –	4,6	6,4	8,0

- Setup has an acceptance of ~53%
- Small size increase in z-direction
- Slight increase in Chamfer distance

Impact of detection efficiency: lead block



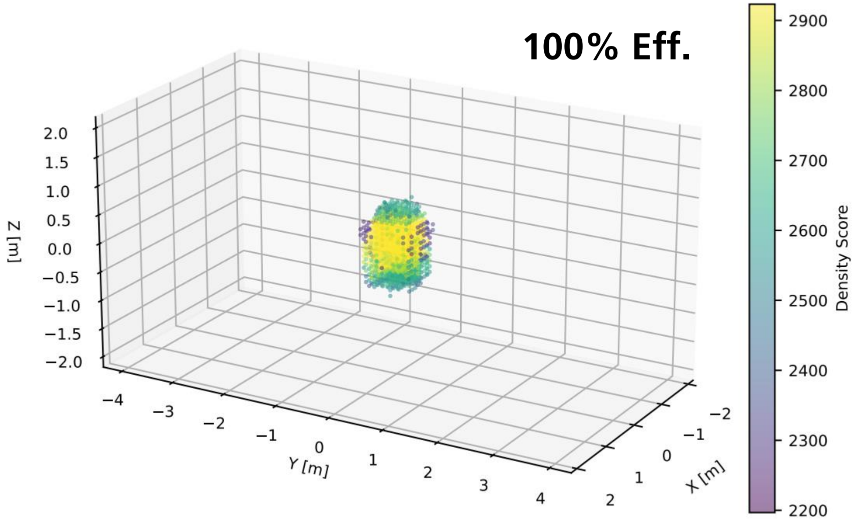


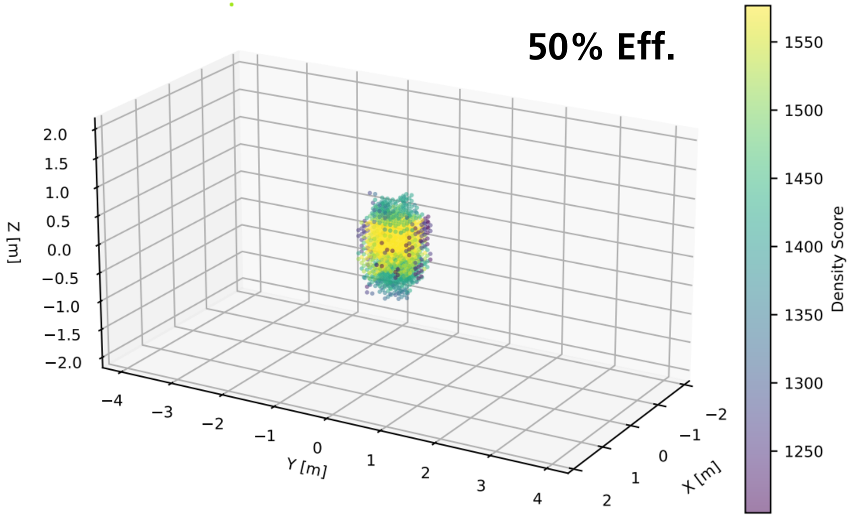
- 10 cm spacing, perfect resolution
- For simplicity, all particles in all energy regimes have same efficiency
- Cor. Score corrects for the loss in effective scan time

	100% Eff.	80% Eff.	60% Eff.	40% Eff.
Cor. Score	5896	6020	6475	7367
Size [m³]	1,388	1,371	1,117	0,627
dx [m]	1,1	1,1	1,1	1,1
dy [m]	1,0	1,1	1,1	1,1
dz [m]	1,9	2,0	1,7	1,6
Chamfer	12,1	14,1	5,3	7,6

- Significant increase in density score with lower efficiency
- Size reduction in z-direction
- Slight decrease in Chamfer distance

