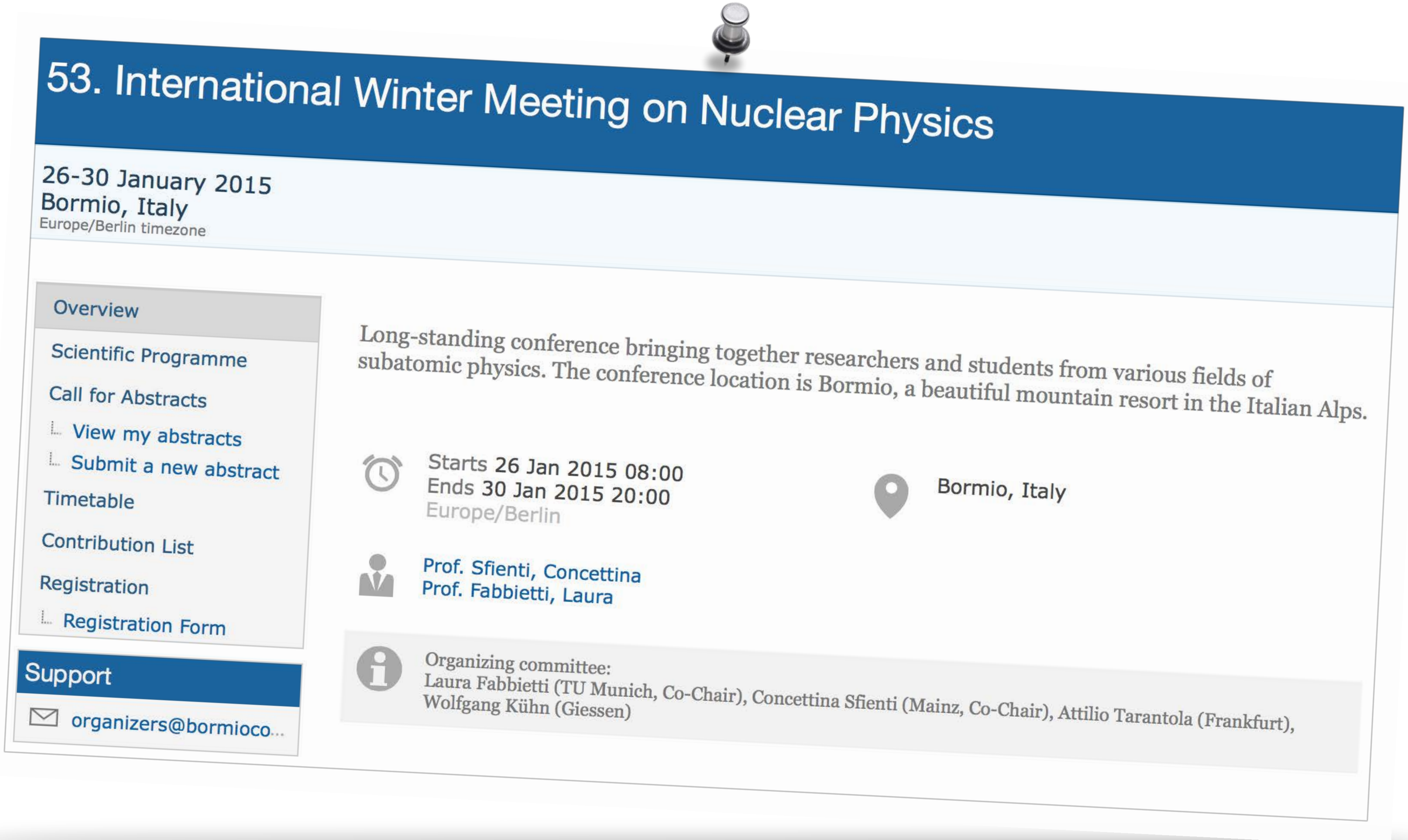
Department of Mechanical and Industrial Engineering
University of Brescia



Muons: civil applications

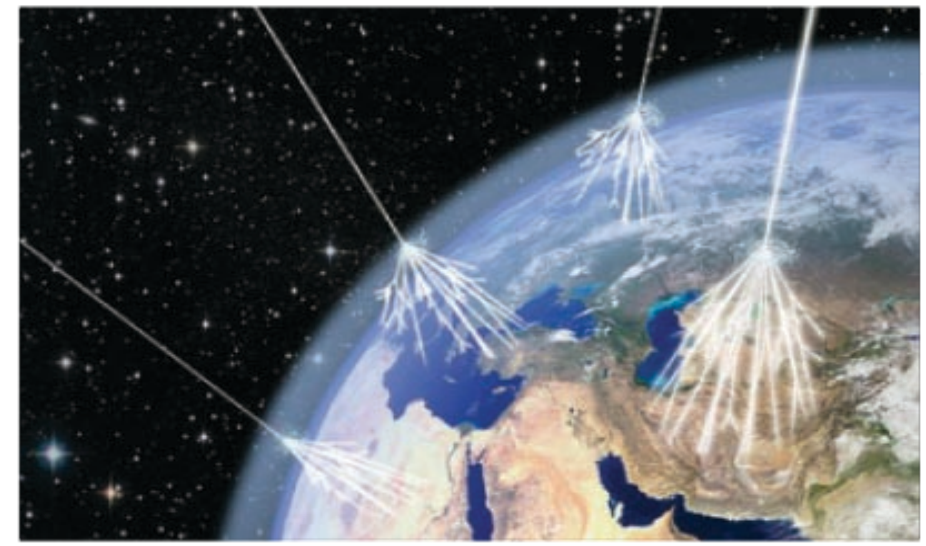
germano bonomi

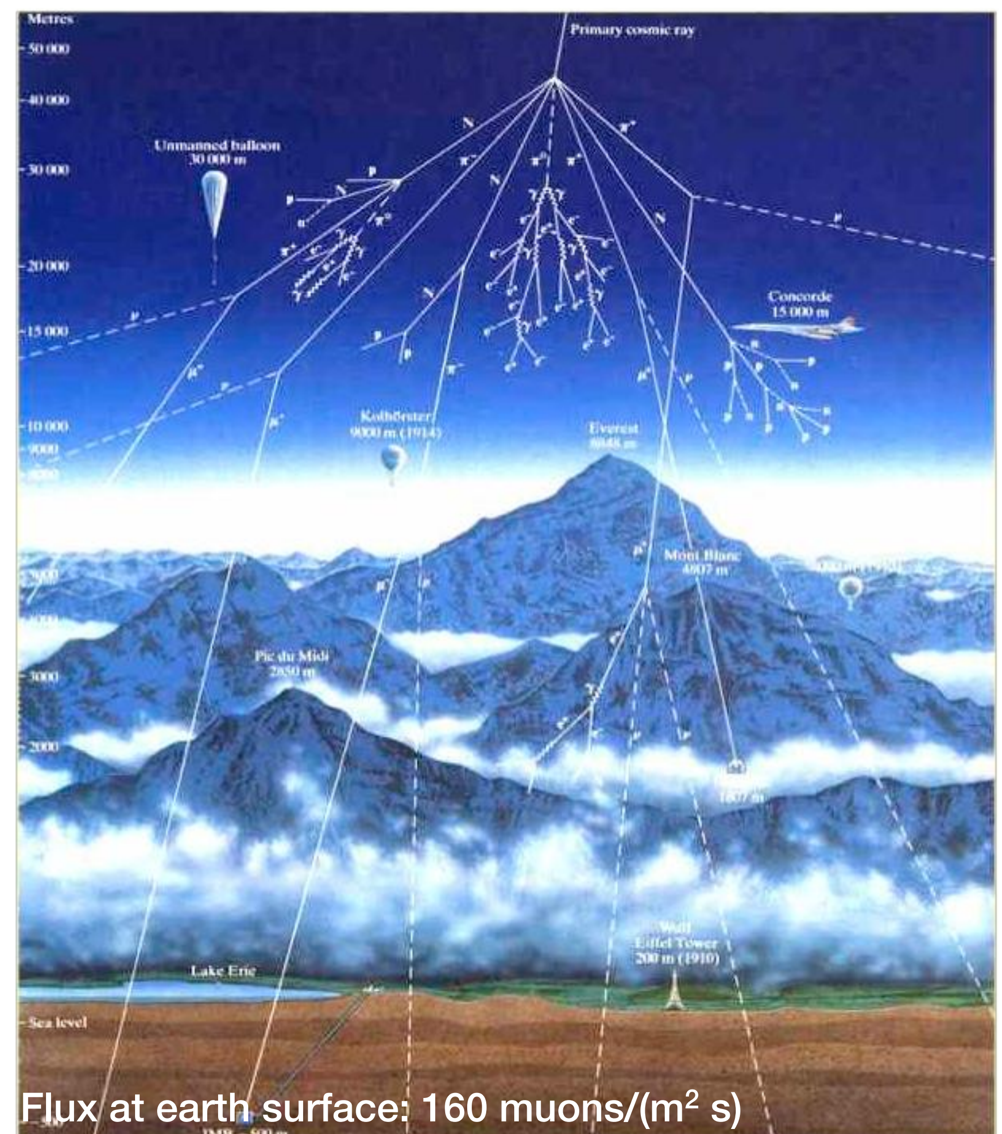
- muons
- radiography (transmission)
- tomography (scattering)
- alignment monitoring (scattering)
- conclusions

Muons

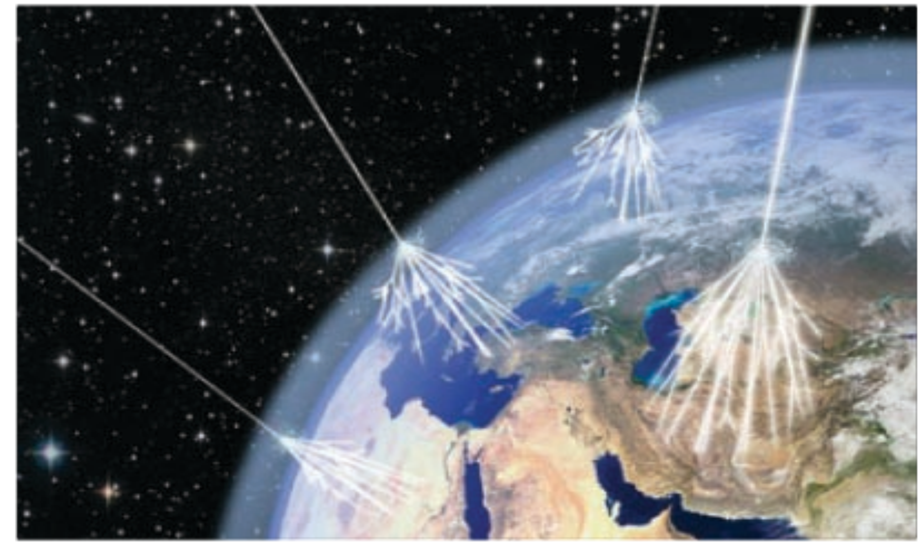
cosmic rays from the cosmo

Cosmic rays



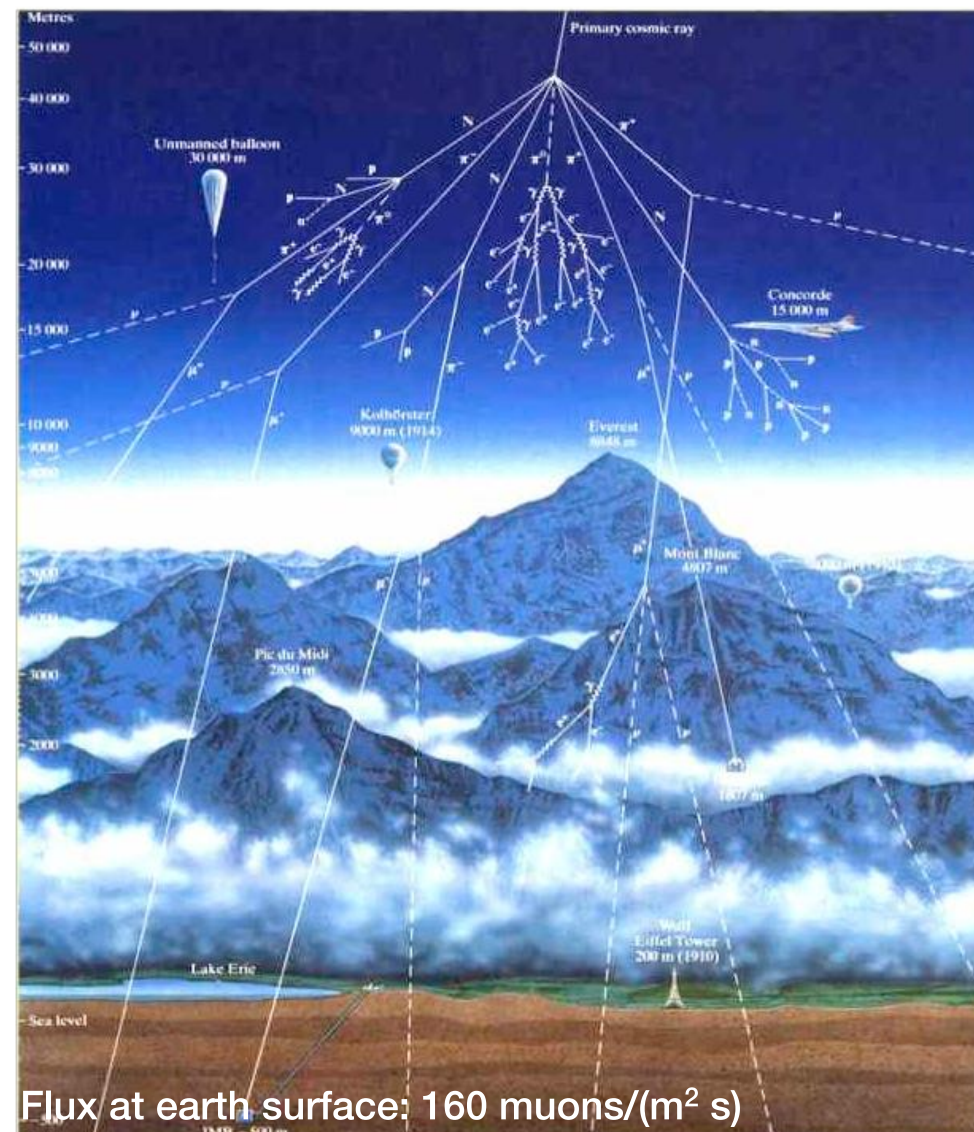

Metres
50 000
40 000
30 000
20 000
15 000
10 000
9000
Primary cosmic ray
Unmanned balloon
30 000 m
Concorde
15 000 m
Mont Blanc
4807 m
Lake Erie
Sea level
Eiffel Tower
200 m (1910)
Flux at earth surface: 160 muons/(m² s)

Cosmic rays

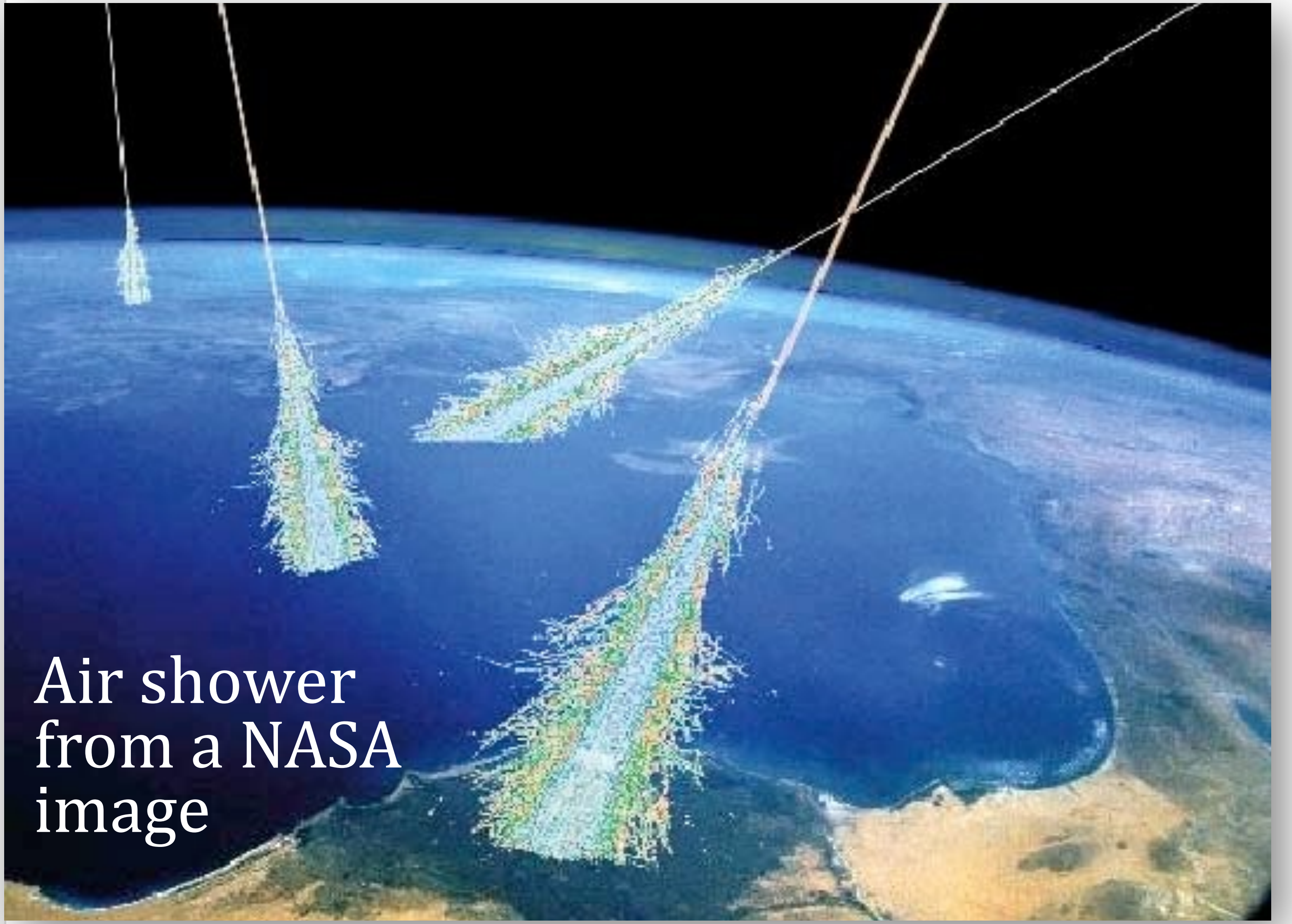


Primary cosmic rays come from the space, mostly originating from the sun

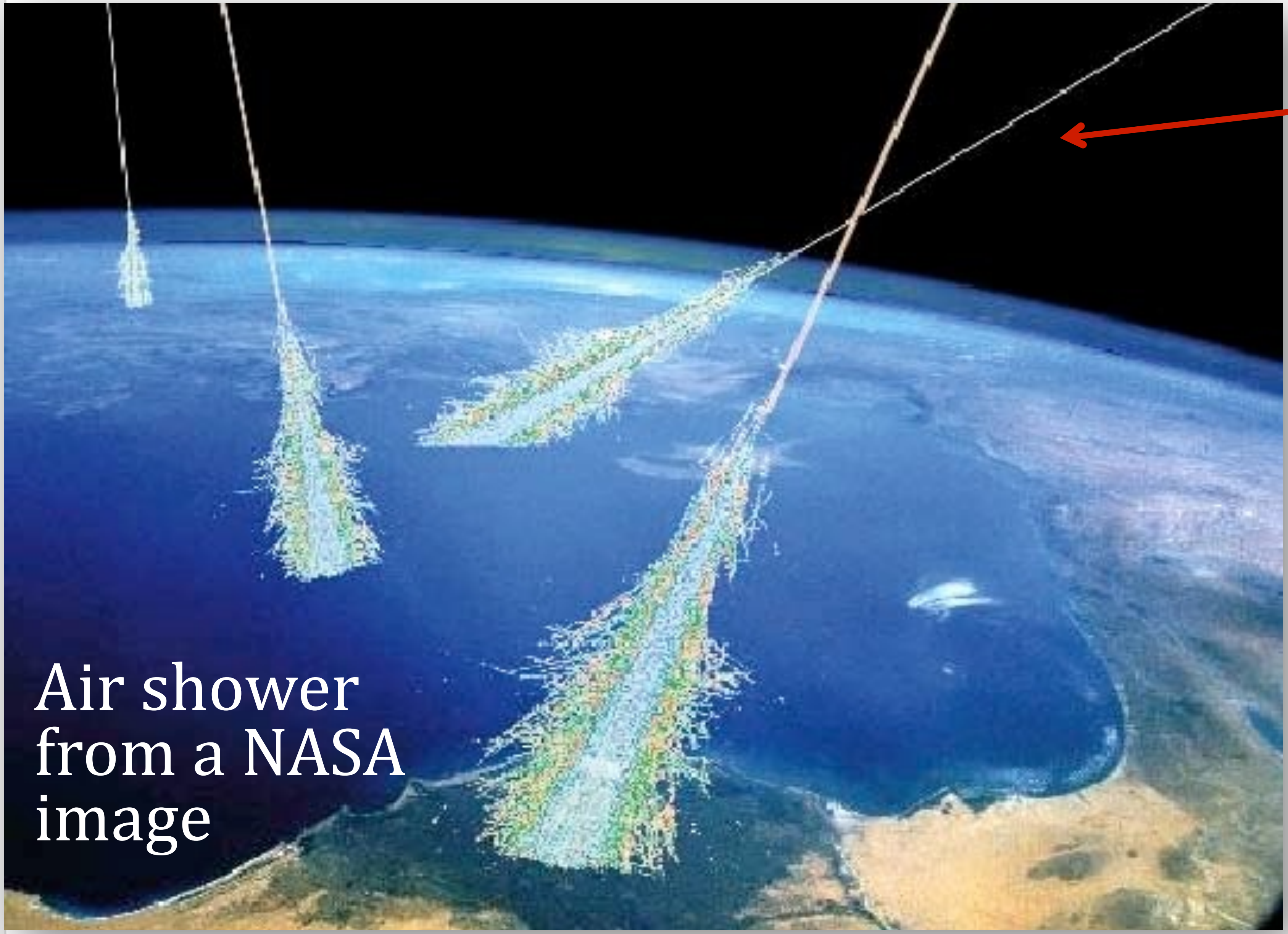
When entering the atmosphere the interact with the atoms of which it is composed and they generate showers that, according to the energy of the primary particle, can have an extremely high number of secondary particles



Cosmic rays

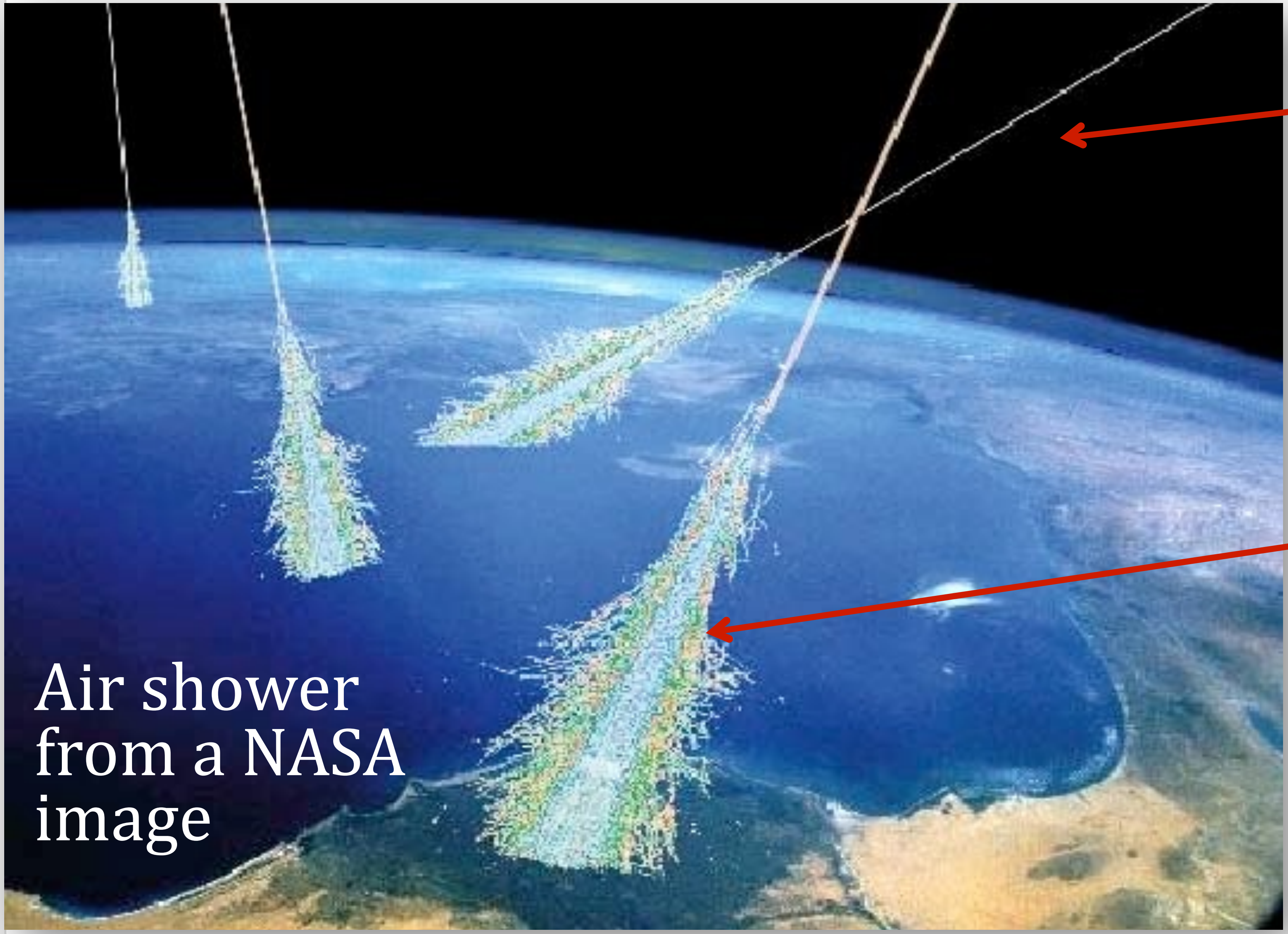


Cosmic rays



Primary cosmic rays
99% are **hydrogen and helium** nuclei from the sun

Cosmic rays



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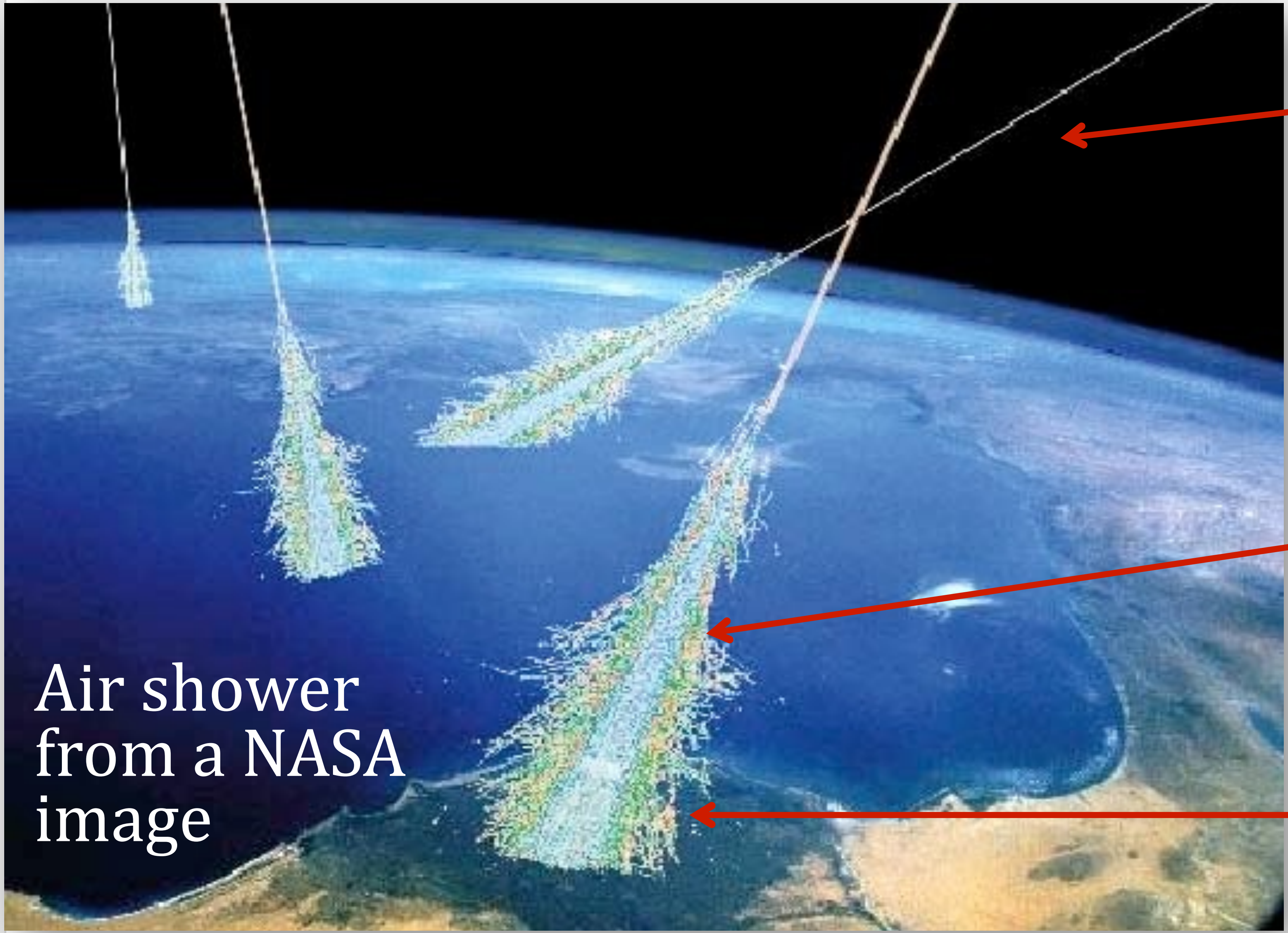
Particle cascade: it originates from the interaction of the cosmic ray with the atmosphere

Cosmic rays



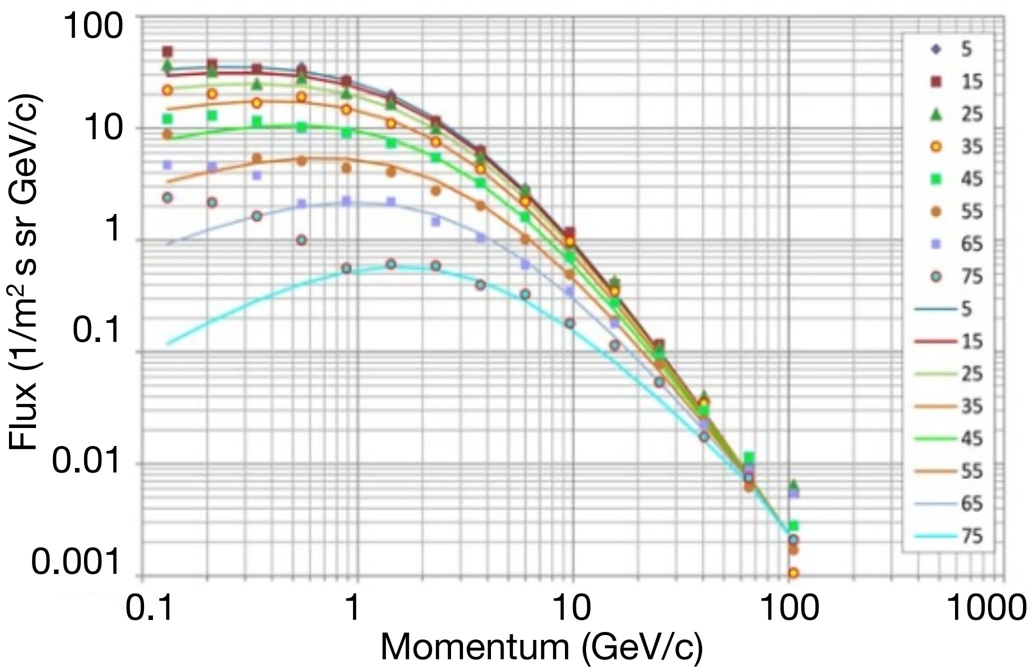
Primary cosmic rays
99% are **hydrogen and helium** nuclei from the sun

Air shower.
Particle cascade: it originates from the interaction of the cosmic ray with the atmosphere

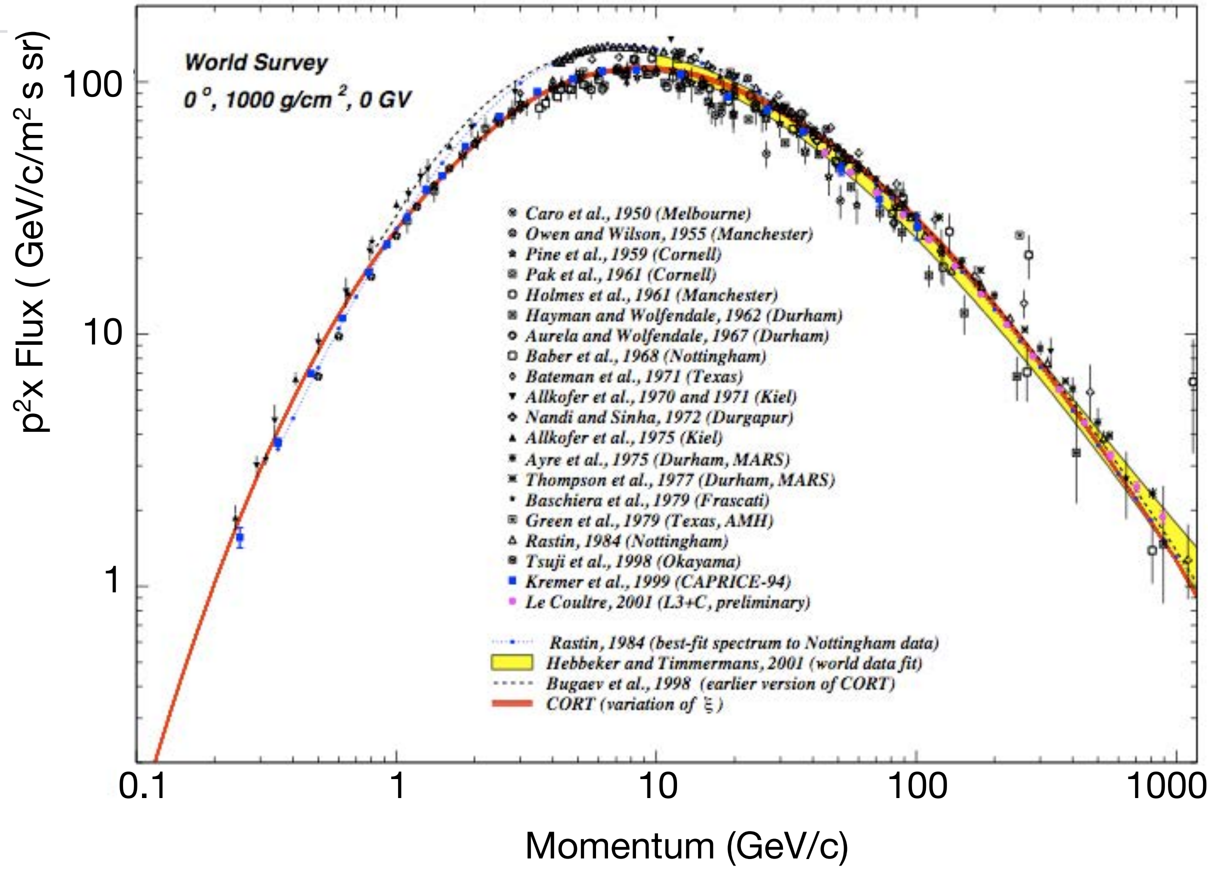
Sea-level cosmic rays.
At sea level most of the surviving rays are **muons (μ)**

Cosmic rays

Differential flux at different angles



flux as a function of the energy



-[SOURCE characteristics:

- **10000** cosmic rays/(minute m²) hit the ground
  (600 of them cross our body every minute)
- at sea level mostly are **muons**, with
  mean energy of 3÷4 GeV
- the flux is maximum at the zenith (vertical) and
  it scales approximately as $\cos^2(\theta)$

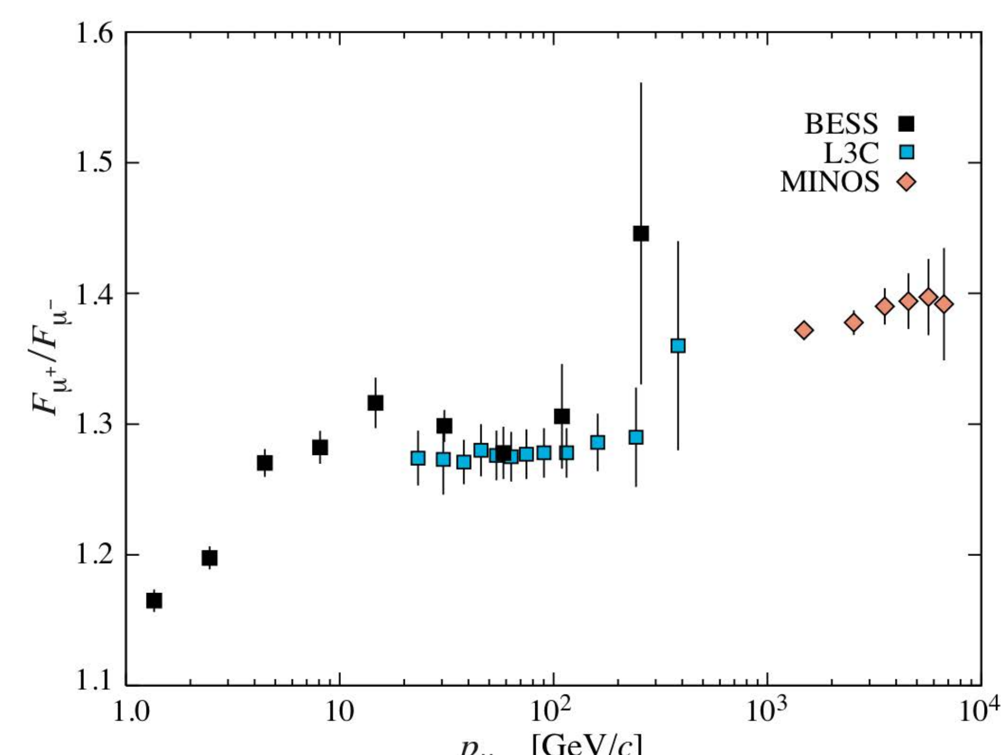


Figure 24.5: Muon charge ratio as a function of the muon momentum from Refs. [44,45,51].

Cosmic rays interaction with matter

INTERACTIONS: When they encounter matter they 1) loose energy (they can be slowed down to rest and absorbed) and 2) they deviate from the original trajectory

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energy loss

- **anelastic collisions** ⇒ excitation or ionization of the crossed medium

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \text{formula di Bethe} - \text{Bloch}$$

- ***bremsstrahlung radiation*** ⇒ emission of photons
- **production of electron-positron couples** (e^-,e^+)

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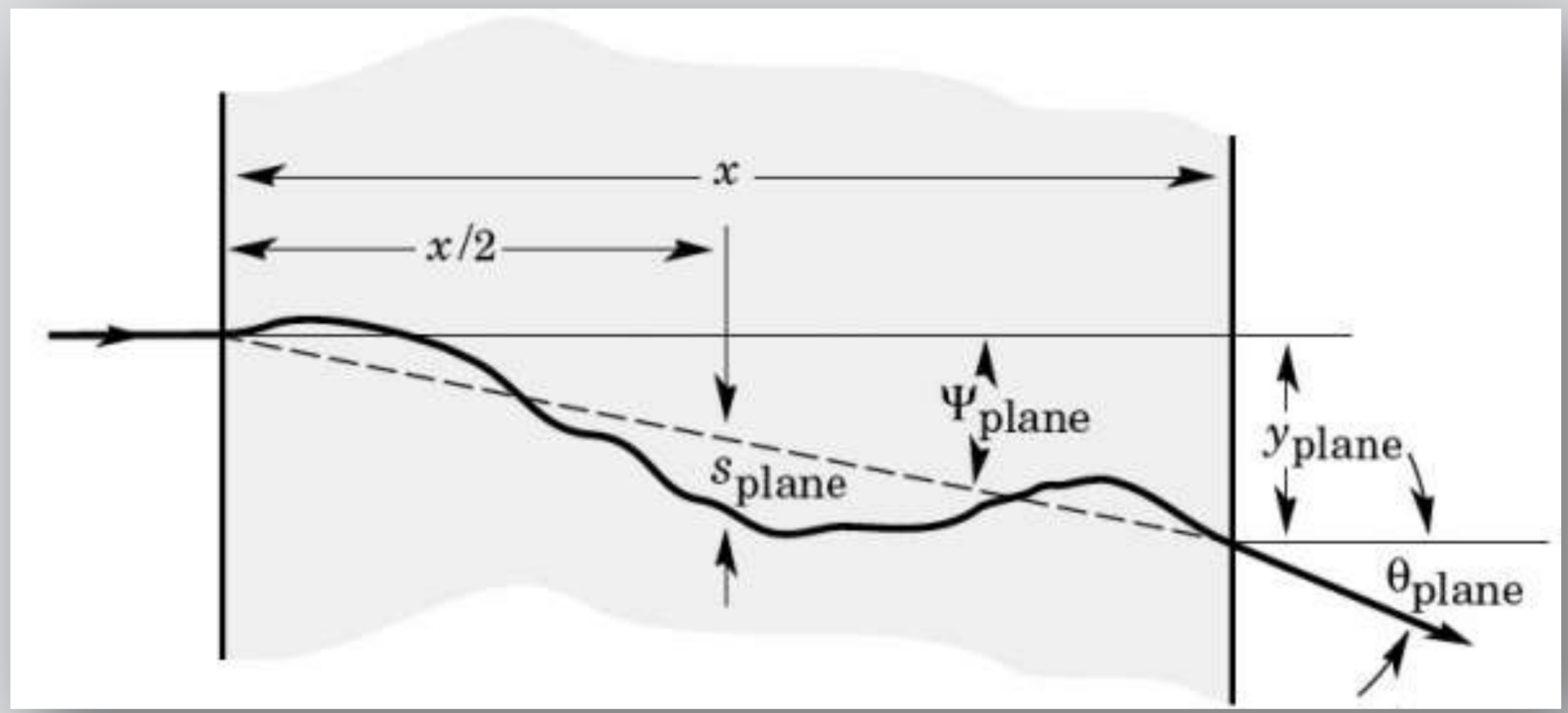
trajectory deviation

- **multiple diffusion** (*MCS – Multiple Coulomb Scattering*)



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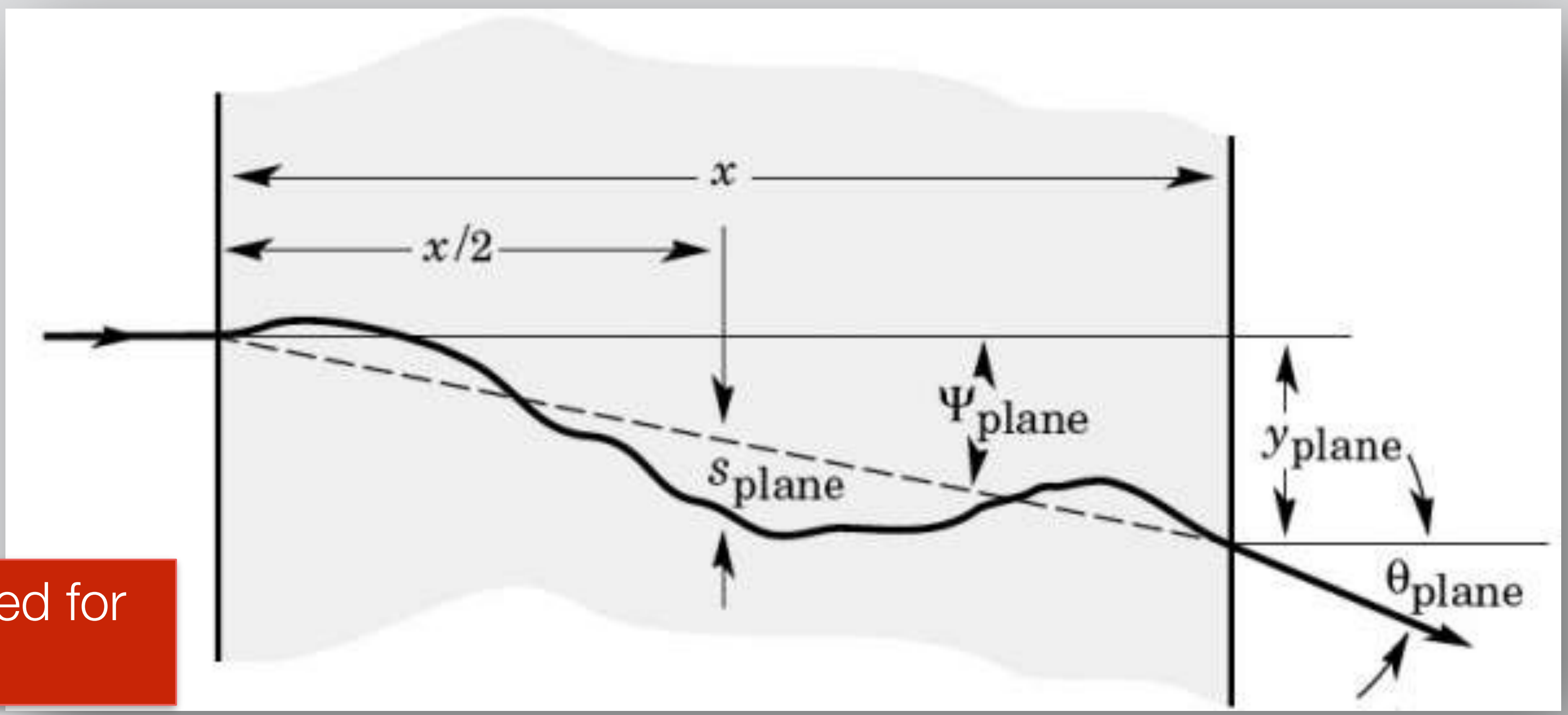
"absorption/ transmission"

trajectory deviation

- **multiple diffusion** (*MCS – Multiple Coulomb Scattering*)

"scattering"



Both effects can be used for civil applications

Muons transmission

radiography

Applications (transmission)

-[first idea:

to use the information on absorption of muons to measure the thickness of the material crossed by the muons themselves

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The **first ever** civil application of the **cosmic rays** to inspect large volumes dates back to 1955 when the thickness of rock above a underground tunnel was measured by E. P. George **[1]**

[1] E. P. George, “Cosmic rays measure overburden of tunnel”, Commonwealth Engineer, (1955), 455.

