A Cosmic Rays Tracking System for the Stability Monitoring of Historical Buildings

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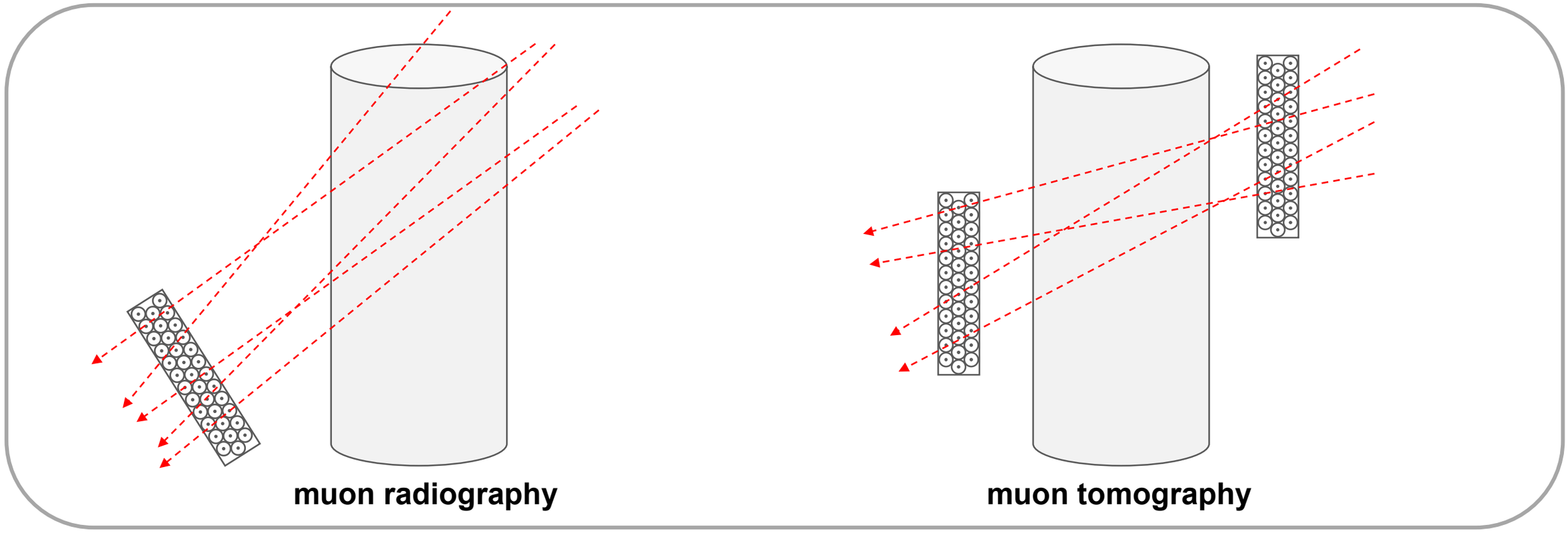
- cosmic ray applications
- stability monitoring
- palazzo della loggia (case)
- small scale prototype
- final remarks

USAGE OF COSMIC RAYS (muons) FOR CIVIL APPLICATIONS



Muon civil applications: muon radiography and tomography

Muon radiography ("**greyscale**" images)
Measure the number of muons surviving the passage through the material, obtaining images the same way as in traditional x-ray radiographies.

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]**

1970: muon radiography of the pyramid of Chefren

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

Muon tomography ("**color**" images) **[2-4]**
Measure the deflection of the muons when crossing a volume: through a sophisticated software, 3D images of the objects inside the volume can be obtained (geometry and "density").

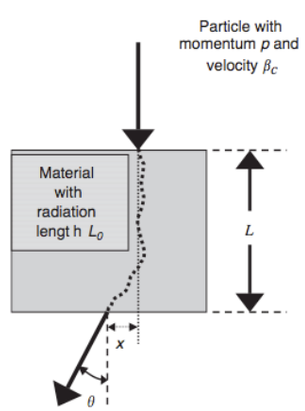


Fig. 1. Multiple Coulomb scattering of a charged particle through material. The magnitude of scattering is exaggerated for illustrative purposes.