Impact of detection efficiency: water block



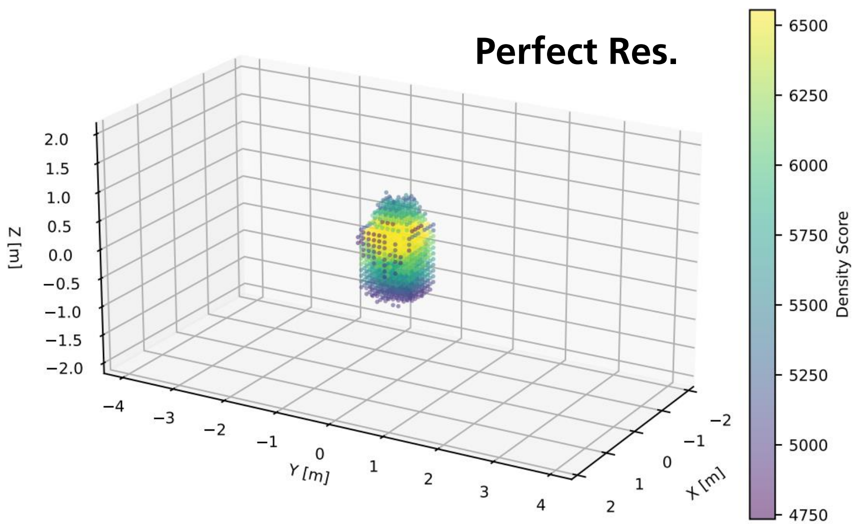


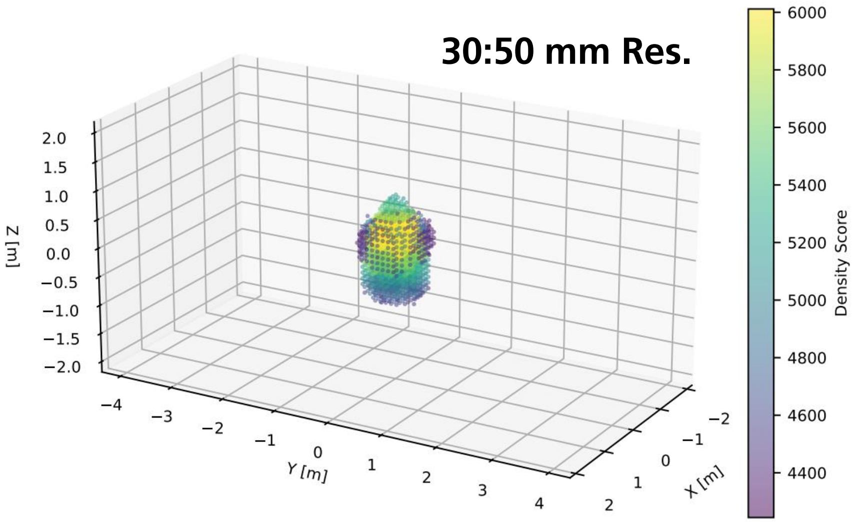
- 10 cm spacing, perfect resolution
- For simplicity, all particles in all energy regimes have same efficiency
- Cor. Score corrects for the loss in effective scan time

	100% Eff.	80% Eff.	60% Eff.	40% Eff.
Cor. Score	2762	2962	3255	3983
Size [m³]	1,078	1,132	1,079	0,551
dx [m]	1,0	1,1	1,1	1,1
dy [m]	1,0	1,1	1,0	1,1
dz [m]	1,7	1,8	1,8	1,5
Chamfer	6,4	10,9	7,1	7,1

- Significant increase in density score with lower efficiency
- Size reduction in z-direction