Applications (transmission)

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Another application much more spectacular was realized by the Physics Nobel Price L.W. **Alvarez** **[2]** that in 1970 made a "radiography" of the Chefren **pyramyd** looking for hidden chambers ... finding none

Radiography

✓Measure the number of muons surviving the passage through the material: "black & white" images

[1] E. P. George, "Cosmic rays measure overburden of tunnel", Commonwealth Engineer, (1955), 455.
[2] L.W. Alvarez et al., "Search for hidden chambers in the pyramids using cosmic rays", Science 167 (1970) 832.

Applications (transmission)

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

The three pyramids of Giza are situated a few miles southwest of Cairo, Egypt. The two largest pyramids stand within a few hundred meters of each other. They were originally of almost exactly the same height (145 meters), but the Great Pyramid of Cheops has a slightly larger square base (230 meters on a side) than the Second Pyramid of Chephren (215.5 meters on a side). A photograph of the pyramids at Giza is shown as Fig. 1. Figure 2 shows the elevation cross sections of the two pyramids and indicates the contrast in architectural design. The simplicity of Chephren's pyramid, compared with the elaborate structure of his father's Great Pyramid, is explained by archeologists in terms of a "period of experimentation," ending with the construction of Cheops's pyramid (*1*). (The complexity of the internal architecture of the pyramids increased during the Fourth Dynasty until the time of Cheops and then gave way to quite simple designs after his time.)

An alternative explanation for the sudden decrease in internal complexity from the Great Pyramid to the Second Pyramid suggested itself to us: perhaps Chephren's architects had been more successful in hiding their upper chambers than were Cheops's. The interior of the Great Pyramid was reached by the tunneling laborers of Caliph Mamun in the 9th century A.D., almost 3400 years after its construction. Of our group only Ahmed Fakhry (author of *The Pyramids*, professor emeritus of archeology, University of Cairo, and member of the Supreme Council of Archeology, Cairo) was trained in archeology. As laymen, we thought it not unlikely that unknown chambers might still be present in the limestone above the "Belzoni Chamber," which is near the center of the base of Chephren's Second Pyramid, and that these chambers had survived undetected for 4500 years. [We learned later that such ideas had occurred to early 19th-century investigators (*2*), who blasted holes in the pyramids with gunpowder in attempts to locate new chambers.]

In 1965 a proposal to probe the Second Pyramid with cosmic rays (*3*) was sent to a representative group of cosmic-ray physicists and archeologists with a request for comments concerning its technical feasibility and archeological interest. The principal novelty of the proposed cosmic-ray detectors involved their ability to measure the angles of arrival of penetrating cosmic-ray muons with great precision, over a large sensitive area. The properties of the penetrating cosmic rays have been sufficiently well known for 30 years to suggest their use in a pyramid-probing experiment, but it was not until the invention of spark chambers with digital read-out features (*4*) that such a use could be considered as a real possibility. [Cosmic-ray detectors with low angular resolution had been used in 1955 to give an independent measure of the thickness of rock overlying an underground powerhouse in Australia's Snowy Mountains Scheme (*5*)].

The favorable response to the proposal led to the establishment by the United Arab Republic and the United States of America of the Joint U.A.R.–U.S.A. Pyramid Project on 14 June 1966. Cosmic-ray detectors were installed in the Belzoni Chamber of the Second Pyramid at Giza in the spring of 1967 by physicists from the Ein Shams University and the University of California, in cooperation with archeologists from the U.A.R. Department of Antiquities. Initial operation had been scheduled for the middle of June 1967, but for reasons beyond our control the schedule was delayed for several months. In early 1968 cosmic-ray data began to be recorded on magnetic tape in our laboratory building, a few hundred meters from the two largest pyramids. Since that time we have accumulated accurate angular measurements on more than a million cosmic-ray muons that have penetrated an average of about 100 meters of limestone on their way to the detectors in the Belzoni Chamber.

Proof of the Method

Before any new technique is used in an exploratory mode, it is essential that the capabilities of the technique be demonstrated on a known system. We gave serious consideration to a proposal that the cosmic-ray detectors be tested first in the Queen's Chamber of the Great Pyramid, to demonstrate that the King's Chamber and the Grand Gallery could be detected. But this suggestion was abandoned because the King's Chamber is so close to the Queen's Chamber and because it subtends such a large solid angle that earlier (low resolution) cosmic-ray experiments had already shown that the upper chamber would give a large signal. It was apparent that the only untested feature of the new technique involved the magnitude of the scattering of high energy muons in solid matter. (An anomalously large scattering would nullify the high angular resolution that had been built into the detectors, in the same way that frosted glass destroys our ability to see distant objects.) We had no reason to doubt the calculated scattering, but we were anxious to be able to demonstrate to our colleagues in the U.A.R. Depart-

The authors are affiliated with the Joint Pyramid Project of the United Arab Republic and the United States of America. They reside either in Cairo, United Arab Republic, or in Berkeley, California. The article is adapted from an address presented by Luis W. Alvarez at the Washington Meeting of the American Physical Society, 30 April 1969.

Applications (transmission)

Recently the same technique has been used to inspect the inner part of a vulcano **[3]**

[3] K. Nagamine et al., “Method of probing inner-structure of geophysical substance with the horizontal cosmic ray muons and possible application to volcanic eruption prediction”, Nucl. Inst. Meth. A 356 (1995), 585.

N·H ELSEVIER

Nuclear Instruments and Methods in Physics Research A 356 (1995) 585–595

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction

K. Nagamine [a,b,*], M. Iwasaki [a], K. Shimomura [a], K. Ishida [b]

[a] *Meson Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo, Japan*

[b] *Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan*

Received 4 July 1994; revised form received 12 September 1994

Abstract

One potential use of cosmic-ray muons arriving nearly horizontally along the earth is a probe of the inner-structure of a gigantic geophysical substance, such as a volcanic mountain. A simple detection system comprising a plastic scintillator hodoscope which is expandable to a larger scale was developed. The first successful measurement of the inner-structure of Mt. Tsukuba is described. The future perspective of the application of the present method towards the prediction of volcanic eruption is discussed.

6. Conclusion

Throughout the present considerations as well as the test measurement on Mt. Tsukuba, it was made clear that nearly horizontal cosmic-ray muons can be used to explore the inner-structure of a gigantic geophysical substance, such as the top region of a volcano. The detection method described here is sufficiently simple and inexpensive to be expanded into a much larger scale. The proposed method can be applied to probe the existence of an anomaly in the density distribution, such as a cavity at the top region of a volcano having a horizontal size of up to a few km. The time-dependence measurement as well as an extension to three-dimensional tomography would contribute to the identification of any anomaly, suggesting a powerful new prediction method of a volcanic eruption.

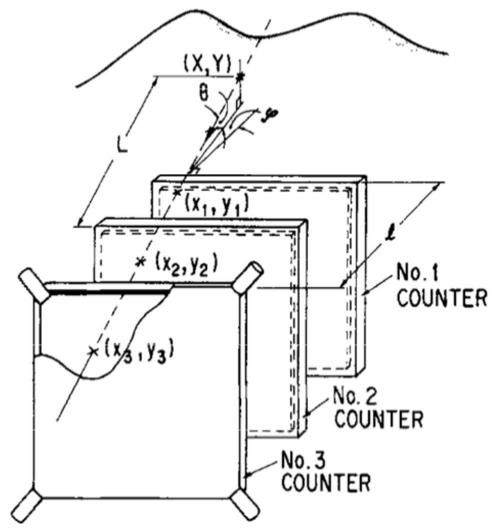
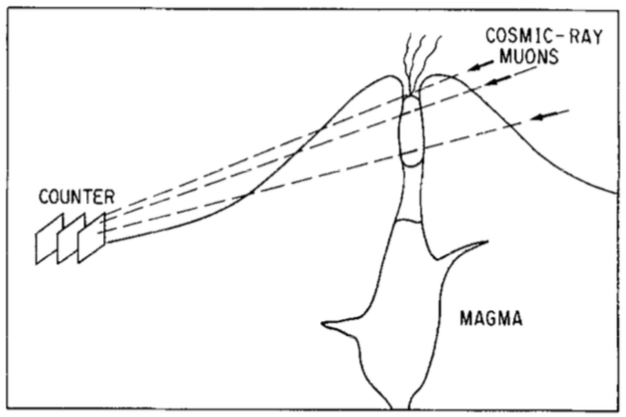
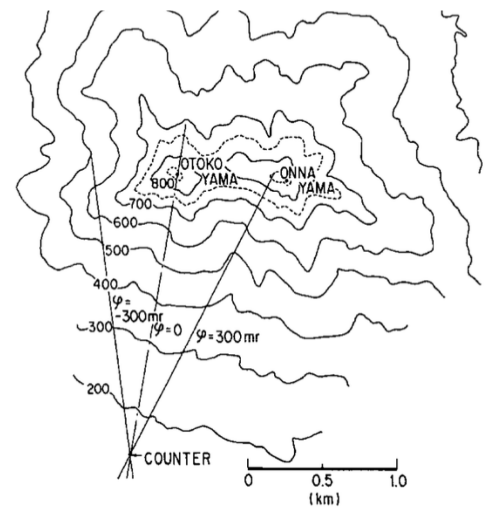
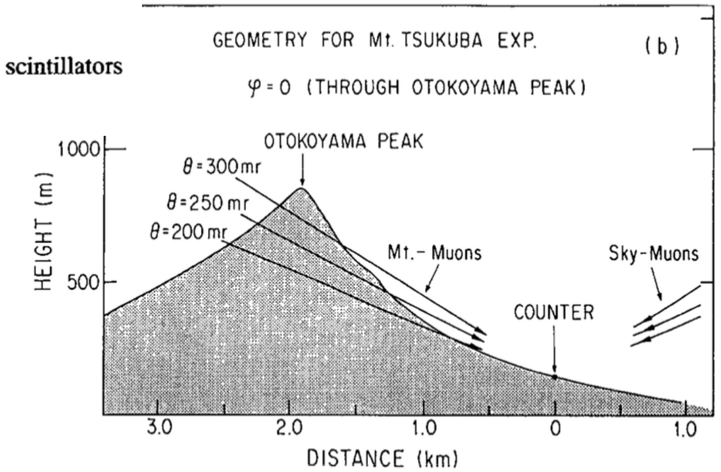


Fig. 3. Counter telescope comprising three plastic scintillators used for the Mt. Tsukuba measurement.







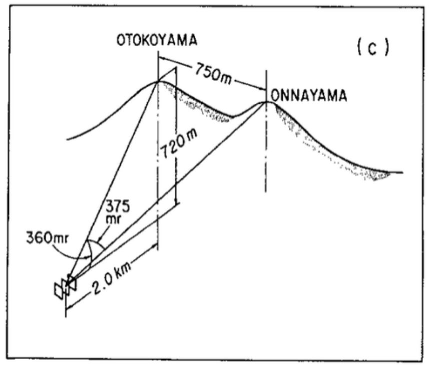


Fig. 5. Geometrical arrangement for the counter versus Mt. Tsukuba taken in the present measurement: (a) horizontal view, (b) vertical view along the plane including counter and the top of Otokoyama and (c) conceptual three-dimensional view.

Applications (transmission)

ARTICLE

Received 13 Aug 2013 | Accepted 5 Feb 2014 | Published 10 Mar 2014 DOI: 10.1038/ncomms4381 OPEN

Radiographic visualization of magma dynamics in an erupting volcano

Hiroyuki K.M. Tanaka[1], Taro Kusagaya[1] & Hiroshi Shinohara[2]

Radiographic imaging of magma dynamics in a volcanic conduit provides detailed information about ascent and descent of magma, the magma flow rate, the conduit diameter and inflation and deflation of magma due to volatile expansion and release. Here we report the first radiographic observation of the ascent and descent of magma along a conduit utilizing atmospheric (cosmic ray) muons (muography) with dynamic radiographic imaging. Time sequential radiographic images show that the top of the magma column ascends right beneath the crater floor through which the eruption column was observed. In addition to the visualization of this magma inflation, we report a sequence of images that show magma descending. We further propose that the monitoring of temporal variations in the gas volume fraction of magma as well as its position in a conduit can be used to support existing eruption prediction procedures.

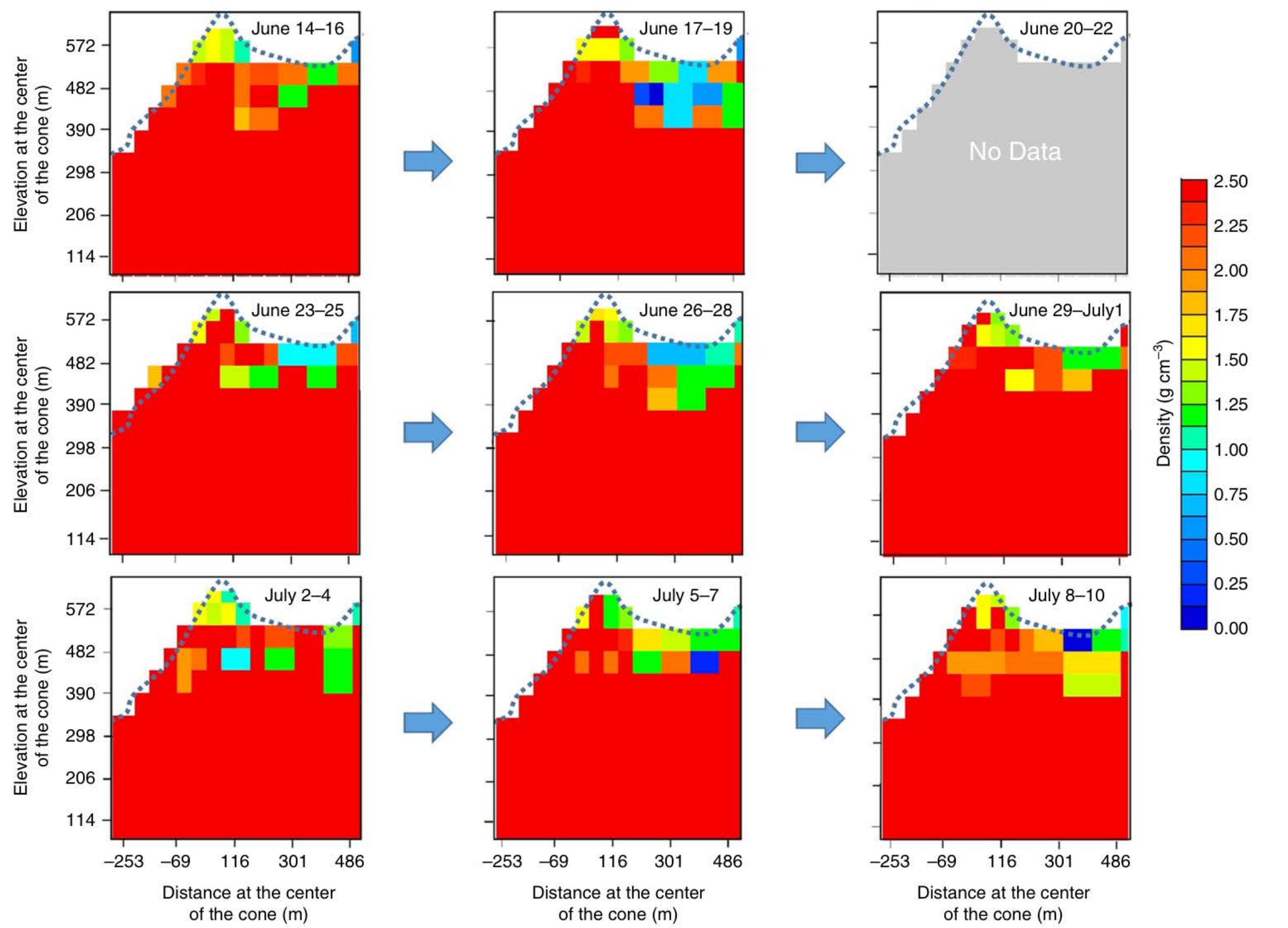
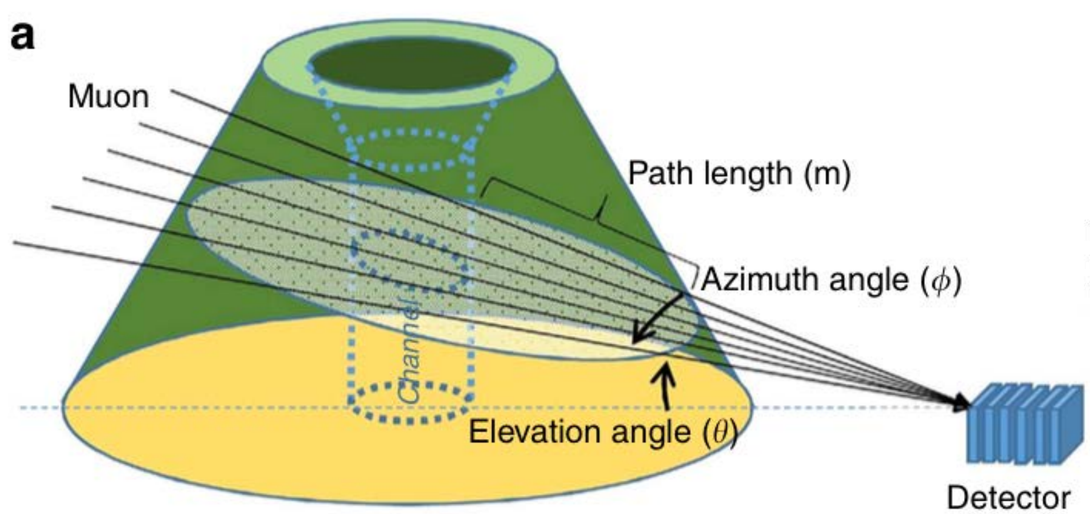
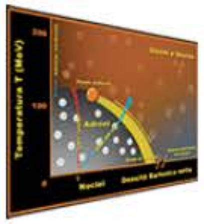


Figure 5 | Time sequential muographic animation. The plots show the angular distribution of 1σ (68% CL) upper limit of the average density along the muon path. The frame rate is 10 FPM. The data were not taken during 20–22 June due to a blackout. Horizontally adjacent two bins were packed in order to achieve higher and more accurate statistics. The elevation and horizontal distances at the centre of the cone are shown.



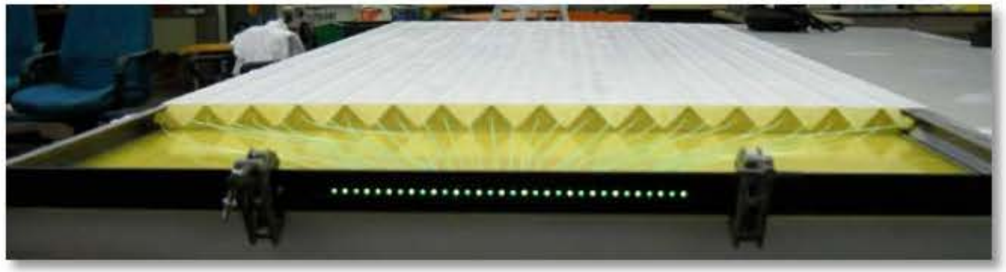
Applications (Napoli-Firenze)



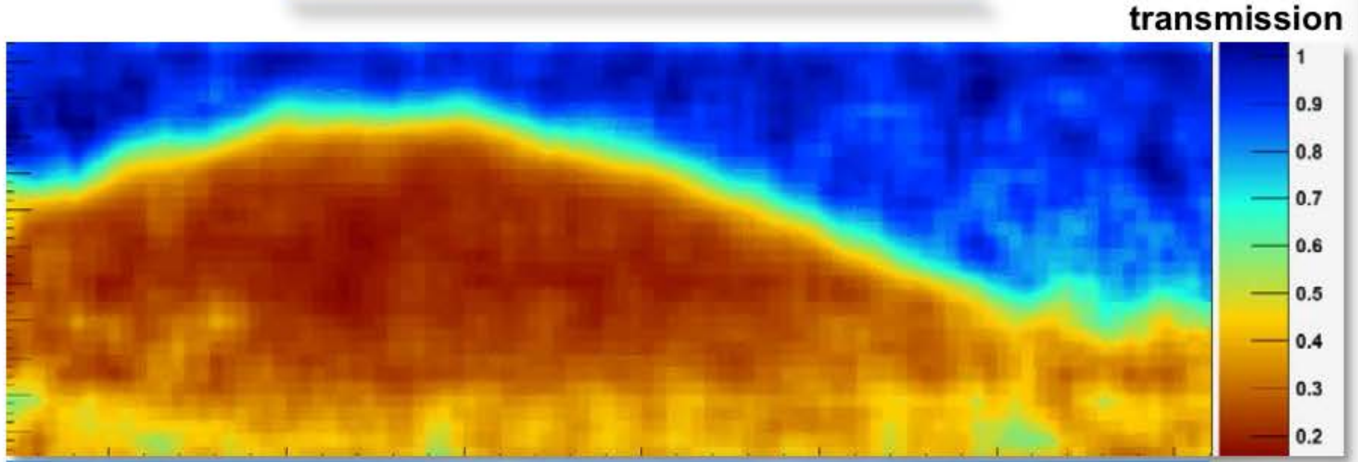
Mu-RAY
Napoli - Firenze

INFN LNS

Muon radiography
same principle as Mu-STEEL
different detector: scintillators+WLS+SiPM



shadow of the Vesuvius



Applications (Budapest)

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Advances in High Energy Physics
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http://dx.doi.org/10.1155/2013/560192

Hindawi

Research Article

Cosmic Muon Detection for Geophysical Applications

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[4] *Geological, Geophysical and Space Science Research Group of the HAS, Eötvös University, 1/C Pázmány P. sétány, 1117 Budapest, Hungary*

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A portable cosmic muon detector has been developed for environmental, geophysical, or industrial applications. The device is a tracking detector based on the Close Cathode Chamber, an MWPC-like technology, allowing operation in natural underground caves or artificial tunnels, far from laboratory conditions. The compact, low power consumption system with sensitive surface of 0.1 m^2 measures the angular distribution of cosmic muons with a resolution of 10 mrad, allowing for a detailed mapping of the rock thickness above the muon detector. Demonstration of applicability of the muon telescope (REGARD Muontomograph) for civil engineering and measurements in artificial underground tunnels or caverns are presented.

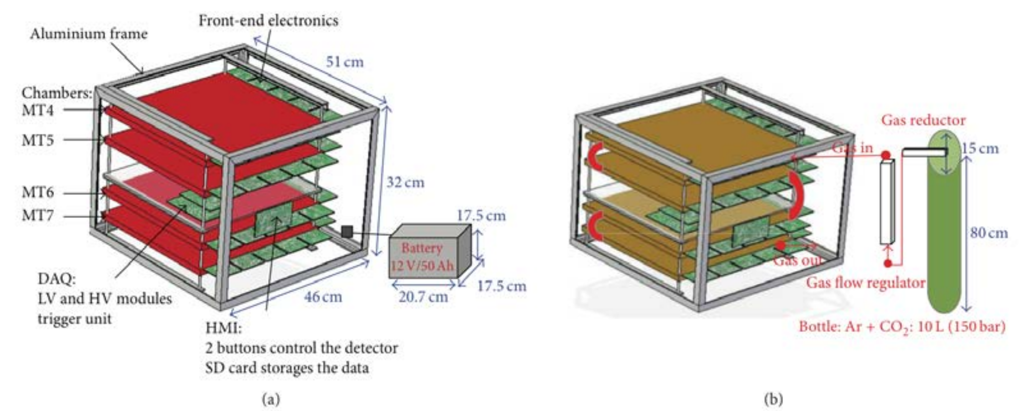

FIGURE 1: The layout and structure of the REGARD Muontomograph, including the power supply (a) and the gas system (b) based on [5, 6].

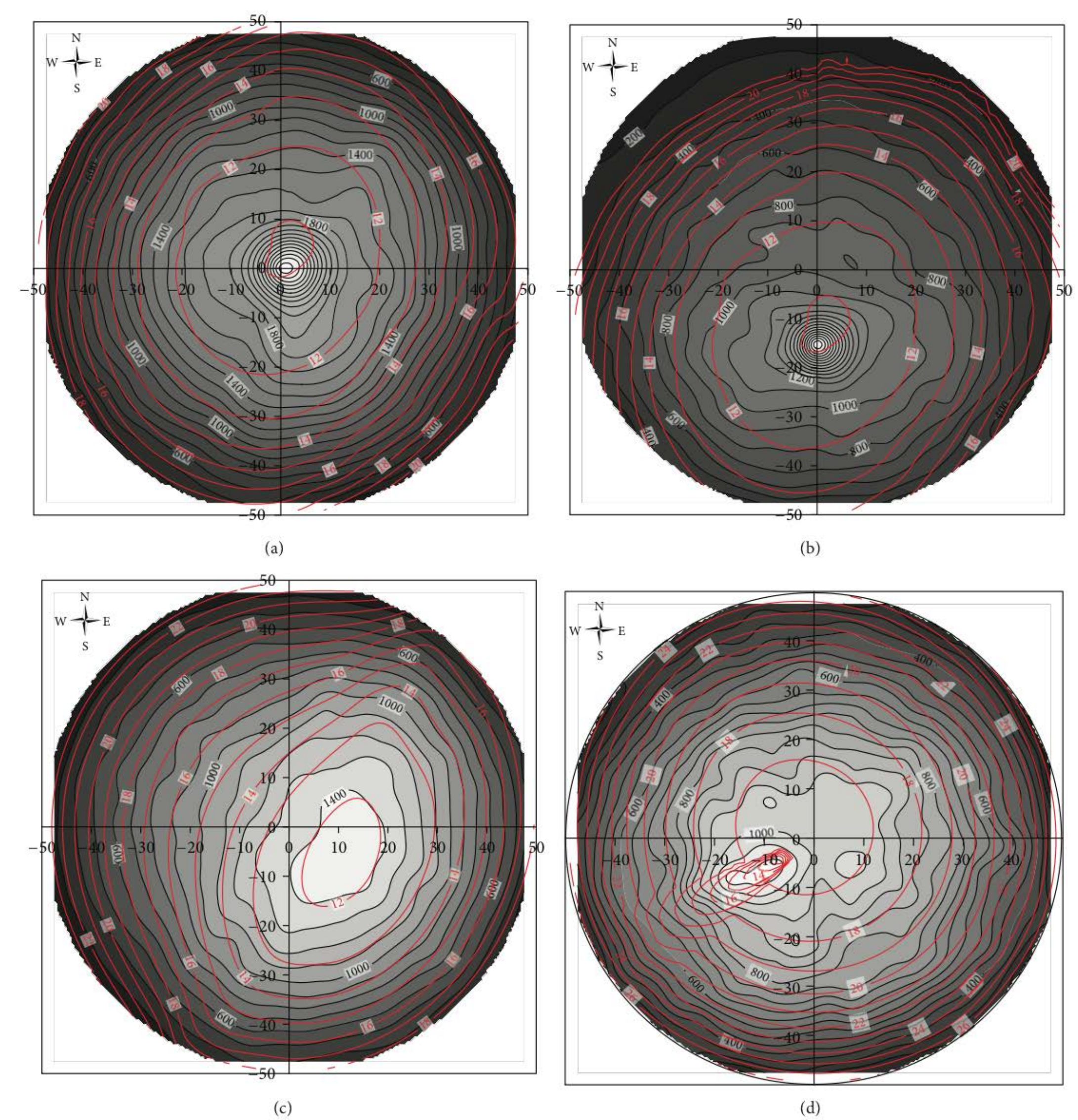

FIGURE 5: Measurements taken at Kőbánya at different places of the artificial tunnel. *Upper row*: Detector was exactly under the axis of the blow hole (a), 15° tilted detector at the same position (b), next to the wall of the tunnel (c), and the shifted detector position (d). *Solid red lines* are for the rock's length to the given direction in angles; *shading* is for the muon distribution after geometrical correction.

Curiosity (transmission)

Cosmic Research, Vol. 40, No. 6, 2002, pp. 559–564. Translated from Kosmicheskie Issledovaniya, Vol. 40, No. 6, 2002, pp. 604–609.

Observation of the Moon Shadow in Cosmic Ray Muons

Yu. M. Andreyev, V. N. Zakidyshev, S. N. Karpov, and V. N. Khodov
Institute for Nuclear Research, Russian Academy of Sciences, 60th October Anniversary pr. 7a, Moscow, 117312 Russia
Received April 25, 2001

Abstract—The effect of cosmic ray shadowing by the Moon is observed by recording the single muon component with the Baksan underground scintillation telescope (BUST). A statistically significant (three standard deviations) deficit of muon intensity in the Moon's direction is discovered. A comparison of the experimental results with the simulation of the shadowing effect for the BUST observations is made. An estimate of the angular resolution of the BUST for the single muon component is derived experimentally for the first time. The results and the technique developed are planned to be used for observations of the Sun's shadow.

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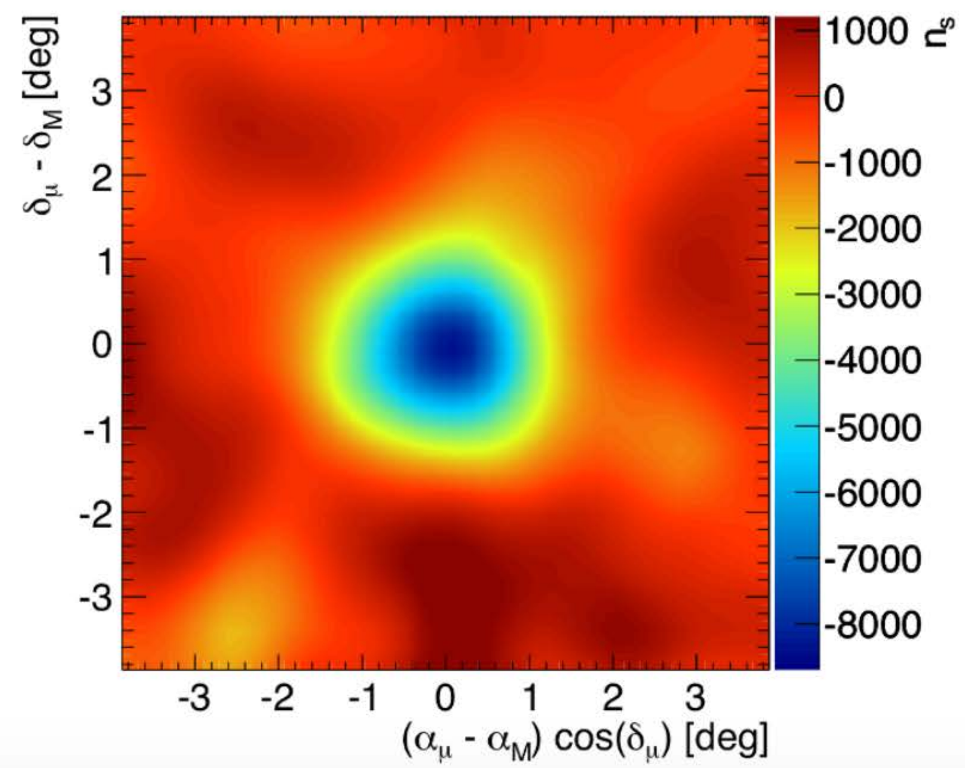
The cosmic-ray Moon shadow seen by IceCube

By Silvia Bravo, 30 May 2013

Like Tweet +1

Cosmic rays, very high-energy particles generated somewhere in outer space, continuously bombard the Earth from all directions. The Moon, however, absorbs those particles that reach its surface after traveling over astronomical distances. Earth-based telescopes such as IceCube use the cosmic-ray shadow cast by the Moon to calibrate their angular resolution and their pointing accuracy for identifying point-like sources. The first impacts on the size of source signal in the detector, while the second constrains the precision with which the detector can estimate the direction of the incoming particles.

The observation of a cosmic-ray deficit from the direction of the Moon with the IceCube Neutrino Observatory is thus an important milestone in proving its potential in the search for point-like sources of astrophysical neutrinos. A recent measurement of the Moon shadow in TeV cosmic rays with the IceCube telescope sets an upper limit on the detector's absolute pointing accuracy to 0.2 degrees. The Antarctic telescope has observed the Moon shadow with a high significance (over 6 sigma), and the Moon's center has been measured to be statistically consistent with its actual location. The IceCube Collaboration presents these results in a paper submitted today to *Physical Review D.*



Curiosity (transmission)

Cosmic Research, Vol. 40, No. 6, 2002, pp. 559–564. Translated from Kosmicheskie Issledovaniya, Vol. 40, No. 6, 2002, pp. 604–609.
Original Russian Text Copyright © 2002 by Andreyev, Zakidyshev, Karpov, Khodov.

Observation of the Moon Shadow in Cosmic Ray Muons

Yu. M. Andreyev, V. N. Zakidyshev, S. N. Karpov, and V. N. Khodov
Institute for Nuclear Research, Russian Academy of Sciences, 60th October Anniversary pr. 7a, Moscow, 117312 Russia
Received April 25, 2001

Abstract—The effect of cosmic ray shadowing by the Moon is observed by recording the single muon component with the Baksan underground scintillation telescope (BUST). A statistically significant (three standard deviations) deficit of muon intensity in the Moon's direction is discovered. A comparison of the experimental results with the simulation of the shadowing effect for the BUST observations is made. An estimate of the angular resolution of the BUST for the single muon component is derived experimentally for the first time. The results and the technique developed are planned to be used for observations of the Sun's shadow.

The cosmic-ray Moon shadow seen by IceCube

By Silvia Bravo, 30 May 2013

Like Tweet +1

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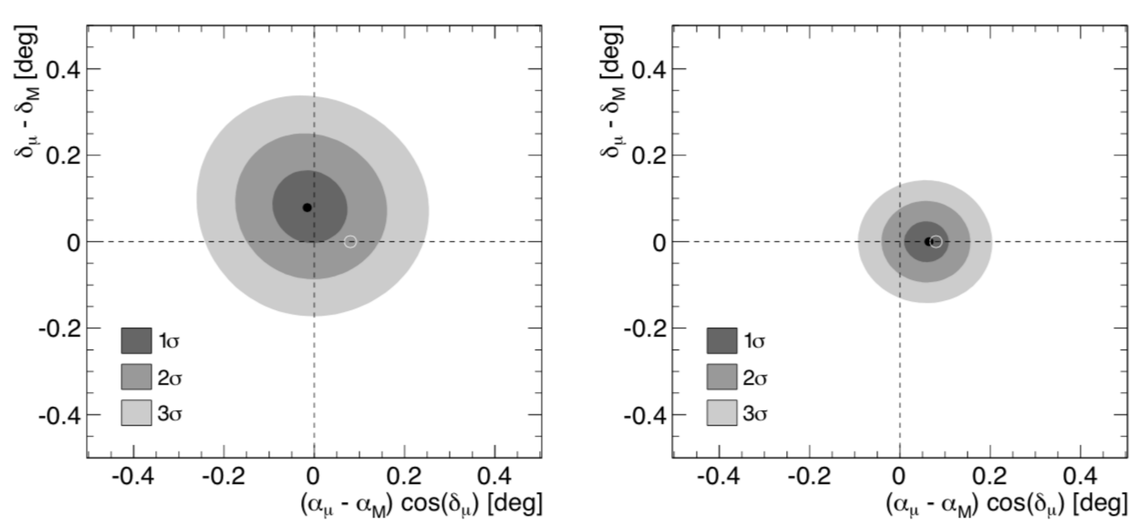
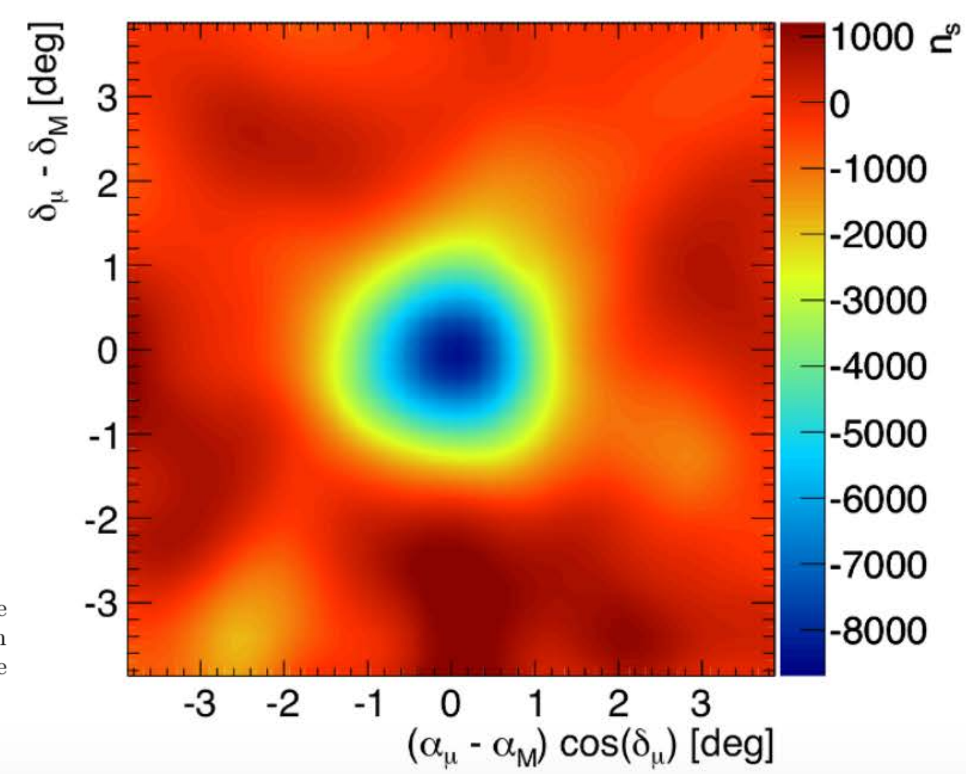


FIG. 8. Contour plot for the position of the minimum of the Moon shadow in the IC40 (*left*) and IC59 data (*right*) in the $(\Delta\alpha, \Delta\delta)$ coordinate system. The reconstructed position for the Moon shadow from the maximum likelihood analysis is shown as a black point, while the expected position of the Moon shadow after accounting for magnetic deflection is shown as a white circle.



Muons scattering

muon tomography

Muon tomography

-[NOVEL IDEA:

exploit the **deflection** of the cosmic rays to perform a **tomography** of a desired volume (Los Alamos Group **[1-3]**)

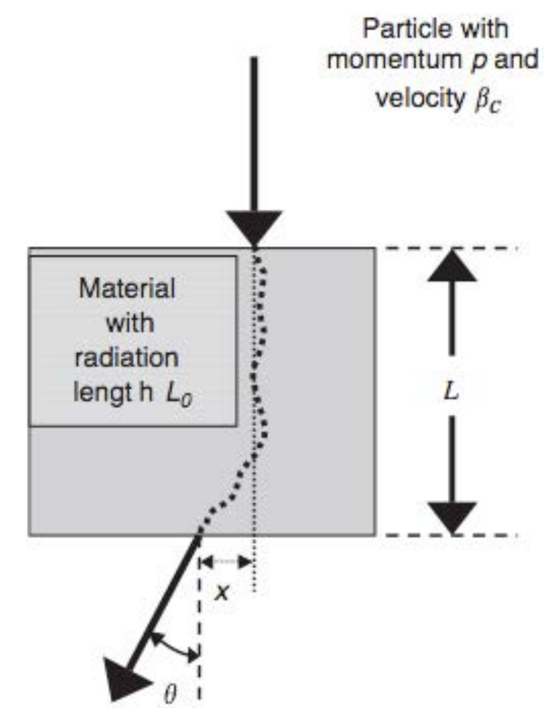


Fig. 1. Multiple Coulomb scattering of a charged particle through material. The magnitude of scattering is exaggerated for illustrative purposes.

[1] K. R. Borozdin et al., "**Radiographic** imaging with cosmic ray muons", Nature 422 (2003) 277.
[2] W. C. Priedhorsky, "Detection of high-Z objects using multiple scattering of cosmic ray muons", Rev. Scient. Inst. 74 (2003) 4294
[3] L. J. Schultz, "Image reconstruction and material Z discrimination via cosmic ray muon radiography", NIM A 519 (2004) 687.

Muon tomography

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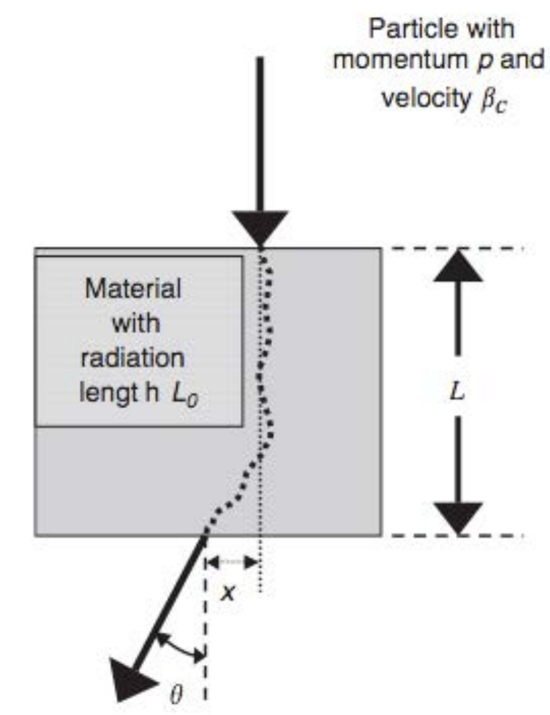
A working prototype of the dimensions of some tens of centimeters has been build and operated. It proved that in principle such technique can be used to scan large volumes



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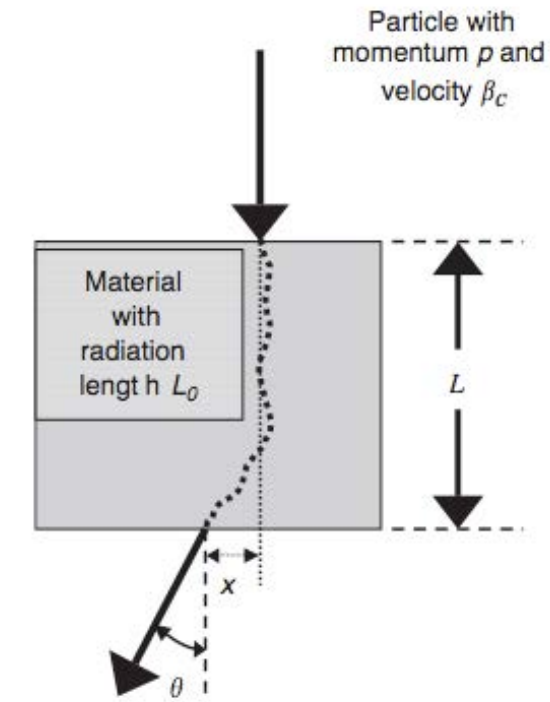

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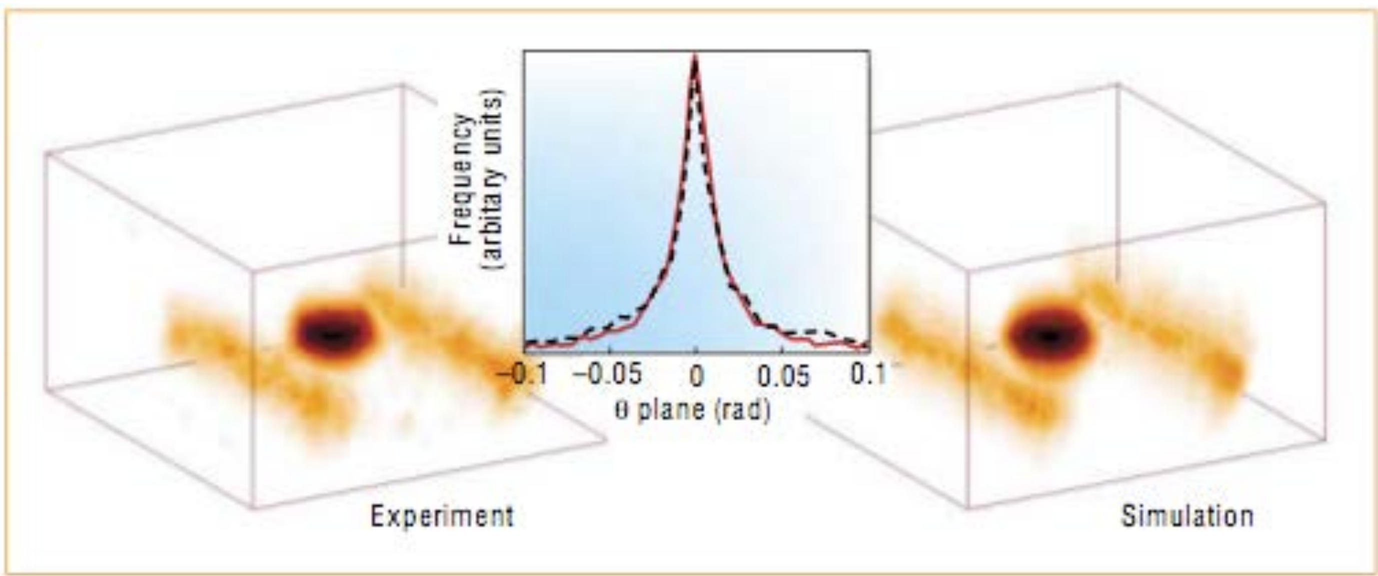

Figure 1 Radiographic imaging with muons of a test object (left) and the reconstructed image of its Monte Carlo simulation (right). The test object is a tungsten cylinder (radius, 5.5 cm; height, 5.7 cm) on a plastic ($35 \times 60 \times 1$ cm^3) plate with two steel support rails. The tungsten cylinder and the iron in the rails are clearly visible in both the experiment and simulation reconstructions. Inset, the widths of the scattering distributions for tracks passing through the tungsten target are very similar for the experimental and simulated data.

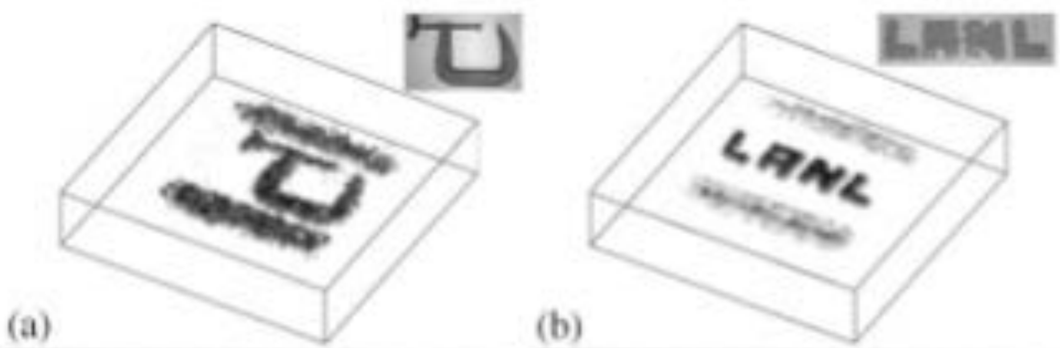

Fig. 5. Experimentally produced cosmic ray muon radiographs of (a) a steel c-clamp, and (b) "LANL" constructed from 1″ lead stock. The bar-like features result from steel beams used to support a plastic object platform.