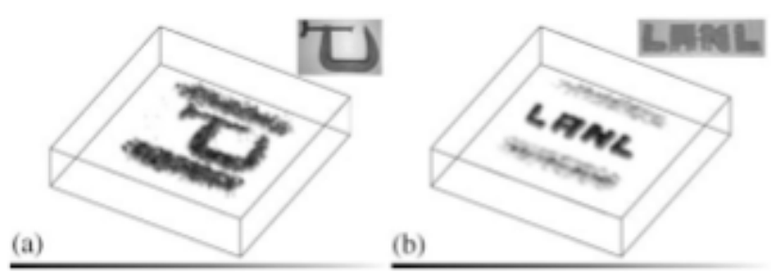


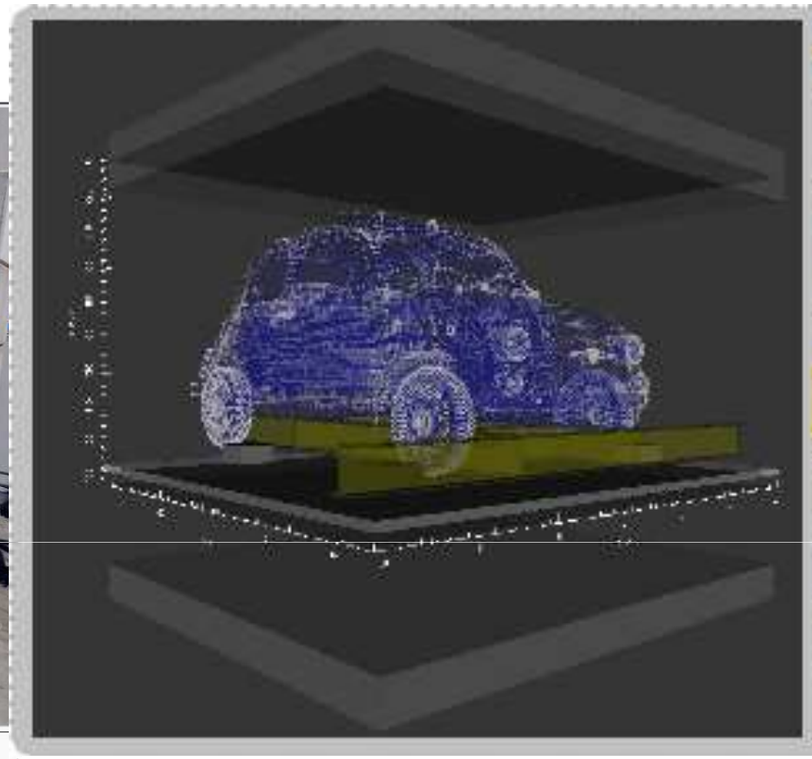
Fig. 5. Experimentally produced cosmic ray muon radiographs of (a) a steel c-clamp, and (b) "LANL" constructed from 1″ lead stock. The bar-like features result from steel beams used to support a plastic object platform.

First experimental demonstration

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

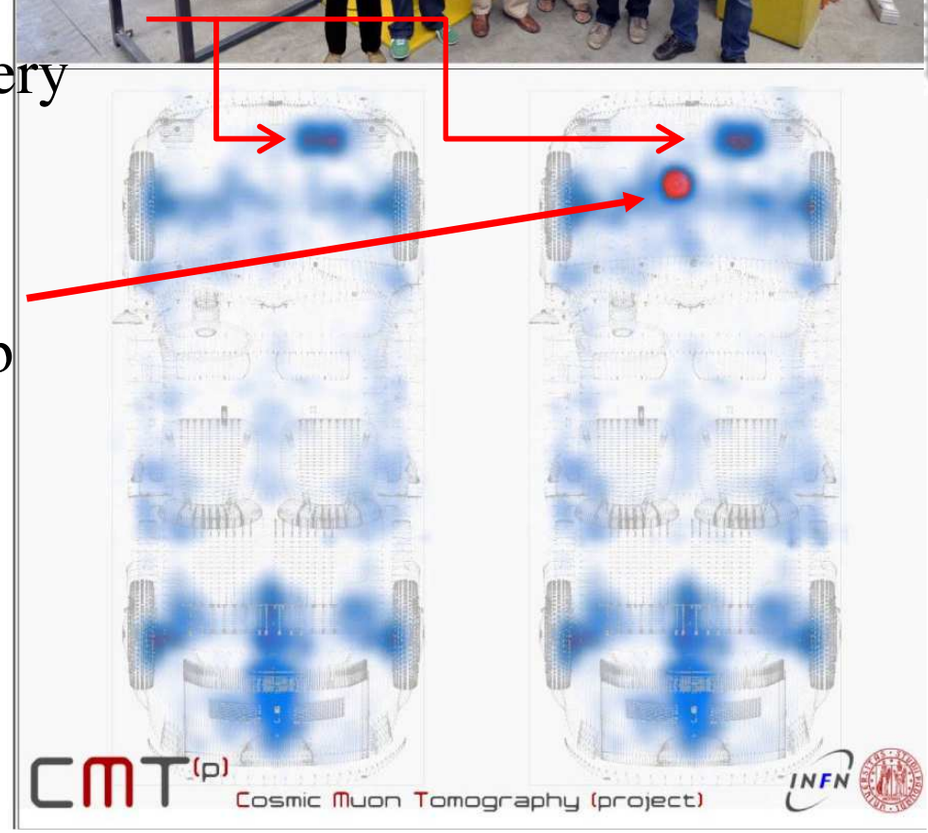
Muon civil applications: muon tomography

A tomographic image of an original FIAT “500”!



Battery

11 Pb



First results

Nuclear Instruments and Methods in Physics Research A 604 (2009) 738–746

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]

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

Muon civil applications: areas of interest

- **security/safety**
  border and port controls, nuclear waste/spent fuel …

- **industry**
  steel foundries (gate truck controls), steel mill inspections …

- **environment**
  volcanos monitoring, geophysical inspections (*see next talk by Oláh*), …

Blast furnace

Can such a huge construction be inspected with cosmic ray muons?