Impact of detection resolution: lead block



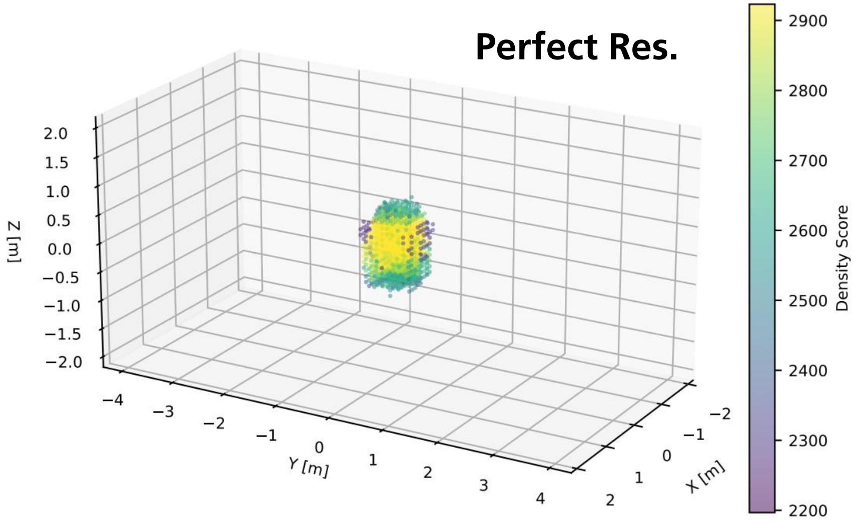


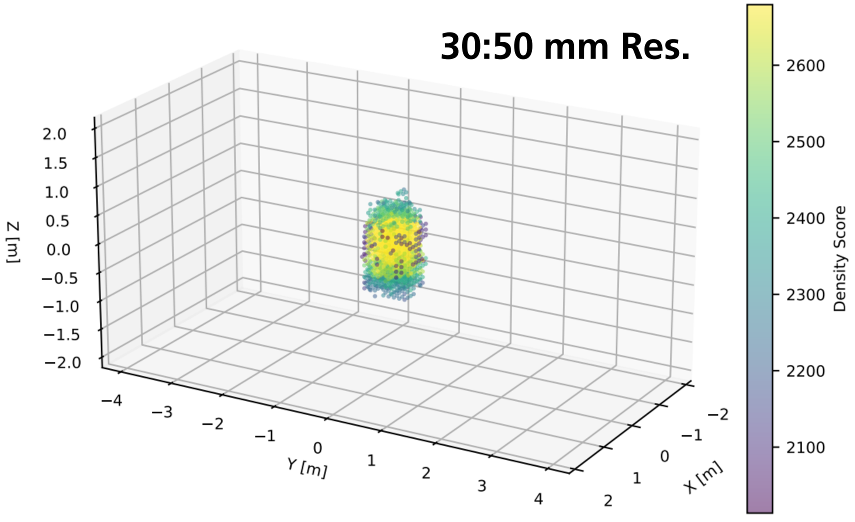
- 10 cm spacing, 100% effciency
- Resolution due to scintillator thickness: 50 mm
- Resolution due to WLS fiber grid spacing: 10 mm, 20 mm, 30 mm
- For simplicity, all particles in all energy regimes have same resolution

	Perfect Res.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	5896	5726	5573	5266
Size [m³]	1,388	1,357	1,352	1,419
dx [m]	1,1	1,0	1,0	1,2
dy [m]	1,0	1,0	1,0	1,2
dz [m]	1,9	2,0	2,0	1,9
Chamfer	12,1	16,3	17,7	11,5

- Small reduction of density score with higher resolution
- Small increase in size, mostly in x- and y-direction with very high resolution

Impact of detection resolution: water block





- 10 cm spacing, 100% effciency
- Resolution due to scintillator thickness: 50 mm
- Resolution due to WLS fiber grid spacing: 10 mm, 20 mm, 30 mm
- For simplicity, all particles in all energy regimes have same resolution

	Perfect Res.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	2762	2697	2640	2505
Size [m³]	1,078	1,053	0,988	1,050
dx [m]	1,0	1,1	0,9	1,1
dy [m]	1,0	1,0	1,0	1,0
dz [m]	1,7	1,7	2,0	1,8
Chamfer	6,4	5,6	9,5	10,7

- Small reduction of density score with higher resolution
- No significant statement about the correlation between size and resolution possible
- Slight increase in Chamfer distance