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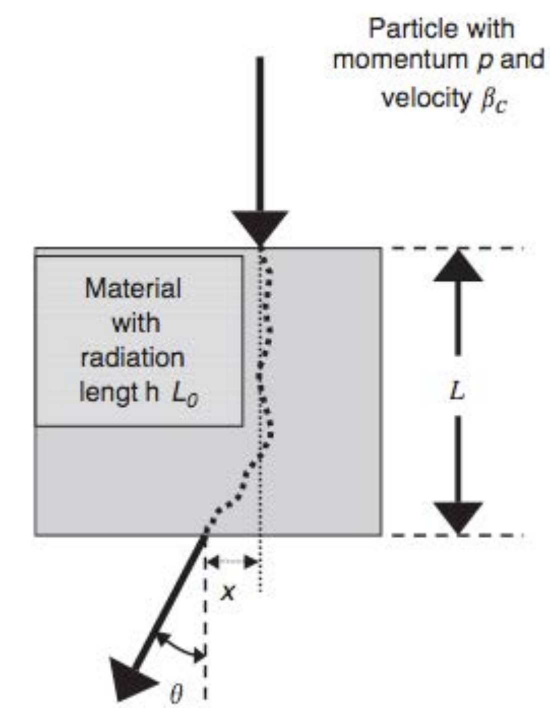

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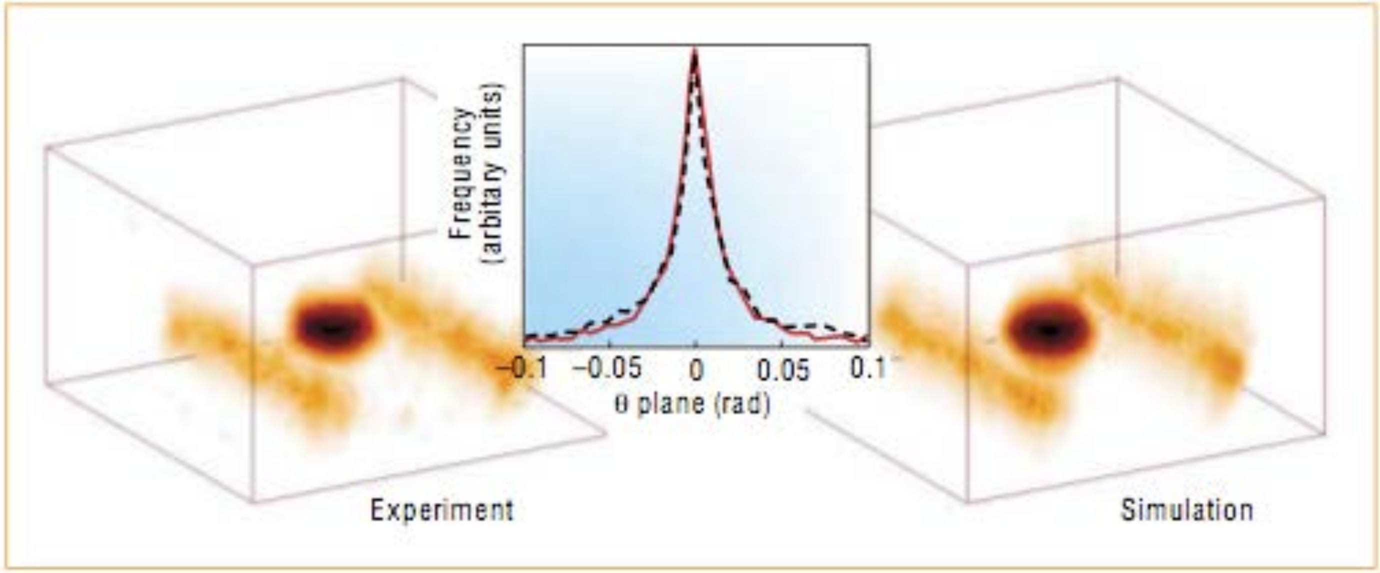

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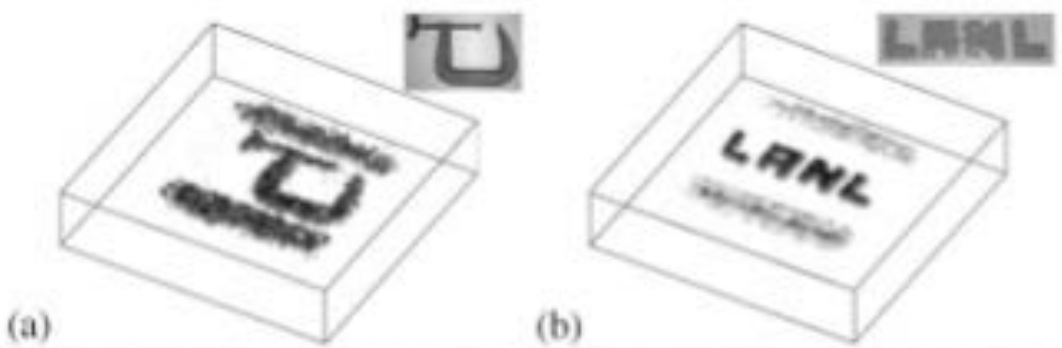

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First experimental demonstration

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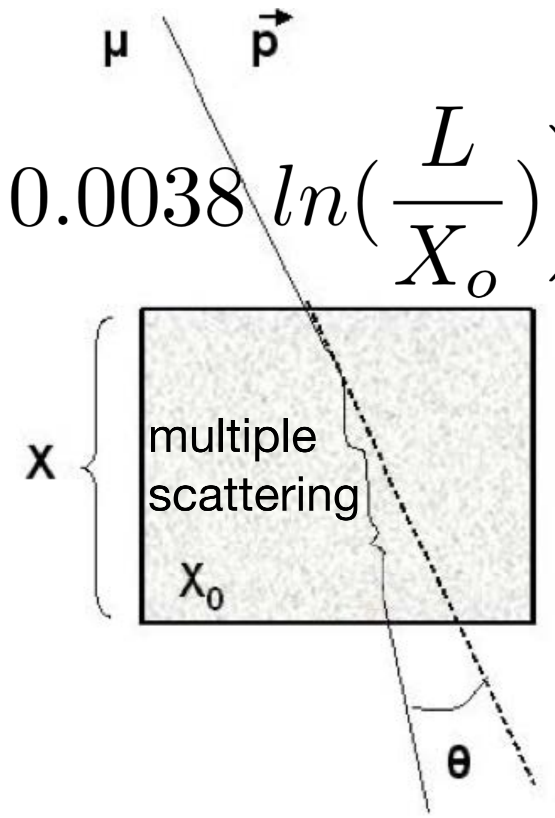
Muon tomography

When they cross matter they are slowed down and they deviate from their original trajectory [they can penetrate meters of steel, km of rock] the deviation angle has a Gaussian distribution, with mean value 0 and RMS (projected on a plane) depending on:

$$\sigma_\theta = \frac{13.6\ MeV}{\beta c p\ (MeV/c)} \sqrt{\frac{L}{X_o}} \left(1 + 0.0038\ ln(\frac{L}{X_o})\right)$$



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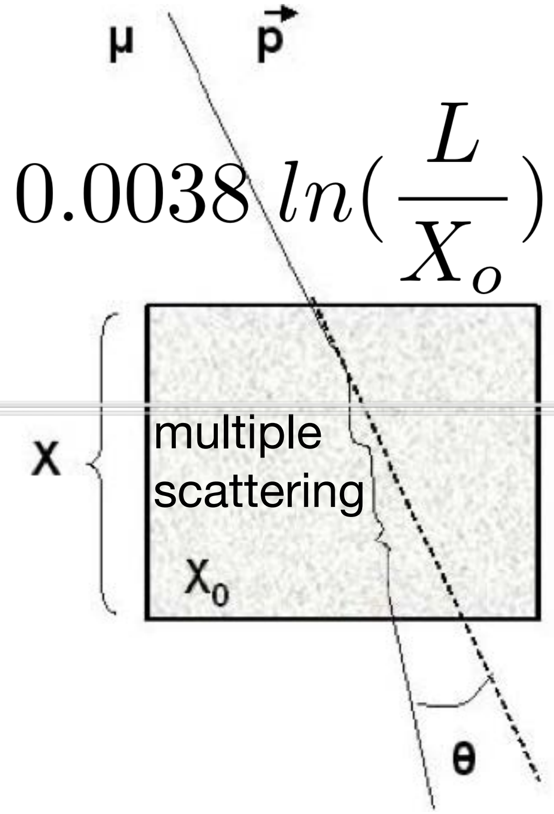

$$X_o = \frac{716.4\ g\ cm^{-2}\ A}{Z(Z+1)\ ln(287/\sqrt{Z})}$$

X_0: the mean distance over which a high-energy electron loses 1/e of its energy by bremsstrahlung

$$\sigma \simeq \frac{1}{p}\sqrt{\frac{L}{X_o}}$$

p = momentum
X_0 = radiation length
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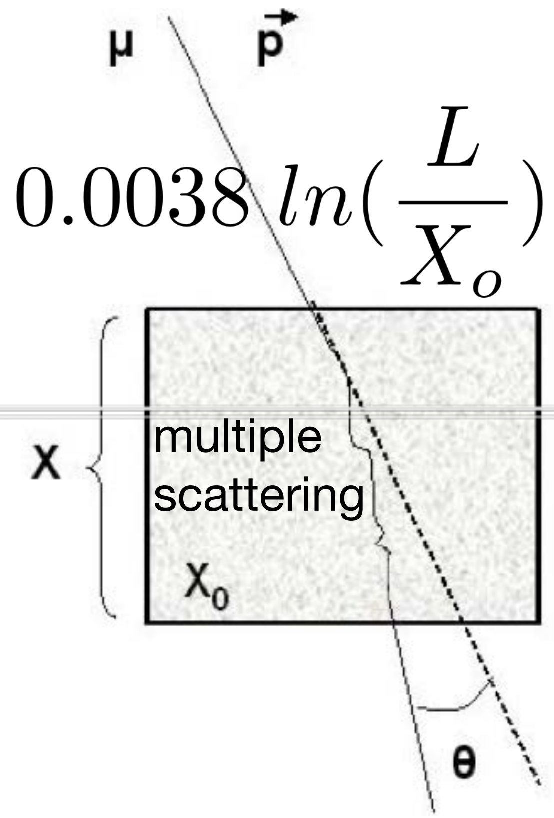

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Multiple scattering for muons passing through 10 cm of various materials				RMS of scattering angle		
Material	Z	ρ (g/cm³)	X_o/ρ (cm)	0.3 GeV/c σ (mrad)	3 GeV/c σ (mrad)	30 GeV/c σ (mrad)
Water	-	1	36,1	26,3	2,6	0,3
Concrete	-		10,7	48,3	4,8	0,5
Iron	26	7,87	1,76	119,2	11,9	1,2
Lead	82	11,34	0,56	211,3	21,1	2,1
Uranium	92	18,97	0,32	279,5	28	2,8

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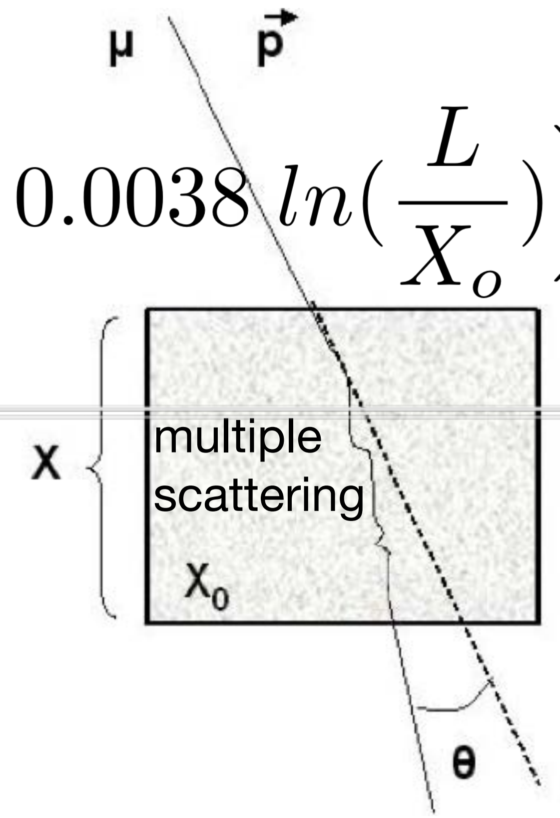

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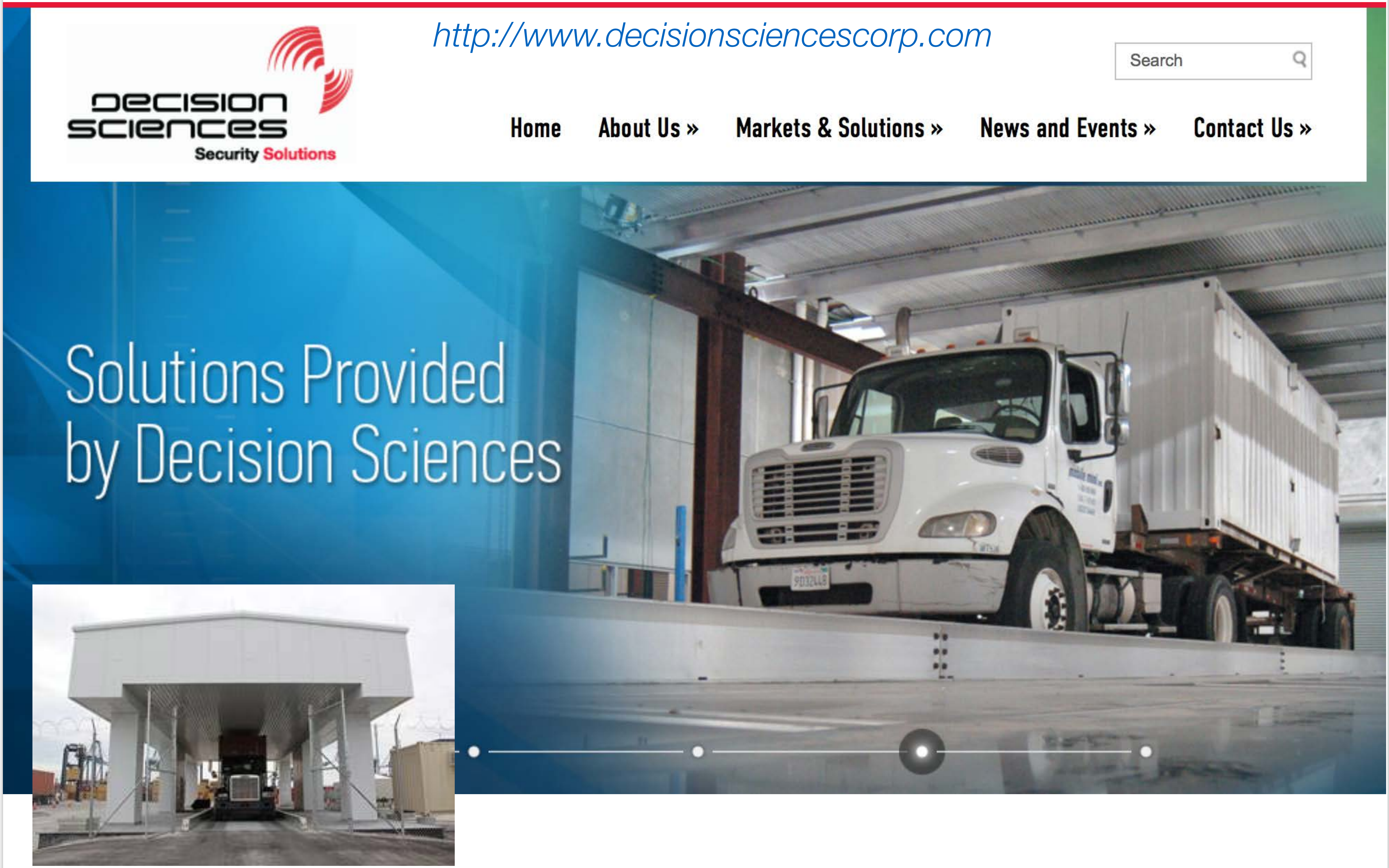
Potentiality to discriminate high Z materials from low and medium Z

Tomography applications

(almost)-comprehensive list

Applications (Decision Sciences)



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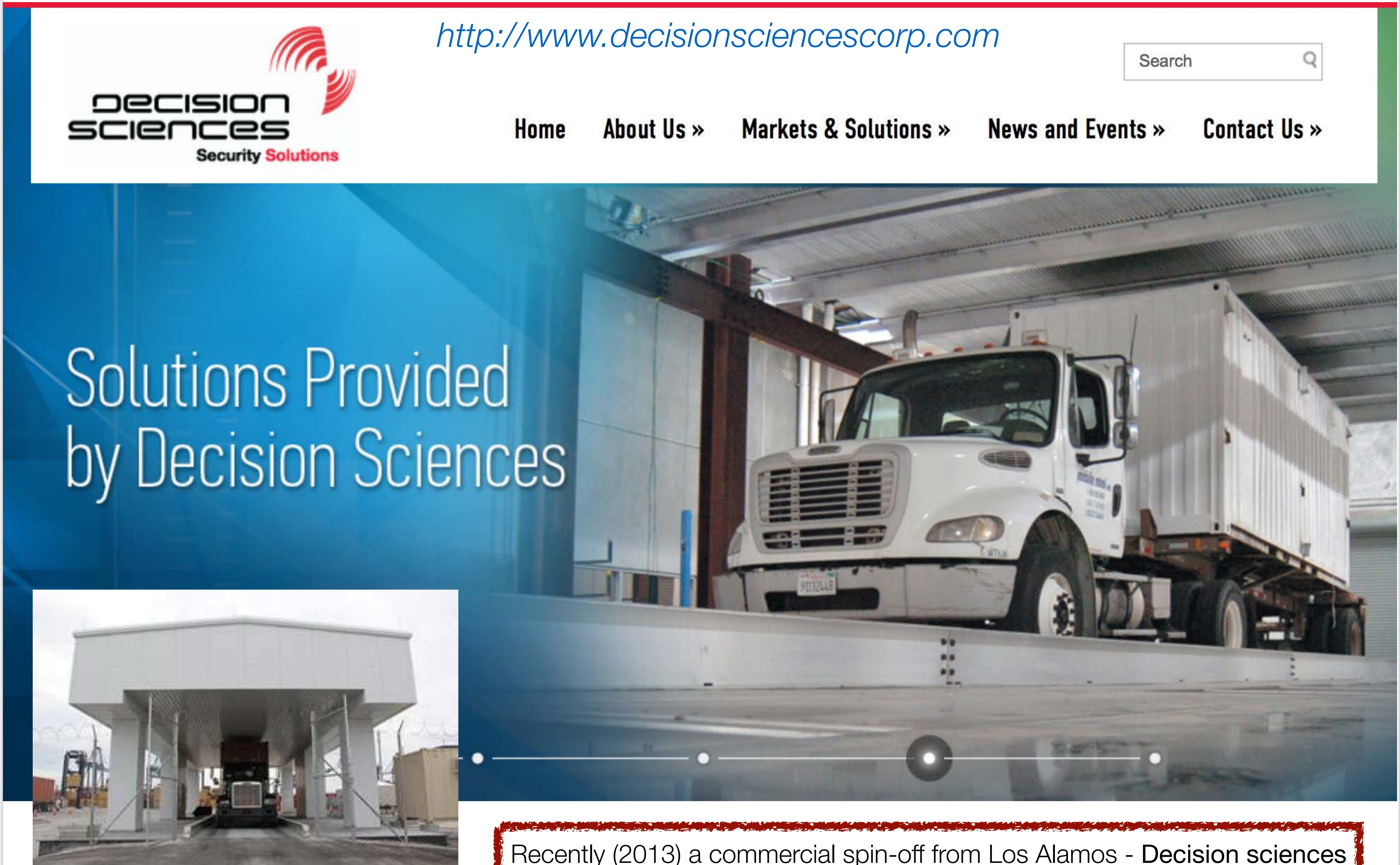


Recently (2013) a commercial spin-off from Los Alamos - **Decision sciences** built a large scale demonstrator (awarded 2.7 million contract with DHS)

Applications (Los Alamos)

At LANL, we have developed Muon Tomography for detecting concealed high-Z material (uranium, etc.)

- **Measure deflection of cosmic muons**
  - tracking before and after passing through object
  - Generate muon "scattering density" image
    - "High-z" materials (like uranium) deflect muons strongly
- **Advantages over other methods:**
  - No artificial radiation
  - Simple technology
  - Inexpensive
  - Can penetrate thick cargoes
  - Automatic Identification

Source: Decision Sciences Corporaton (licensee)

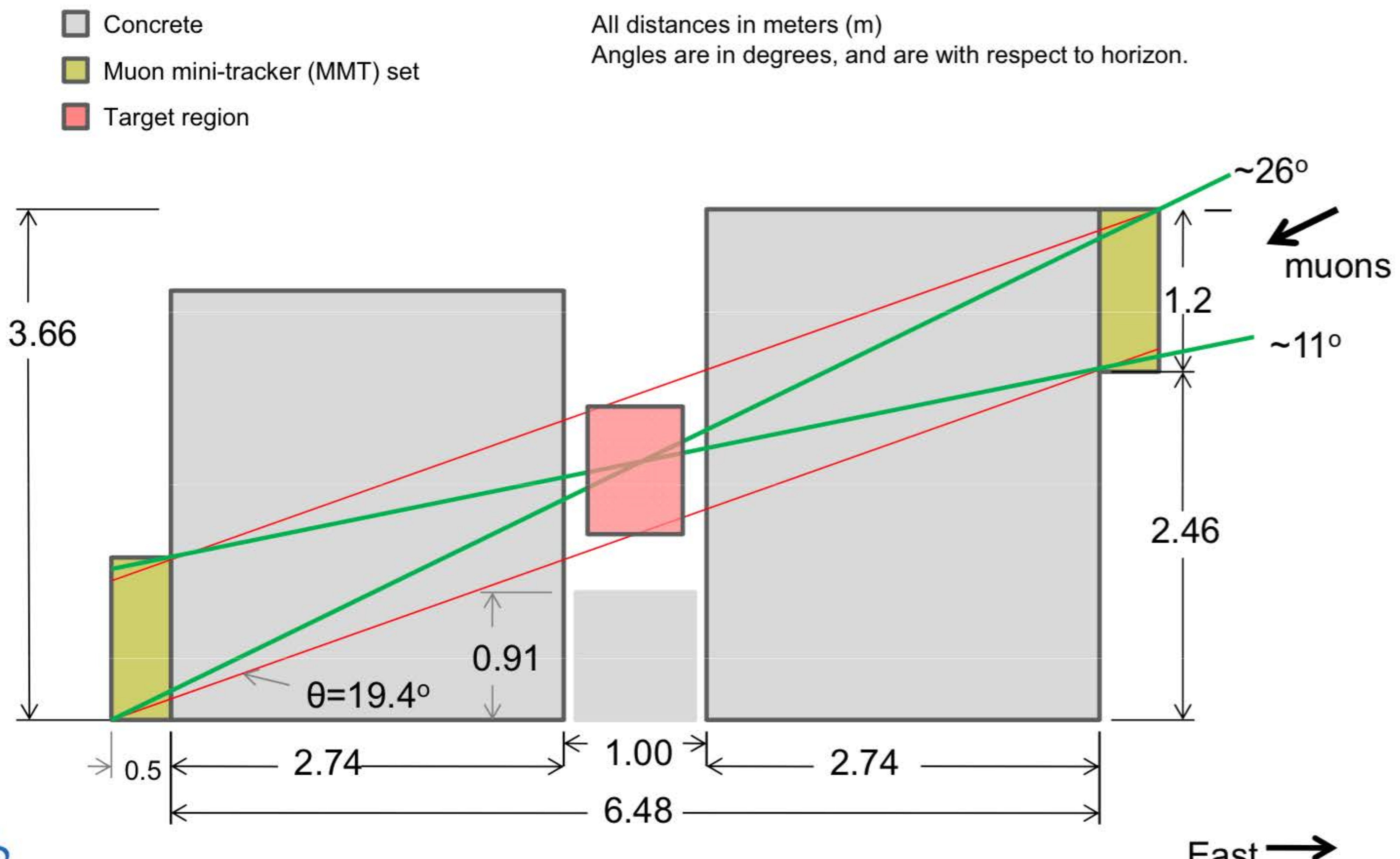
Los Alamos NATIONAL LABORATORY EST. 1943

Operated by Los Alamos National Security, LLC for NNSA

Physics

Applications (Los Alamos)

We have extended Muon Tomography to the task of imaging thick objects in very thick shielding.



Los Alamos NATIONAL LABORATORY EST.1943
Operated by Los Alamos National Security, LLC for NNSA

Applications (Los Alamos)

September 12, 2012 Accepted to Physical Review Letters

Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors.

Konstantin Borozdin,[1] Steven Greene,[1] Zarija Lukic,[2] Edward Milner,[1] Haruo Miyadera,[1] Christopher Morris,[1a] and John Perry[1]

[1]*Los Alamos National Laboratory, Los Alamos, NM, USA 87544*

[2]*Larwence Berkeley National Laboratory, Berkeley, CA, USA 94720*

Abstract The passage of muons through matter is dominated by the Coulomb interaction with electrons and nuclei. The interaction with the electrons leads to continuous energy loss and stopping of the muons. The interaction with nuclei leads to angle "diffusion". Two muon-imaging methods that use flux attenuation and multiple Coulomb scattering of cosmic-ray muons are being studied as tools for diagnosing the damaged cores of the Fukushima reactors. Here we compare these two methods. We conclude that the scattering method can provide detailed information about the core. Attenuation has low contrast and little sensitivity to the core.

Applications (Catania)

Search for hidden high-Z materials inside containers with the Muon Portal Project

P. La Rocca,[a,b,1] **V. Antonuccio,**[c] **M. Bandieramonte,**[a,c] **U. Becciani,**[c] **F. Belluomo,**[f] **M. Belluso,**[c] **S. Billotta,**[c] **A.A. Blancato,**[a] **D. Bonanno,**[a] **G. Bonanno,**[c] **A. Costa,**[c] **G. Fallica,**[d] **S. Garozzo,**[c] **V. Indelicato,**[a] **E. Leonora,**[b] **F. Longhitano,**[b] **S. Longo,**[e] **D. Lo Presti,**[a,b] **P. Massimino,**[c] **C. Petta,**[a,b] **C. Pistagna,**[c] **C. Pugliatti,**[a,b] **M. Puglisi,**[f] **N. Randazzo,**[b] **F. Riggi,**[a,b] **S. Riggi,**[c] **G. Romeo,**[c] **G.V. Russo,**[a,b] **G. Santagati,**[a,b] **G. Valvo,**[d] **F. Vitello,**[c] **A. Zaia**[e] **and G. Zappalà**[a]

[a] *Dipartimento di Fisica e Astronomia,*
Via S. Sofia 64, 95123 Catania, Italy
[b] *INFN Sezione di Catania,*
Via S. Sofia 64, 95123 Catania, Italy
[c] *INAF — Osservatorio Astrofisico di Catania,*
Via S. Sofia 78, 95123 Catania, Italy
[d] *STMicroelectronics,*
Strada Primosole 50, 95121 Catania, Italy
[e] *Insirio,*
Via Nino Bixio 76, 98100 Messina, Italy
[f] *Meridionale Impianti Welding Technology,*
Bivio Aspro Str. Prov. Piano Tavola Belpasso, 95040 Belpasso, Italy

E-mail: paola.larocca@ct.infn.it

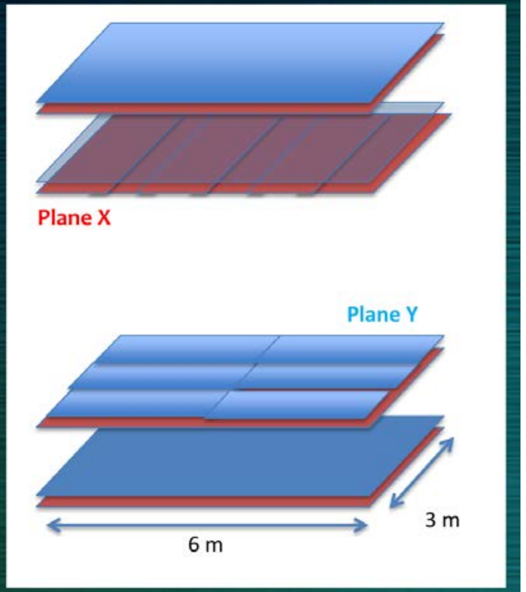
ABSTRACT: The Muon Portal is a recently born project that plans to build a large area muon detector for a noninvasive inspection of shipping containers in the ports, searching for the presence of potential fissile (U, Pu) threats. The technique employed by the project is the well-known muon tomography, based on cosmic muon scattering from high-Z materials. The design and operational parameters of the muon portal under construction will be described in this paper, together with preliminary simulation and test results.

2014 JINST 9 C01056

Applications (Catania)

The Muon Portal Project in Catania

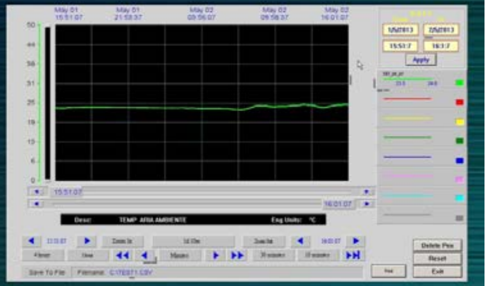
- ✓ Basic architecture based on 8 physical detection planes (4 XY logical planes) segmented into 48 detection modules (1 m x 3m)
- ✓ Modules segmented into 100 strips of extruded scintillator with double WLS fibre readout
- ✓ High PDE, high fill-factor Silicon photomultipliers as readout sensors
- ✓ 9600 channels with a readout compression technique
- ✓ Distance between top and bottom planes 5-7 m
- ✓ Angular resolution around 3 mrad

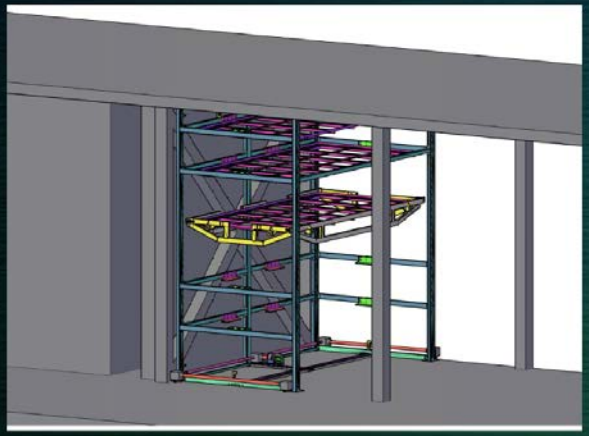


IPRD13 7 - 10 October 2013 Siena, Italy

Mechanical structure

- ✓ Mechanical structure under control with PLC
- ✓ Monitoring and storage of various parameters
- ✓ Sensors for alignment and alarms





- ✓ Assembly tools

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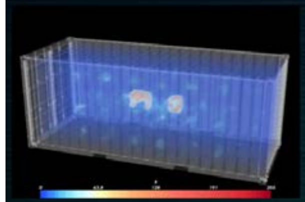
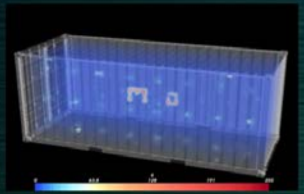
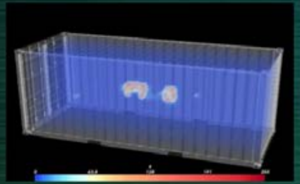
Results from the 3 algorithms



Poca Volume rendering



EM-ML Volume rendering



Clustering Volume rendering

IPRD13 7 - 10 October 2013 Siena, Italy

The partners

- Dept. Of Physics & Astronomy, University of Catania
- INAF, Astrophysical Observatory, Catania
- STMicroelectronics S.r.l. Catania
- Insirio SPA
- Meridionale Impianti Welding Technology

IPRD13 7 - 10 October 2013 Siena, Italy

Applications (Catania)

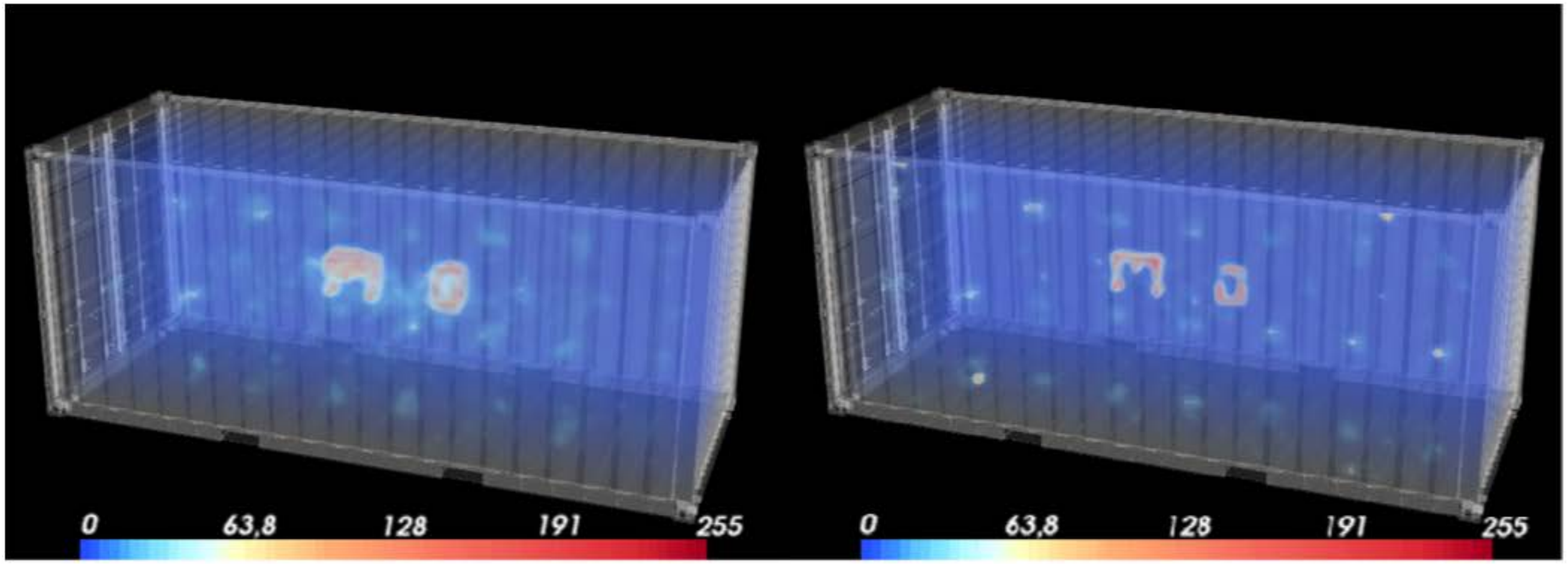


Figure 6. Tomographic imaging of the simulated scenario obtained with the POCA (left) and EM-ML (right) method.

Applications (Glasgow)

University of Glasgow NATIONAL NUCLEAR LABORATORY

The Glasgow/NNL Muon Tomography Project

University of Glasgow

A. Clarkson, D. J. Hamilton, G. D. Hill, M. Hoek, D. G. Ireland, R. Kaiser, T. Keri, S. Lumsden, D. F. Mahon, B. McKinnon, M. Murray, S. Nutbeam-Tuffs and G. Yang

Nuclear Physics Group, SUPA, School of Physics and Astronomy, University of Glasgow

NATIONAL NUCLEAR LABORATORY

J. R. Johnstone, P. Knight, C. Shearer, C. Staines and C. Zimmerman

UK National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG, England, UK

- Feasibility study
- Image spatial distribution of elements in 500 litre ILW barrel

Sellafield Ltd NDA Nuclear Decommissioning Authority

Nuclear Waste Container monitor

Applications (Glasgow)

EPJ Web of Conferences **66**, 10005 (2014)
DOI: 10.1051/epjconf/20146610005

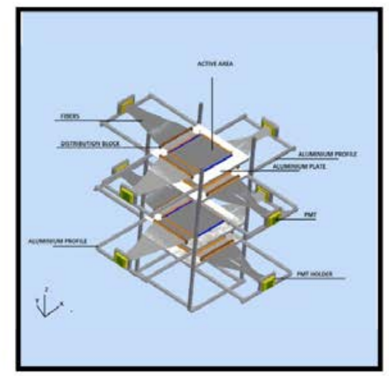
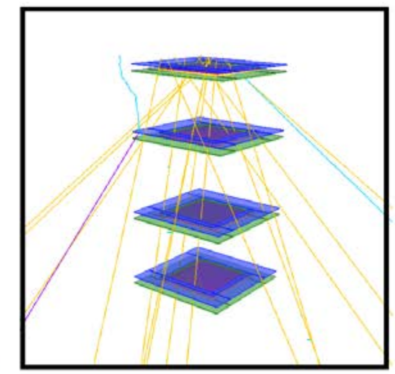
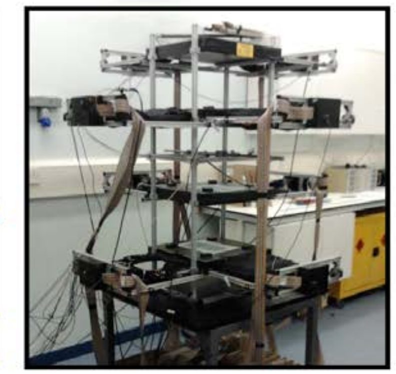
University of Glasgow

The Glasgow MT Detector

A Prototype Scintillating-Fibre Tracker for the Cosmic-ray Muon Tomography of Legacy Nuclear Waste Containers

R. Kaiser[1,a], A. Clarkson[1], D. J. Hamilton[1], M. Hoek[1], D. G. Ireland[1], J. R. Johnston[2], T. Keri[1], S. Lumsden[1], D. F. Mahon[1], B. McKinnon[1], M. Murray[1], S. Nutbeam-Tuffs[1], C. Shearer[2], C. Staines[2], G. Yang[1], and C. Zimmerman[2]

[1] *Nuclear Physics Group, University of Glasgow, University Avenue, Glasgow, G12 8QQ, Scotland, UK*
[2] *National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG, England, UK*

Abstract. Cosmic-ray muons are highly-penetrative charged particles observed at sea level with a flux of approximately 1 $\mathrm{cm^{-2}\,min^{-1}}$. They interact with matter primarily through Coulomb scattering which can be exploited in muon tomography to image objects within industrial nuclear waste containers. This paper presents the prototype scintillating-fibre detector developed for this application at the University of Glasgow. Experimental results taken with test objects are shown in comparison to results from GEANT4 simulations. These results verify the simulation and show discrimination between the low, medium and high-Z materials imaged.

5 Results

First image reconstruction results from experimental data taken using this prototype detector system are presented in Figure 2 in comparison to the corresponding simulation data for the same geometry and duration. In both the results from experimental and simulated data, sensitivity to atomic number Z and discrimination between the λ values of the stainless-steel bar, the two high-Z materials, and the surrounding air is observed.

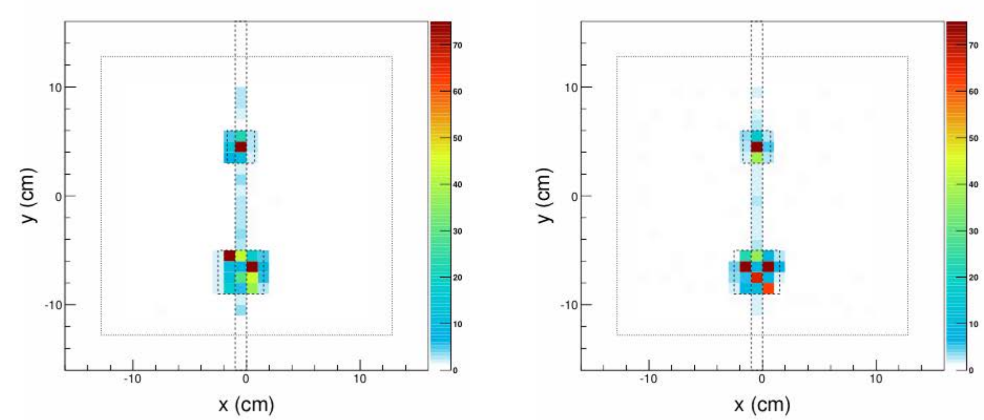


Figure 2. Comparison between images reconstructed from several weeks of exposure to cosmic-ray muons for experimental data (left) and Geant4 simulation (right). Shown is a 1 cm slice in the xy-plane *i.e.* parallel to the detector modules. The dashed lines provide an estimate of the location and dimensions of the test objects in the assay volume.

Applications (Bristol)

University of BRISTOL

AWE

Muon scattering tomography with resistive plate chambers

RPC2012 - XI Workshop on Resistive Plate Chambers and Related Detectors

Speaker: Paolo Baesso – University of Bristol

David Cussans – University of Bristol
Christian Thomay – University of Bristol
Jaap Velthuis – University of Bristol
Steve Quillin – Atomic Weapon Establishment
Stacey Robertson – Atomic Weapon Establishment
Chris Steer – Atomic Weapon Establishment

Applications (Bristol)

Setup – Hardware overview

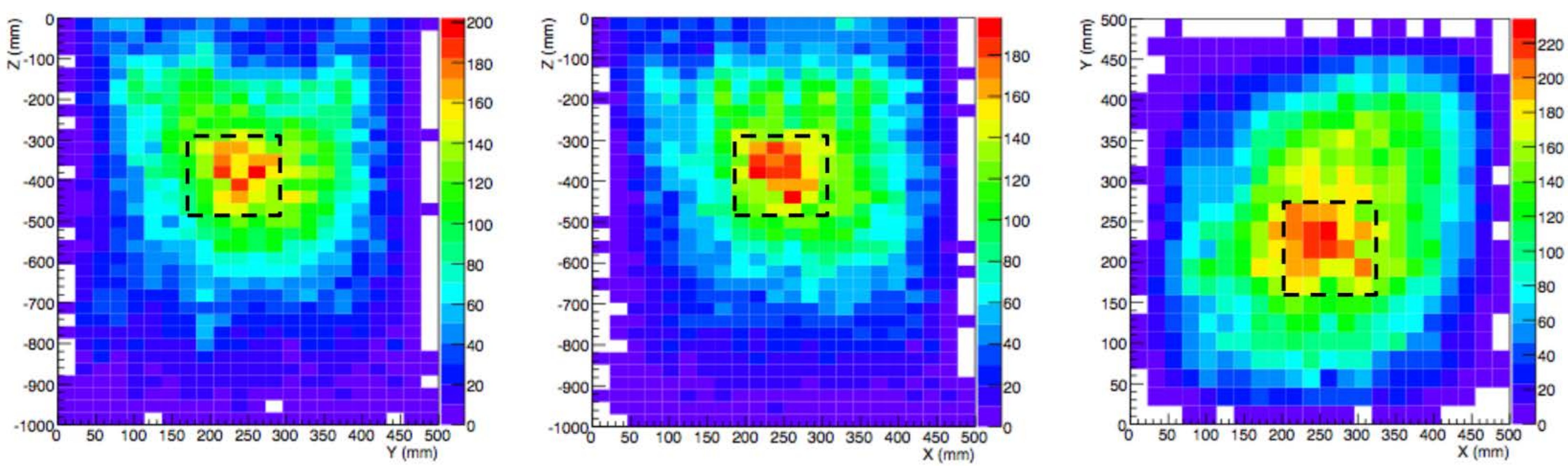
- 6 readout planes (cassettes):
  - 2 glass RPC per cassette (X,Y)
  - Front-end electronic (Helix)
  - Auxiliary electronics
  - Gas and high voltage connectors
  - Easy to swap/change configuration
- The cabinet includes the gas mixing rig and HV distribution.
- Cabinet size:
  - ~100 cm x 100 x 250 cm
- Scanning volume:
  - ~50 cm x 50 cm x 100 cm

10/02/2012

Applications (Bristol)

Test with lead blocks

- 10 cm x 10 cm x 15 cm lead block.
- Point of closest approach algorithm (simple but effective for our tests).
- Cut on χ^2 of the tracks.
- Bin only tracks which show a scattering angle above 30 mrad.
- Simple analysis made in Bristol to check the detector.
- AWE will work on algorithms for proper tomography.
- Bristol to develop alternative techniques to complement the analysis.



YZ Plane XZ Plane XY Plane

Applications (Boulby)

STFC
Boulby Underground Laboratory

SEARCH

STFC Home > Boulby Underground Laboratory Home > Current projects > Muon Tomography > Muon Tomography - Deep Carbon, MuScan, Muon-Tides

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- Current projects
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  - SKY-ZERO
  - Muon Tomography
  - Astrobiology
  - Ultra-low Background Gamma Spectrometry
  - Future Projects
- Outreach and media
  Outreach and media
- Contact us
  Contact the Boulby Underground Laboratory team...

Muon Tomography - Deep Carbon, MuScan, Muon-Tides

Studies are underway to explore the use of Muon Tomography for deep 3D geological surveying applications. Muons are highly penetrating charged particles that are produced by cosmic rays from space and bombard the Earths atmosphere. On the Earth's surface about 1 muon passes through an area the size of your hand per second.

Deep underground muons are attenuated by many orders of magnitude but the muons that do penetrate can potentially be used to produce an 'image' of the structures above. The technique, 'Muon Tomography', is similar to CT scanning in medical imaging, but as muons are more penetrating than X-rays much larger and deeper structures can be imaged.

Muon tomography has already been successfully used to image deep structures such as the interior of volcanoes and pyramids. Work is now underway to explore the use of the technique for imaging even deeper structures, with possible applications in mining and in monitoring for deep sub-surface storage initiatives such as Carbon Capture and Storage (CCS). With its existing deep underground science facility, its depth and ease of access to underground spaces of various depths Boulby is uniquely well suited to the development of muon tomography techniques and instrumentation.

Participating institutions:

- STFC Rutherford Appleton Laboratory
- Durham University
- Sheffield University
- Bath University
- Jet Propulsion Lab (JPL)

Quick links

- Contact Us
- STFC website
- Boulby Underground Laboratory
- Cleveland Potash Ltd
- Twitter
- YouTube channel

Tomography applications

a deep look into one of the projects

The Mu-Steel project (RFCS CT-2010-000033) [mid 2010-end 2012]

MU-STEEL

Research Fund for Coal & Steel

Muon tomography technology

MU-STEEL Project

MUONS SCANNER TO DETECT RADIOACTIVE SOURCES HIDDEN IN SCRAP METAL CONTAINERS

Project carried out with a grant of the European Commission within the Research Fund for Coal and Steel

PARTNERS INVOLVED IN PROJECT ACTIVITIES DEVELOPMENT

tecnogamma

SRB COSTRUZIONI

GRUPPO AFV BELTRAME

Università di Brescia
Dip.to di Ingegneria Meccanica e Industriale

Università di Padova
Dip.to di Fisica

INFN
Istituto Nazionale Fisica Nazionale, Padova

Project objectives

Study the feasibility of building a portal to monitor the truck containers filled with scrap metals entering steel mills foundries to detect shielded radioactive source.