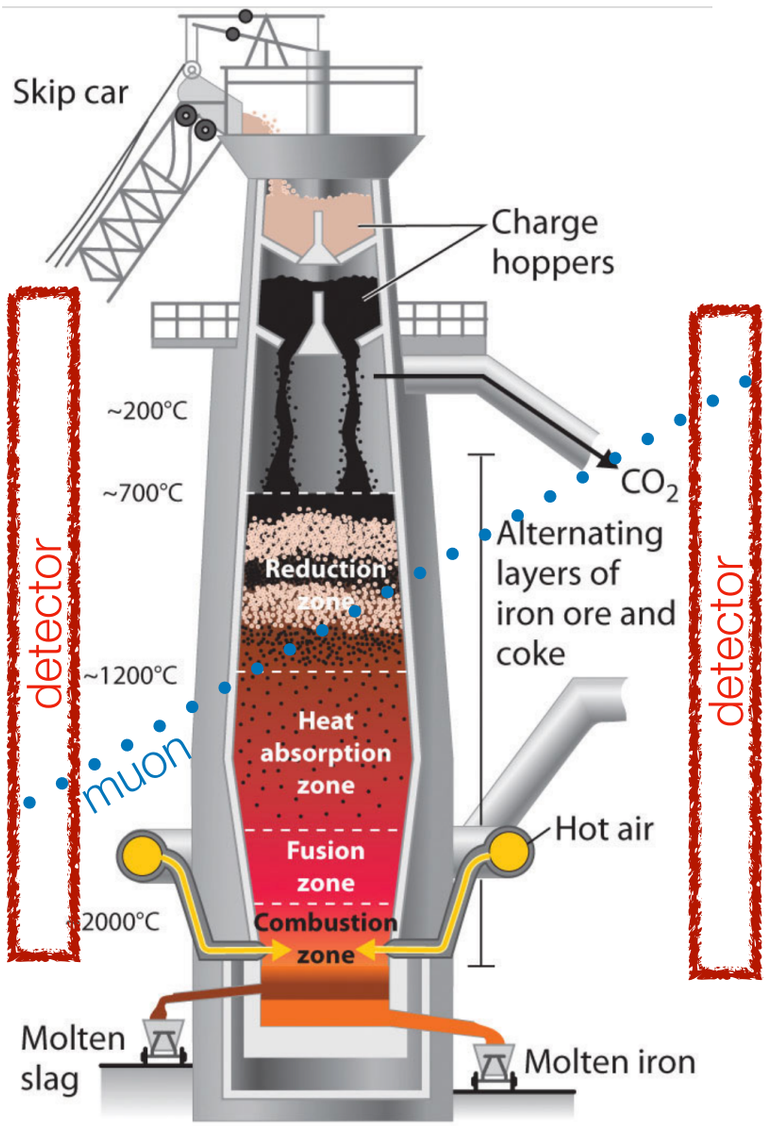
Muon civil applications: blust furnace

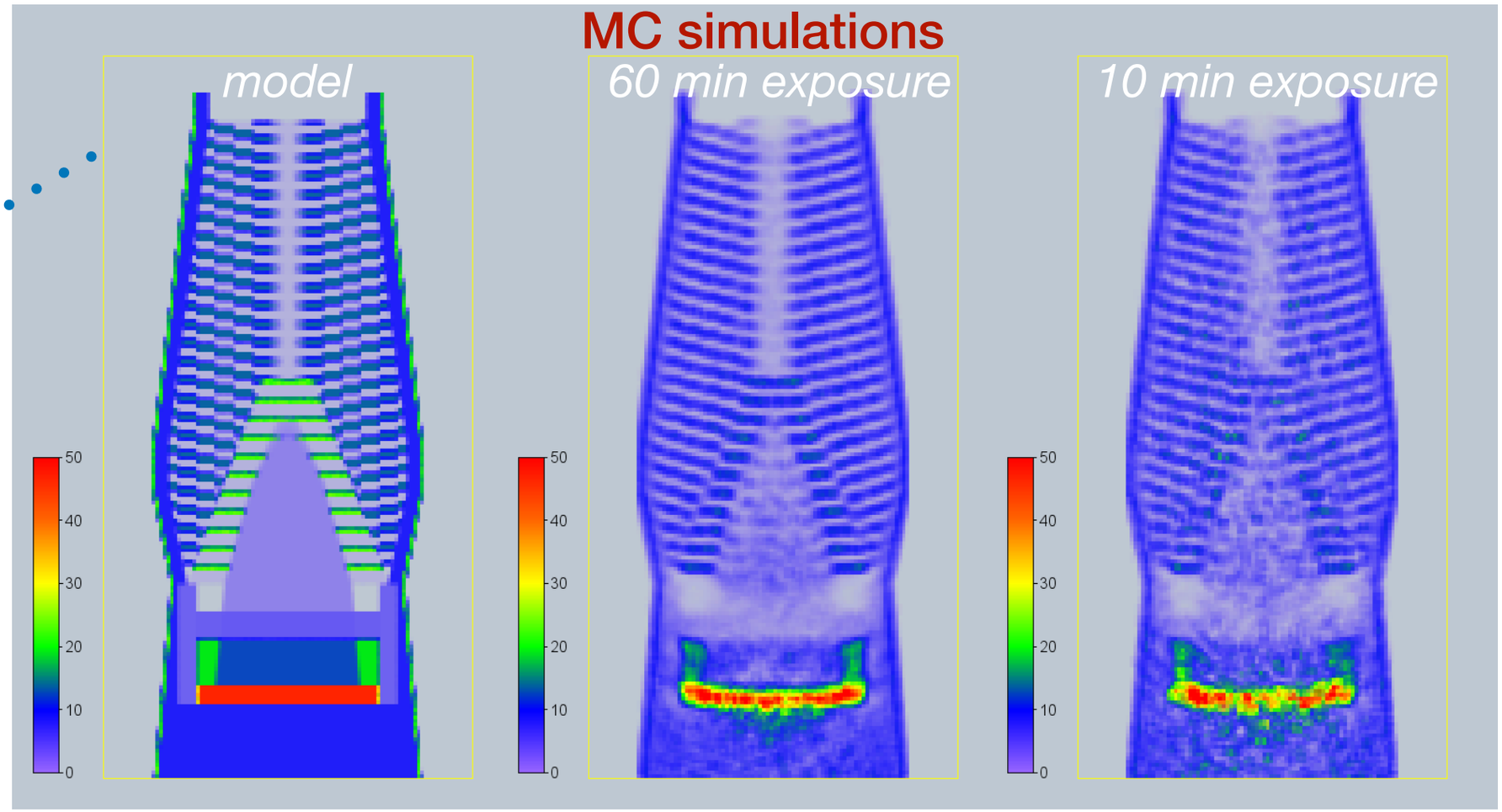
mid 2014- mid 2016

How can we inspect the inner structure of a blast furnace?