Impact of layer spacing

Calculate ratio 10 cm / 20 cm layer spacing scenario for density score and size

Water	Perfect Eff. & Res.	80% Eff.	60% Eff.	40% Eff.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	1,003	1,014	1,020	1,017	0,996	0,961	0,926
Size [m³]	1,011	1,154	1,255	1,611	1,021	1,035	1,087

Lead	Perfect Eff. & Res.	80% Eff.	60% Eff.	40% Eff.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	1,040	1,039	1,066	1,040	1,020	1,007	0,967
Size [m³]	1,042	1,011	0,882	1,161	0,996	0,988	1,065

→ Only small difference between spacing scenarios for lead block, no difference for water block

→ Only small or no significant difference for efficiency and resolution variations

→ Allows for some variability in the optimal detector layout

Impact on material discrimination

Calculate ratio lead / water block scenario for density score and size

10 cm layer spacing	Perfect Eff. & Res.	80% Eff.	60% Eff.	40% Eff.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	2,135	2,032	1,989	1,849	2,123	2,111	2,102
Size [m³]	1,288	1,211	1,035	1,138	1,289	1,368	1,351

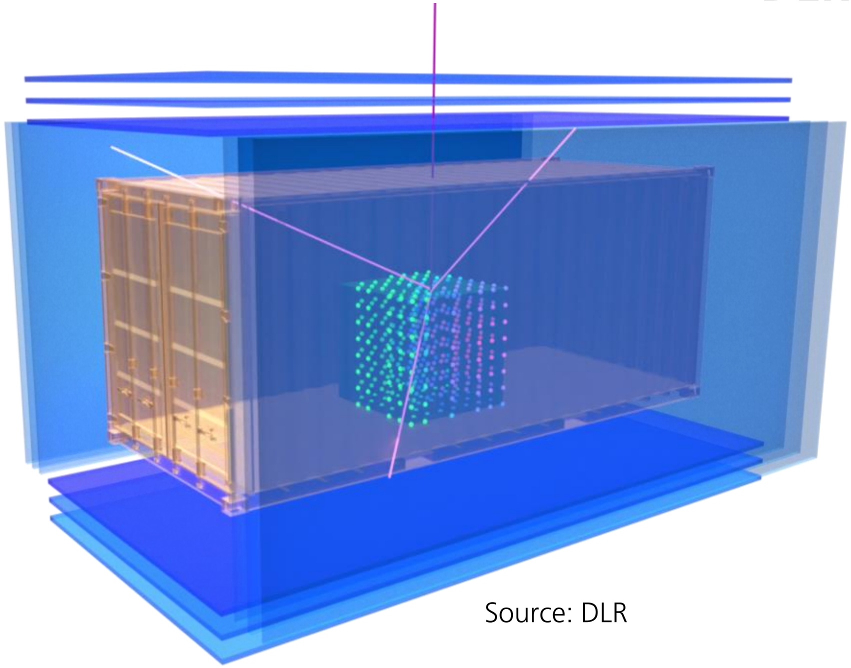
20 cm layer spacing	Perfect Eff. & Res.	80% Eff.	60% Eff.	40% Eff.	10:50 mm Res.	20:50 mm Res.	30:50 mm Res.
Score	2,057	1,983	1,904	1,809	2,072	2,016	2,013
Size [m³]	1,250	1,382	1,473	1,579	1,322	1,434	1,379

→ Only small or no significant difference for efficiency and resolution variations

→ Material discrimination is possible and stable for realistic efficiencies and resolutions

Final remarks

- The usage of secondary particles provides a promising and complimentary approach for cosmic-ray tomography
- The discussed detector conditions simulate realistic material budget, resolution and efficiency
- Even with a more realistic detection setup, our stand-alone method can succesfully reconstruct simple geometric objects located inside a container and discriminate their material



Source: DLR

- Further work will try to optimize the setup, considering a wider range of detector materials
- Further planed improvements: machine learning based reconstruction, automized material parameter scan, …