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In particular:

[1] develop a complete design of a portal

[2] build a detector prototype for the final portal

[3] develop the 3D tomographic software

An important goal of the project is therefore the assessment of the relation between four key elements:

- Scanning and processing time
- Minimum amount of shielding material to be detected
- Detection efficiency
- Percentage of false positives

Project goals

The scanning portal must not be a bottleneck in the normal inflow of scrap metal. The experience in the Beltrame site in Vicenza shows that the maximum flow has been in the past of about 300 trucks/day, or 1 truck every 3 minutes in average. We assume therefore that a reasonable inspection time per truck should fall in the range of 3 to 10 minutes

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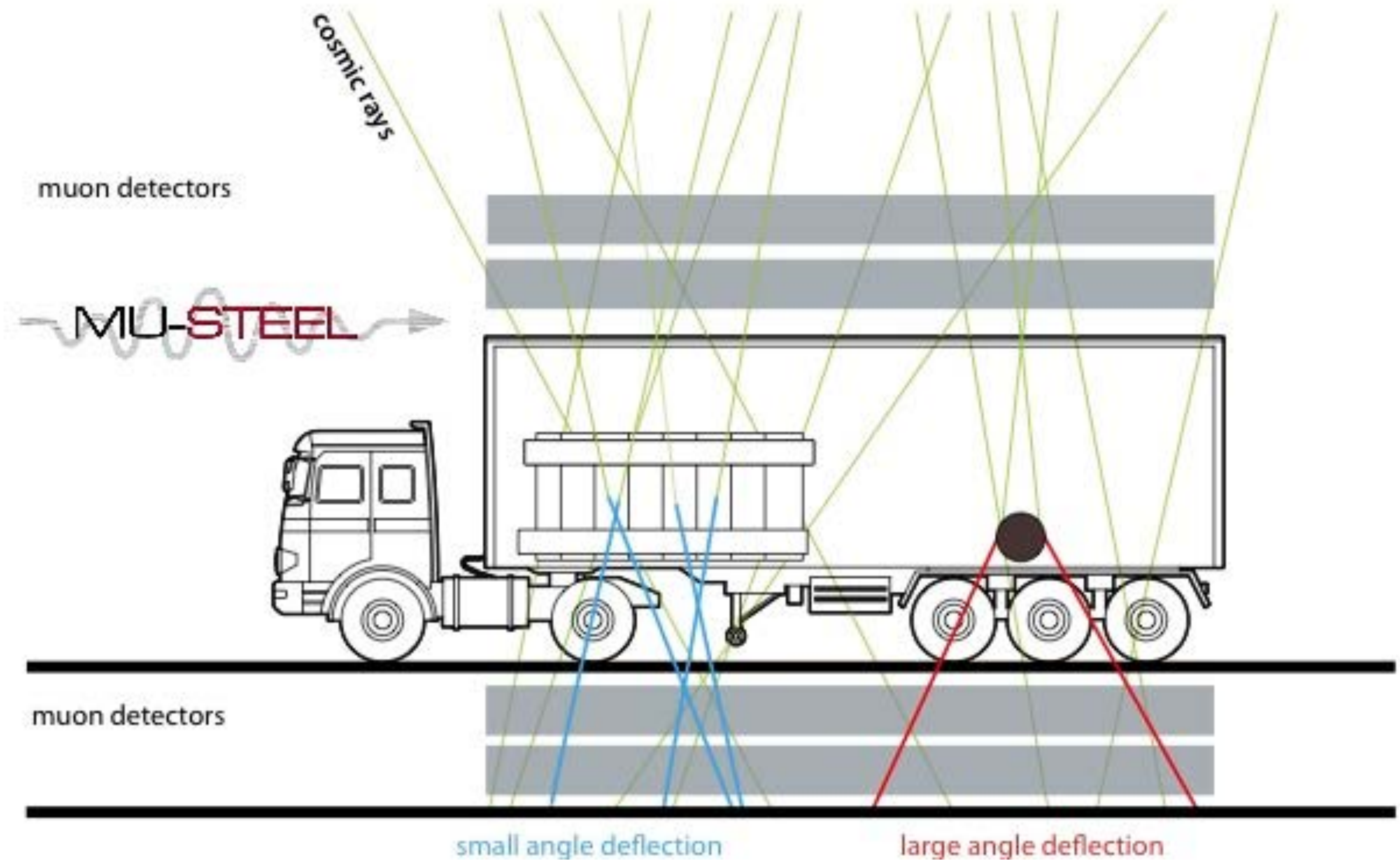
is it possible to detect a source shield in 3-10 minutes using muon tomography technology?

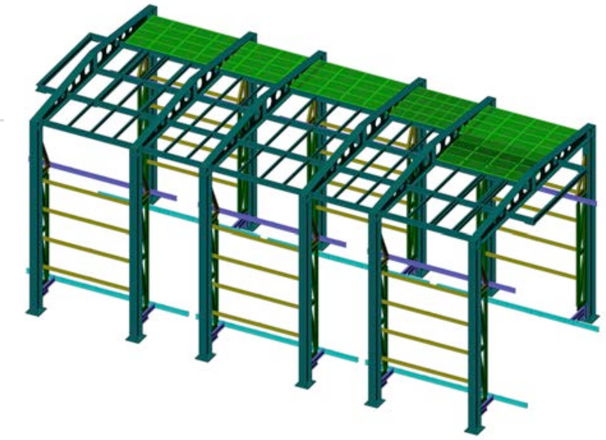
Muon tomography - basic principle

- two detectors above and below the volume under study to measure the muon trajectory deviation from a straight line

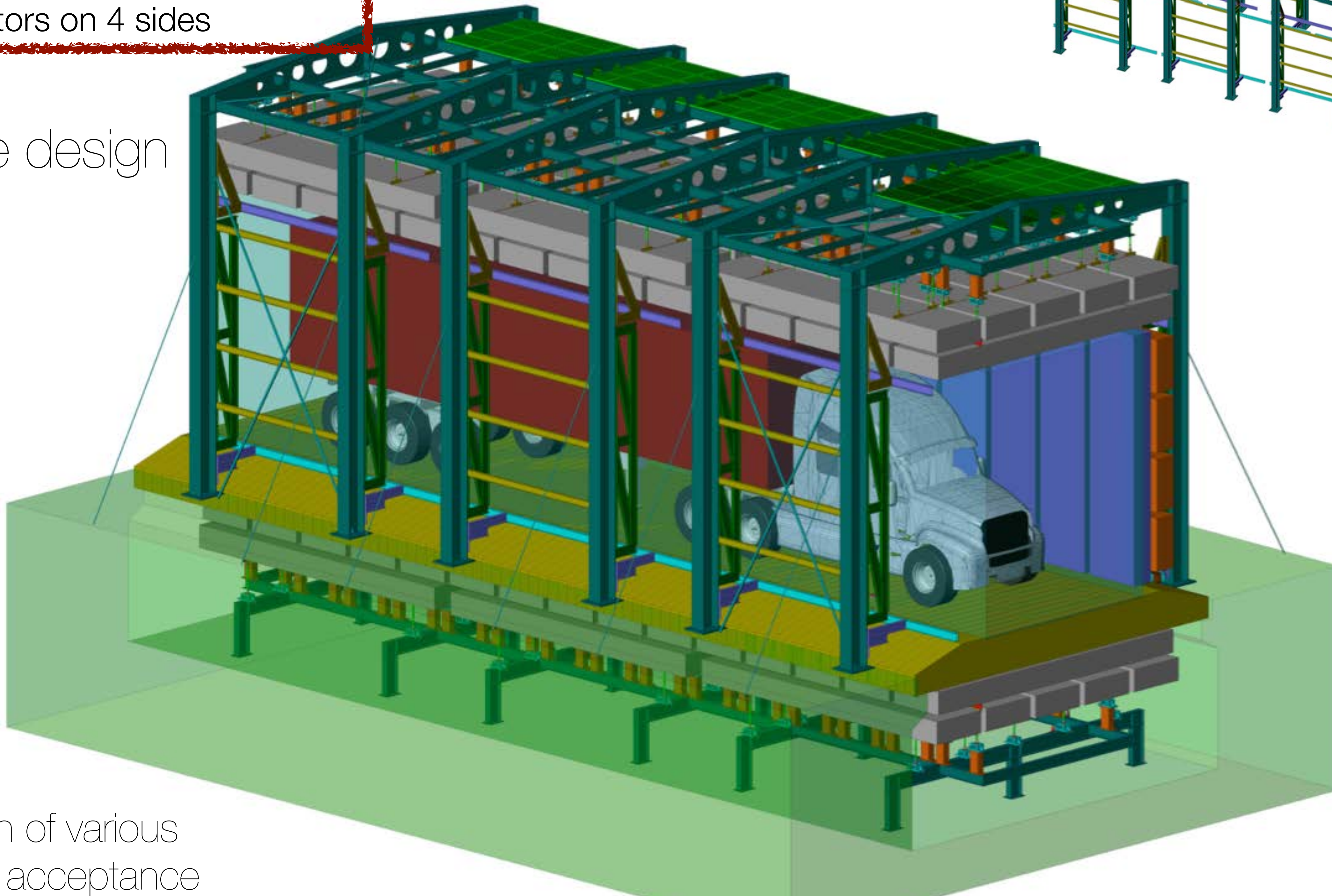


The Mu-Steel project: [1] portal design

- Maximization of the acceptance
  - detectors on 4 sides



Complete design

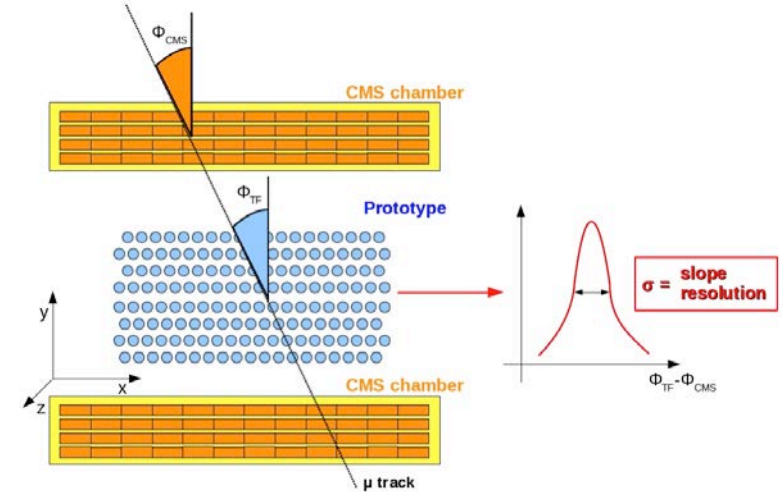


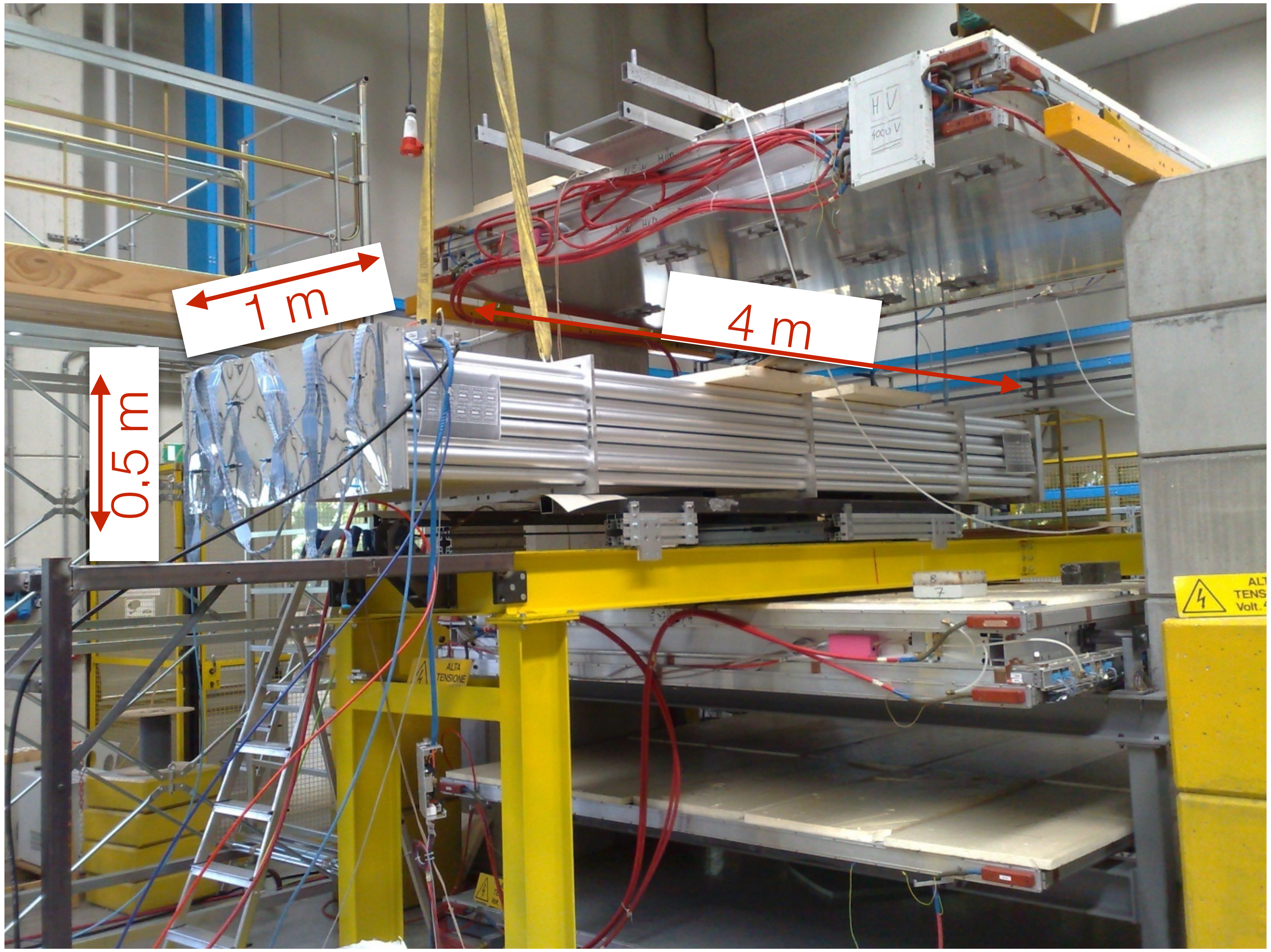
Optimization of various aspects (i.e. acceptance vs cost) can still be made

Minimization of the material between the upper and lower detectors
- upper detector is held from the top, lower detector from the bottom
- the floor has been designed in wood

The Mu-Steel project: [2] detector prototype

The detector prototype performances have been tested inserting it in the LNL muon tomography prototype





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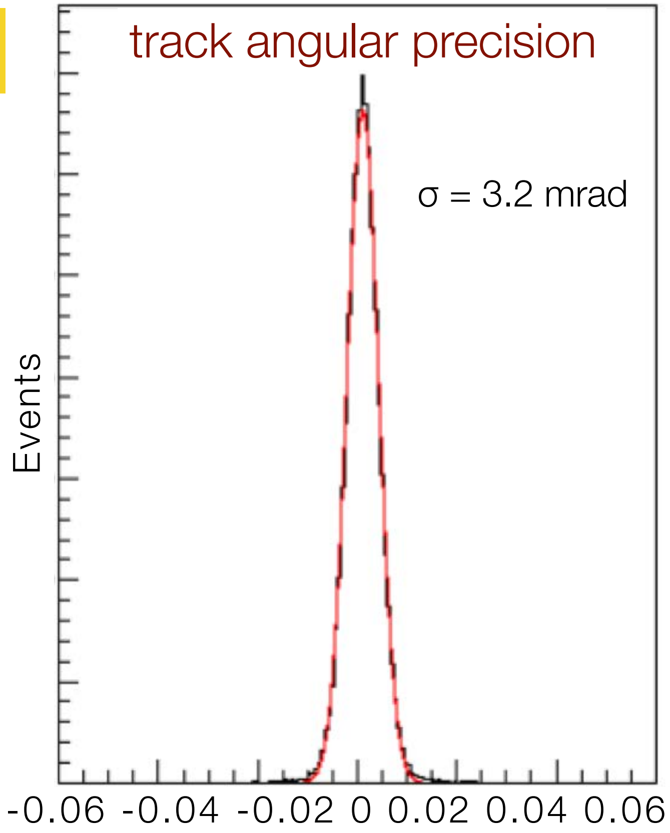
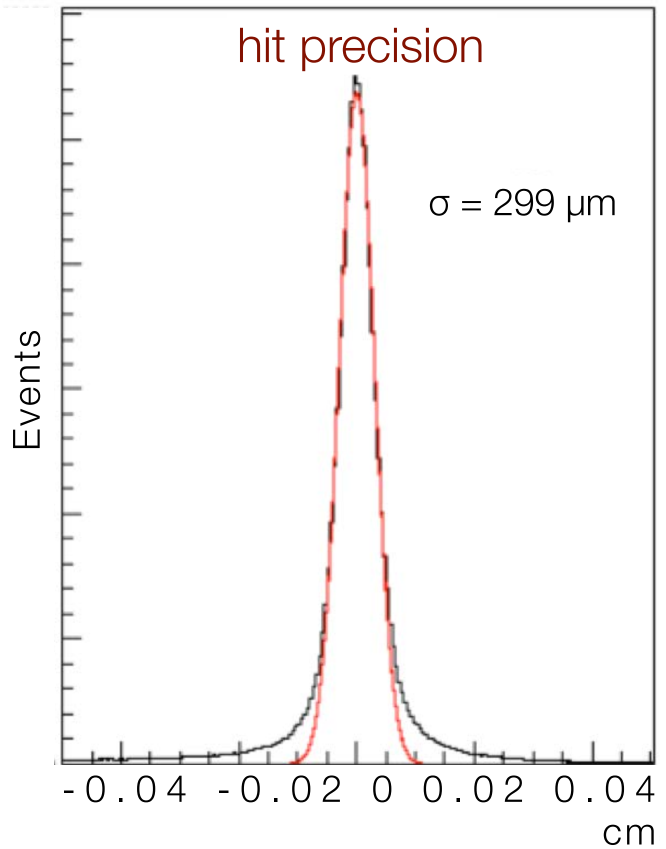


around 90% efficiency



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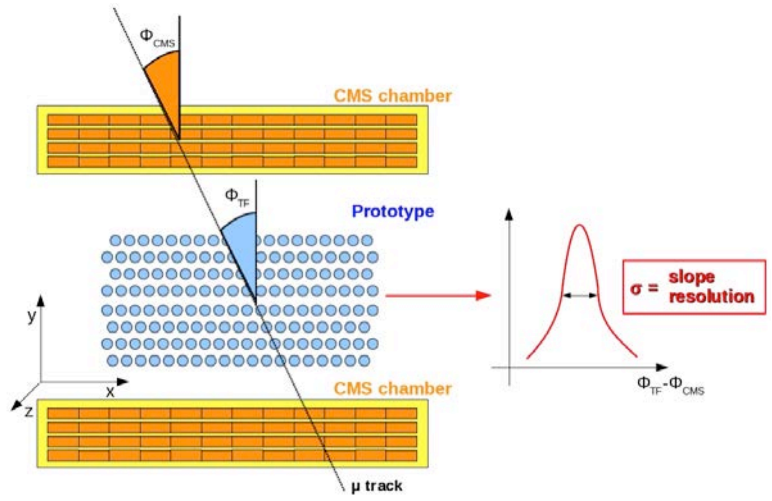
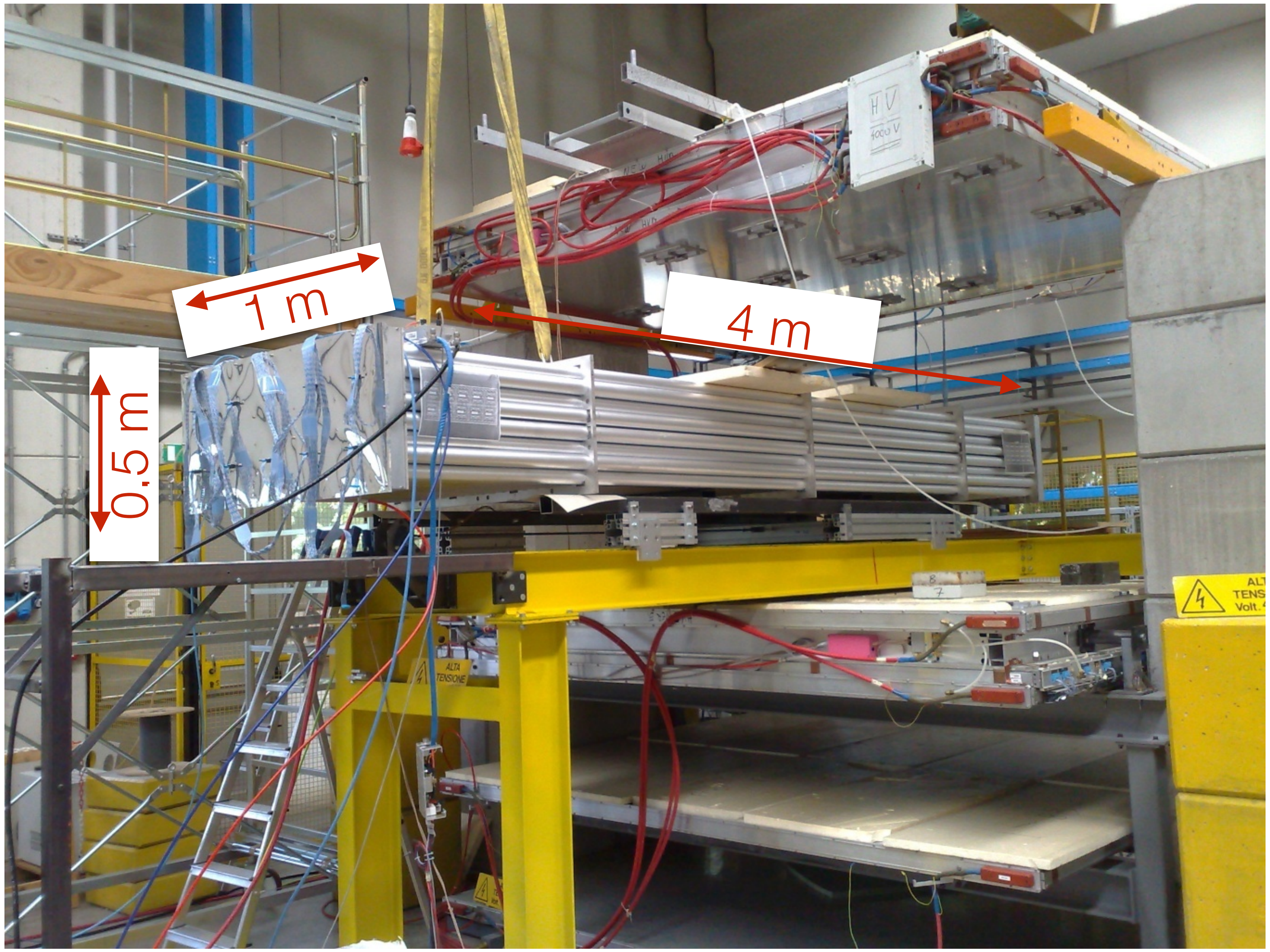
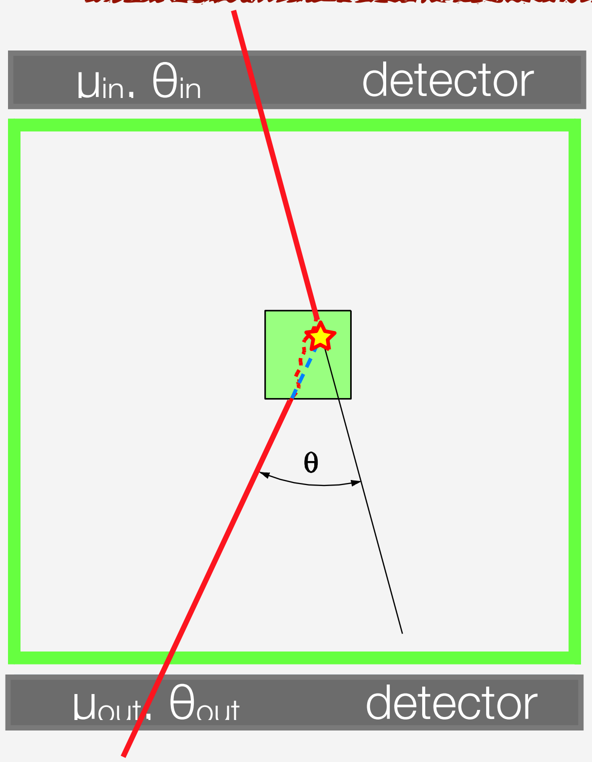




The Mu-Steel project: [3] image tomographic reconstruction

Simplest method:
Single Scattering Approximation (SSA).
In space: Point of Closest Approach (PoCA) of 2 straight lines



It works fine with a single scattering point

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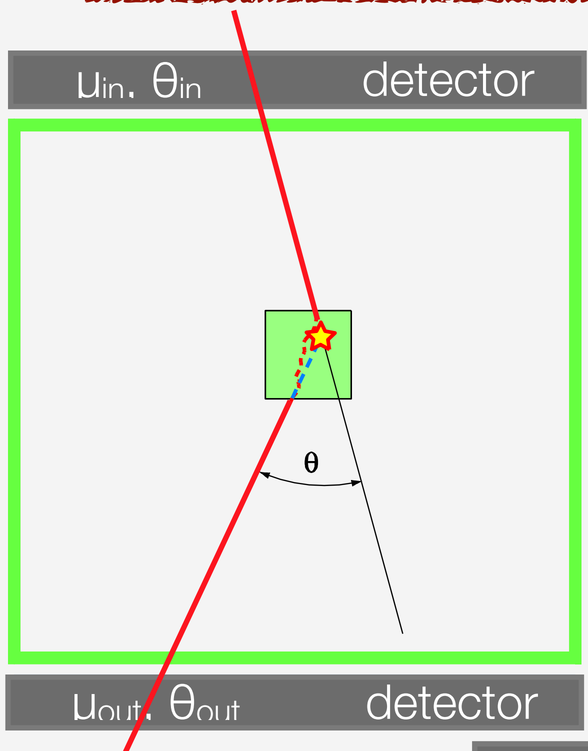
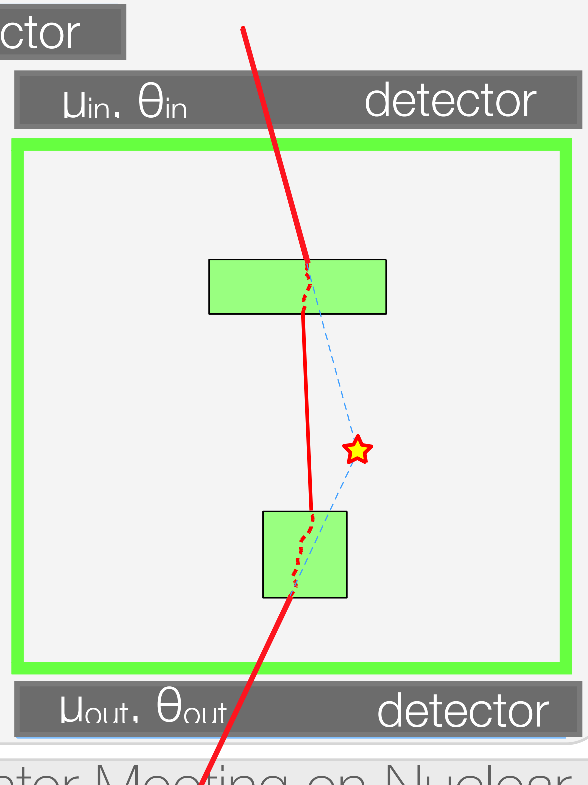


It works fine with a single scattering point

It fails for several scattering centers



It doesn't use all the information coming from a sample of muons

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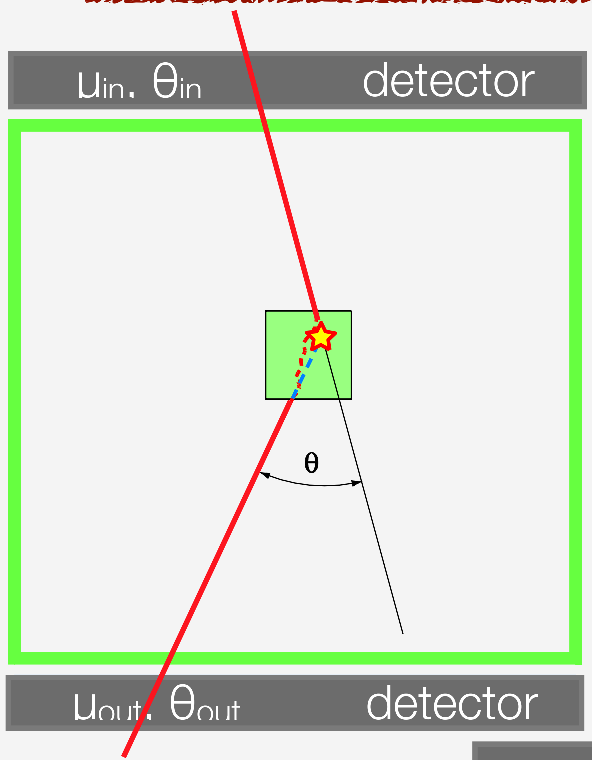

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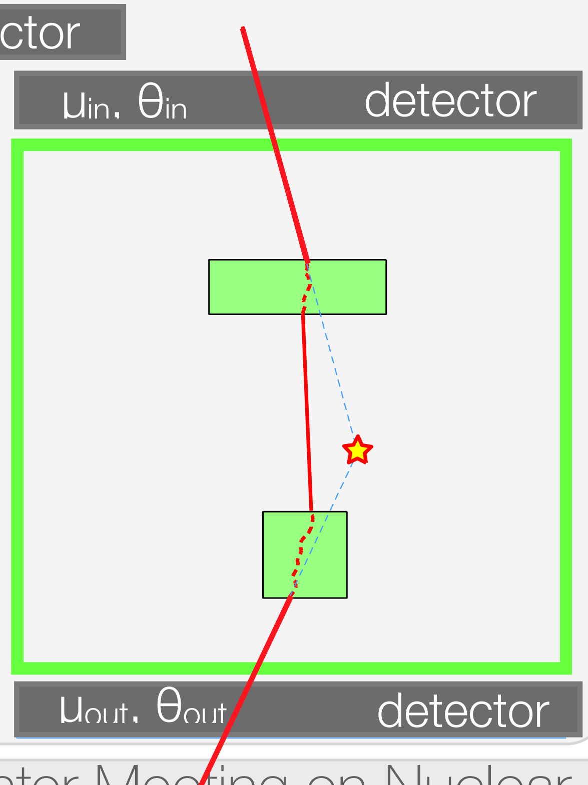

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... for a more efficient approach

... let's define "scattering density" for a material as:

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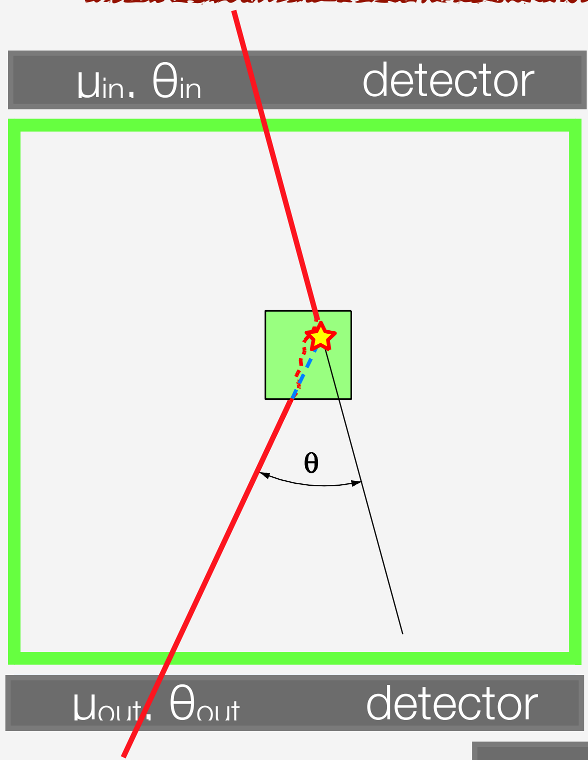

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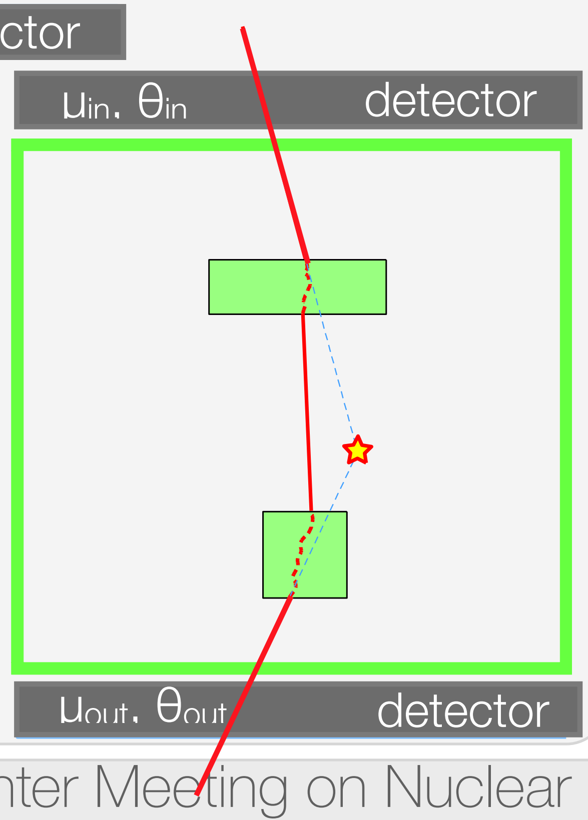

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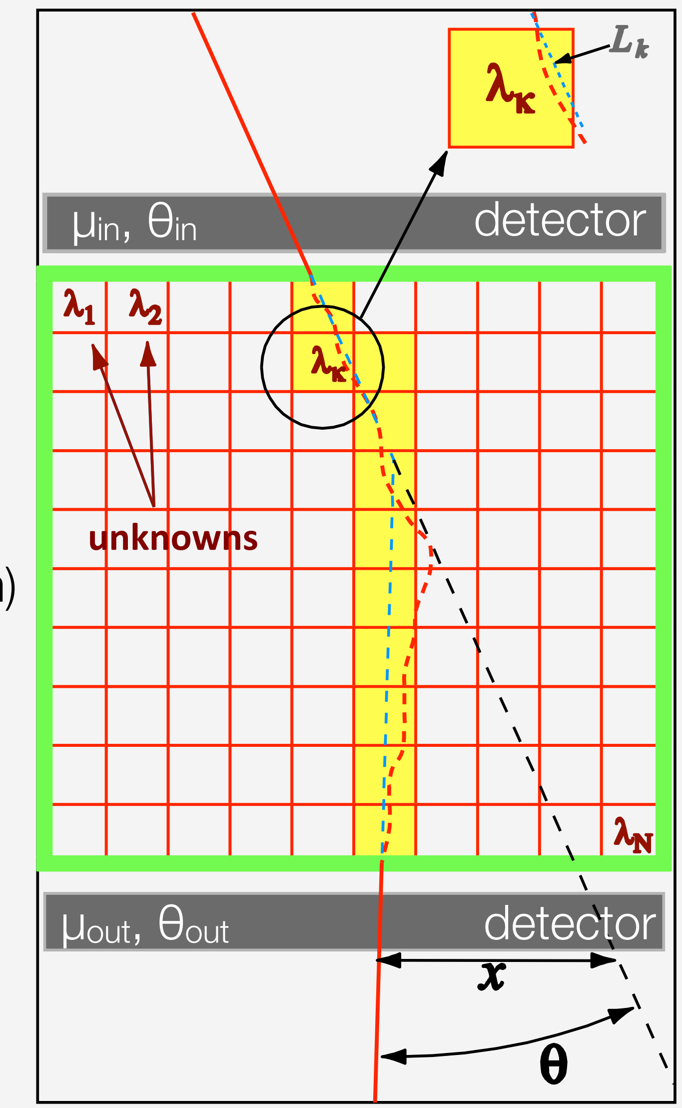
The volume can be then divided into N cubic voxels (the density is assumed constant inside a single voxel)

Unknown quantities: λ_k

An iterative optimization algorithm (LMIA, List Mode Iterative Algorithm) applied to a Maximum Log-likelihood function can solve the system



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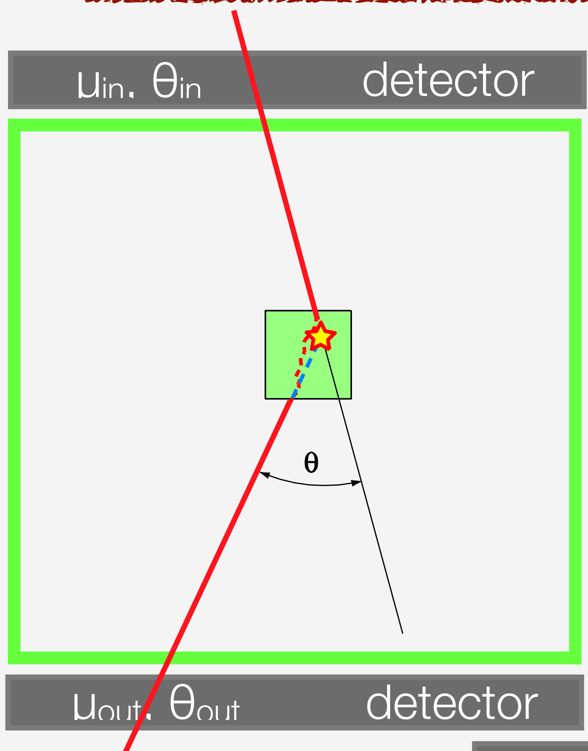

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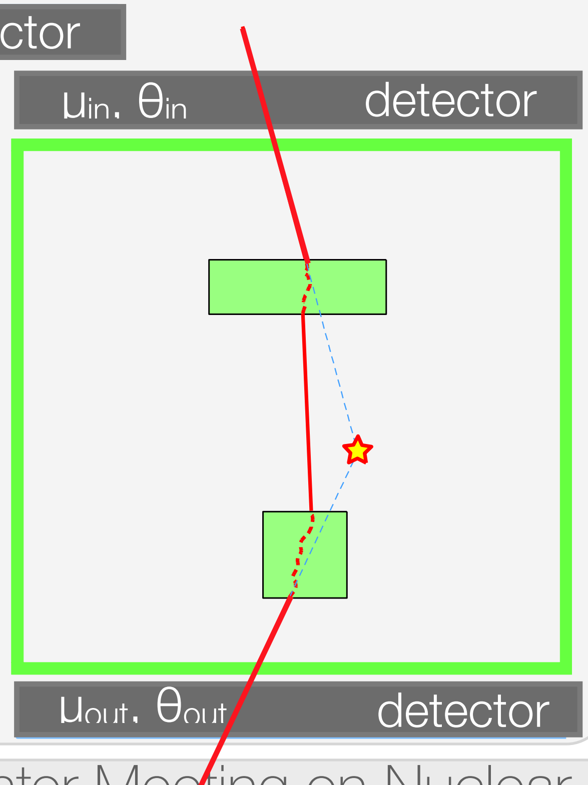

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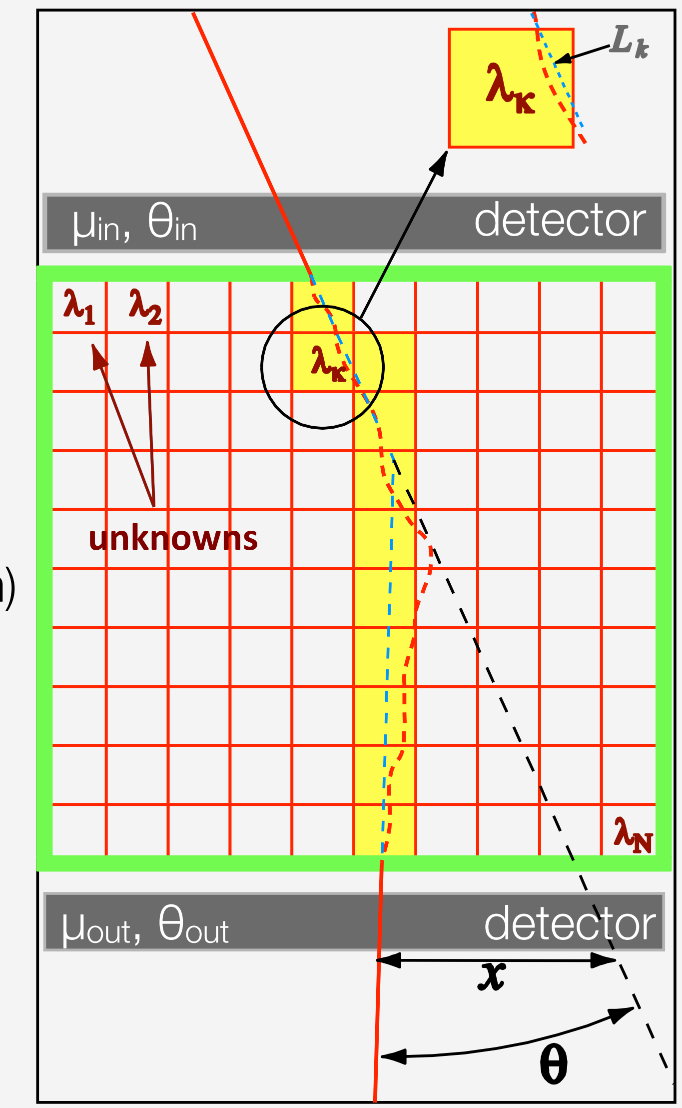
Each single muon gives a statistical information on the set of voxels it crosses



With a sufficient statistics it is possible to estimate λ_k for each voxel: in other words it is possible to
reconstruct a 3D "density" image of the volume under study

The Mu-Steel project: [3] image tomographic reconstruction

"Practical objective":
detect 2 (13 cm side cube) or 5 liters (17 cm side cube) source shield in 3-10 minutes

the volume (7 x 3.6 x 3 m^3) has been divided in 604800 voxels (5x5x5 cm^3)

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Challenges:
- great computational effort [I]
- high noise to signal ratio (some voxel with few muons) [II]
- there is no information of the muon momentum p [III]

[large scattering can be due to both low p muon through low density material or to high p muon through high density material]

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- Cache alignment
- Memory optimization
- Parallel processing
- GPU testing
- Application-specific libraries
- Linear algebra-optimized libraries
- Faster workstations

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Post-processing and in-processing image filters

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Muon momentum estimate through multiple scattering in detectors

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Muon momentum estimate through multiple scattering in detectors

In the following, image reconstructions will be presented

Complete GEANT4 simulation:
- muon generator
- full portal
- truck container with scrap metal (average density ~ 0.5 - 0.7 g/cm^3)

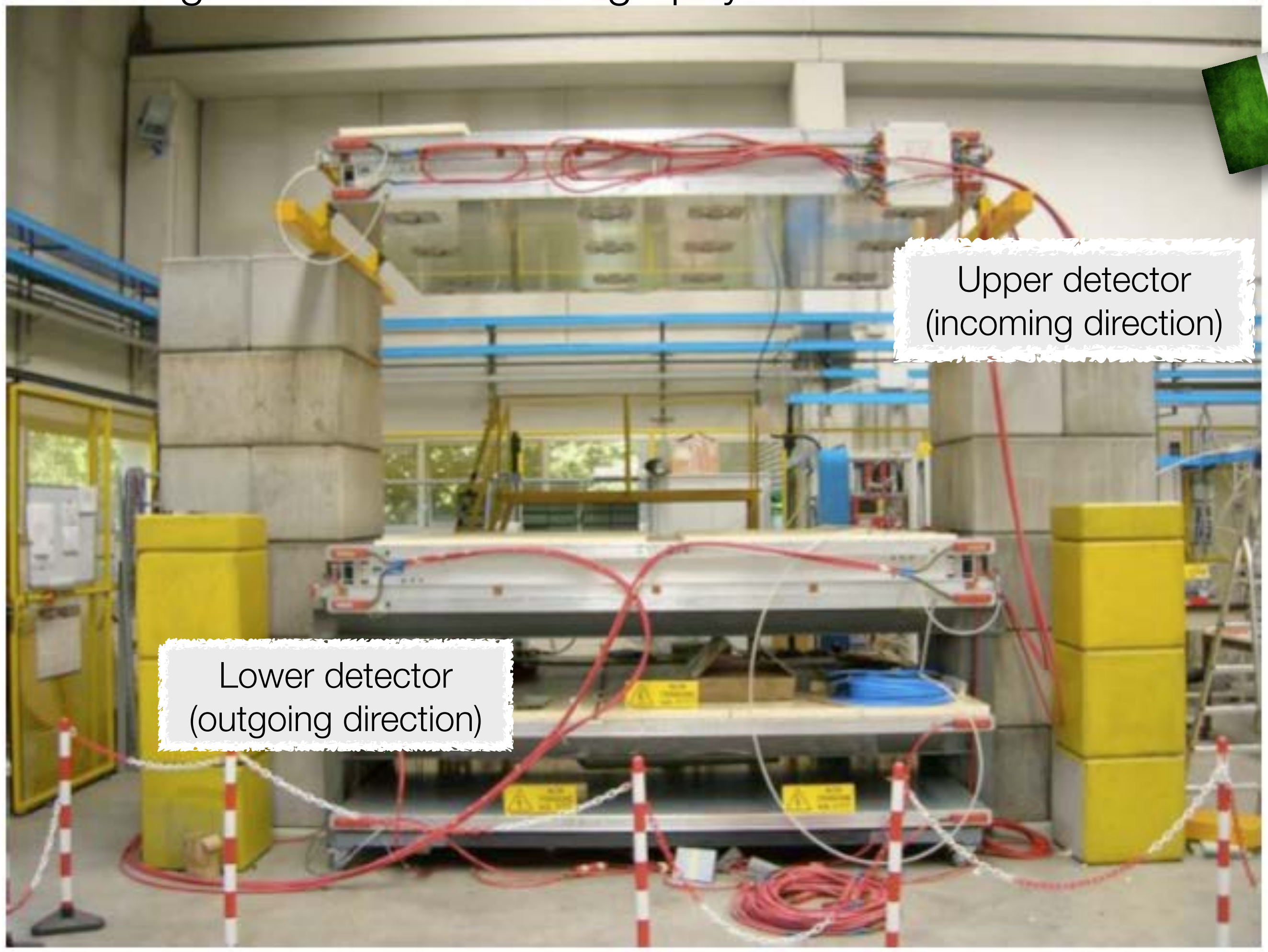
The LNL muon tomography prototype

a “test bed” for the Monte Carlo and for the
3D image reconstruction software

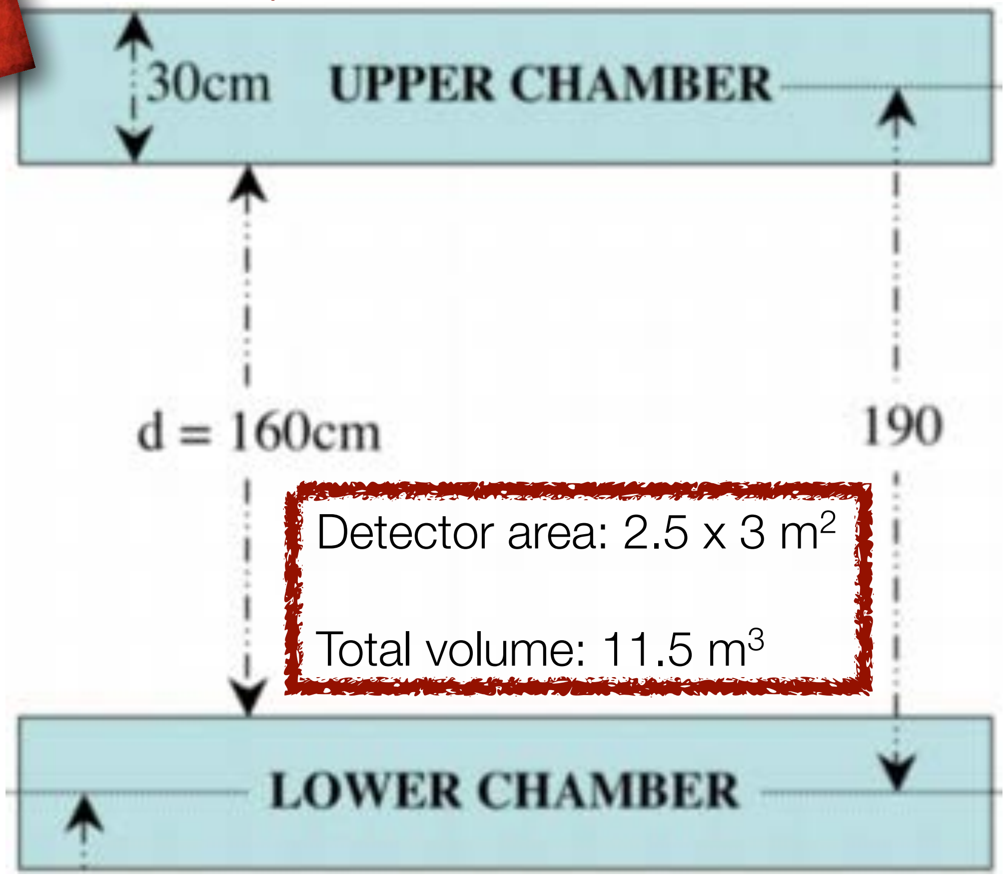
The LNL muon tomography prototype 2008

Padova University · INFN · Brescia University · Genova University

The first “large-scale” muon tomography ever built is hosted in the INFN-LNL “Laboratori Nazionali di Legnaro” (Padova)