Research Fund for Coal & Steel

Mu-Blast - RFCS CT-2014-00027





Project output:

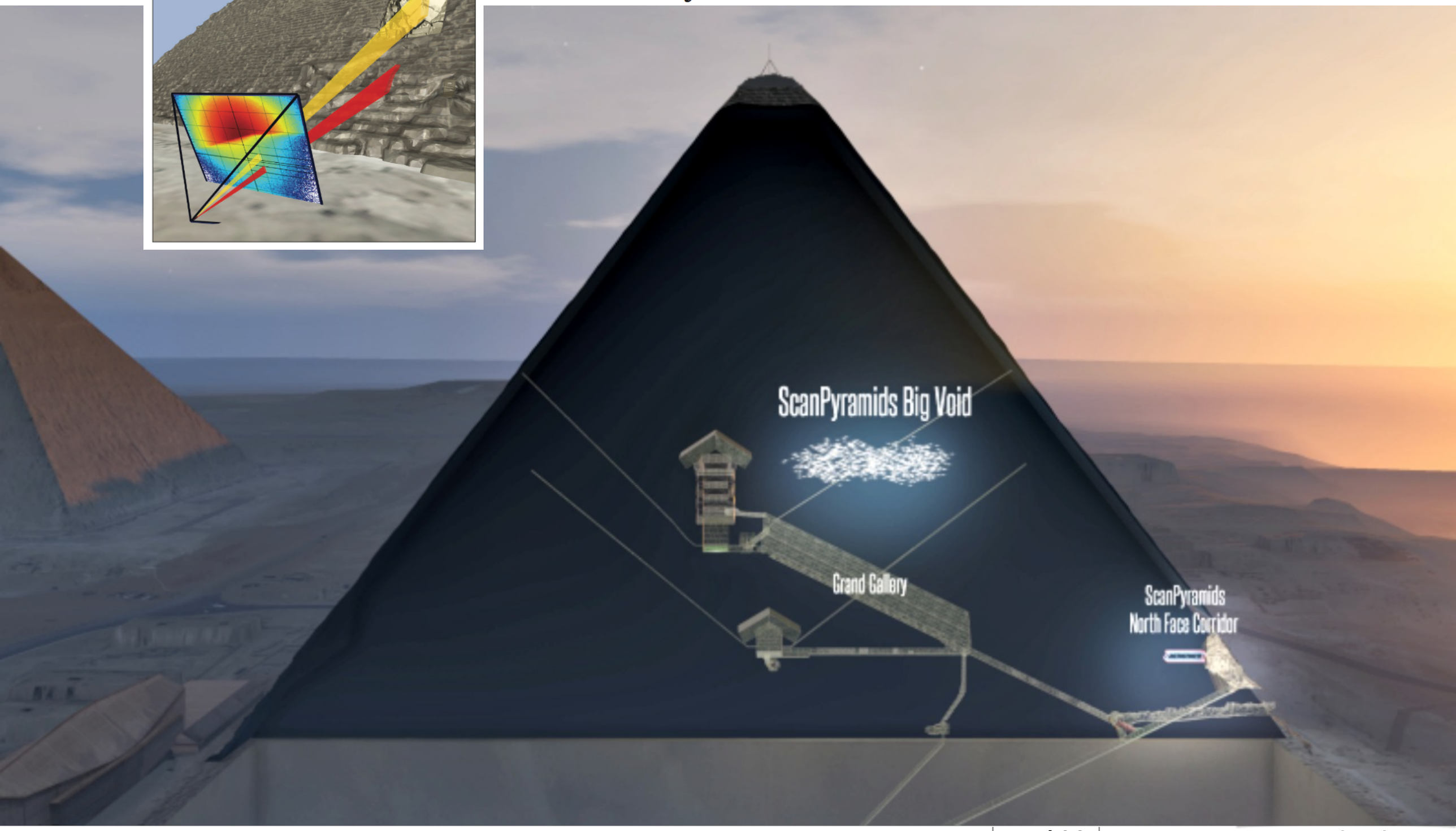
- despite the low number of “almost horizontal” muons and the movement of the burden, muon tomography imaging of the interior of a BF is possible. The detectors should be designed carefully to work in such a tough environment (a rough estimate of the momentum would also help)

Muon civil applications: pyramids

nature

LETTER
doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons *Kunihiro Morishima et al.*



STABILITY MONITORING

A different idea: stability systems with cosmic ray muons

- In particle and nuclear physics, muons are often used to “calibrate” the experimental apparatuses, that is, to measure the relative position of different detectors with respect one to each other.

Can we do the same for civil applications?