CMS spare muon “chamber” detectors



Detector area: 2.5 x 3 m^2

Total volume: 11.5 m^3

The LNL muon tomography prototype 2008

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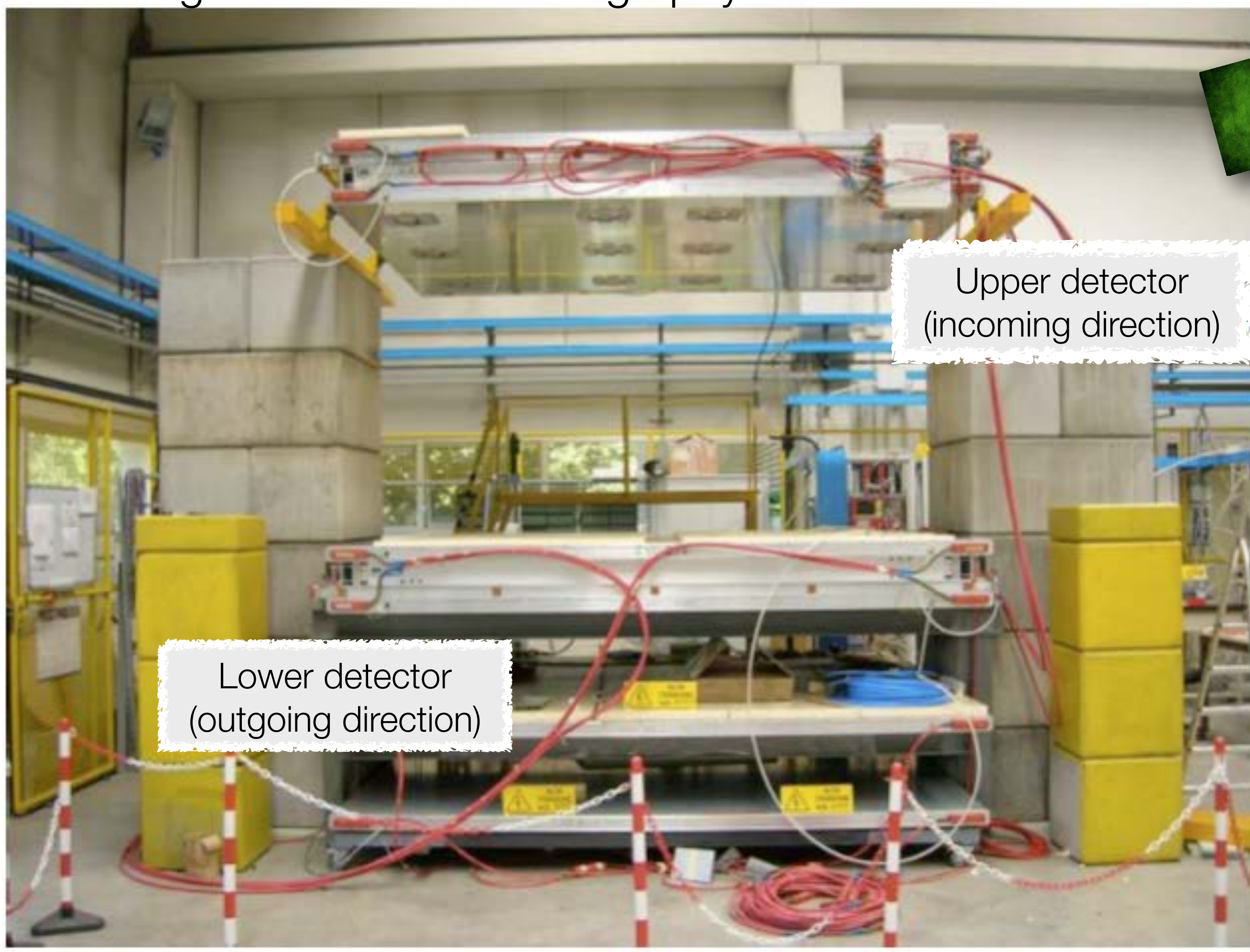

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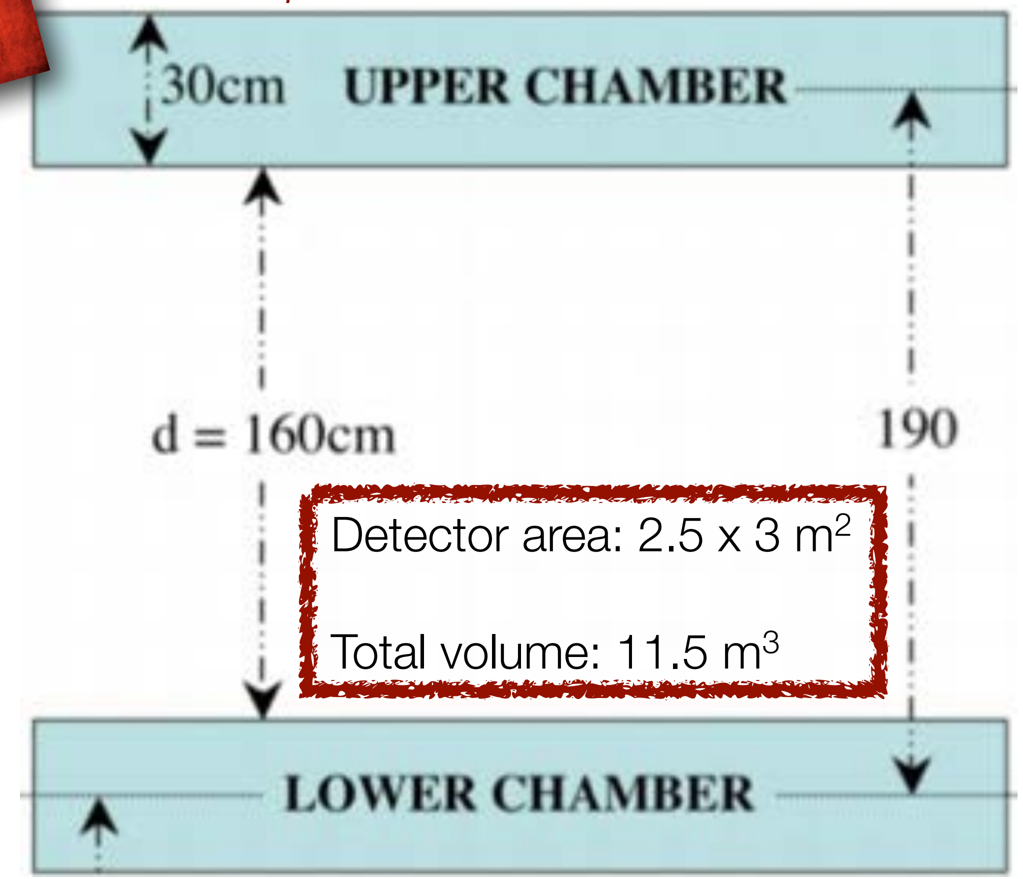

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First results

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

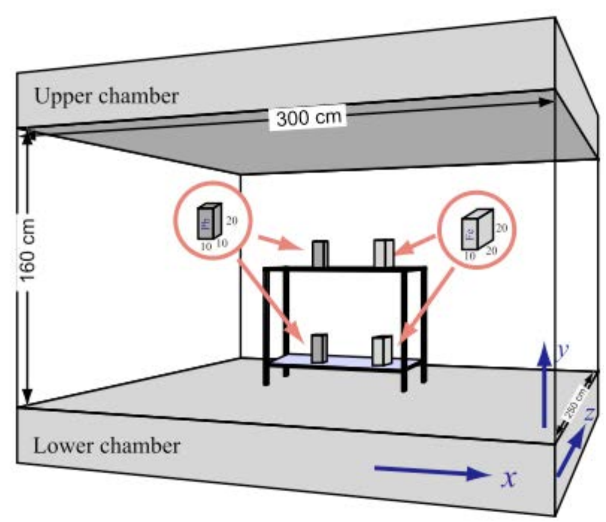
journal homepage: www.elsevier.com/locate/nima

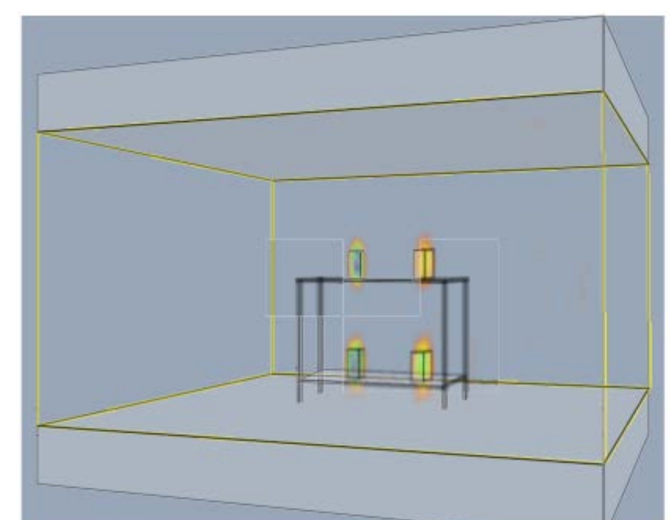
First results on material identification and imaging with a large-volume muon tomography prototype

S. Pesente[a], S. Vanini[d,*], M. Benettoni[a], G. Bonomi[b], P. Calvini[c], P. Checchia[a], E. Conti[a], F. Gonella[a], G. Nebbia[a], S. Squarcia[c], G. Viesti[d], A. Zenoni[b], G. Zumerle[d]

[a] INFN Sezione di Padova, via Marzolo 8, 35131 Padova, Italy
[b] University of Brescia, via Branze 38, 25123 Brescia and INFN Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy
[c] University of Genova and INFN Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy
[d] University of Padova and INFN Sezione di Padova, via Marzolo 8, 35131 Padova, Italy

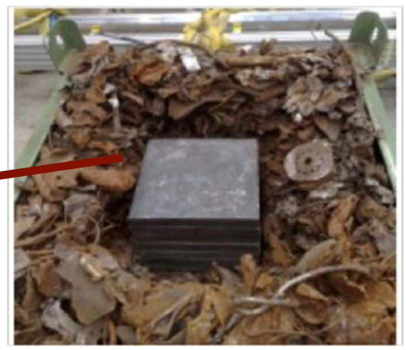
Nucl. Instr. and Meth. A 604 (2009) 738





The LNL muon tomography prototype

- For the Mu-Steel project the LNL muon tomography prototype has been used to detect a lead block inserted inside a container of scrap metals [realistic conditions]



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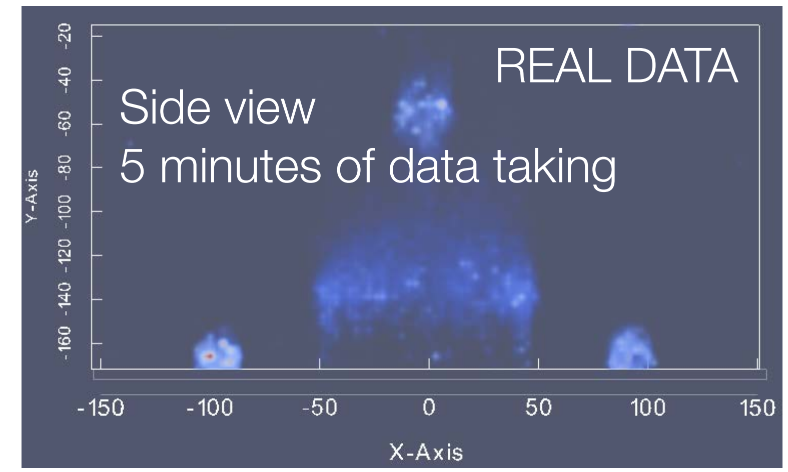

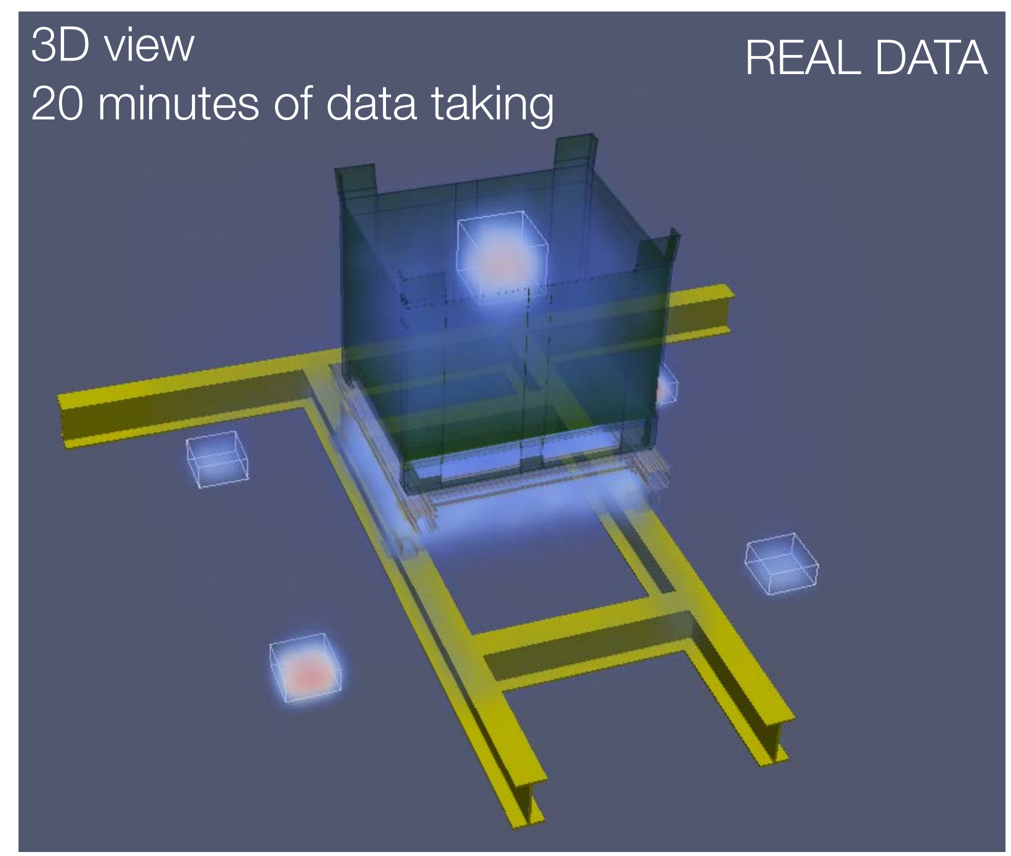

Great improvements have been implemented in the 3D image tomographic reconstruction software

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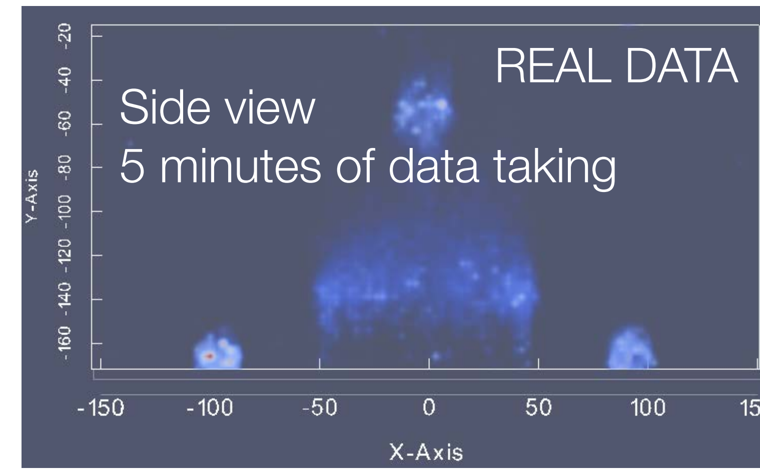
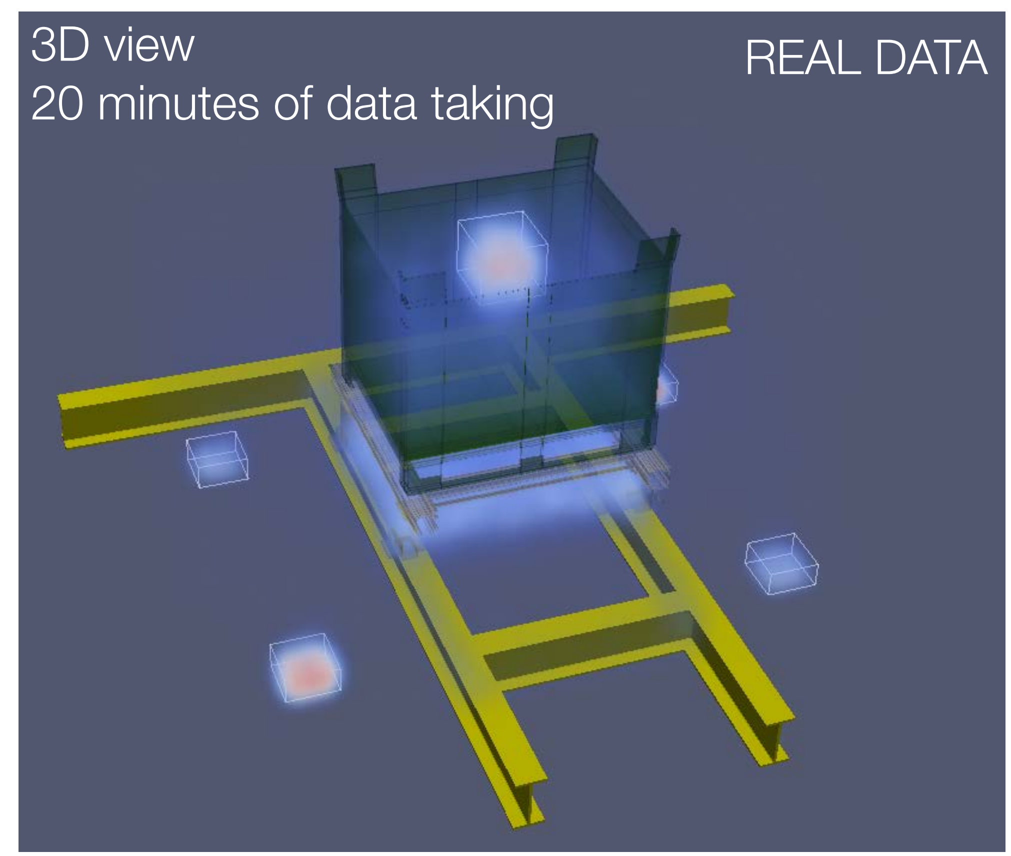
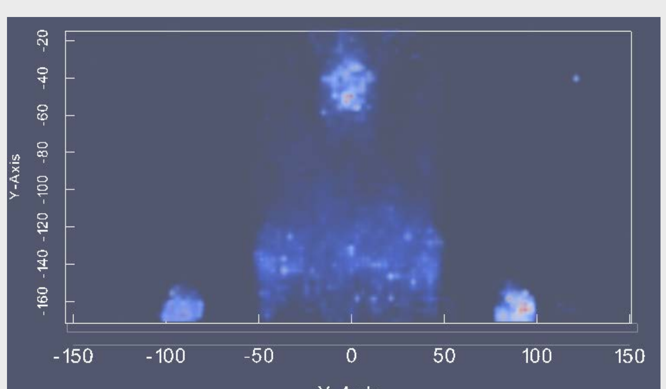


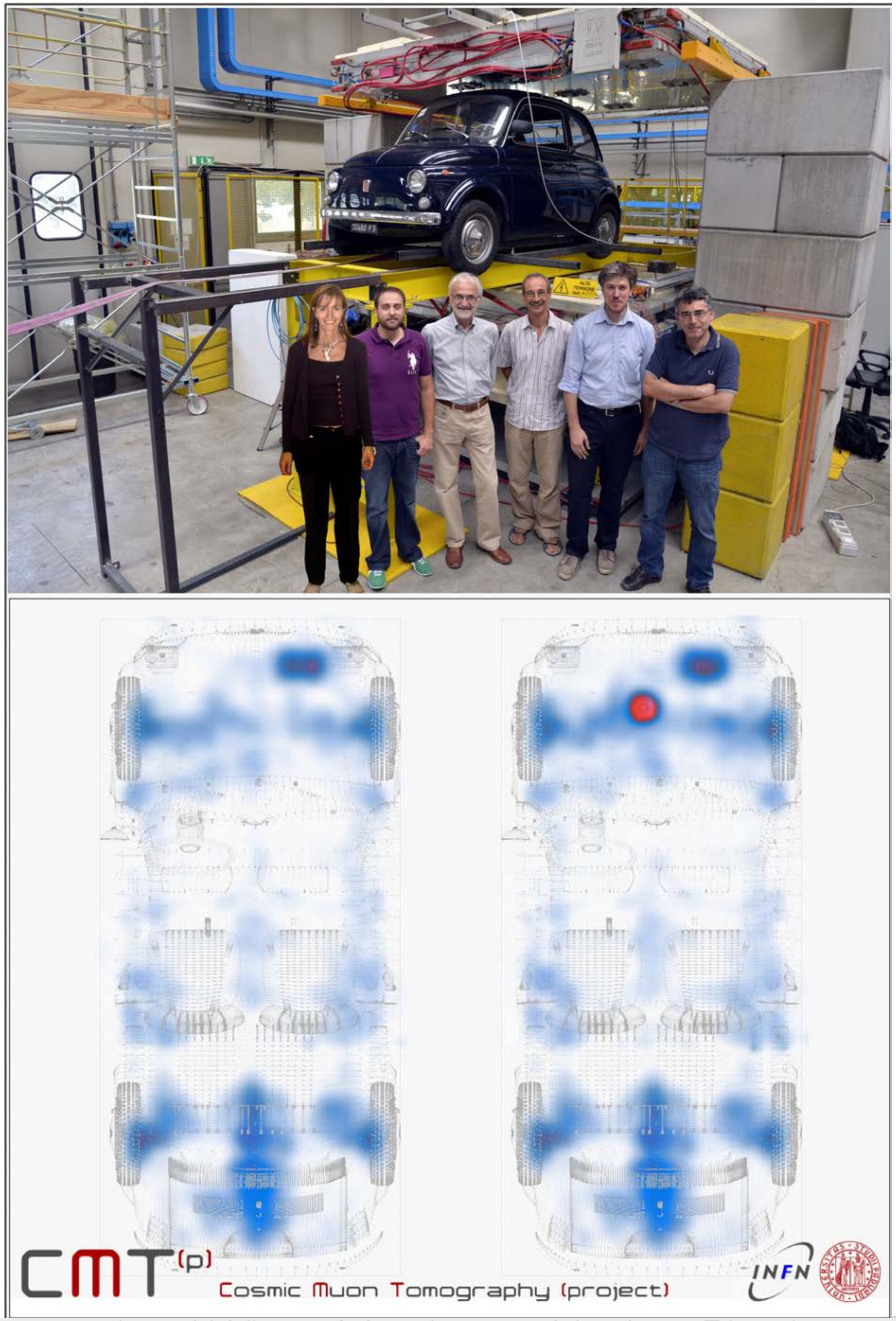


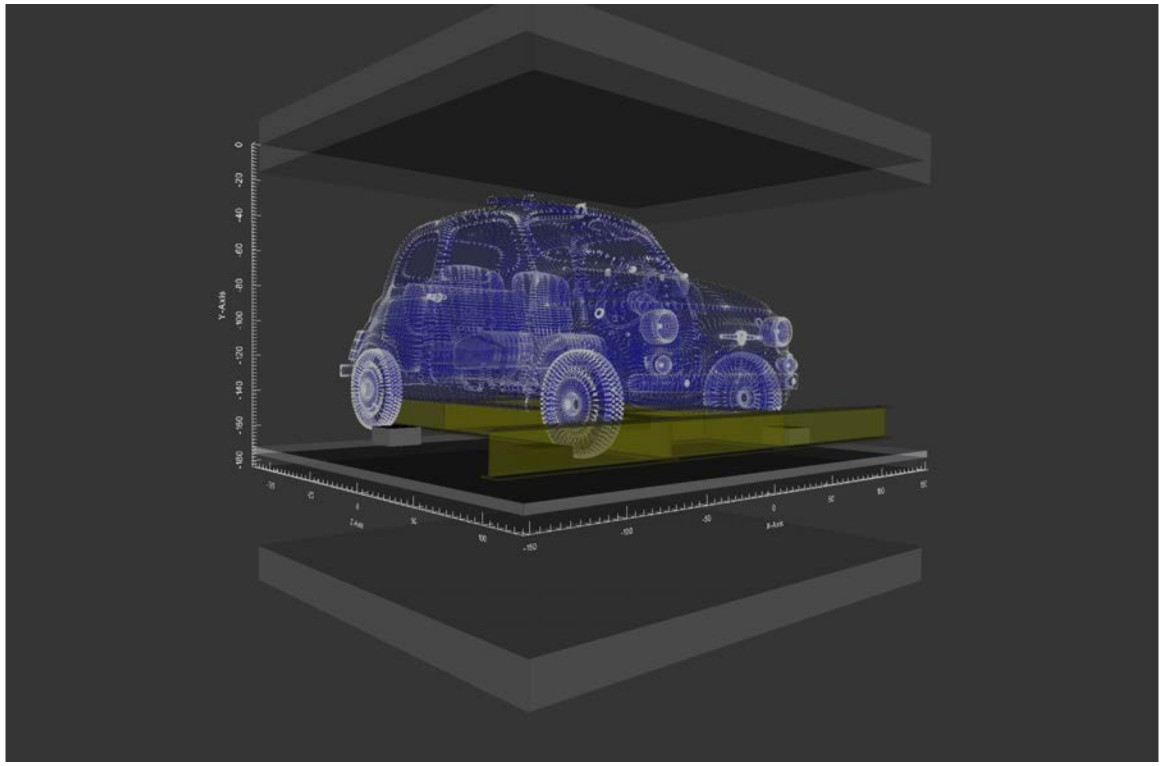
Great improvements have been implemented in the 3D image tomographic reconstruction software

The prototype has been modeled and simulated using the GEANT4 package.
The Monte Carlo has been tuned to match the experimental results



Monte Carlo simulation [corresponding to 5 minutes of data taking]

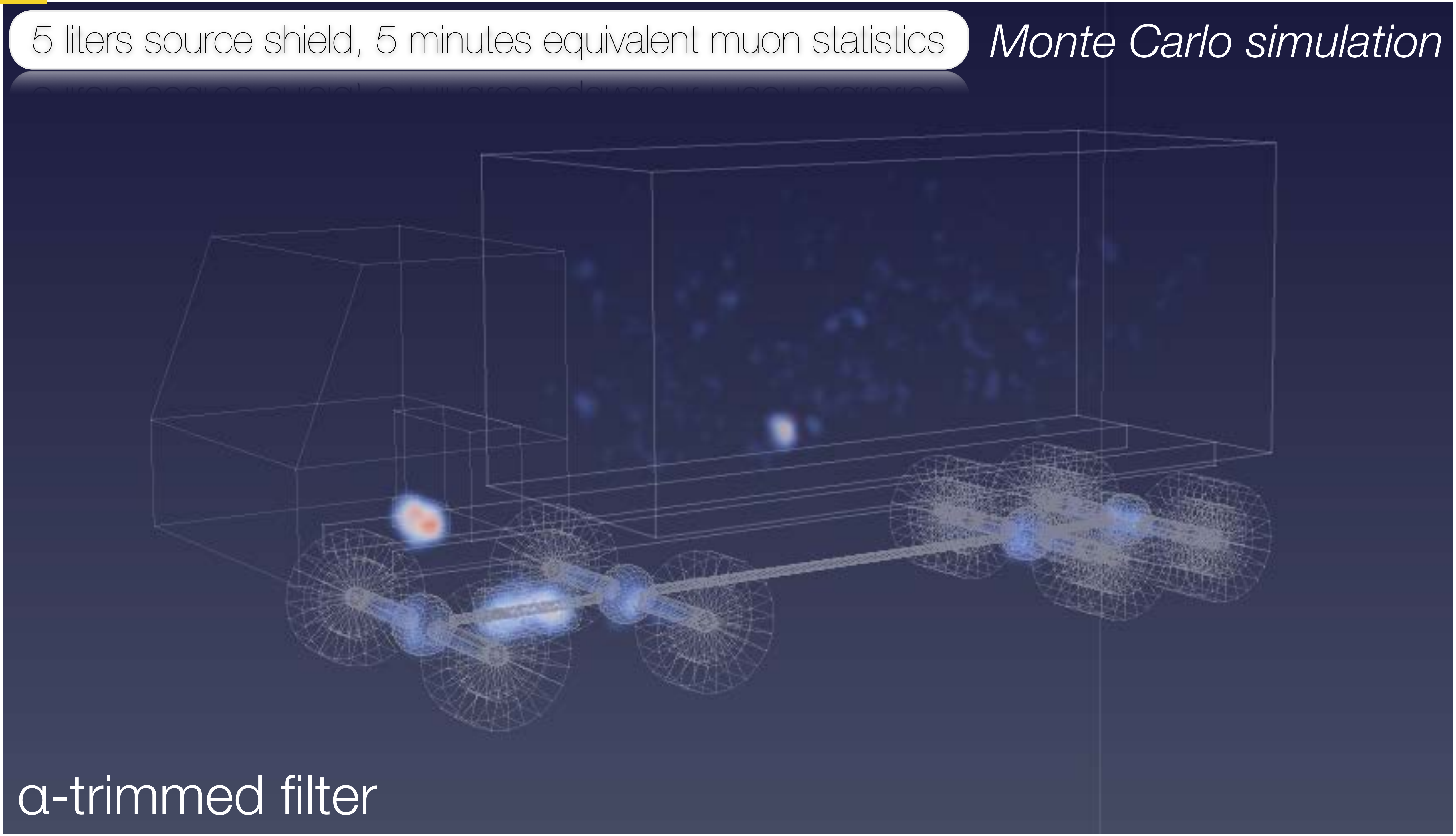

CMT(p)
Cosmic Muon Tomography (project)
INFN



The LNL muon tomography prototype

a “test bed” for the Monte Carlo and for the
3D image reconstruction software

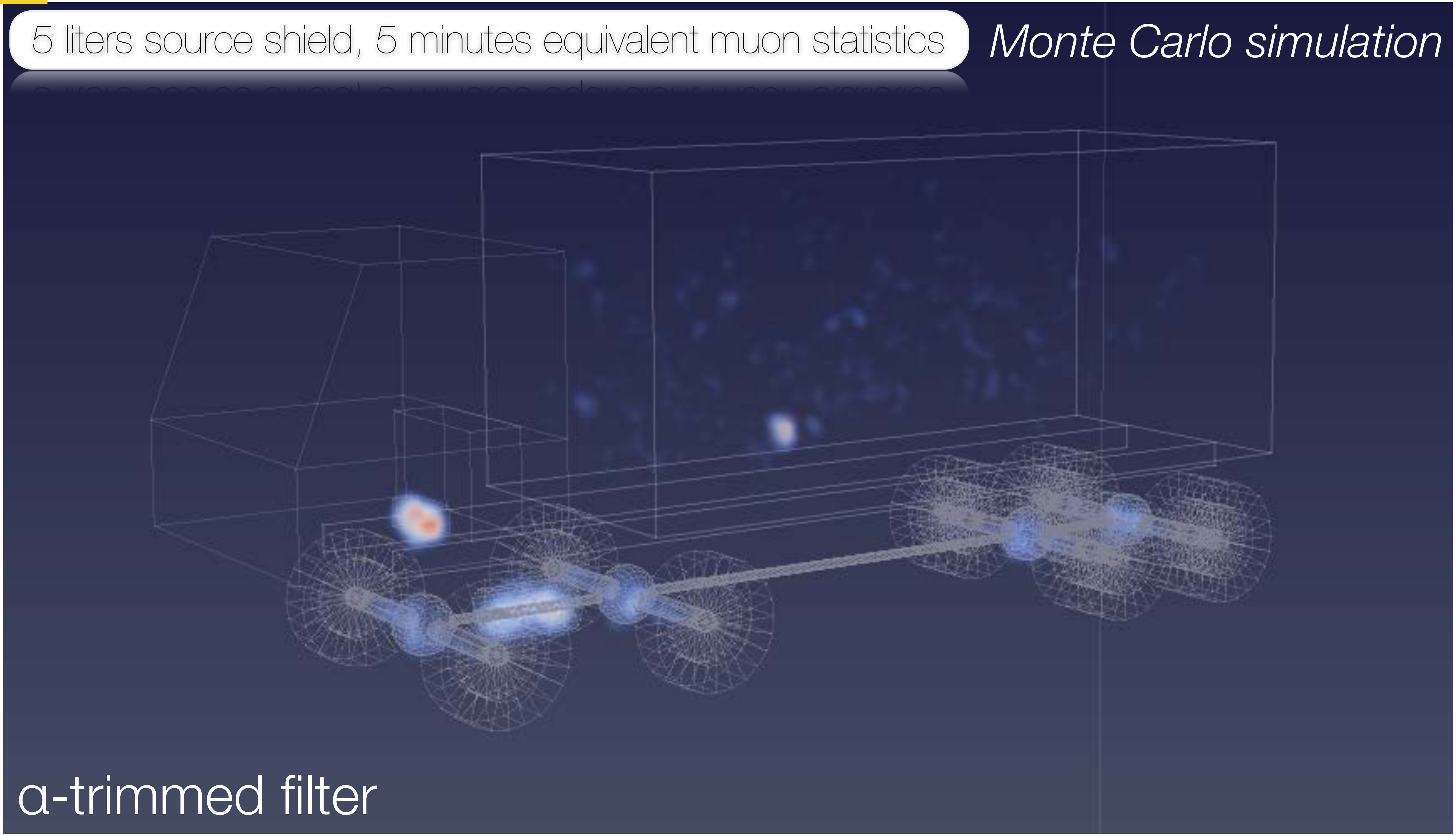
The Mu-Steel project: [3] image tomographic reconstruction



look at neighbourhood of every voxel, discard the most atypical elements and calculate the mean value using the rest of them

cubic 5x5x5 voxels mask
Gaussian shaped smoothing

The Mu-Steel project: [3] image tomographic reconstruction



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Gaussian shaped smoothing

not satisfactory

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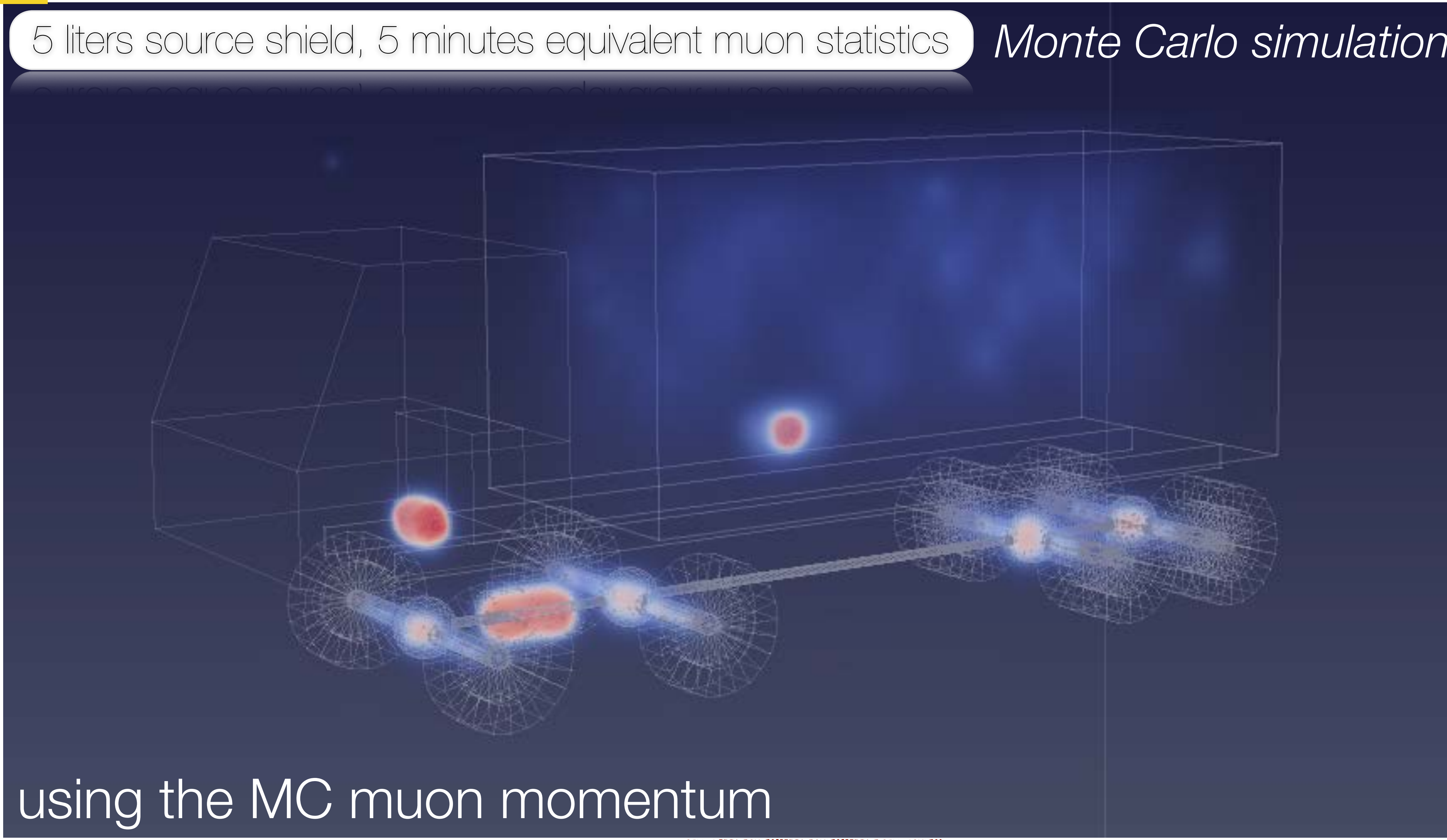
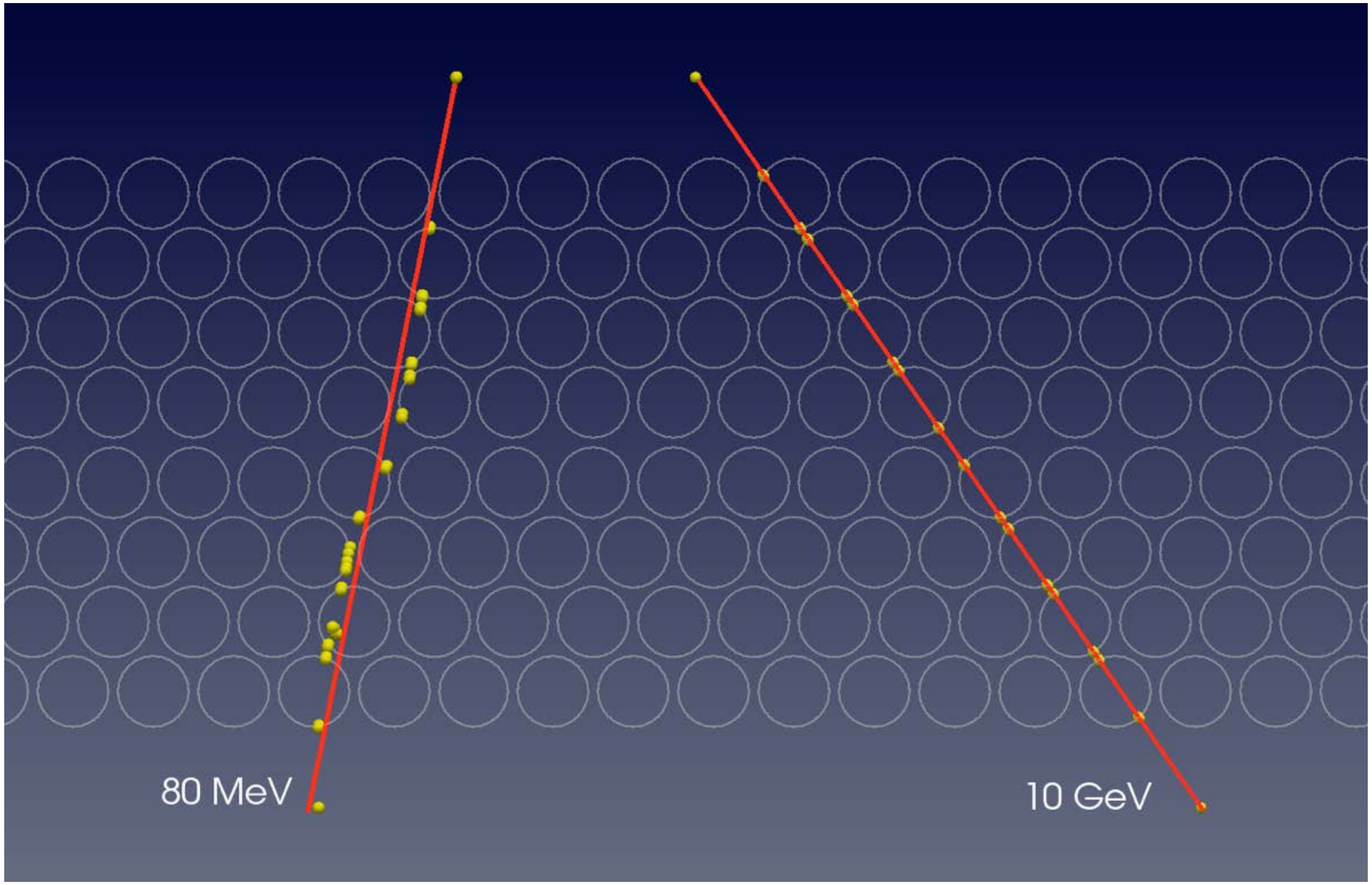


$$\sigma \simeq \frac{1}{p}\sqrt{\frac{L}{X_o}}$$

The Mu-Steel project: muon momentum estimate

- Multiple scattering in the detector is heavier for low momentum muons



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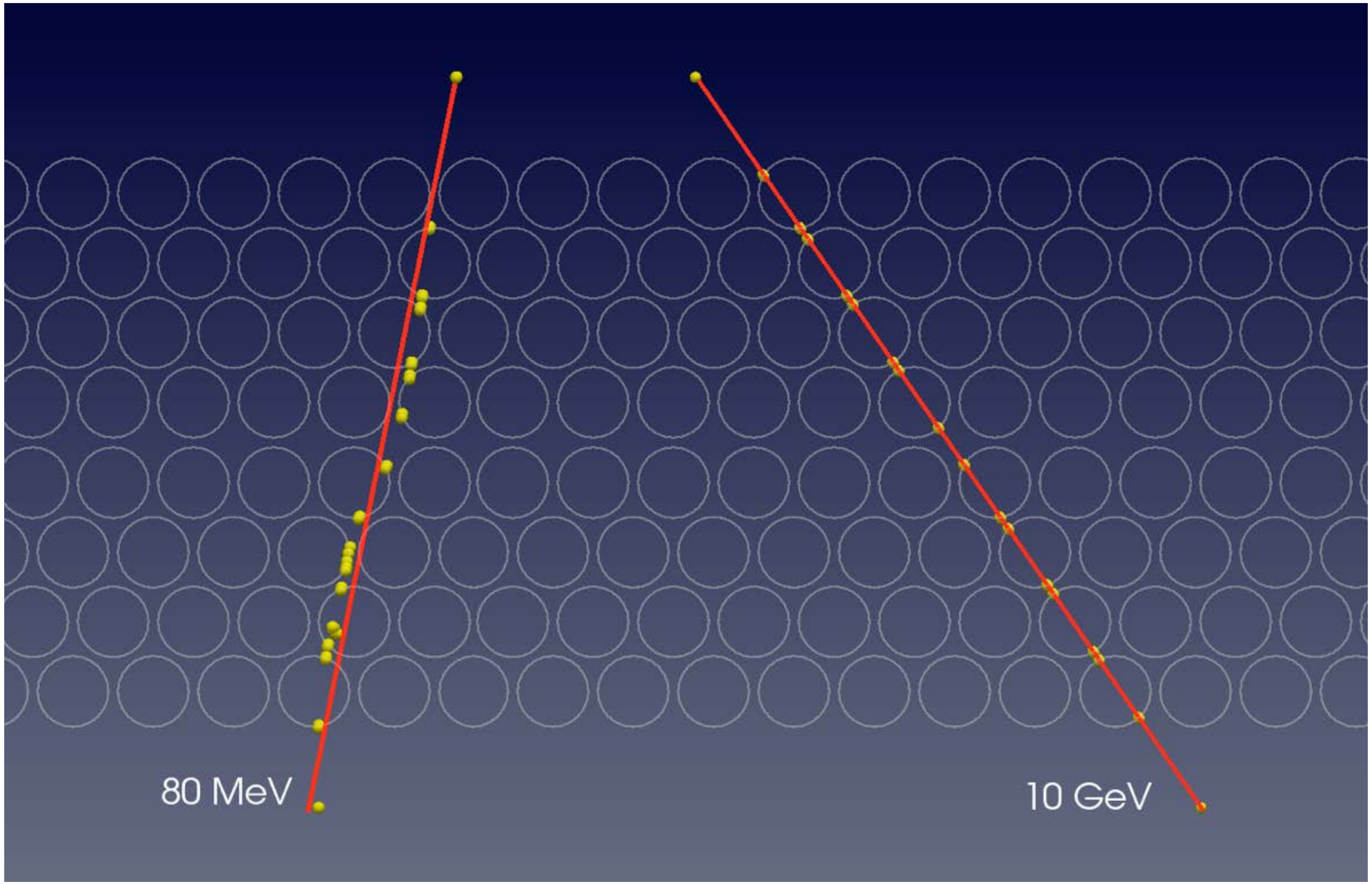
A rough (but very precious) estimate of the muon momentum can be derived from the measurement of the "**residuals**" (difference between the best "straight line" fit and single hits)



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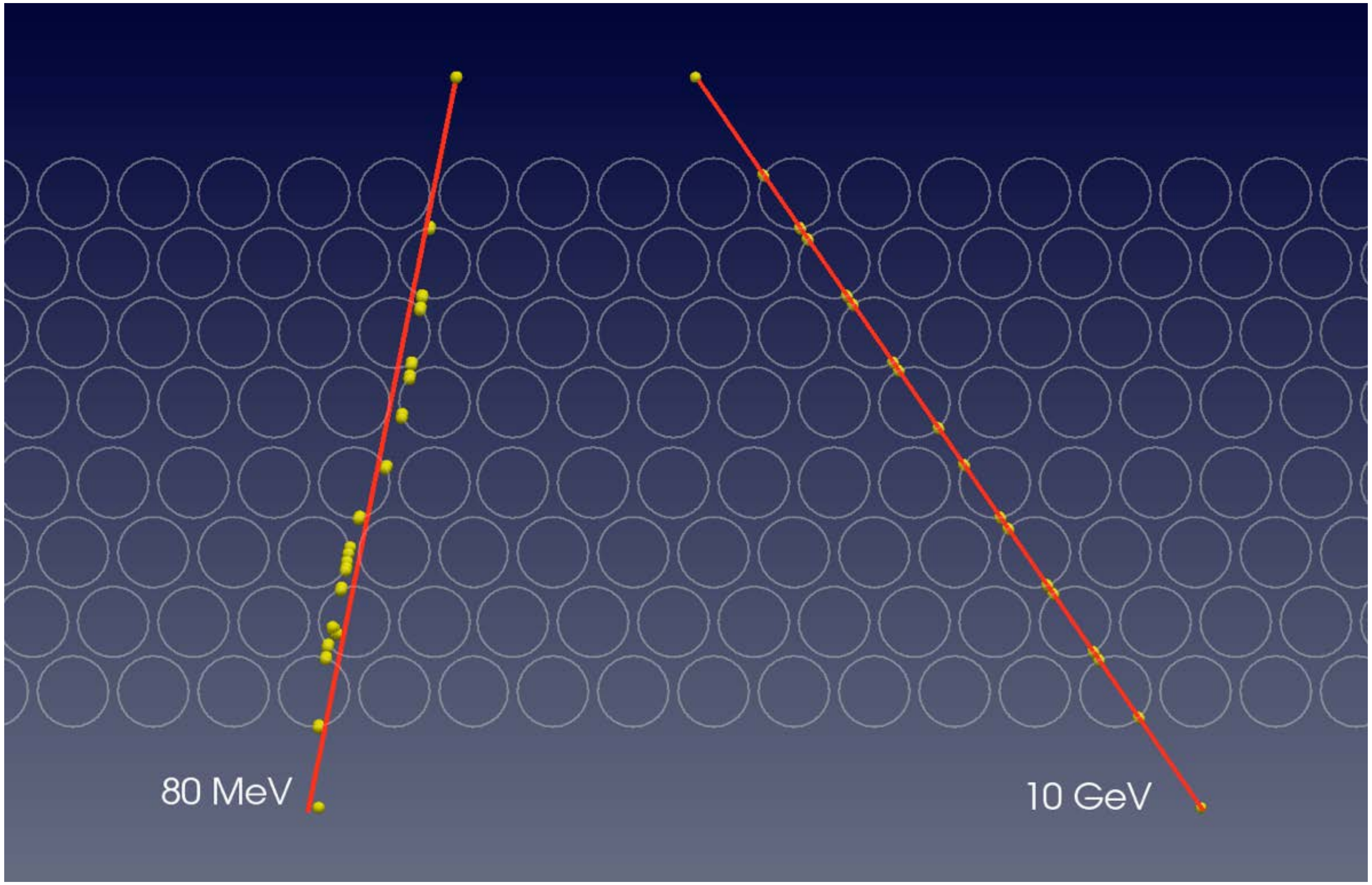
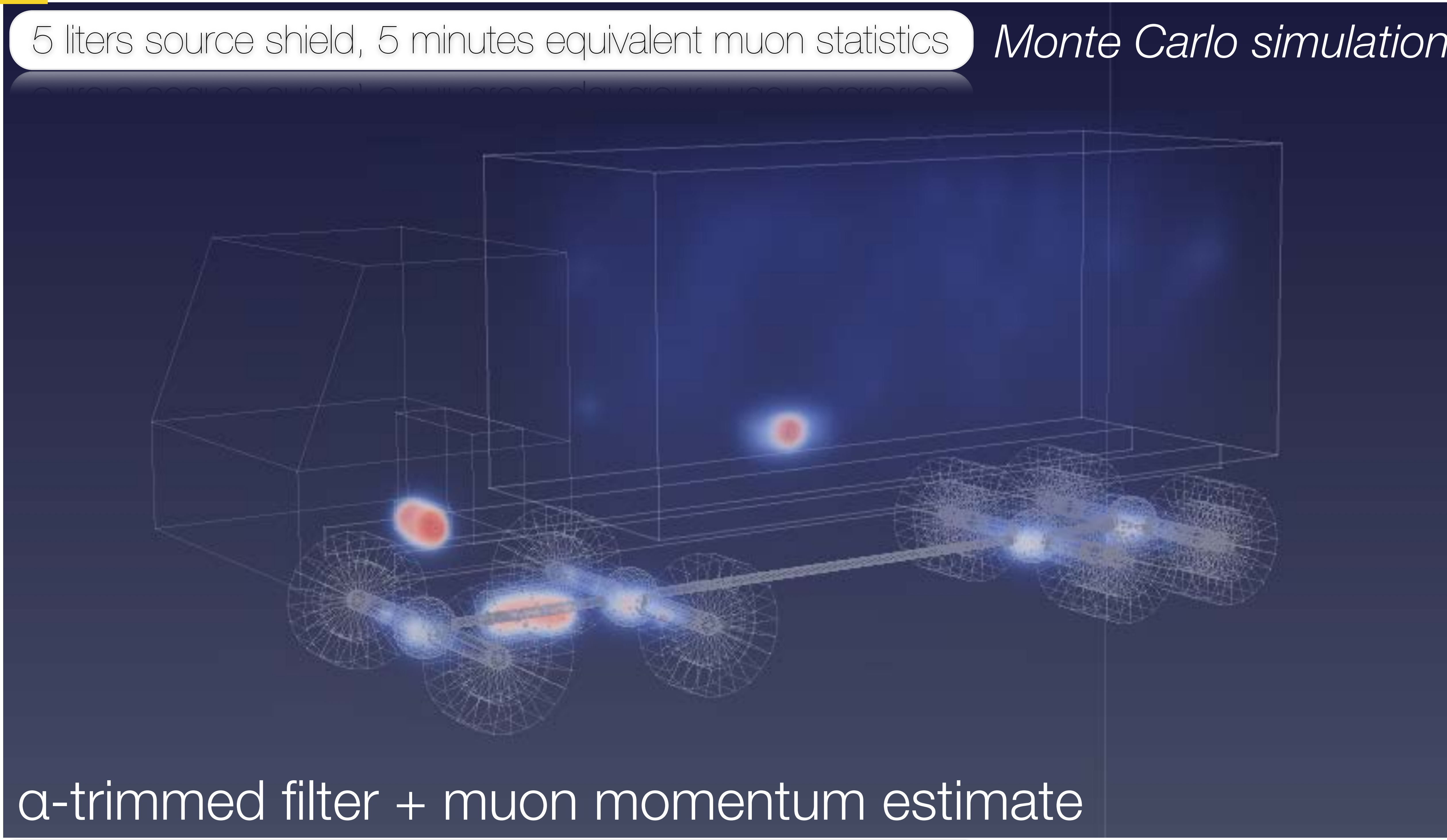


Muons are thus divided **in few categories** (from low to high momentum) and for each of them the average momentum of the range is used in the minimization process

The Mu-Steel project: [3] image tomographic reconstruction



5 [2 liters] liters source shield (17x17x17 cm^3 [13x13x13 cm^3]) is detected in 4 [7] minutes with 100% efficiency and 0% false alarms

cubic 5x5x5 voxels mask
Gaussian shaped smoothing (σ = 0.5)
muon momentum in-processing

The Mu-Blast project (RFCS CT-2014-00027)

[mid 2014-mid 2016]

Partners

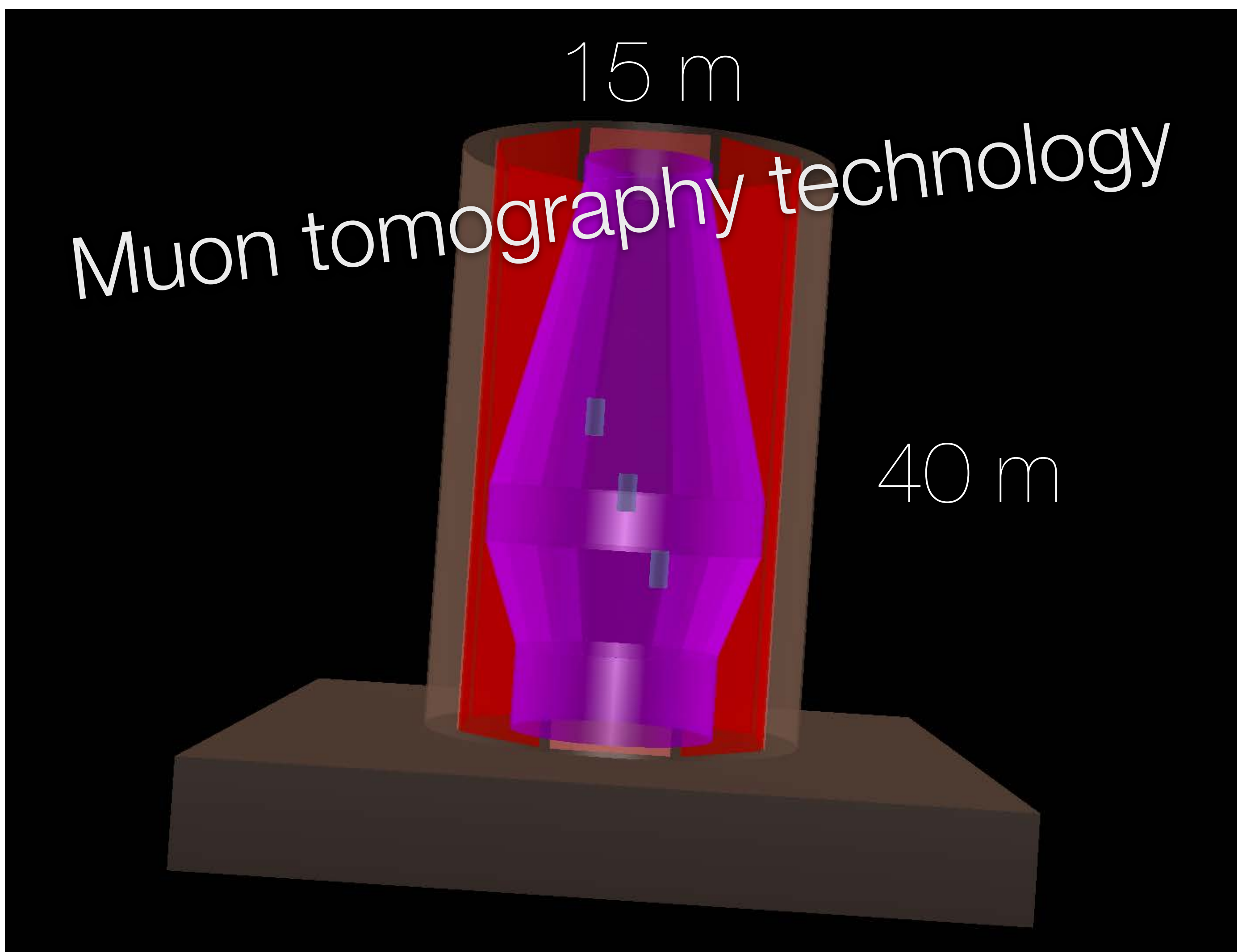
University of Padova (Italy)
INFN (Italy)
Centro Sviluppo Materiali (Italy)
University of Brescia (Italy)
Swerea Mefos (Sweeden)
Luossavaara-Kiirunavaara AB - LKAB (Sweeden)

Budget

896.123 €

European Commission

Research Fund for Coal & Steel



Project objectives

Study the feasibility of building a system able to inspect the inner structure of a blast furnace (otherwise impossible to investigate).

[tomographic measurements with the LNL system of samples extracted from a blust furnace, development of the simulation tool and of the required 3D reconstruction software]

Muon-based monitoring systems

an example

Yet another idea

- thickness measurements
- muon tomography
- muon based monitoring systems

Yet another idea

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- muon tomography
- muon based monitoring systems
  - use the cosmic rays to monitor the alignment of physical part of a given structure (tower, pillar, mechanical press, etc., etc.)

  original idea of a physicist A. Zenoni and an engineer D. Cambiaghi of the University of Brescia that collaborated to the construction of the apparatus holder of the FINUDA experiment, then “aligned” with cosmic rays

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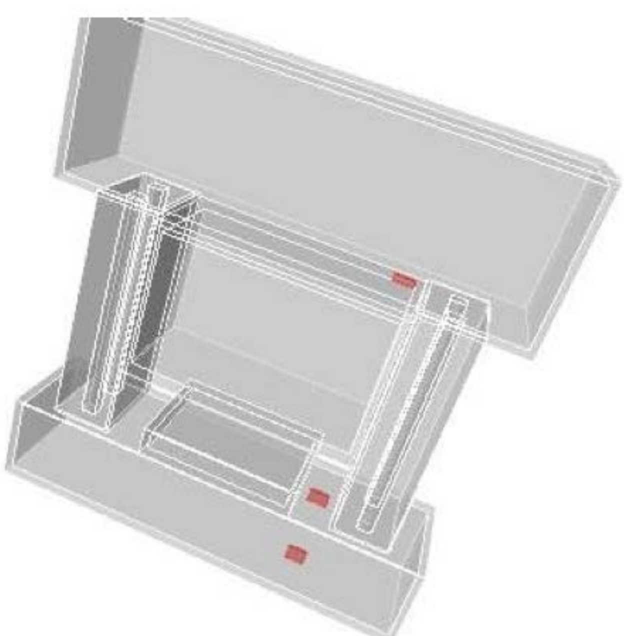

Cosmic rays detection based measurement systems: a preliminary study

I Bodini[1], G Bonomi[1,2], D Cambiaghi[1], A Magalini[1], and A Zenoni[1,2]

[1] Università degli Studi di Brescia, Facoltà di Ingegneria, Dipartimento di Ingegneria Meccanica ed Industriale. Via Branze, 38 - 25123 Brescia - Italy

[2] Istituto Nazionale di Fisica Nucleare. Via Bassi 6 - 27100 Pavia - Italy

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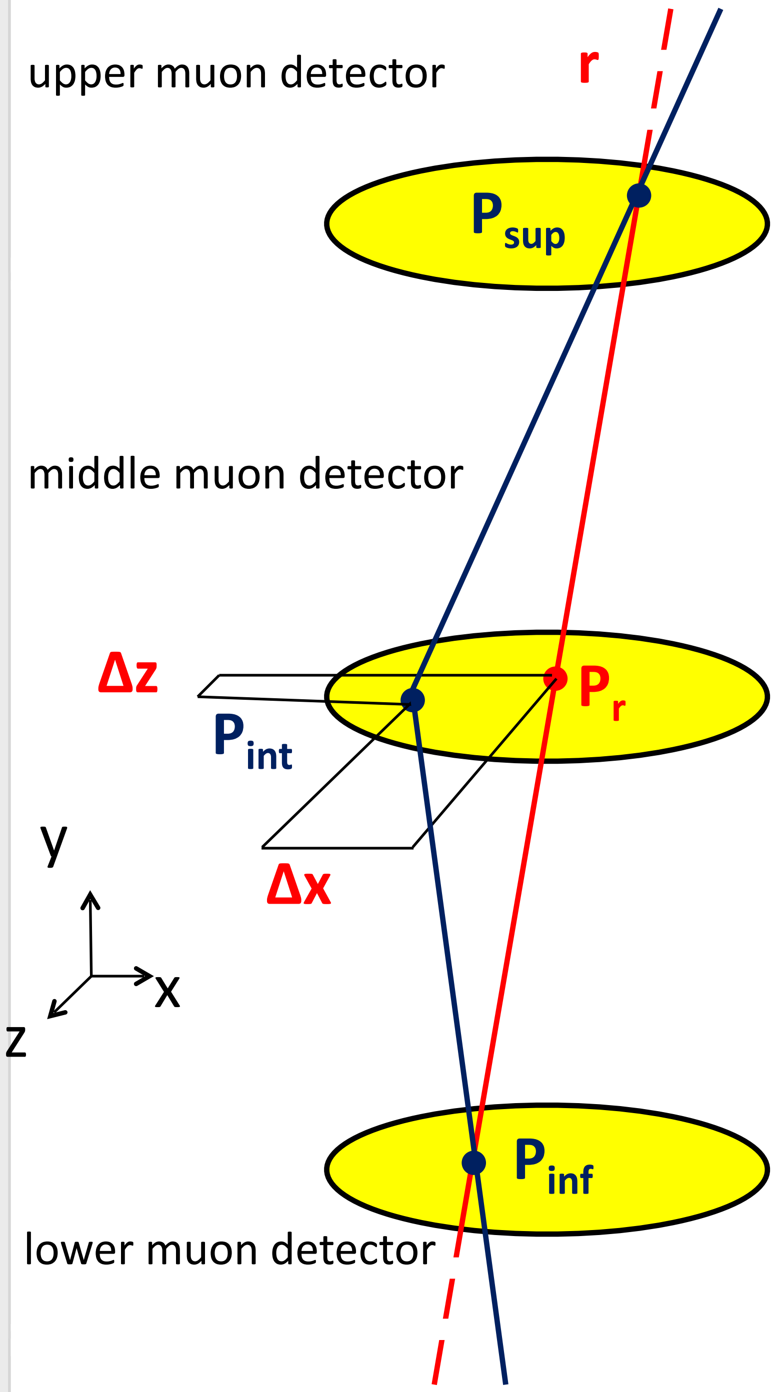
Abstract. Cosmic rays, mostly composed by high energy muons, hit continuously the Earth surface (at sea level the rate is about 10000 m^{-2} min^{-1}). Various technologies are adopted for their detection and are widespread in the field of Particle and Nuclear Physics. In this paper, cosmic ray muon detection techniques are assessed for measurement applications in Engineering, where these methods could be suitable for several applications, with specific reference to situations where environmental conditions are weakly-controlled and/or where the parts to be measured are hardly accessible. Since cosmic ray showering phenomena show statistical nature, the Monte Carlo technique has been adopted to numerically simulate a particular application, where a set of muon detectors are employed for alignment measurements on an industrial press. An analysis has been performed to estimate the expected measurement uncertainty and system resolution, which result to be strongly dependent on the dimensions and geometry of the set-up, on the presence of materials interposed between detectors and ultimately, on the elapsed time available for the data taking.

published in "Measurement Science and Technology"

Keywords: Cosmic ray muons, multiple scattering, mechanical alignment monitoring, Monte Carlo simulations, elementary particle detectors, position measurements.

Basic principle



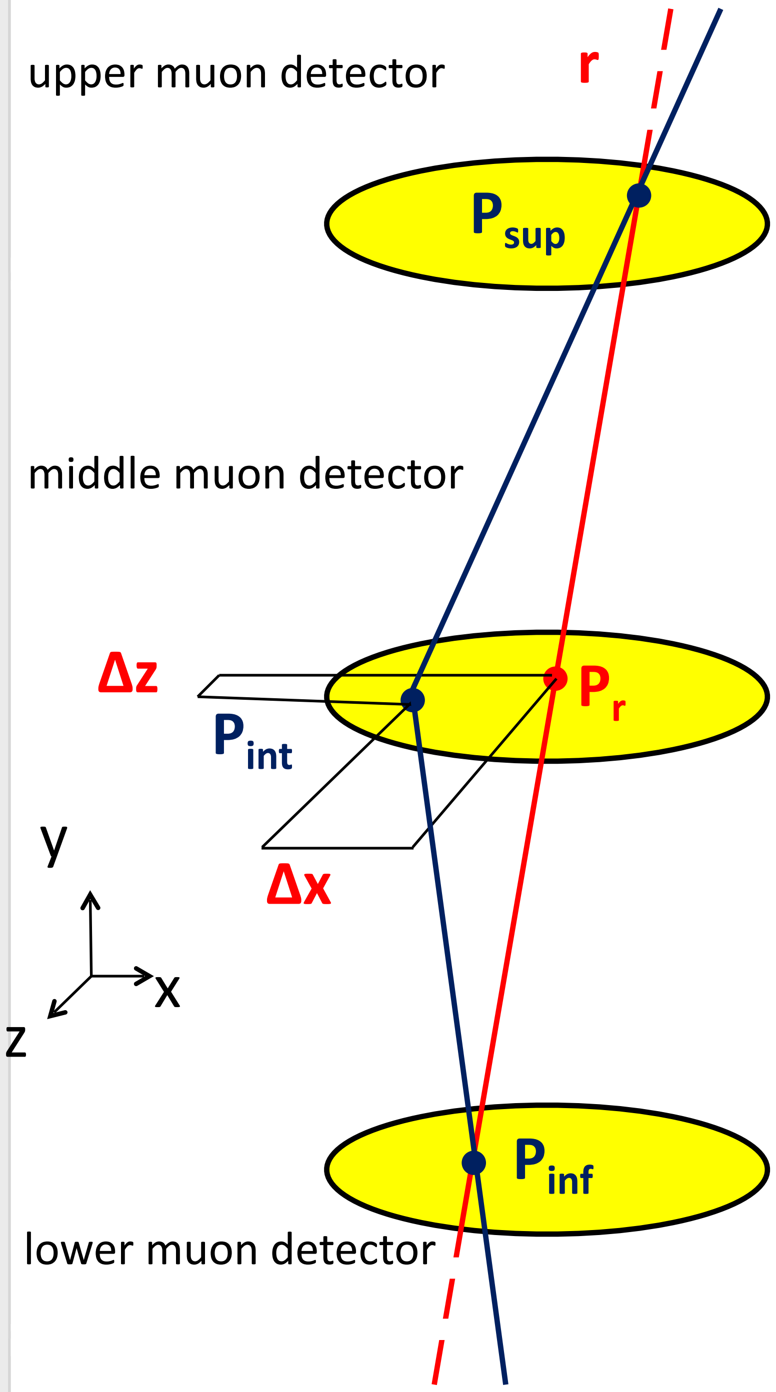
Basic principle

Statistical variables

$$\begin{cases} \Delta x = x_{int} - x_r \\ \Delta z = z_{int} - z_r \end{cases}$$

and their distributions

position of the middle detector with respect to the other two



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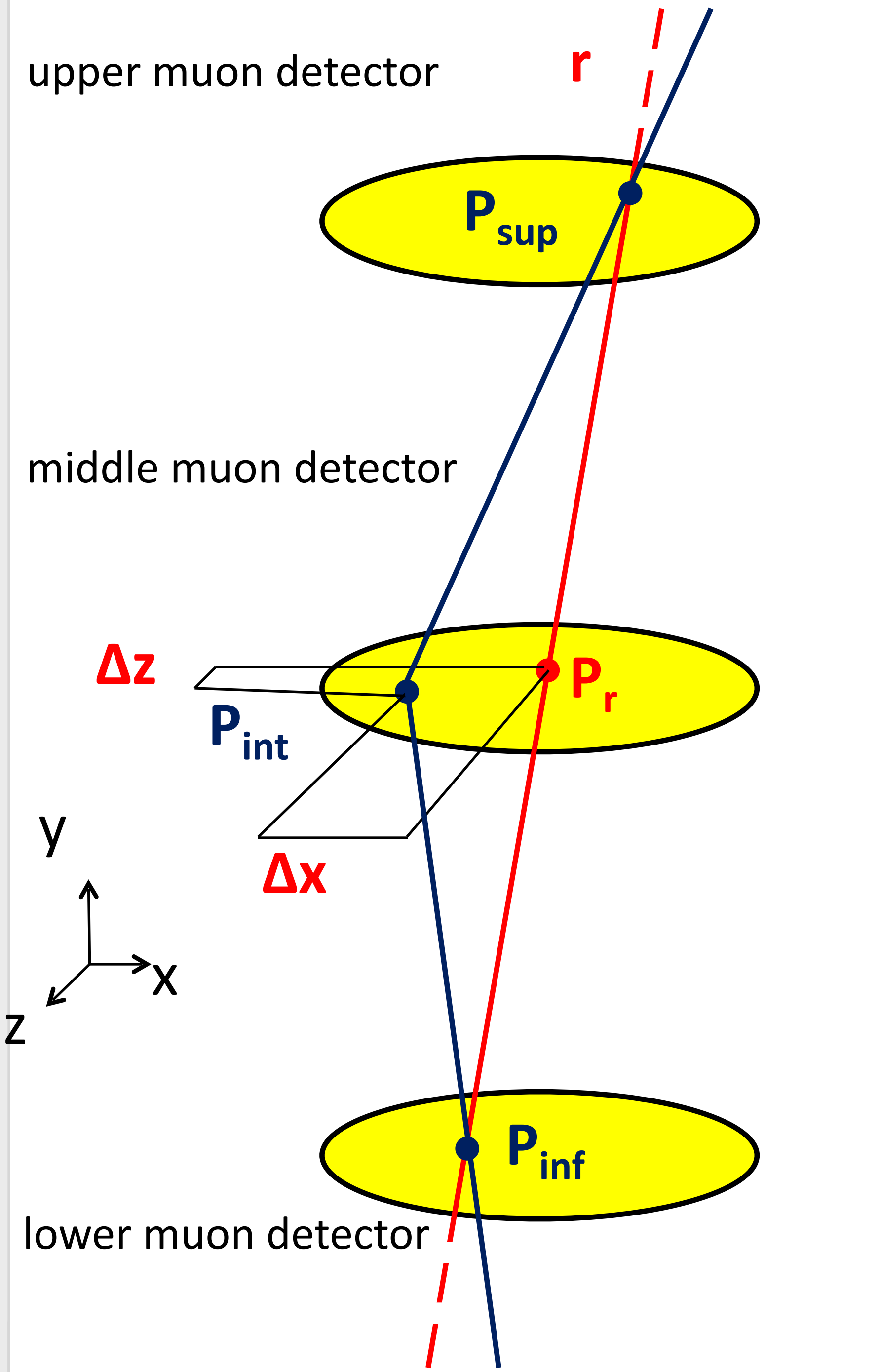

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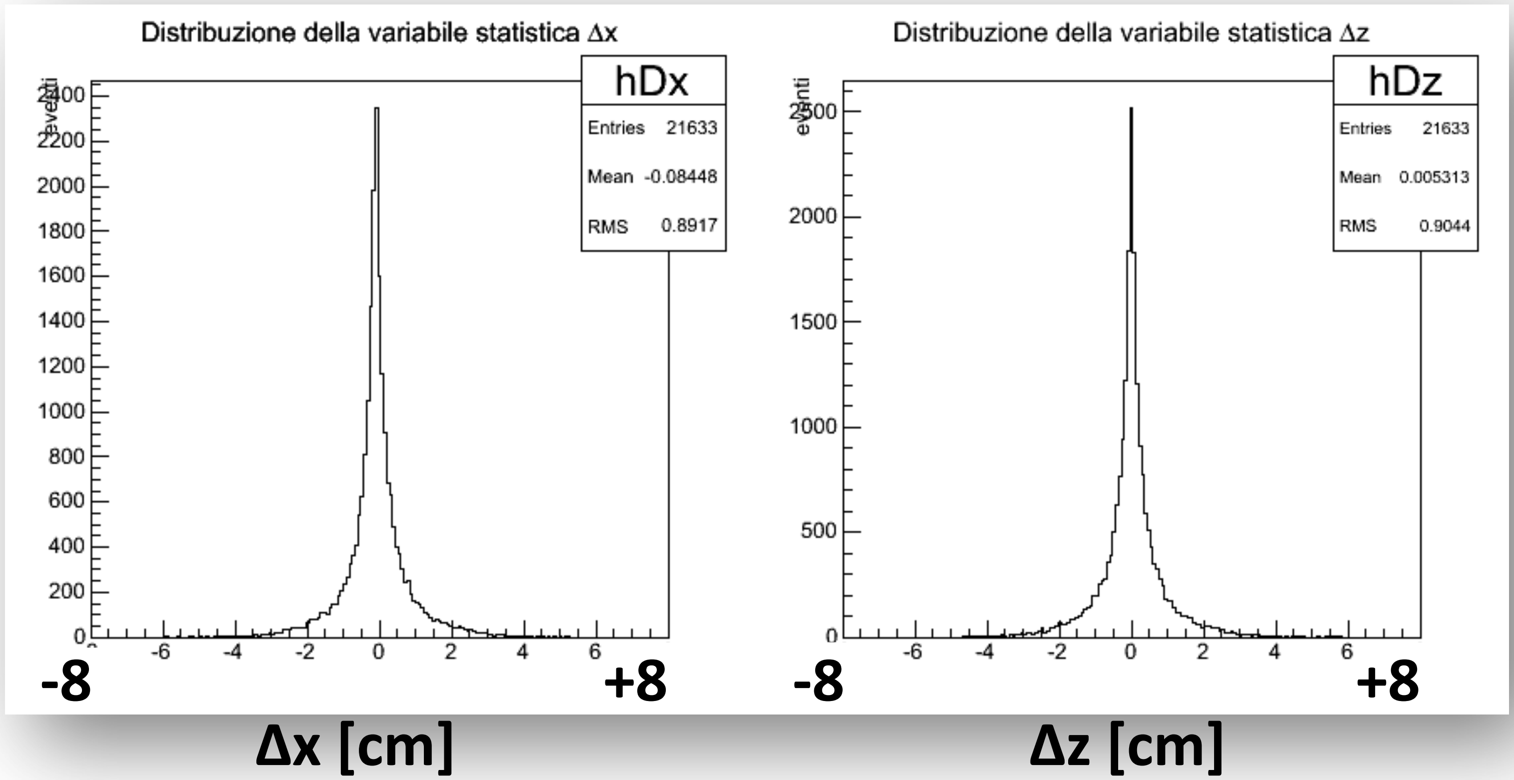

The “mean” of the distribution gives the relative position of the middle detector with respect to the other two. Once “measured” this position at a given time defined as t = 0 [through a calibration campaign] it is the possible to monitor it as a function of time to detect relative displacements

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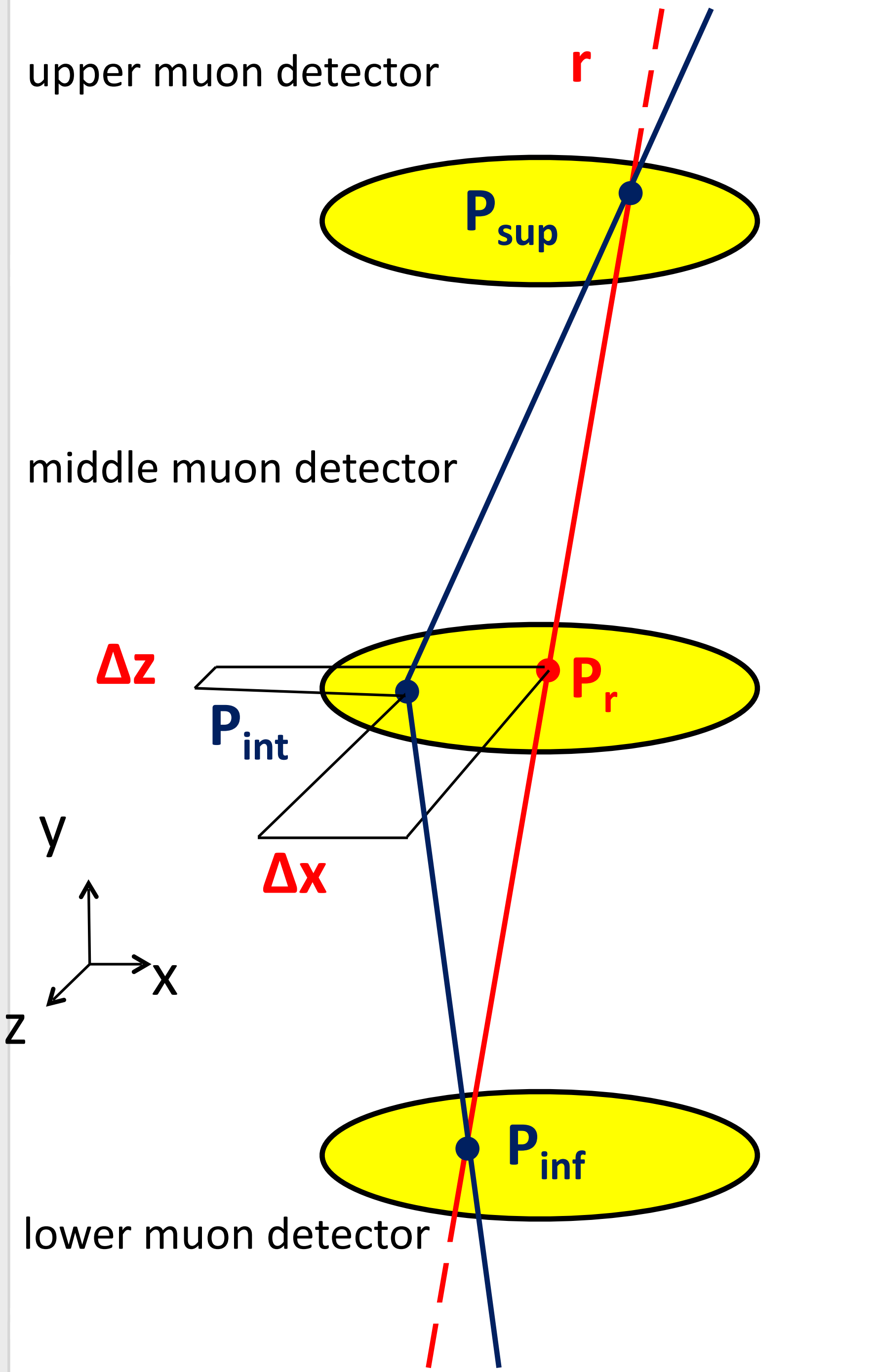

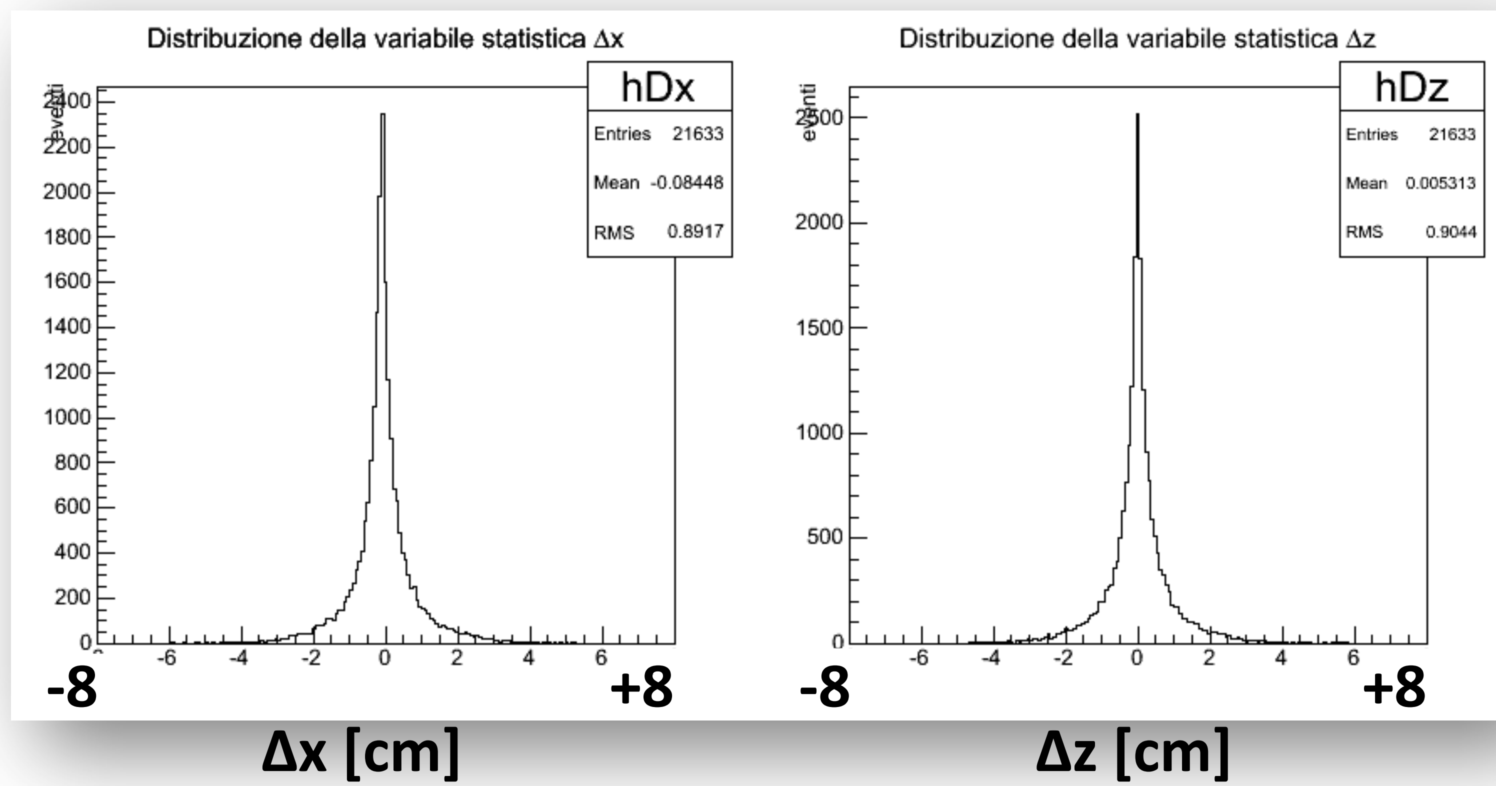

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The effects that "widen" **the distributions** [and make the measurements less accurate] are:

- **physical effects** [interaction of muons with matter]
- **detector spatial uncertainty**

Simulation of a specific case

MONSTER&CO PROJECT (2013-15)

MONitoraggio di STrutture Edili mediante Raggi Cosmici

A project financed by the Dipartimento di Ingegneria Meccanica e Industriale, Università di Brescia

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[3] Dipartimento di Fisica e Astronomia, University of Padova

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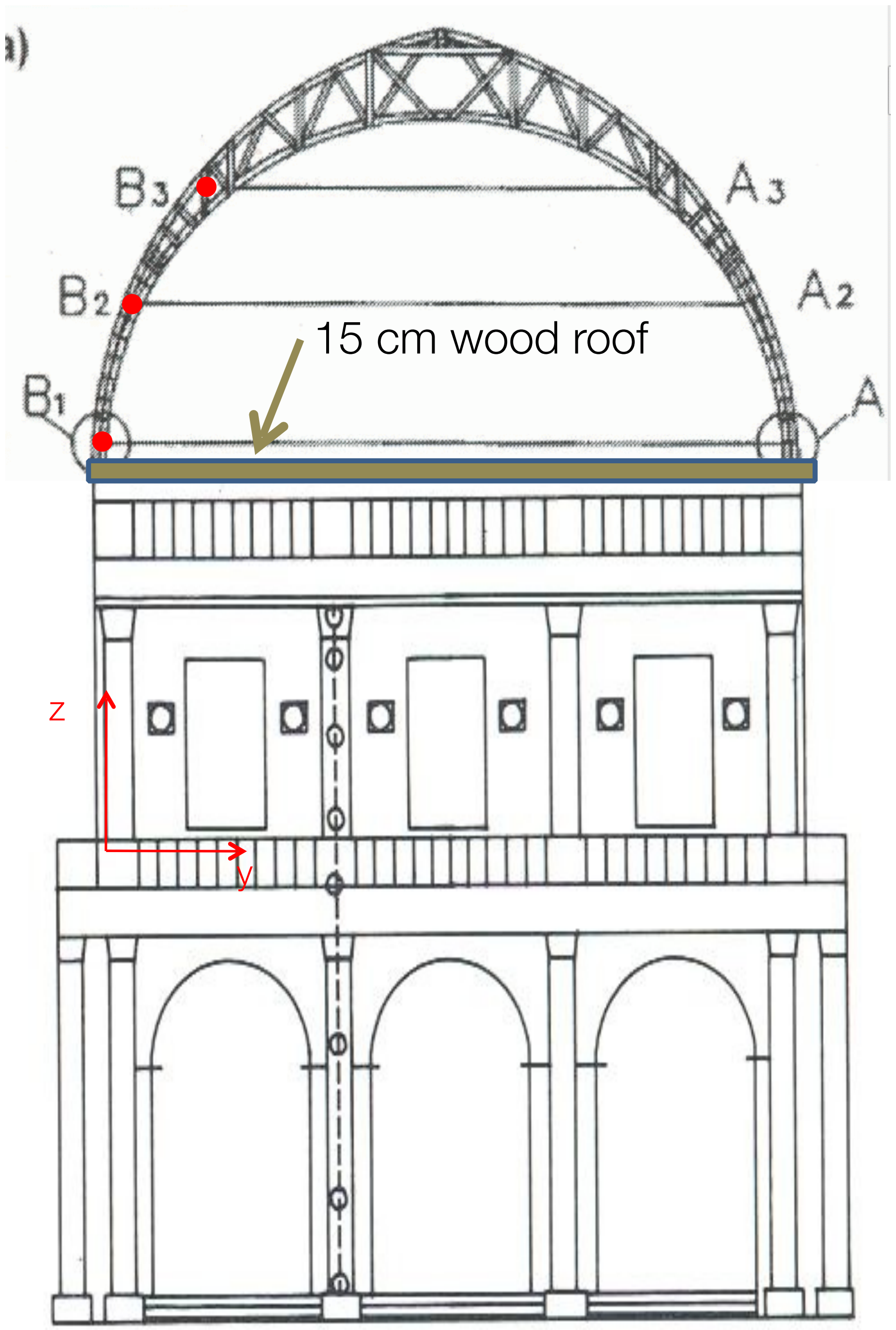
Basic idea of the project "MONSTER&CO"

the simulation contains: a muon generator, the geometry and the materials of the detectors and also the relevant structure of the building (such as the 15 cm wood roof)



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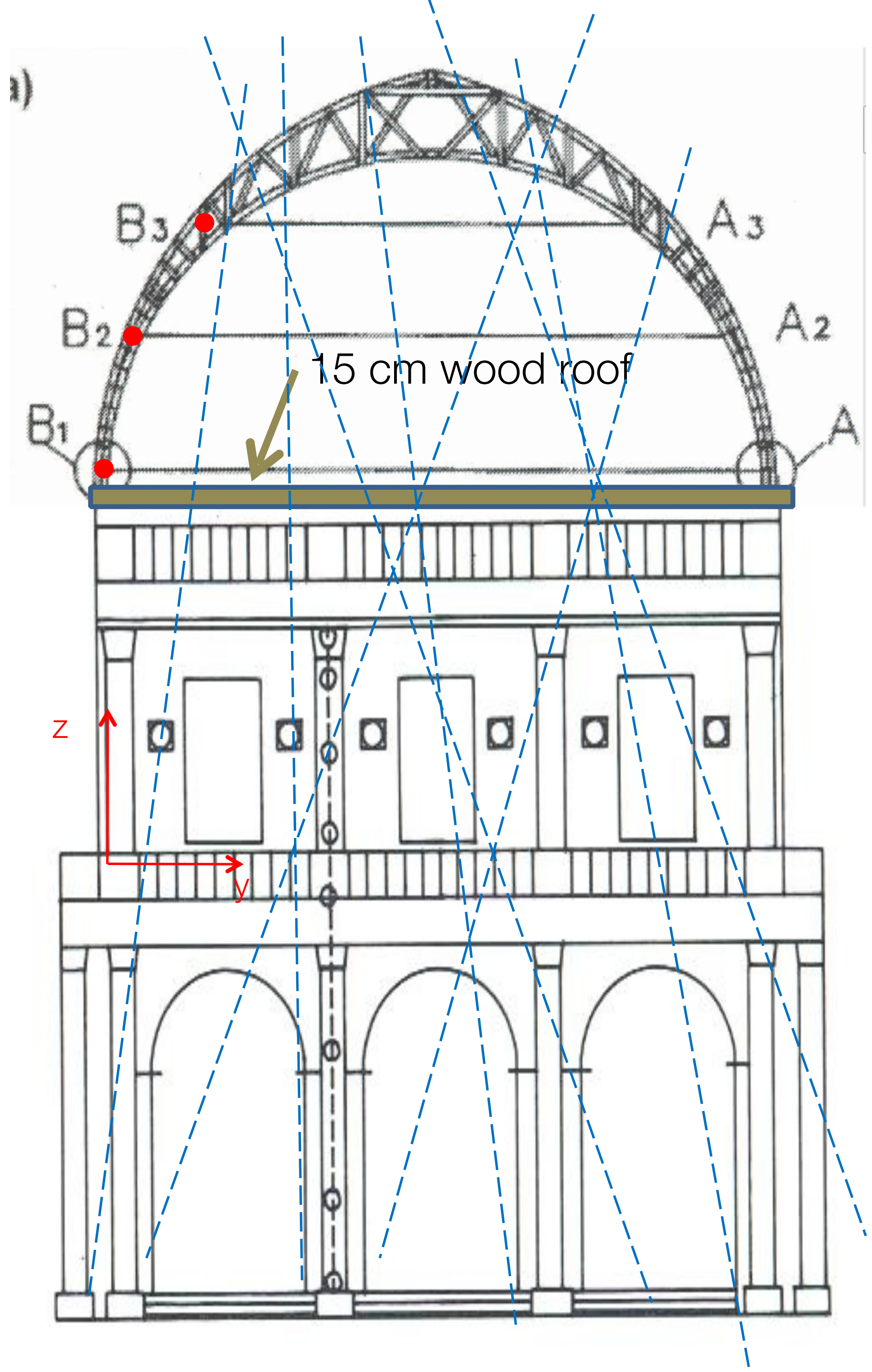