The question arose from a discussion between 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

- We started to investigate the possibility to use of the cosmic ray muons to monitor the alignment of physical part of a vertical structure (tower, pillar, mechanical press, etc., etc.)

A different idea: stability systems with cosmic ray muons

IOP Publishing — Measurement Science and Technology
Meas. Sci. Technol. **18** (2007) 3537–3546 — doi:10.1088/0957-0233/18/11/038

Cosmic ray 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]

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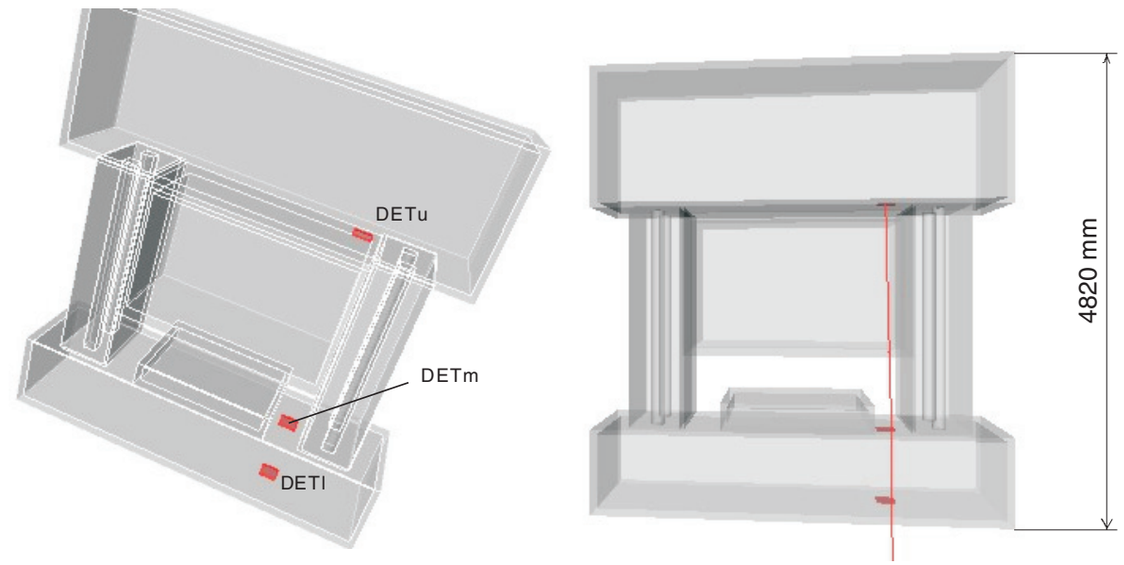


Figure 1. Pictures of the simulated configuration for the structure of the industrial press and the detectors, crossed by a cosmic ray. The upper (DETu), middle (DETm) and lower (DETl) detectors constitute the detection system, called telescope. They are mechanically connected to the parts of the structure whose relative positions have to be monitored.

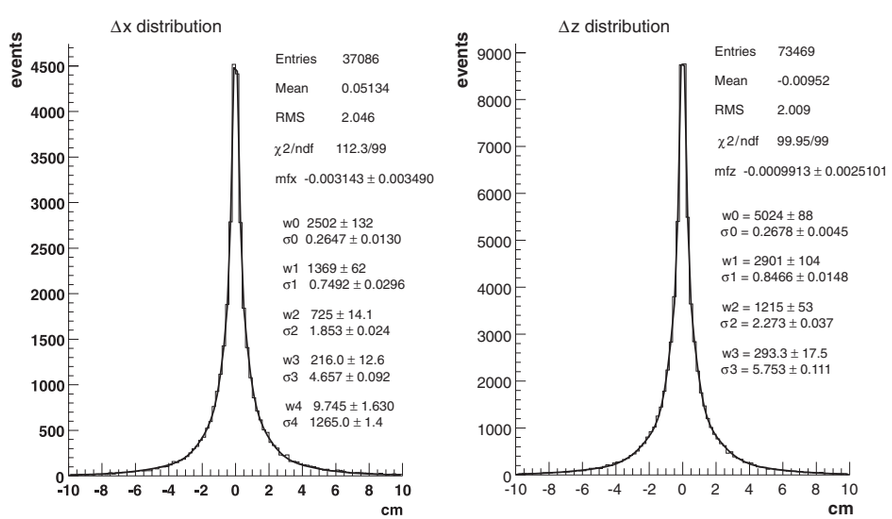


Figure 4. In these two figures the best-fit functions are superimposed on their respective Monte Carlo distributions for Δx and Δz statistical variables. Moreover the reduced χ^2 values, the best-fit function mean values (m_{f_x} and m_{f_z}) and the values of the (σ_i, w_i) parameters are reported.

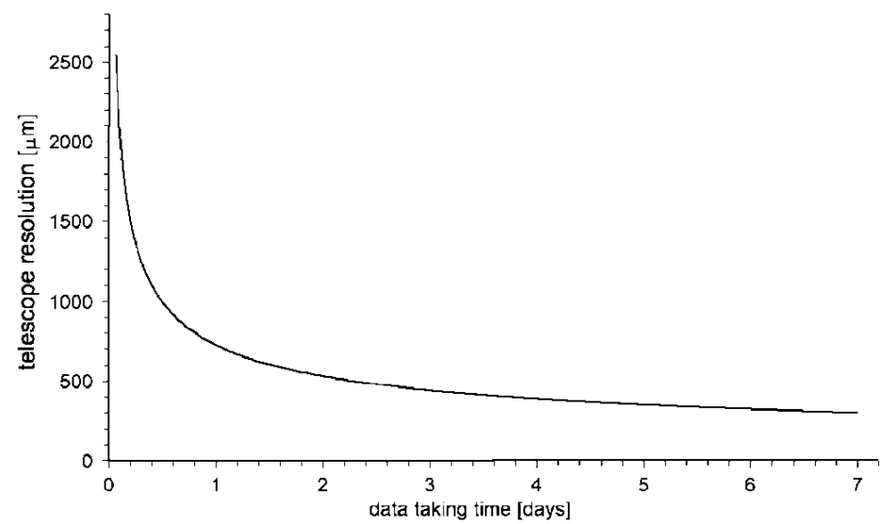


Figure 9. Resolution of the measurement system as a function of the data-taking time calculated for the considered geometry and supposing a calibration data taking of 1 week.

A different idea: stability systems with cosmic ray muons

- stability monitoring of “vertical structures” (towers, pillars, skyscrapers, historical buildings, etc.) is often fundamental
  - in many cases mechanical or optical systems are the only available options
    - invasiveness (meters of rods) limits the use for building with high historical and cultural value
    - large distances or floors limit the use of optical systems
  - after the “mechanical press” study, we investigated the possibility of using cosmic muons for the stability monitoring of historical building

👍 use of a free natural source of radiation
👍 μ are highly penetrating → walls and floors are easily traversed
👍 no need of visibility or empty spaces
👍 limited invasiveness
👍 possibility to design a global monitoring system
👎 fixed rate of cosmic muons → (relatively) long data taking

PALAZZO DELLA LOGGIA (a study case)

history of the palace

Palazzo della Loggia: where

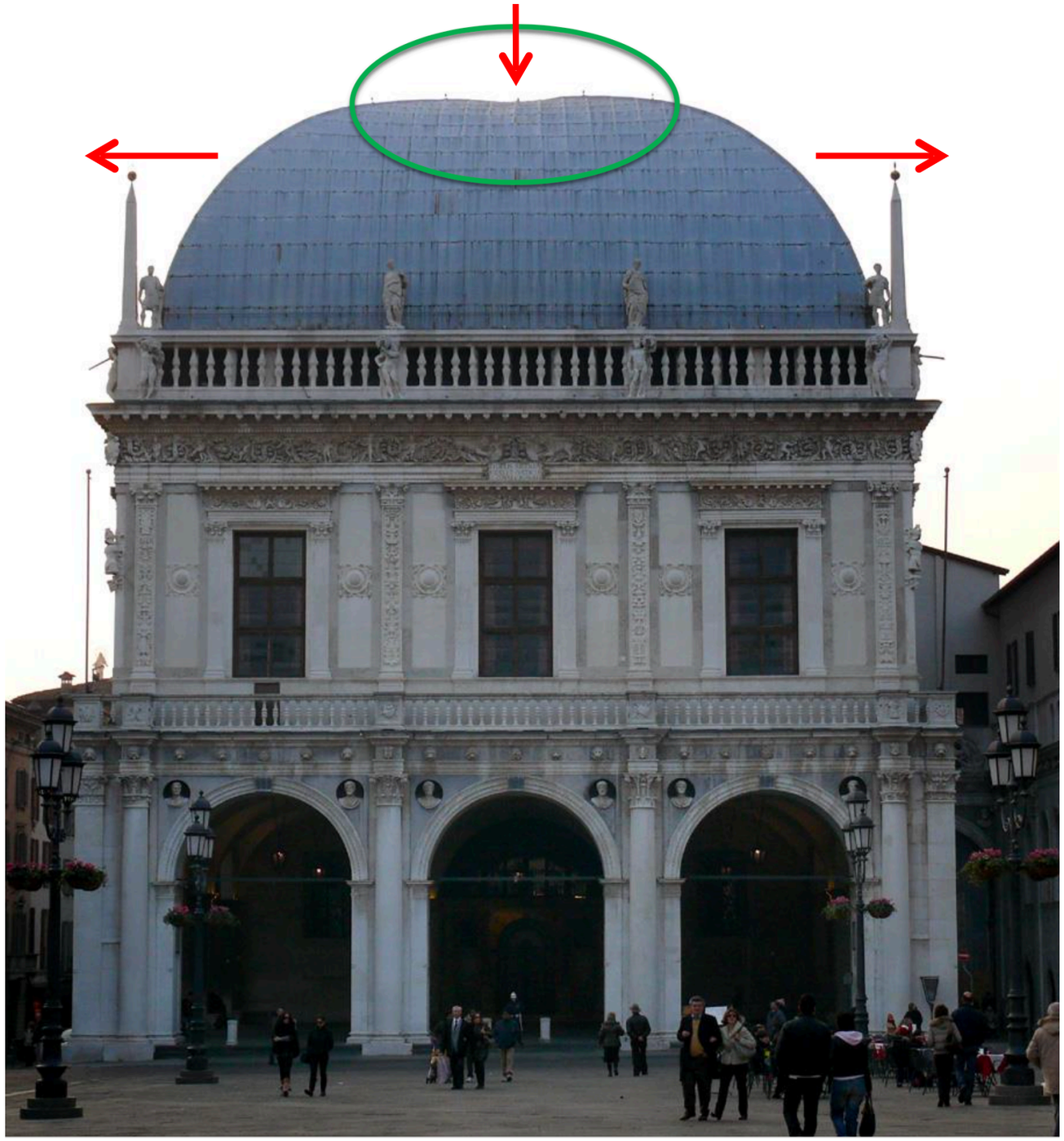
Palazzo della Loggia: history

First built in between 1492 and 1575, in 1914 a new dome, based on the original project, replaced the 1769 attic