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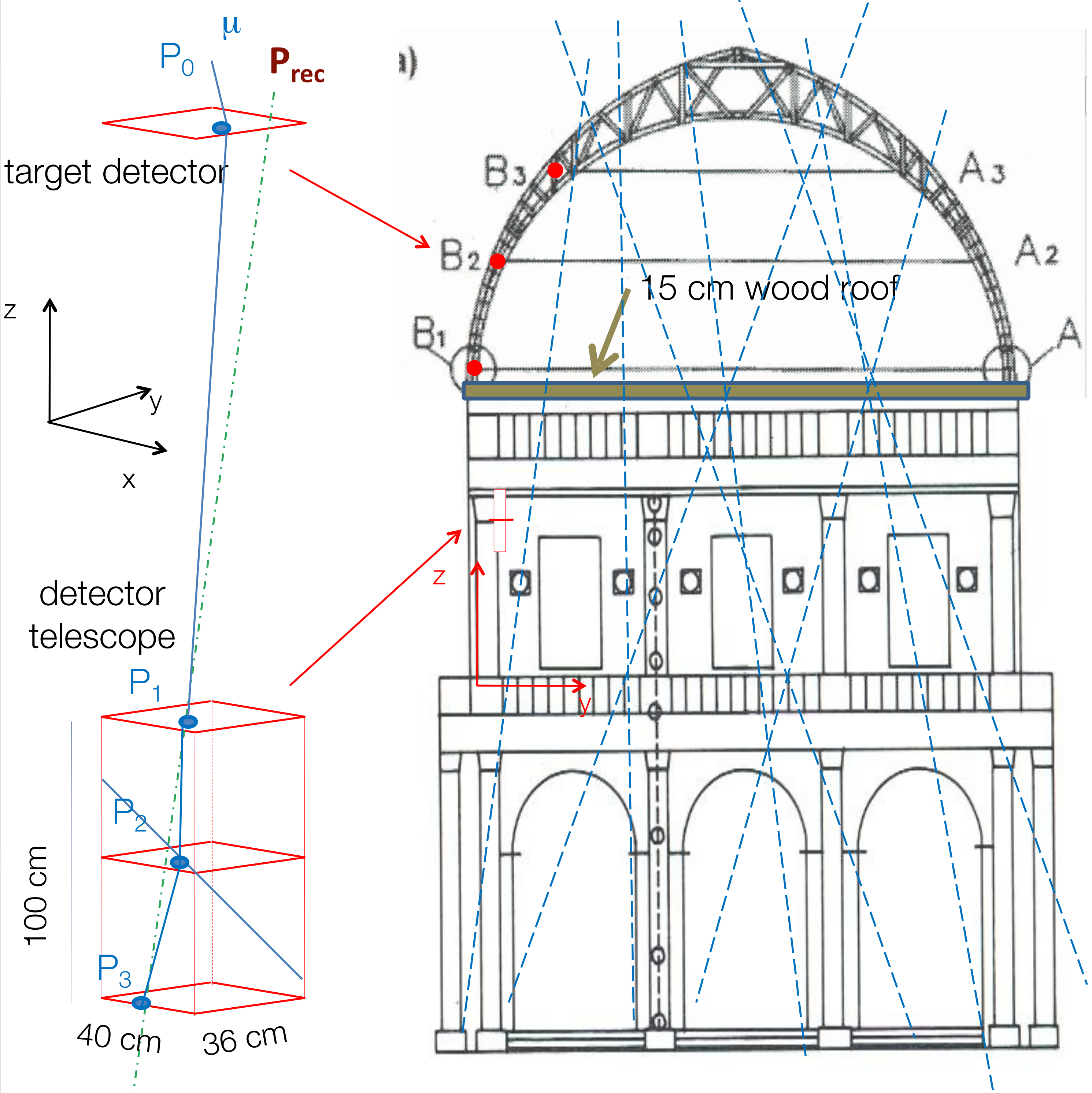

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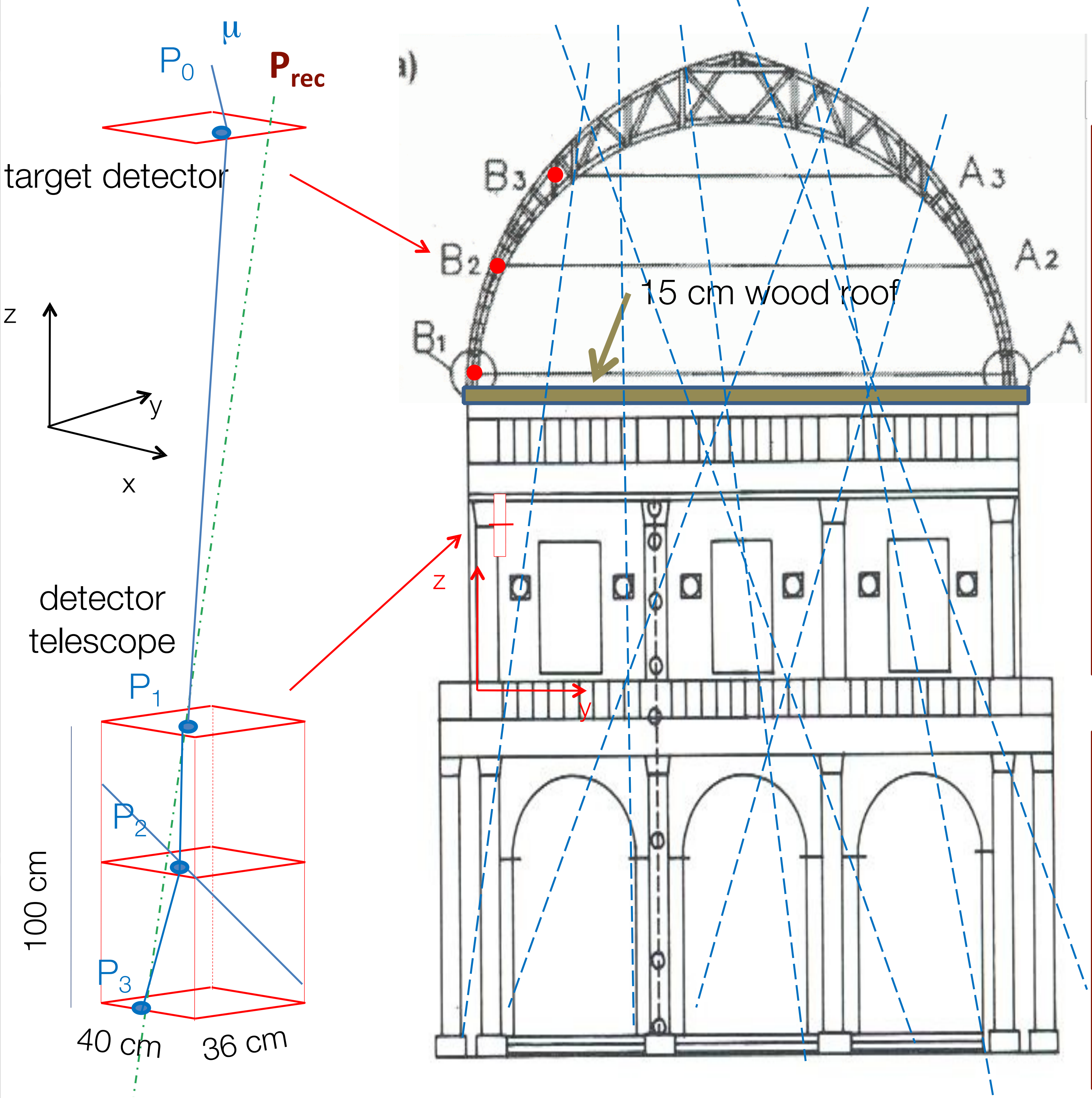


Cosmic rays

Pros

✓natural radiation, continuous

✓ no artificial source, no radiological risks

✓muons cross materials such as wooden floors with small deviations (with optical system is impossible)

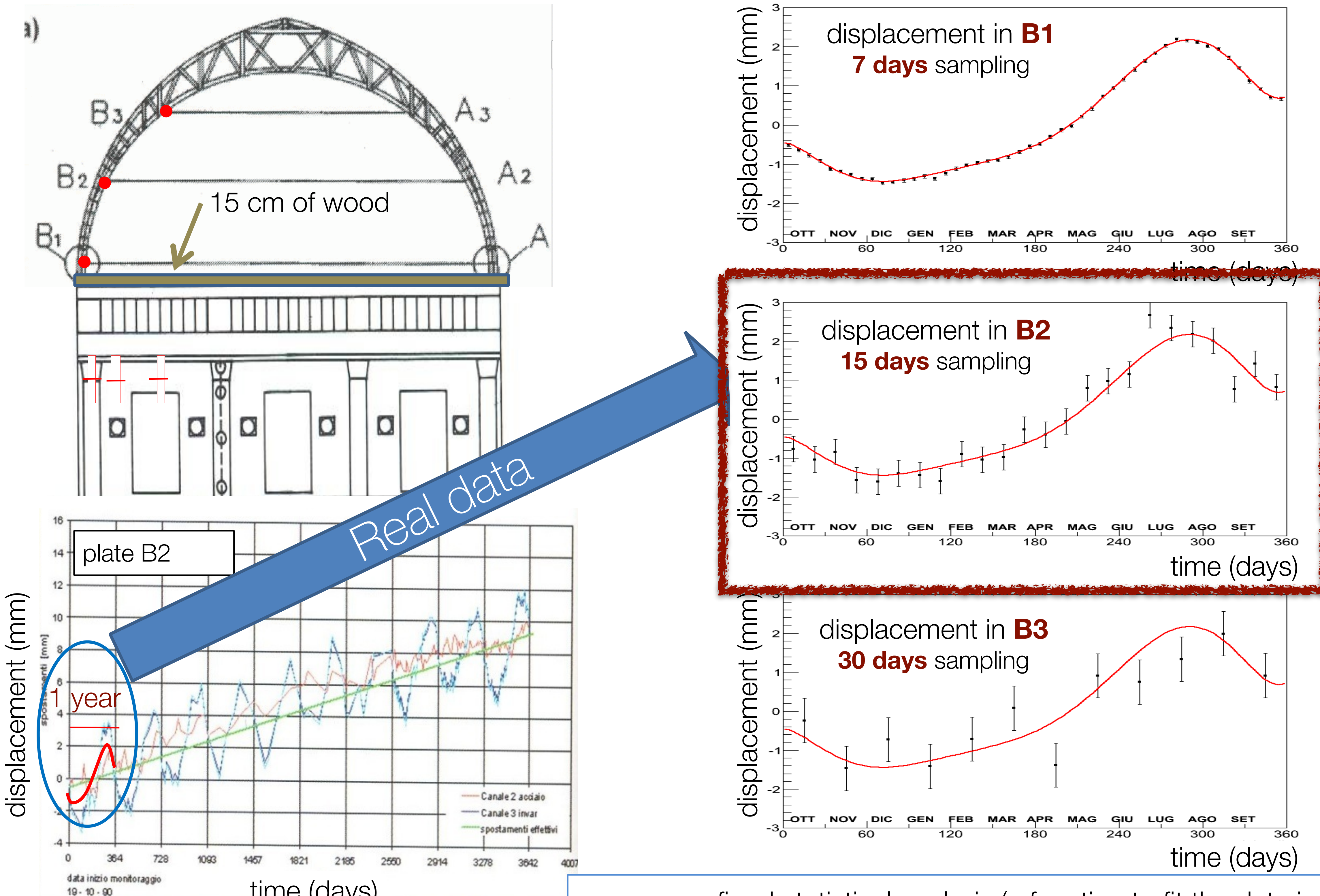
✓ easy measurements with "standard" techniques in physics

Cons

✓ the presence of statistical deviations requires the usage of distributions

✓ the need to accumulate enough statistics and thus wait the required time

Simulation of the “seasonal displacement”

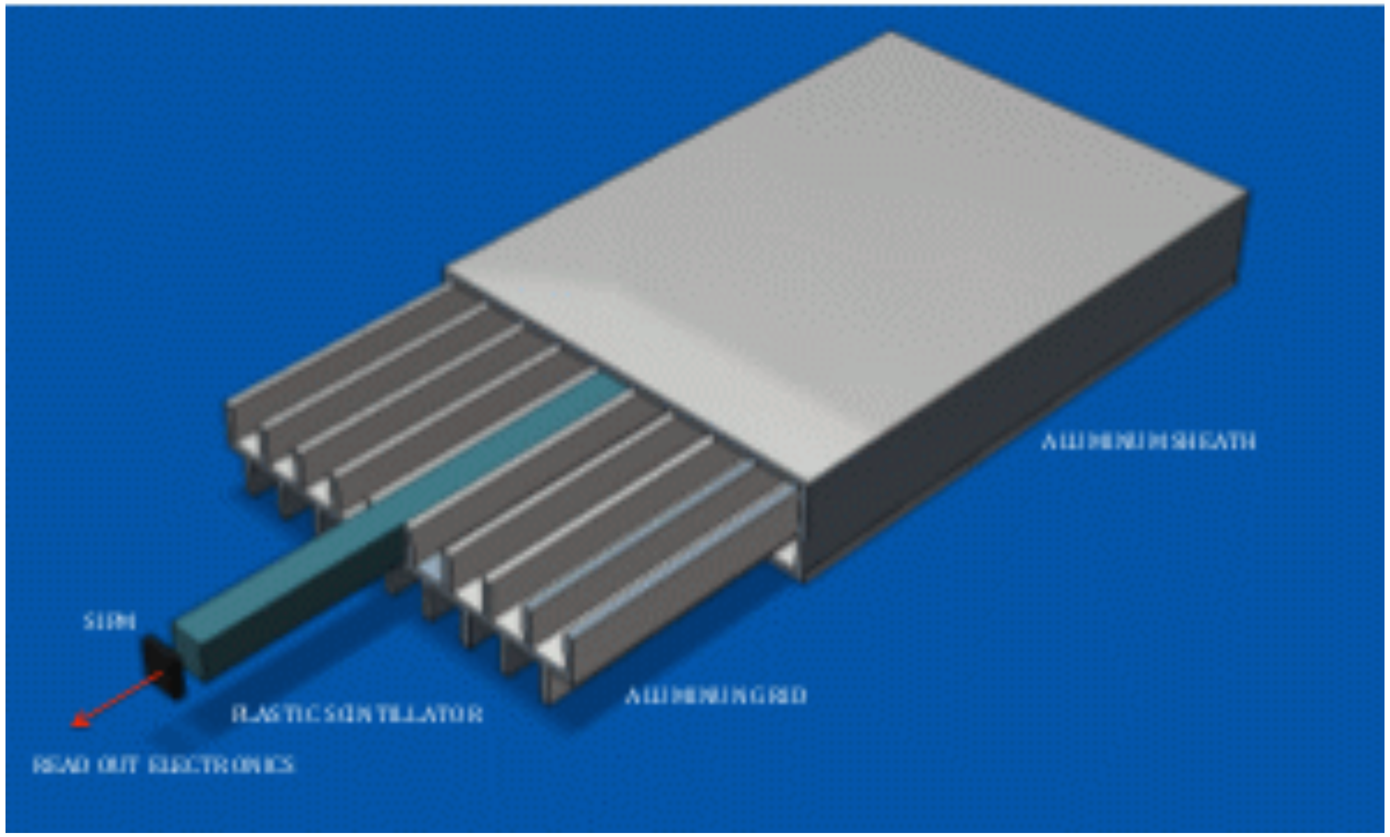


a more refined statistical analysis (a function to fit the data instead of using the mean of the distribution) can improve the resolution, if required

Building a demonstrator detector system

Features required for a muon detector

- ✓ stability, robustness and long life
- ✓ simplicity of usage (no HV, no gas)
- ✓ low construction cost, low operating cost
- ✓ compactness and stand-alone capability
- ✓ reasonable spatial resolution
- ✓ use of standard techniques



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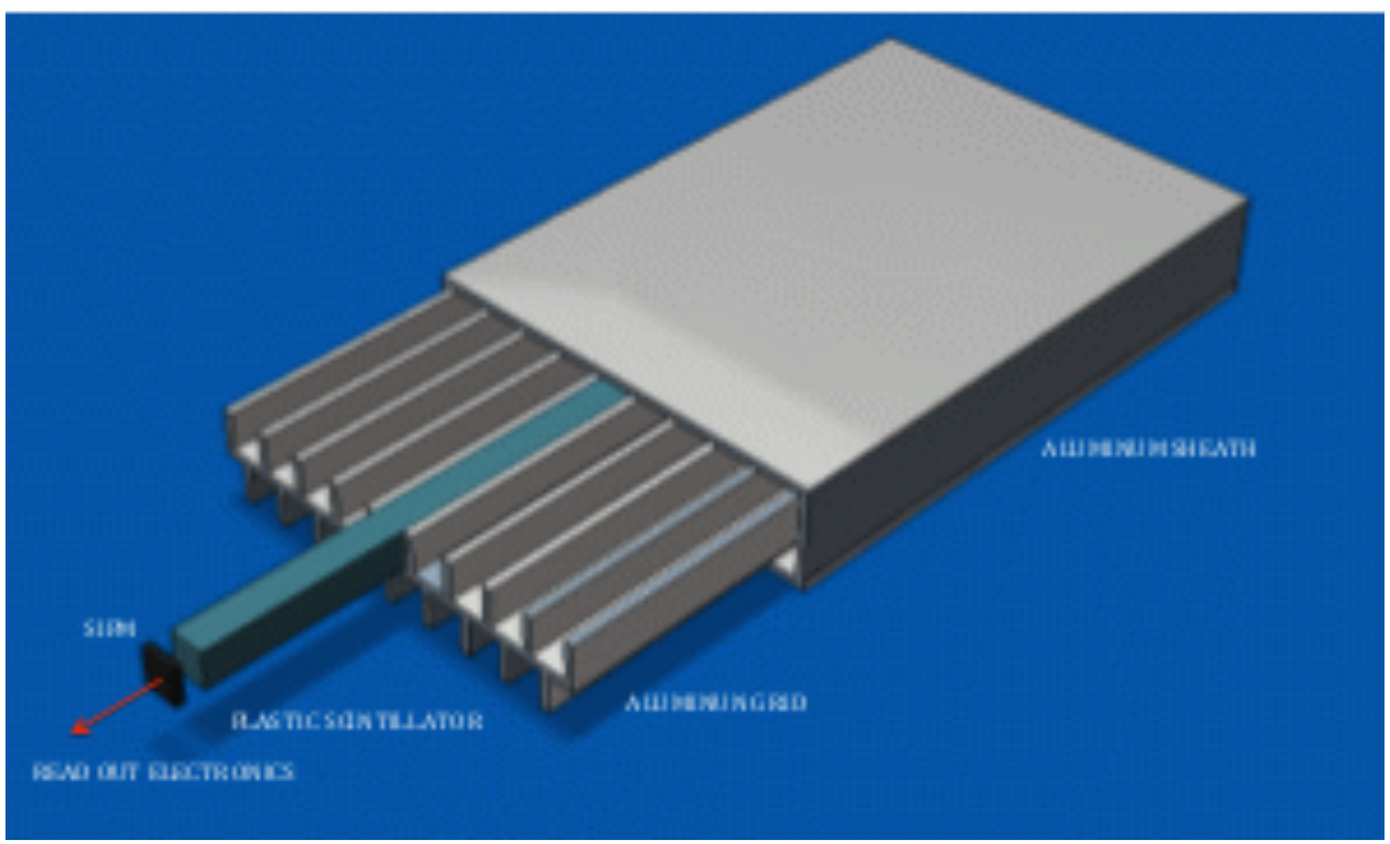
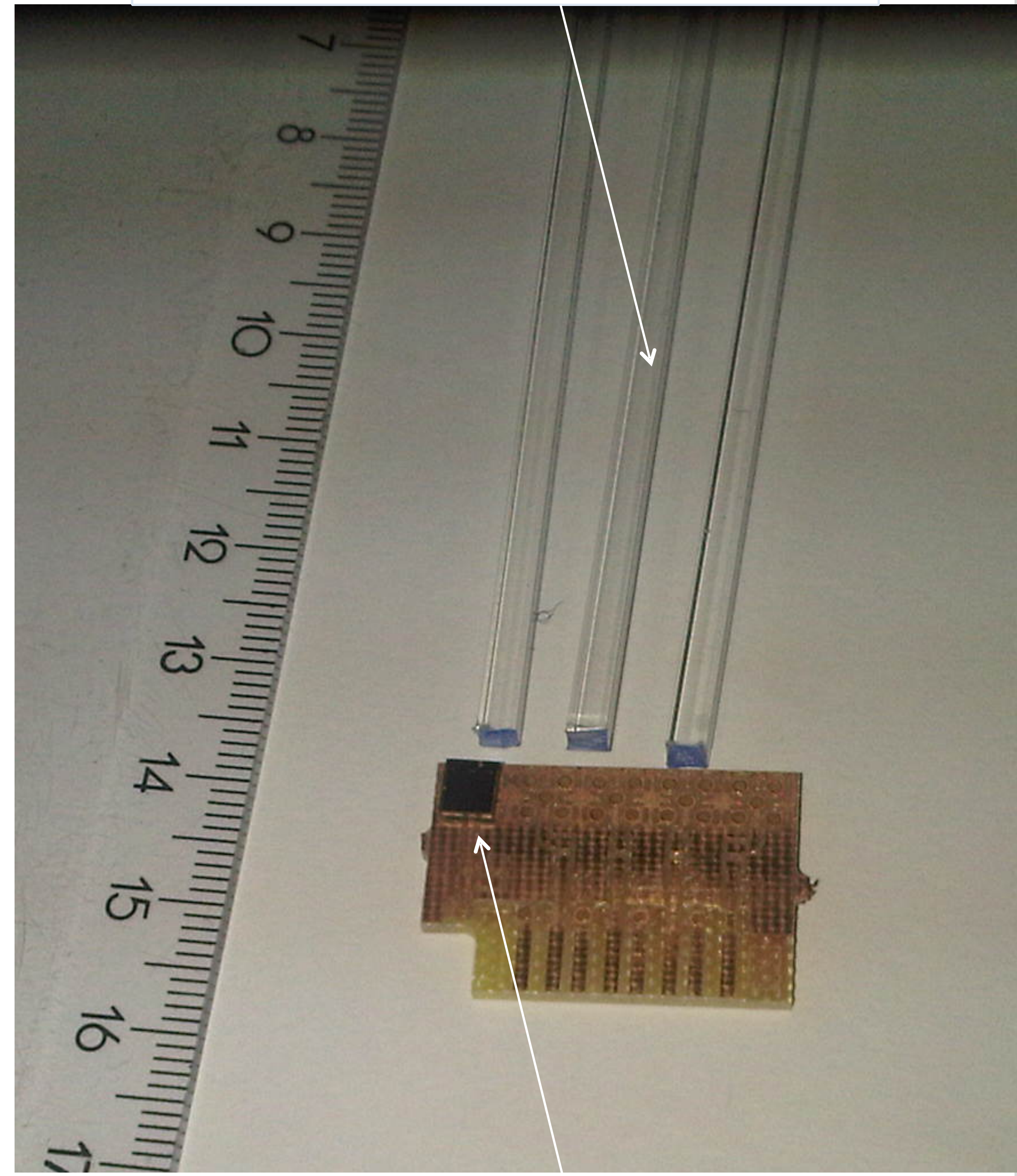
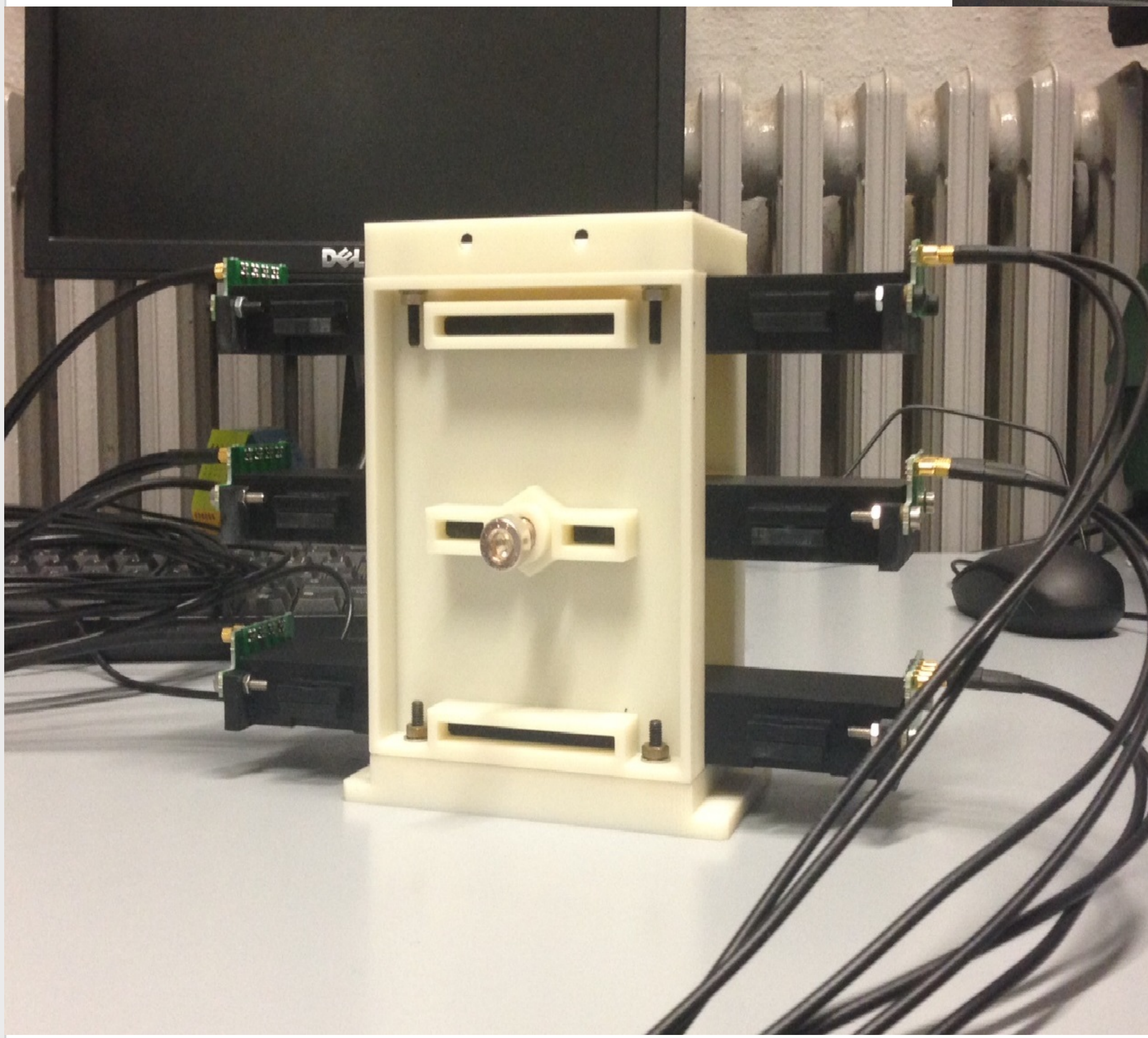


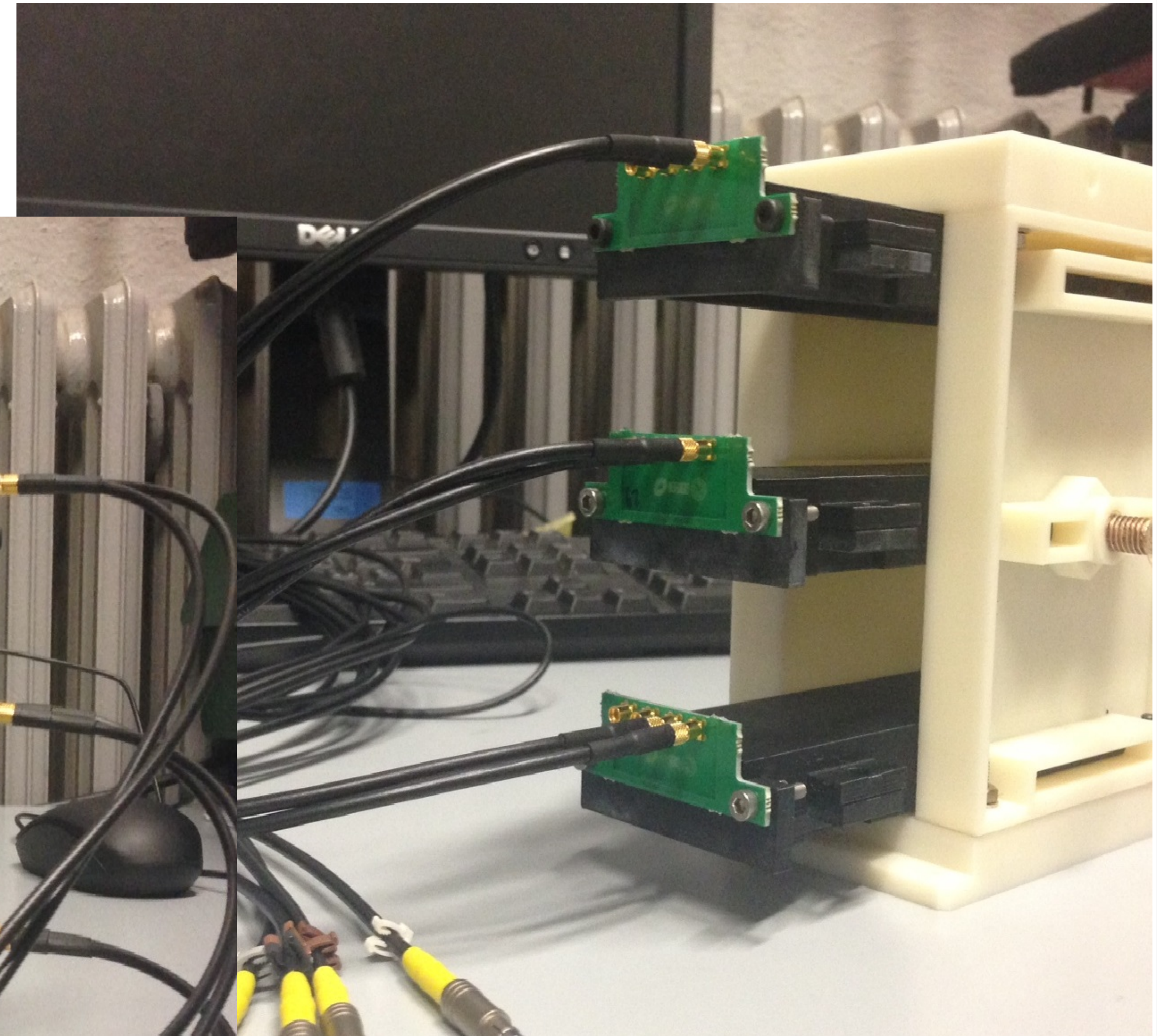
Scintillating fibers 3mm x 3 mm



Silicon Photomultipliers SiPM
MPPC 3mm x 3mm

Building a demonstrator detector system





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- both "transmission" and "scattering" effects of muons when crossing materials are used in various applications
  (inspections of large volumes such as volcanos and blast furnaces, geological inspections, monitoring of nuclear waste, detection of "hidden" nuclear materials, monitoring of stability, etc. etc.)

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- many applications are promising, one (Decision Sciences) seems not far away from being a "commercial product", others have demonstrated to work, others are in a demonstration stage … let's wait few more years …

Conclusions

- … as in many other fields of physics, the progress in research can generate applications for everyday life …

- the technology of nuclear and particle detectors, that has been used for decades in physics research, is now mature for civil applications

- specifically detectors for the muons, after a pioneering era (Alvarez and the pyramids), are now used in various applications

- both "transmission" and "scattering" effects of muons when crossing materials are used in various applications
(inspections of large volumes such as volcanos and blast furnaces, geological inspections, monitoring of nuclear waste, detection of "hidden" nuclear materials, monitoring of stability, etc. etc.)

- many applications are promising, one (Decision Sciences) seems not far away from being a "commercial product", others have demonstrated to work, others are in a demonstration stage … let's wait few more years …

Thank you for your attention

Spares

The Mu-Steel project: efficiency vs false alarms

Efficiency/Inefficiency: How many trucks **with a source shield** will (not) trigger an alarm?

False alarms: How many trucks **without a source shield** will trigger an alarm?

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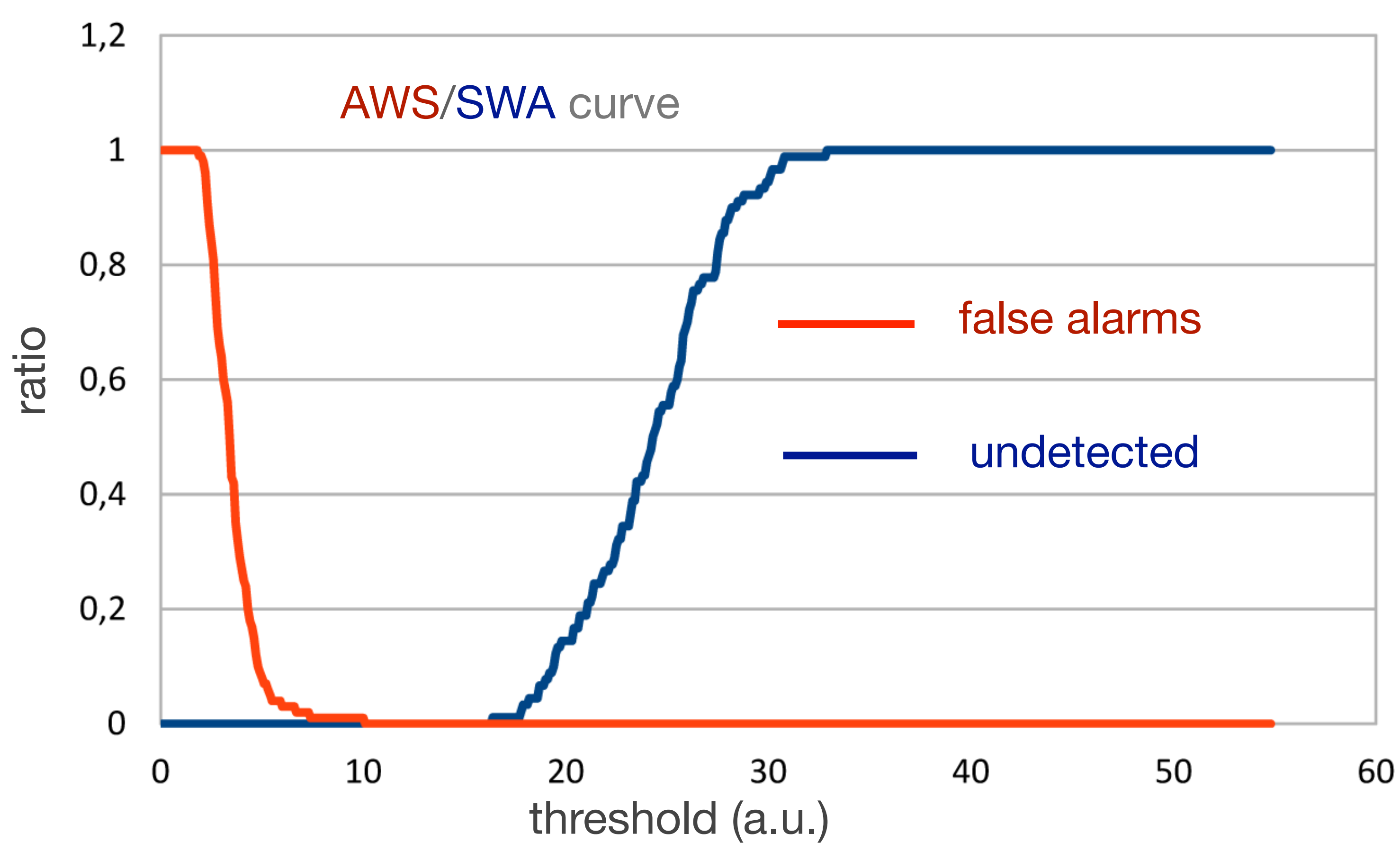

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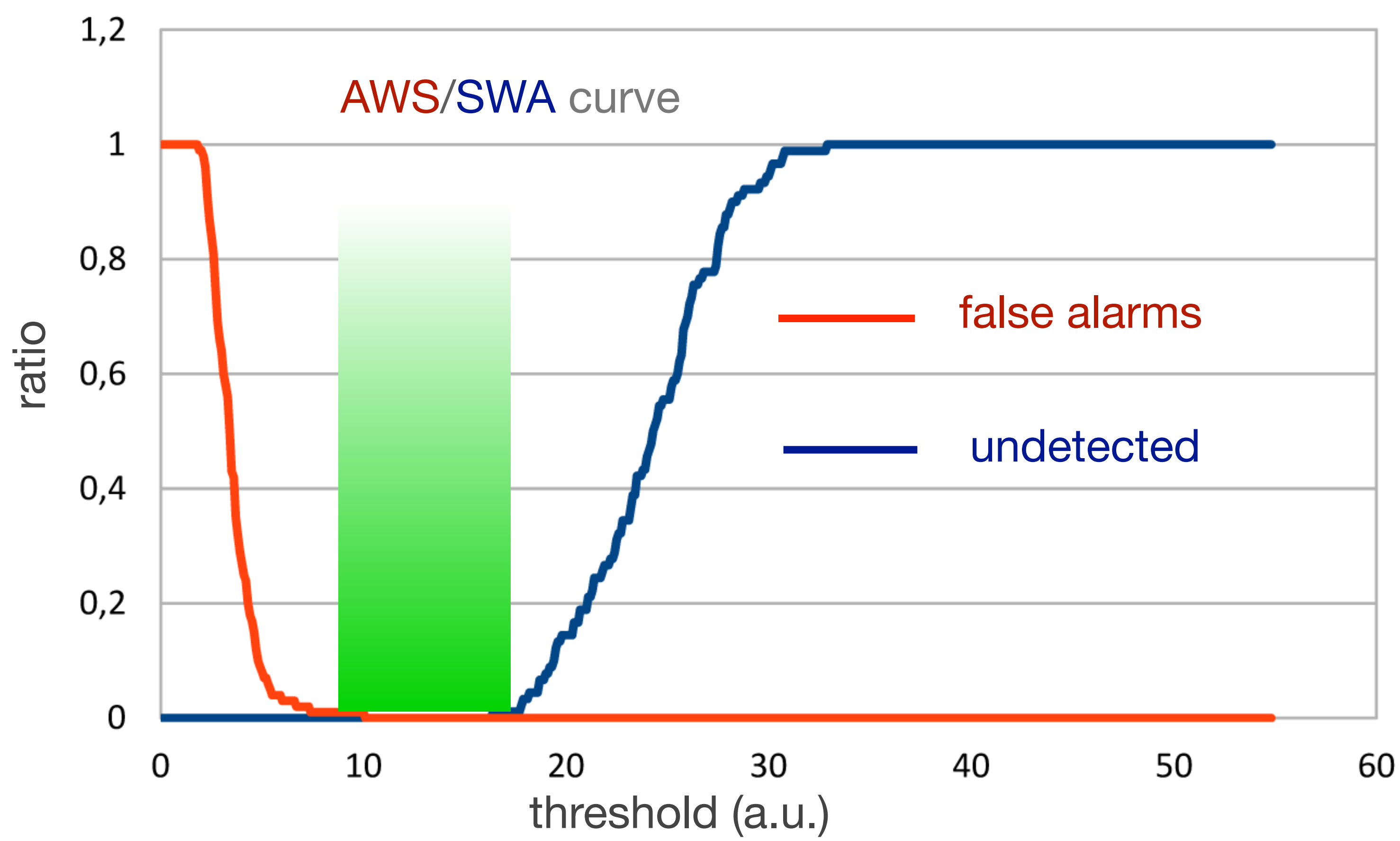
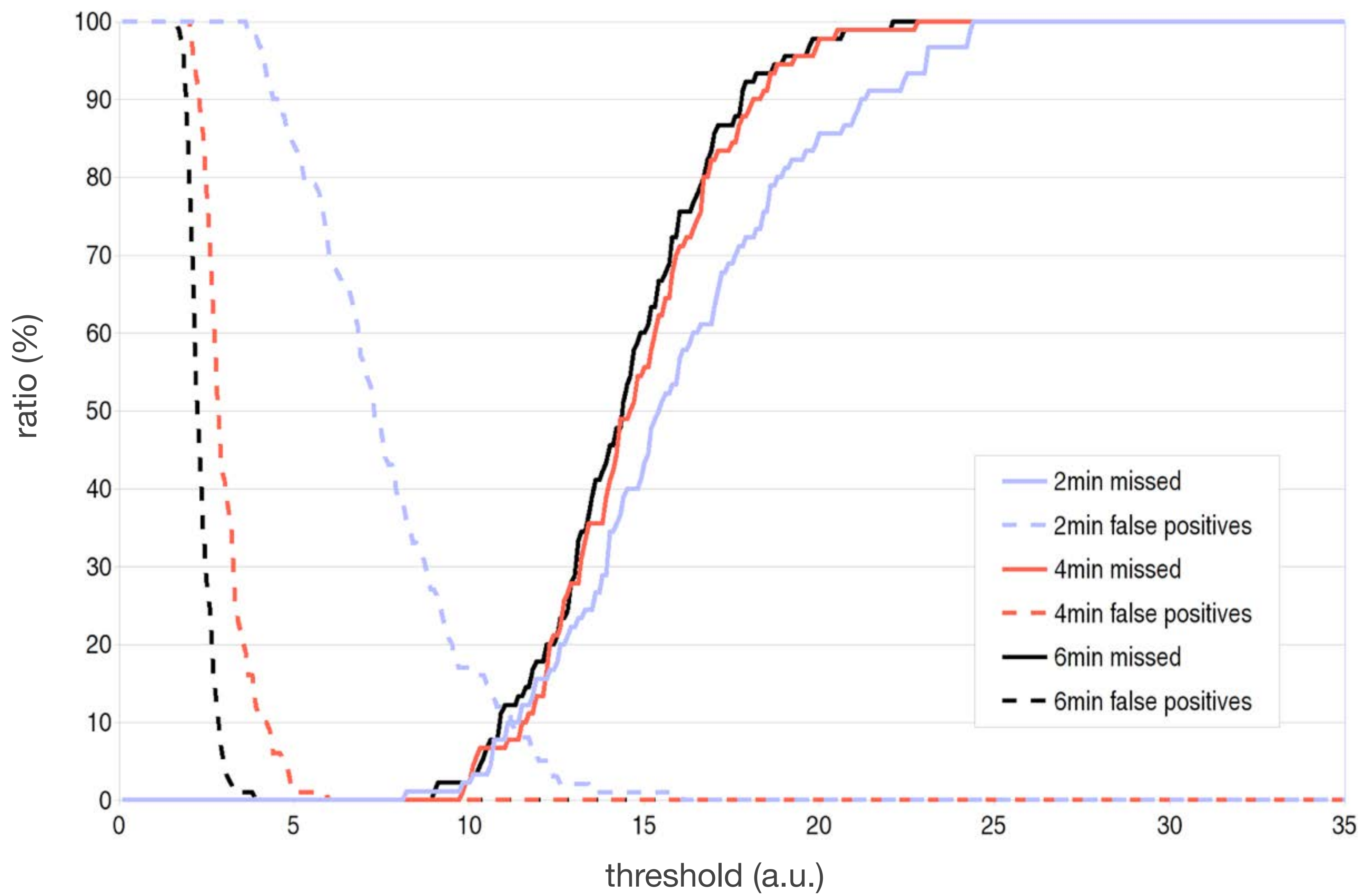


when both curves are zero
it means 100% efficiency
and 0% false alarms

The Mu-Steel project: efficiency vs false alarms

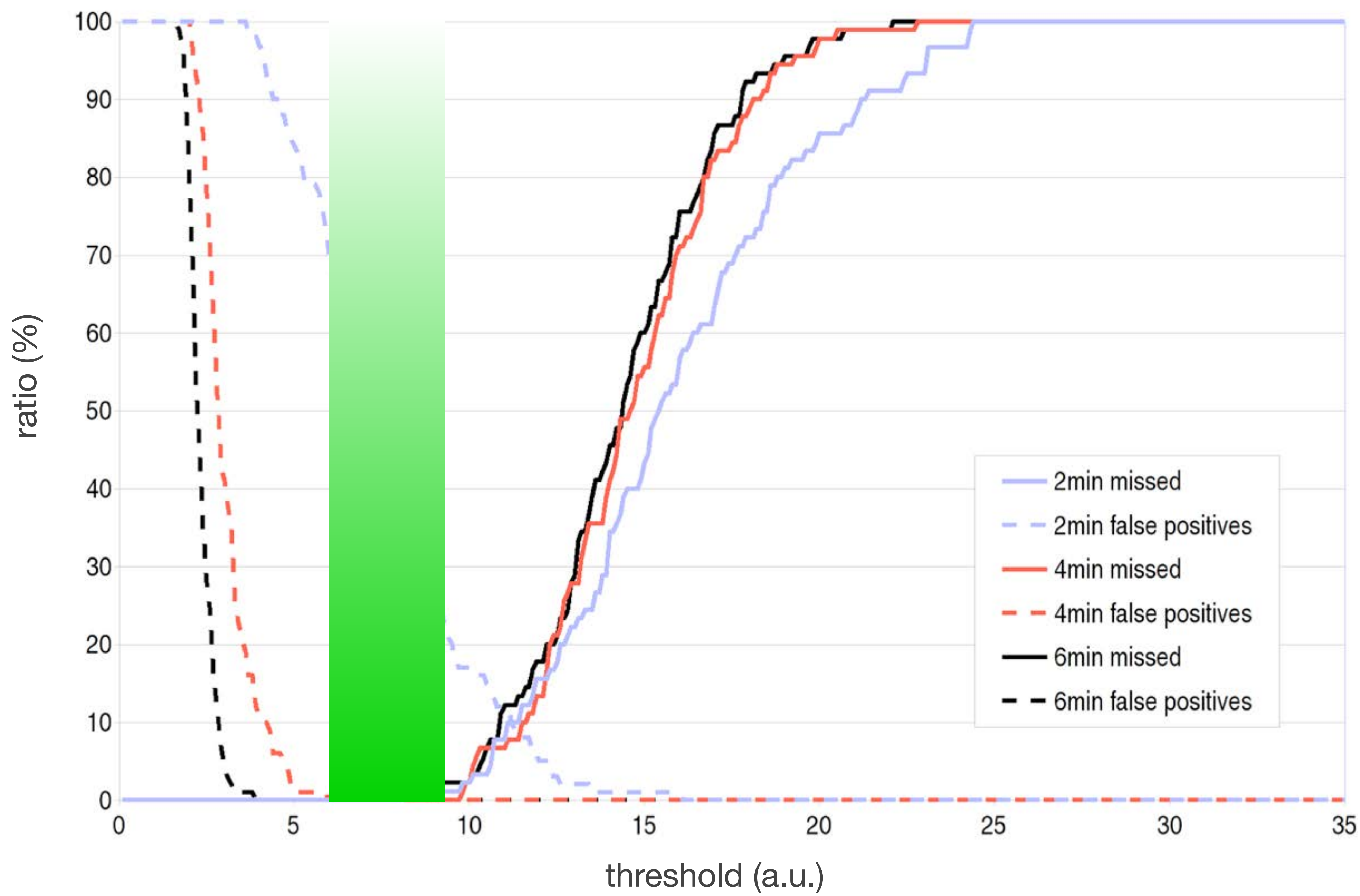
AWS/SWA curve



5 liters source shield (17x17x17 cm^3) is detected in 4 minutes with 100% efficiency and 0% false alarms