Brescia, Palazzo della Loggia, 1574

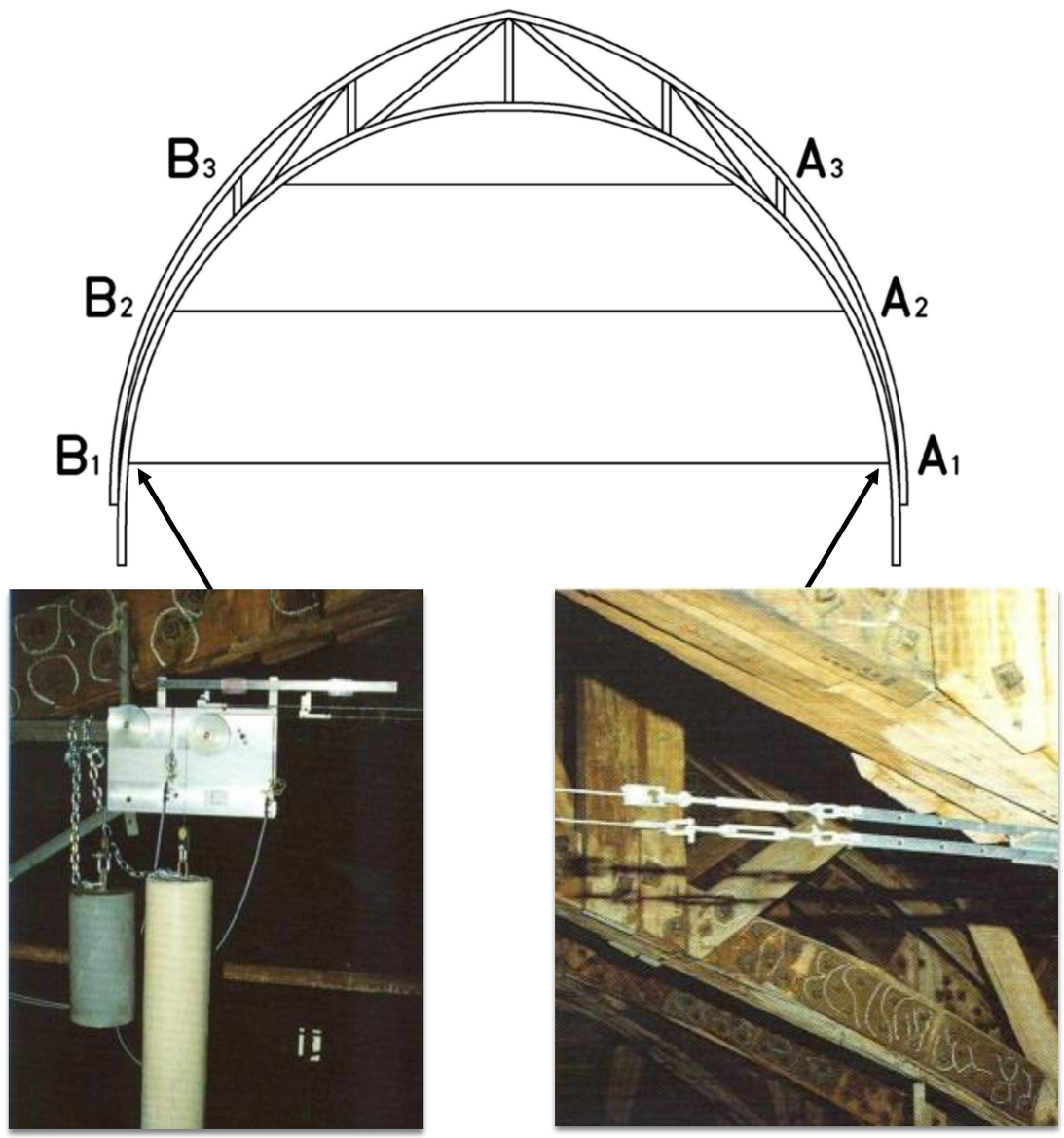
Palazzo della Loggia: roof deformation

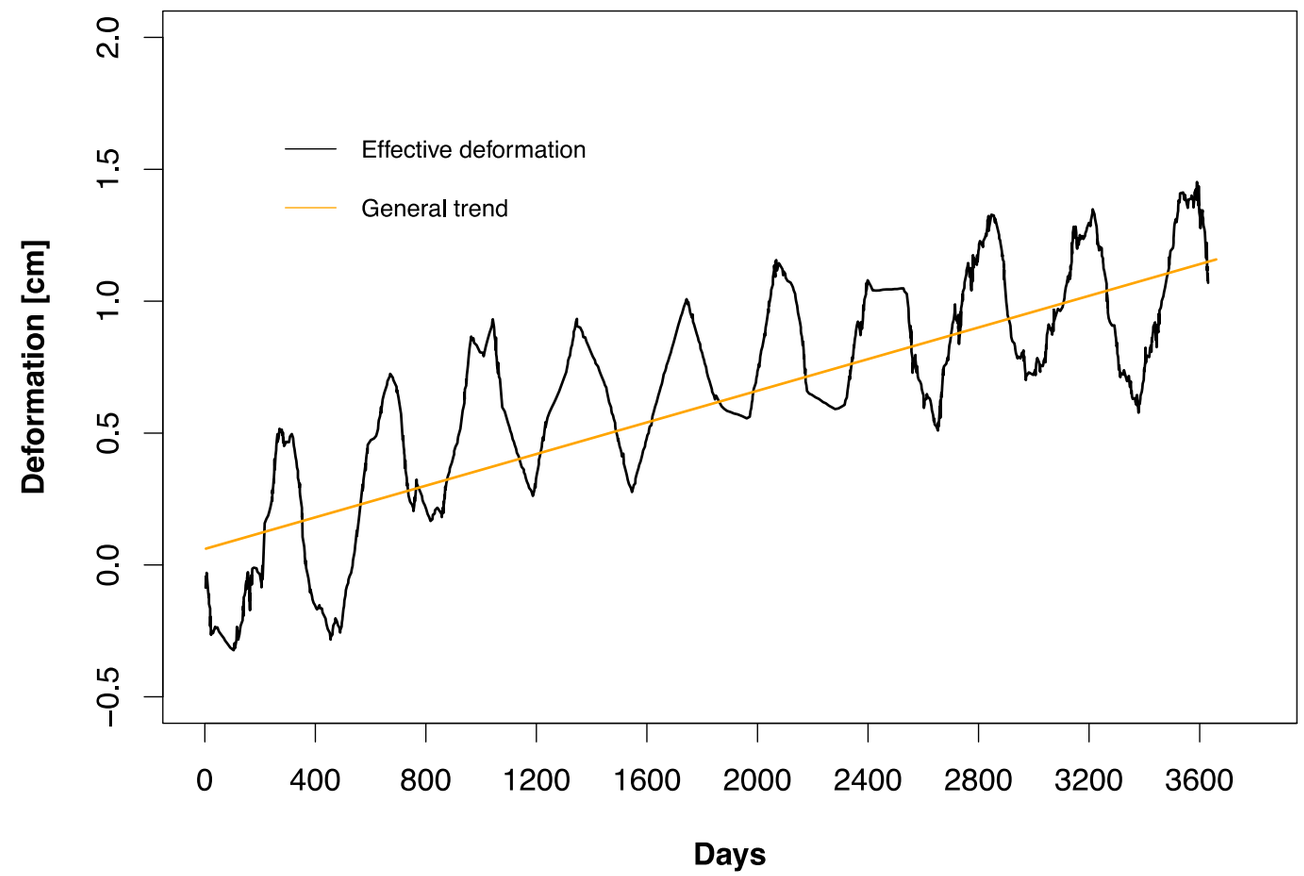
The dome immediately after its completion showed progressive deformation



Palazzo della Loggia: monitoring campaign

For this reason a systematic campaign of monitoring of the dome was performed by using (invasive) extensometers