The Mu-Steel project: efficiency vs false alarms

AWS/SWA curve



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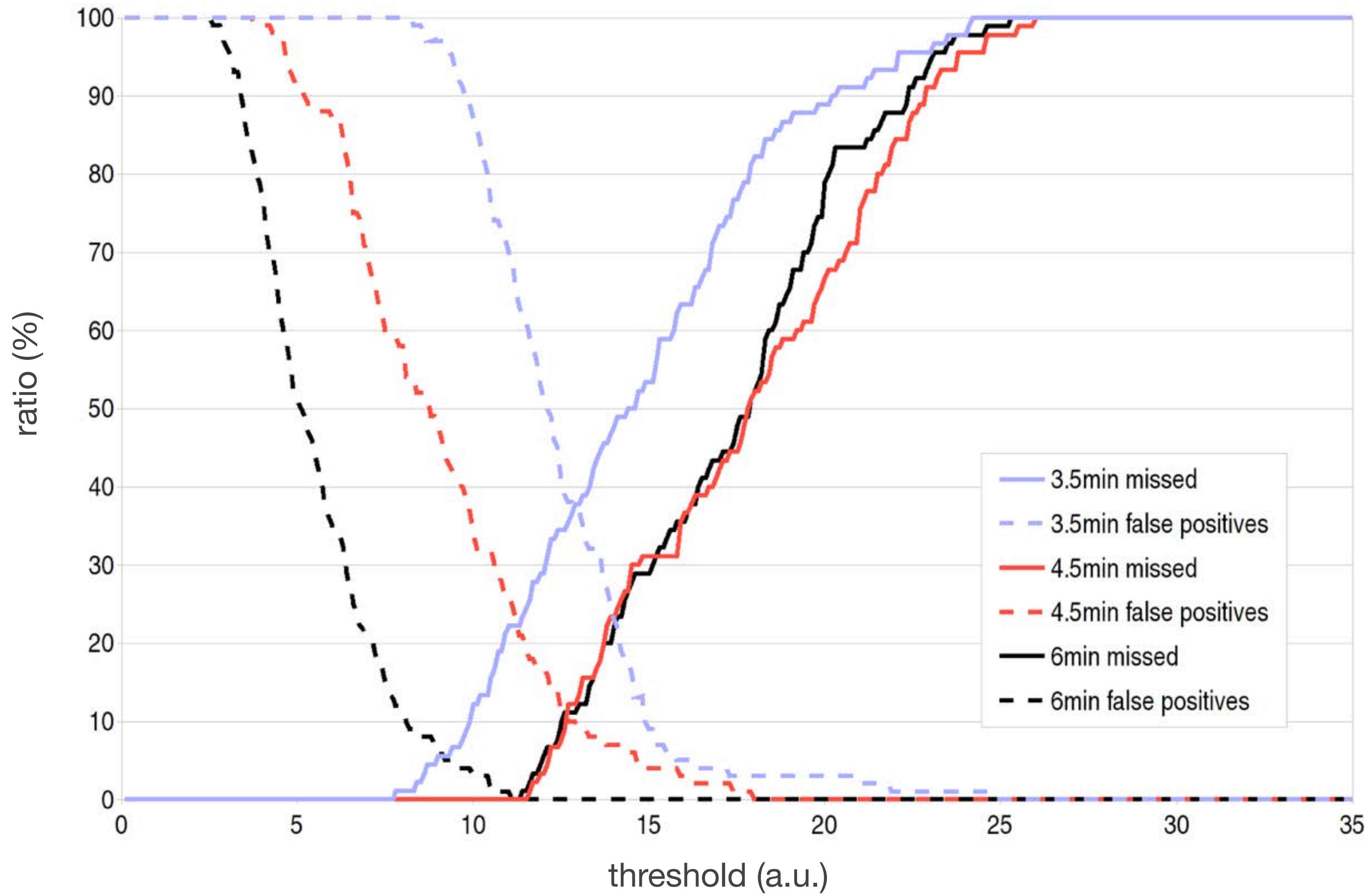

2 liters source shield (13x13x13 cm^3) is detected in 6-7 minutes with 100% efficiency and 0% false alarms

The Mu-Steel project: efficiency vs false alarms

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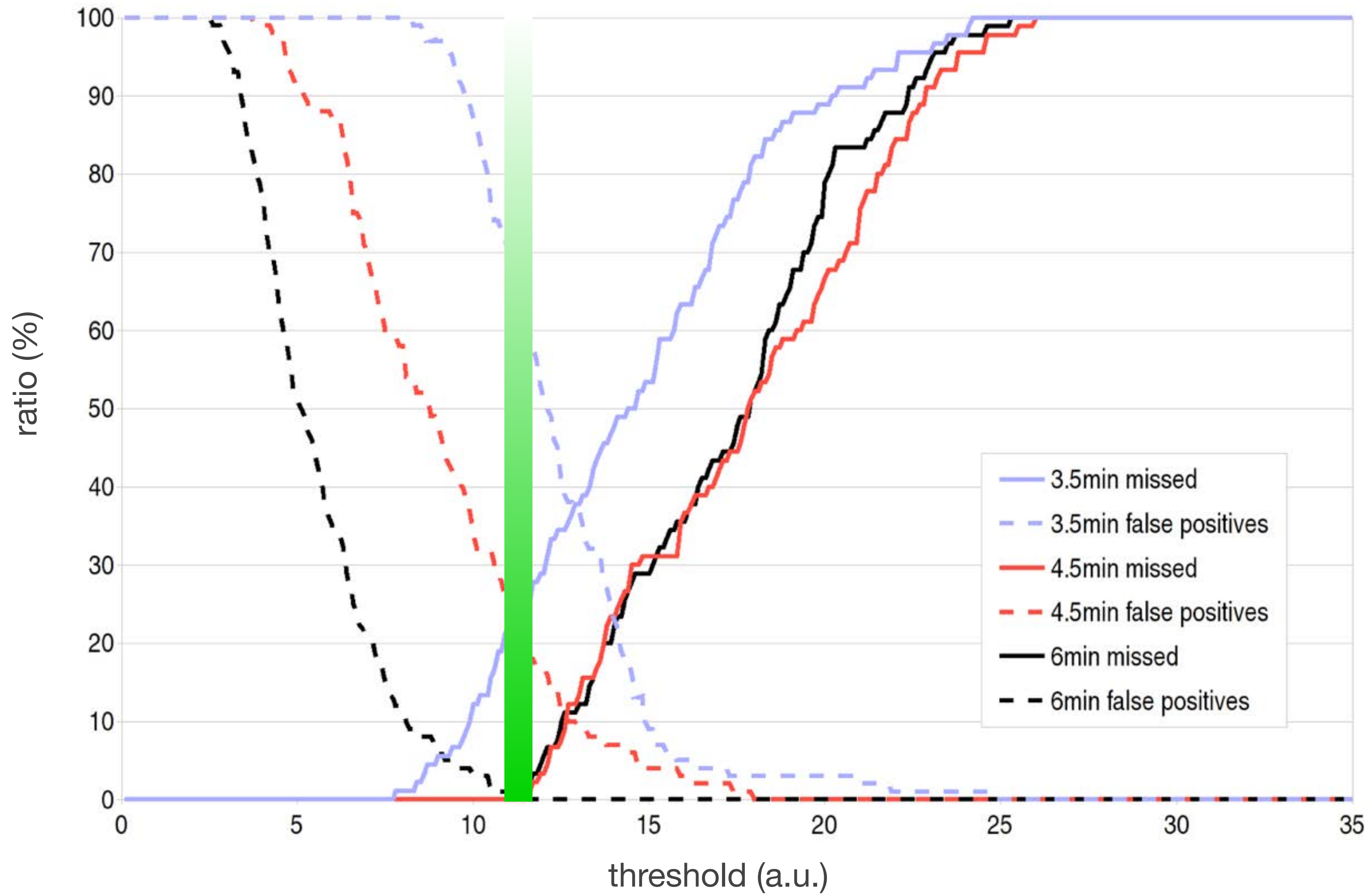

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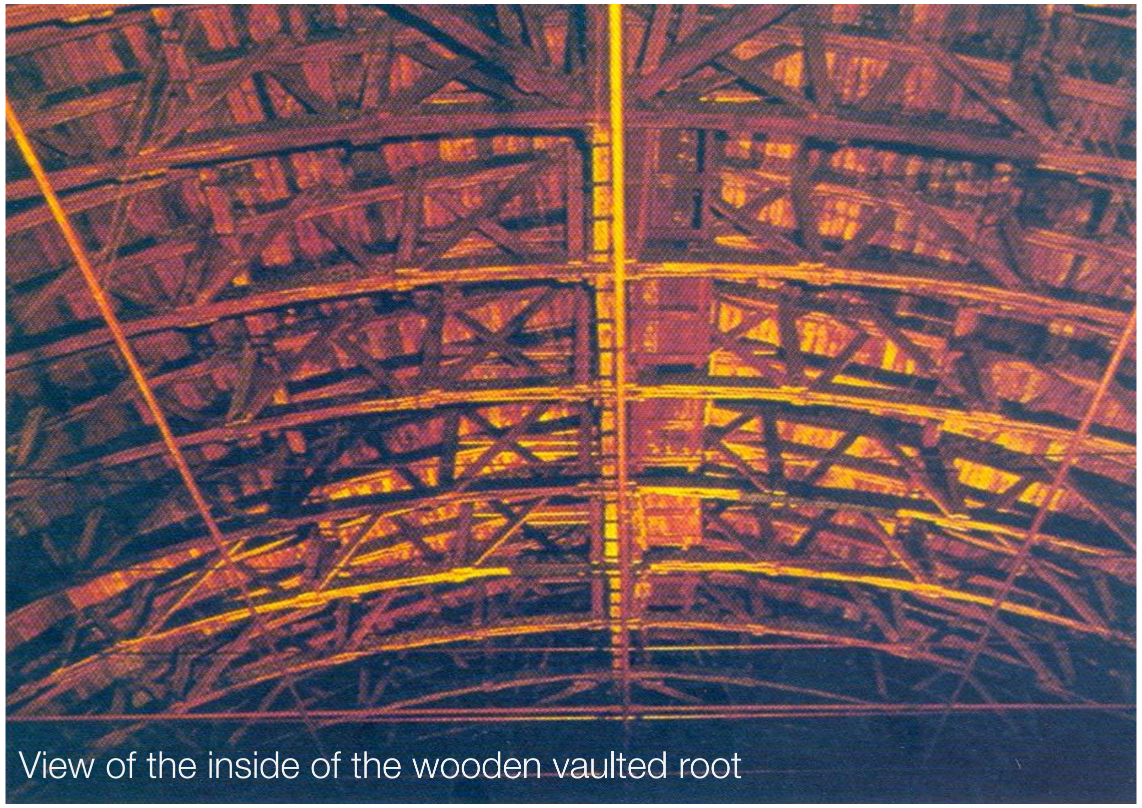
The problem of the Brescia "Palazzo della Loggia"


Construction of the actual roof, 1914
Brescia, Palazzo della Loggia, 1574


View of the inside of the wooden vaulted root


Details of a joint

Studies reported here have been performed by the
"Centro di studio e ricerca per la conservazione ed il recupero dei beni architettonici ed ambientali"
Dipartimento di Ingegneria Civile, University of Brescia

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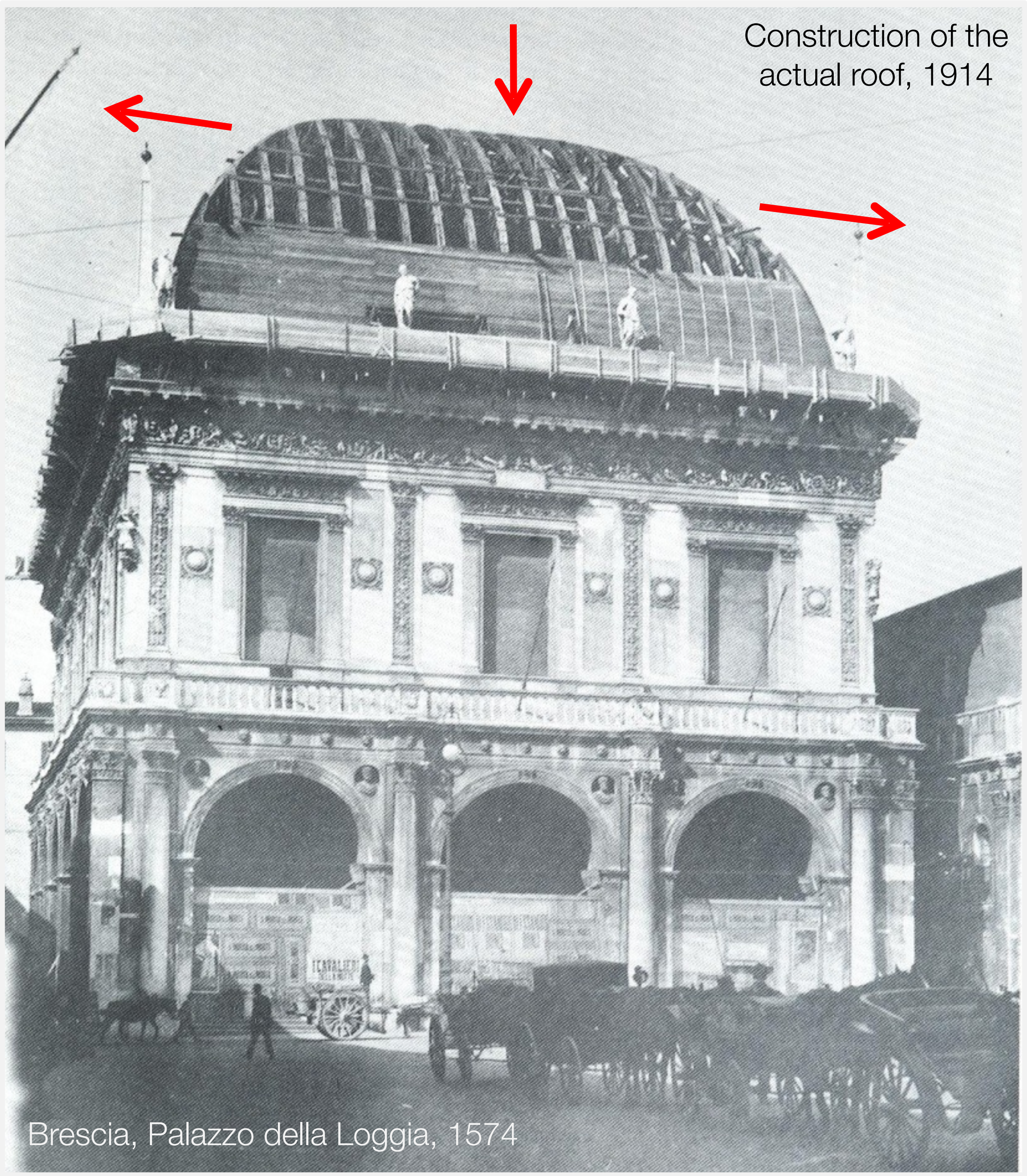
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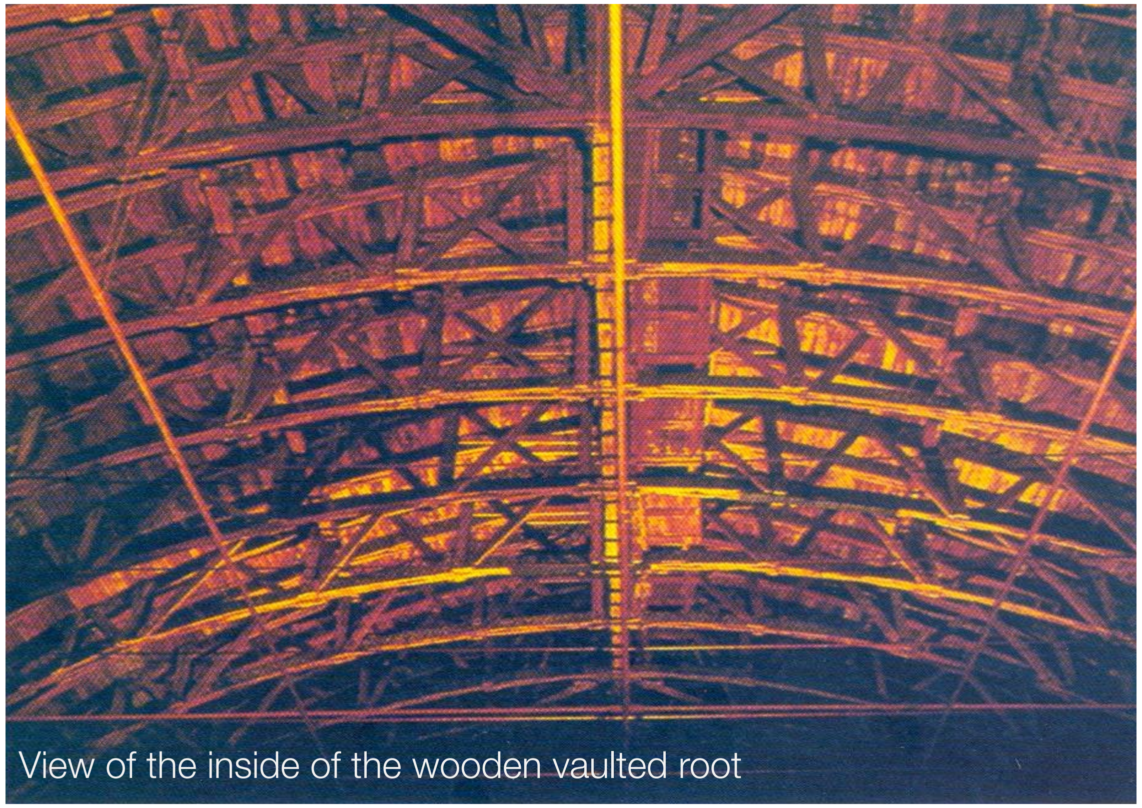
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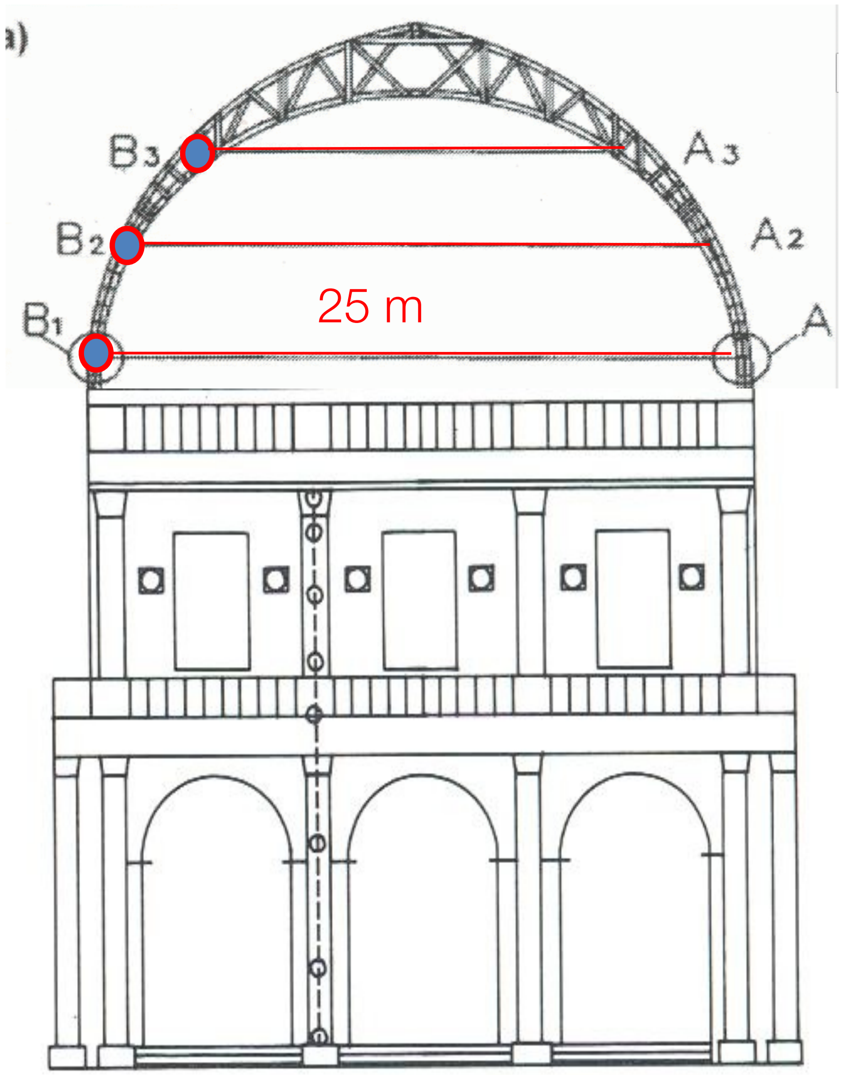
The monitoring campaign of the "Palazzo" (1990-2001)



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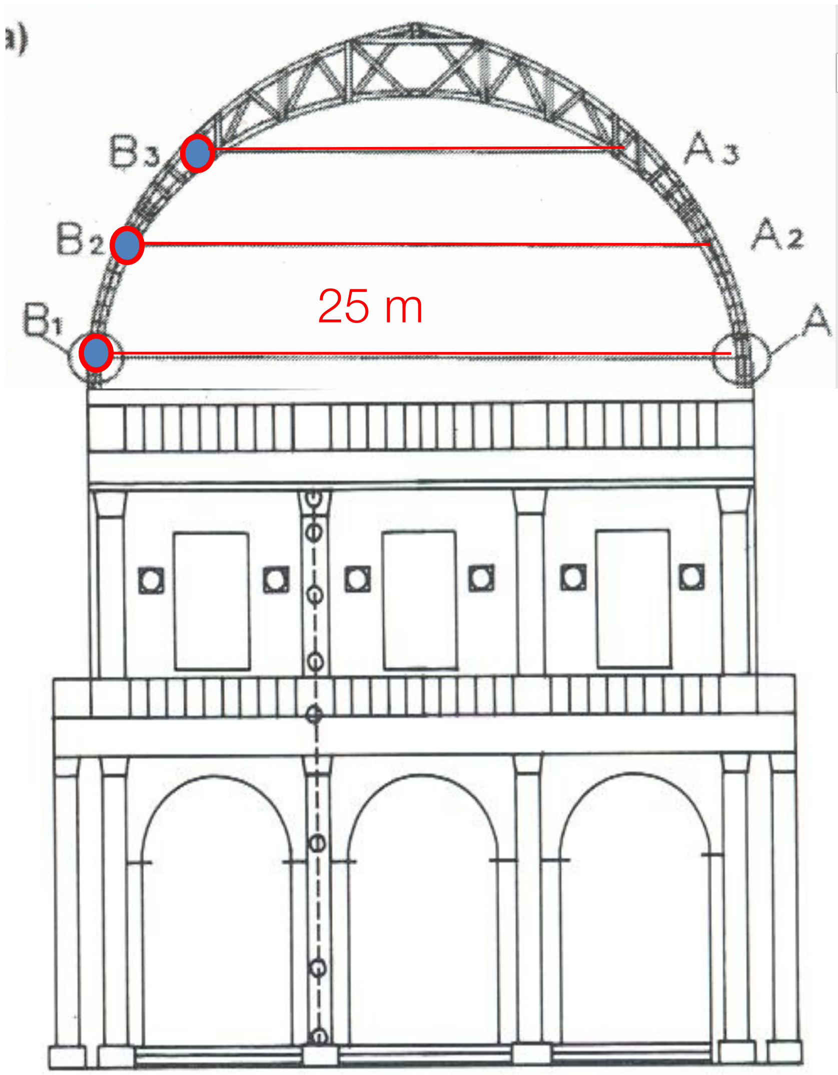
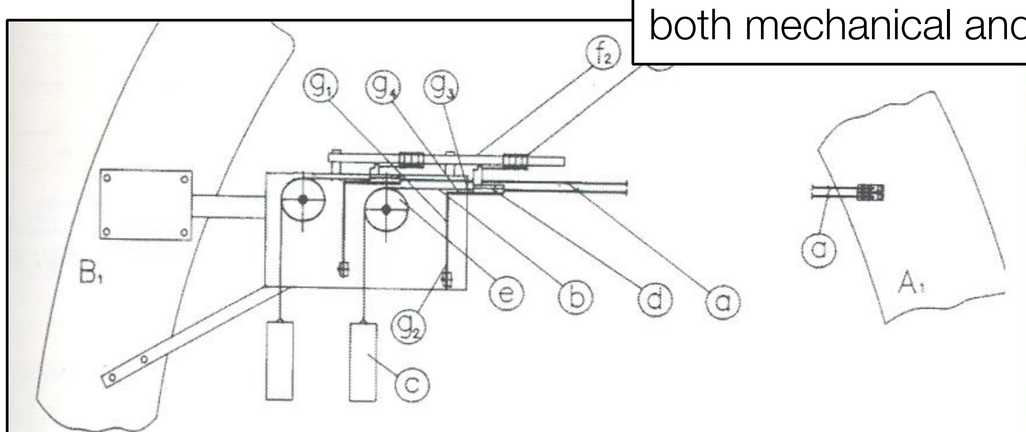
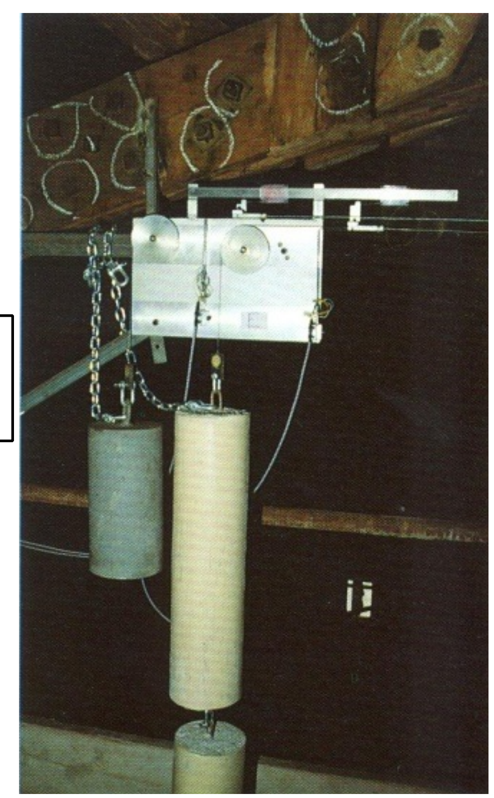


Sensors consisted in a couple of wires of invar (nickel-iron alloy) and steel to compensate for thermic variations

Measurement of elongation both mechanical and electronic





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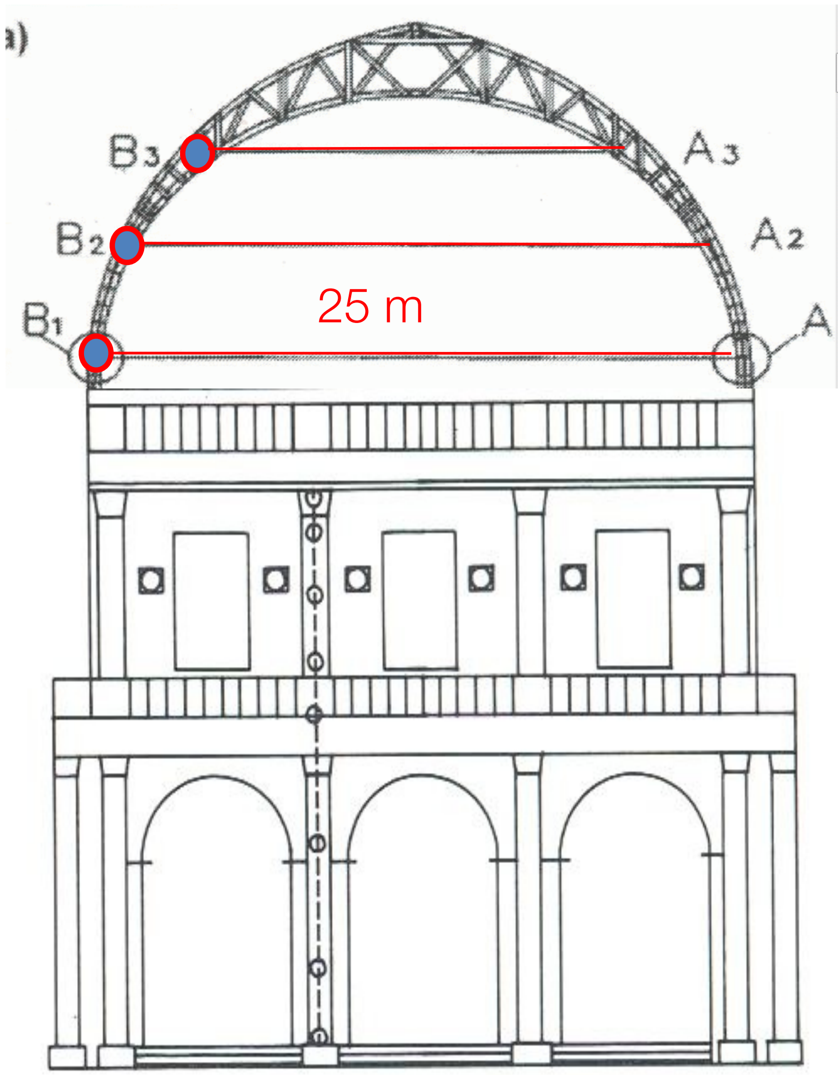

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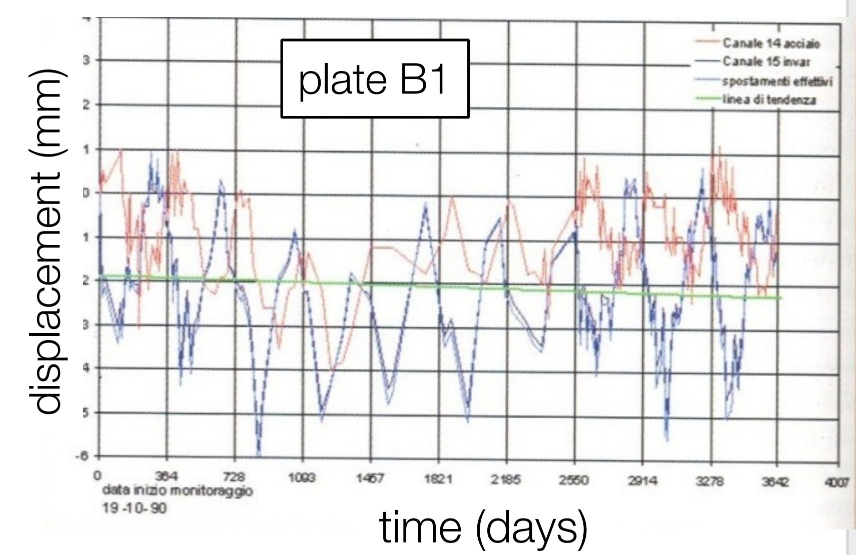
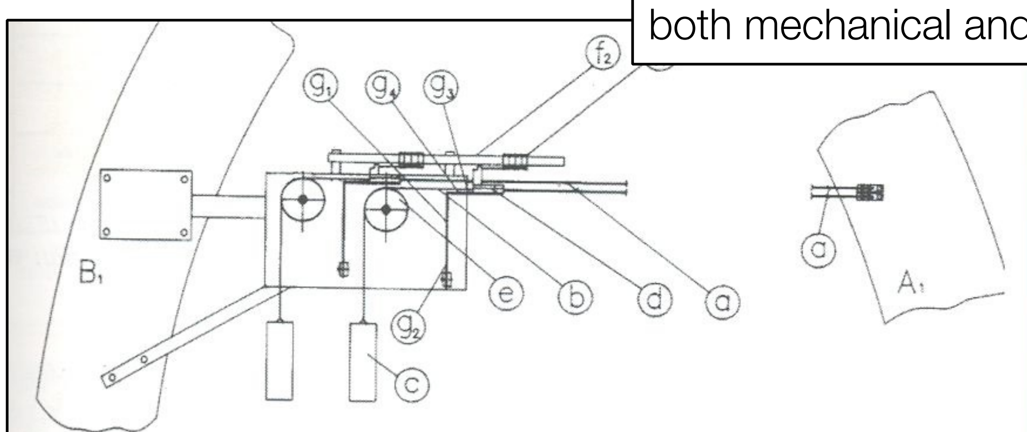
11 years





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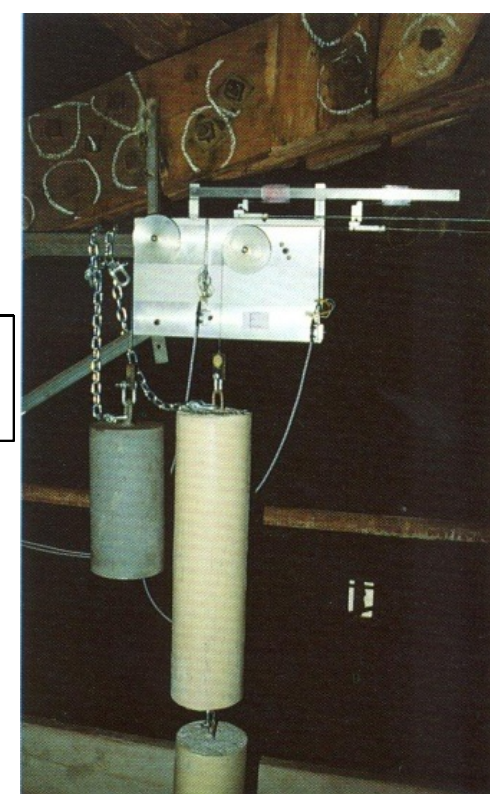
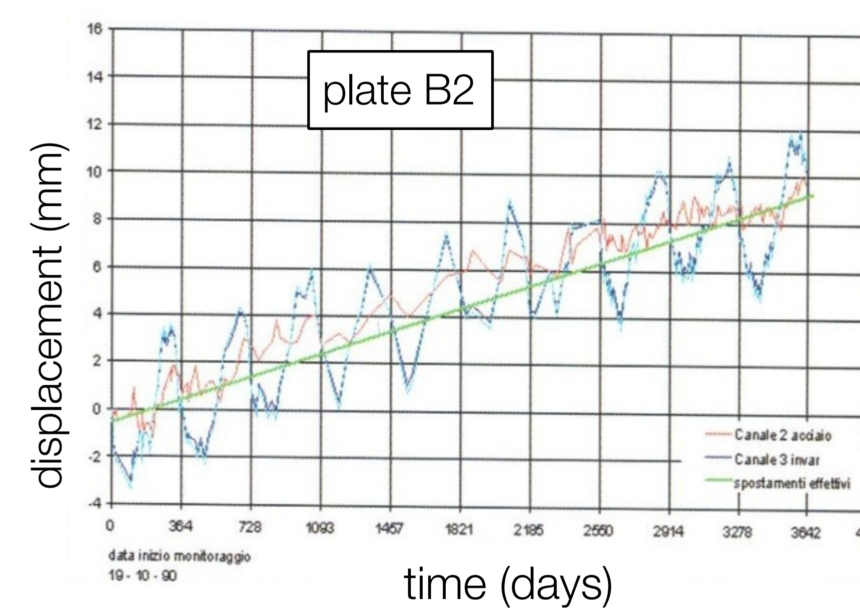
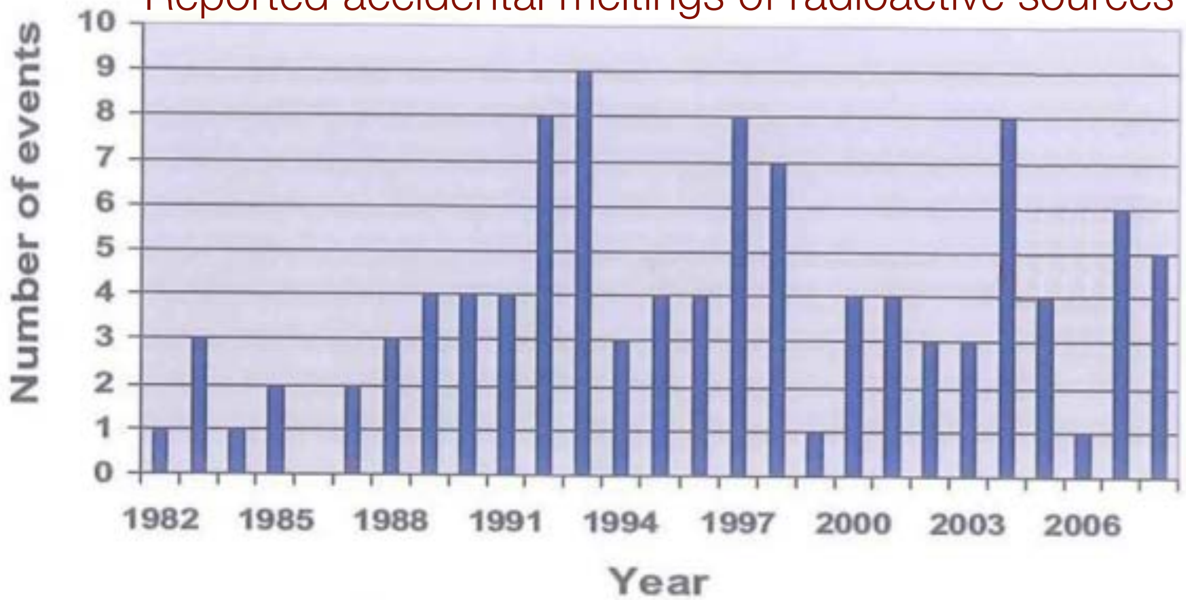




The problem of hidden (orphan) radioactive sources

Reported accidental meltings of radioactive sources



Accidental Meltings of Radioactive Materials in the USA

Year	Metal	Location	Isotope	Activity *(GBq)*
multiple	gold	multiple	Pb-210, Bi-210 Po-210	unknown
1983	steel	Auburn Steel, NY	Co-60	930
1983	gold	unknown, NY	Am-241	unknown
1984	steel	U.S. Pipe & Foundry, AL	Cs-137	0.37-1.9
1985	steel	Tamco, CA	Cs-137	56
1987	steel	Florida Steel, FL	Cs-137	0.93
1987	aluminum	United Technology, IN	Ra-226	0.74
1988	lead	ALCO Pacific, CA	Cs-137	0.74-0.93
1988	copper	Warrington, MO	accelerator	unknown
1989	steel	Bayou Steel, LA	Cs-137	19
1989	steel	Cytemp. PA	Th	unknown
1990	steel	NUCOR Steel, UT	Cs-137	unknown
1991	aluminum	Alcan Recycling, TN	Th	unknown
1992	steel	Newport Steel, KY	Cs-137	12
1992	aluminum	Reynolds, VA	Ra-226	unknown
1992	steel	Border Steel, TX	Cs-137	4.6-7.4
1992	steel	Keystone Wire, IL	Cs-137	unknown
1993	steel	Auburn Steel. NY	Cs-137	37
1993	steel	Newport Steel, KY	Cs-137	7.4
1993	steel	Chaparral Steel, TX	Cs-137	unknown
1993	zinc	Southern Zinc, GA	depleted U	unknown
1993	steel	Florida Steel, FL	Cs-137	unknown
1994	steel	Austeel Lemont, IL	Cs-137	0.074
1994	steel	US Pipe & Foundry, CA	Cs-137	unknown
1996	aluminum	Bluegrass Recycling, KY	Th-232	unknown
1997	aluminum	White Salvage Co., TN	Am-241	unknown
1997	sleel	WCI, OH	Co-60	0.9(?)
1997	steel	Kentucky Electric, KY	Cs-137	1.3
1997	steel	Birmingham Steel, AL	CS-137/Am-241	7 Bq/g
1997	steel	Bethlehem Steel, IN	Co-60	0.2
1998	aluminum	Southern Aluminum, AL	Th	unknown

Note: Table is compiled from database maintained by James Yusko, CHP, Pennsylvania Dept. of Environmental Protection, 400 Waterfront Drive, Pittsburgh, PA, 15222-4745, USA.

example of two shielded sources

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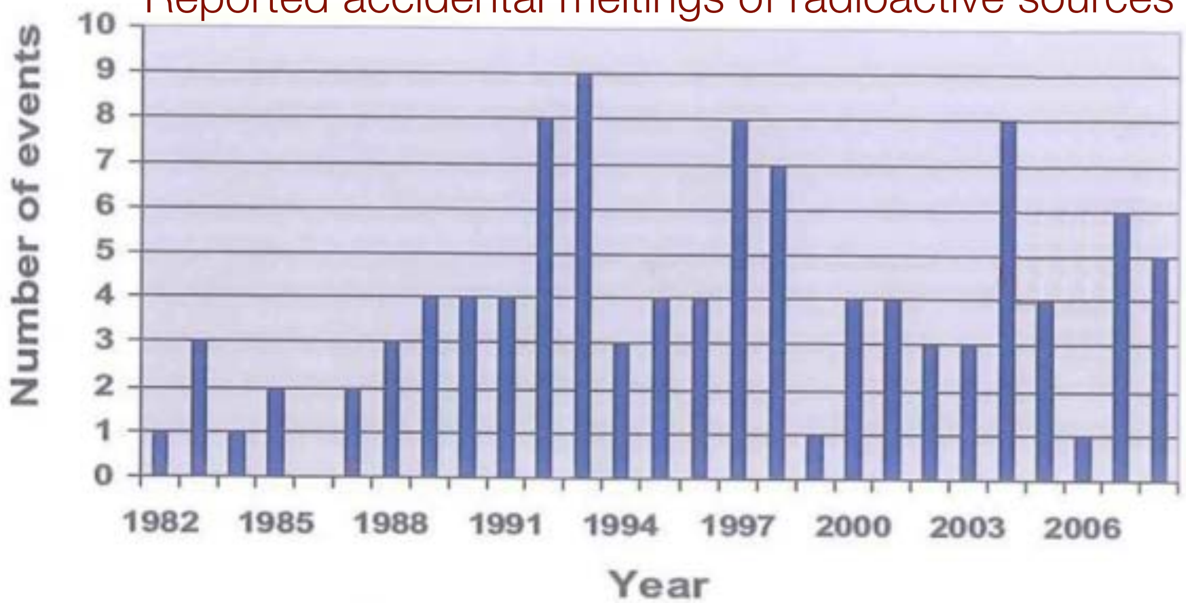

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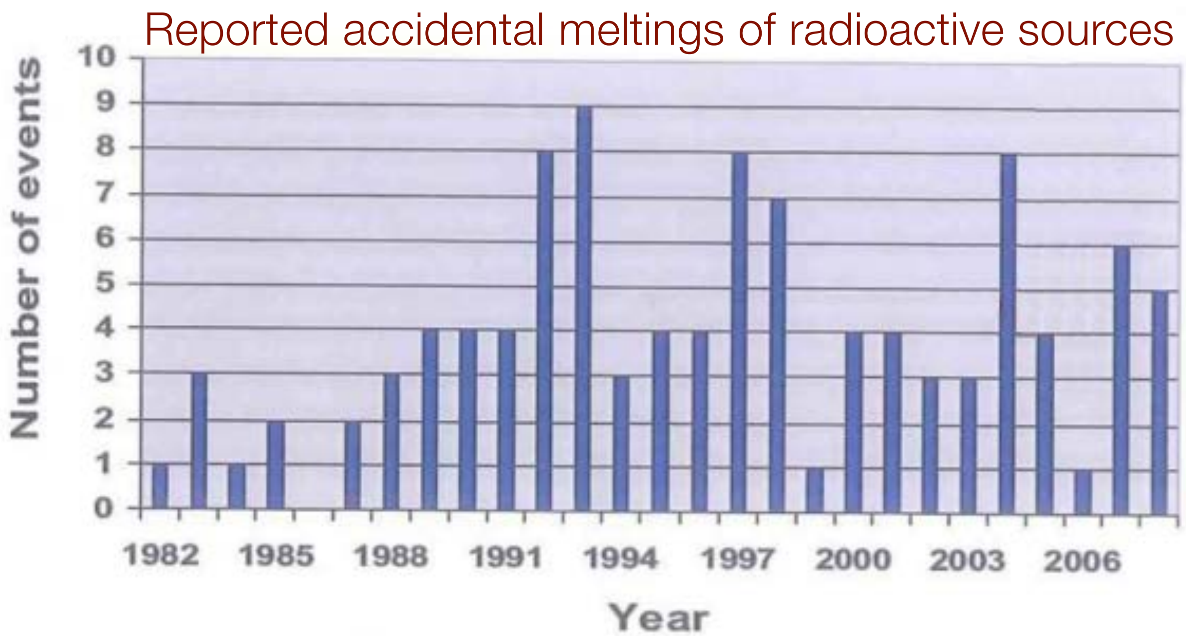
example of two shielded sources

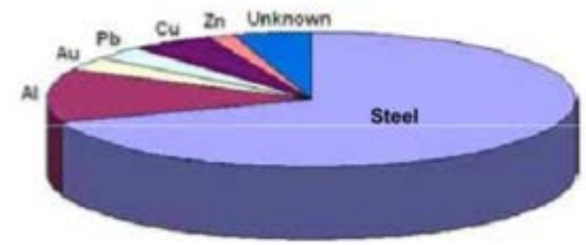
Huge environmental and economical impact

- radioactive contamination of workers, buildings, neighborhood, production lines, materials, etc. etc.

- huge costs for the company
  disposal of contaminated materials
  decontamination of environment
  decontamination of products
  decontamination of production lines
  few weeks of production stand-by
  lost of orders
  etc. etc.
  .... many millions (be it in € or in $)

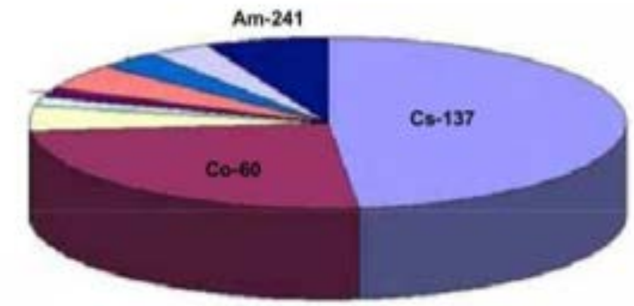
The problem of hidden (orphan) radioactive sources





Meltings by metal (80% steel)

Meltings by radioactive element (mostly Co-60, Cs-137)



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