A. Bellini et al., “Il Palazzo della Loggia di Brescia - Indagini e progetti per la conservazione”, Starrylink editrice, 2007

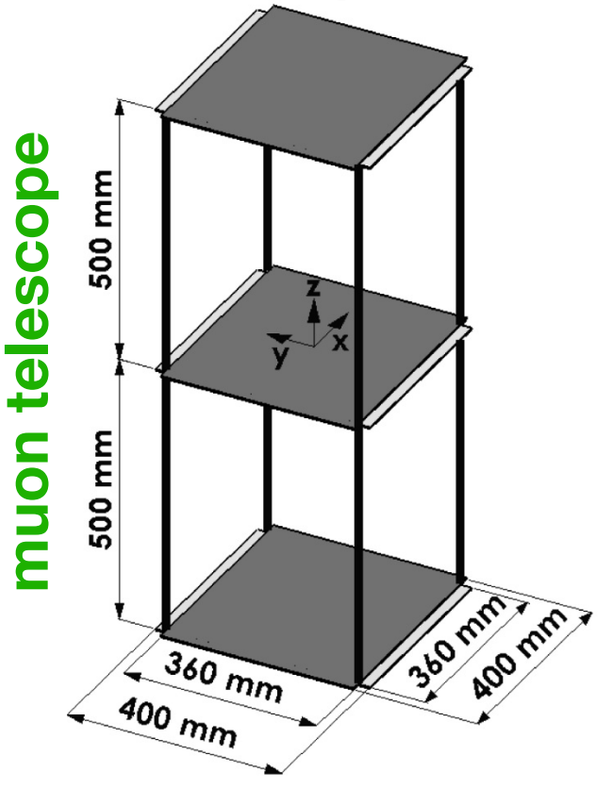
Palazzo della Loggia: monitoring (invasive) campaign

The dome started immediately after to slowly collapse

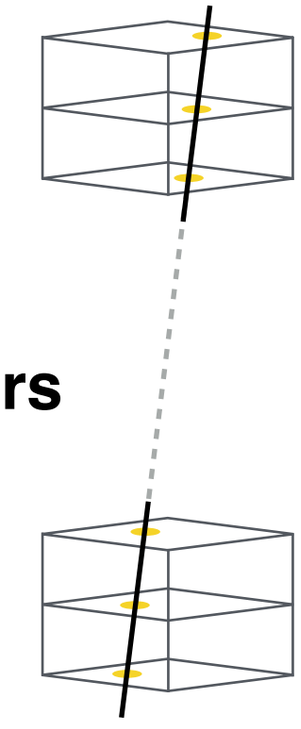
PALAZZO DELLA LOGGIA (a study case)

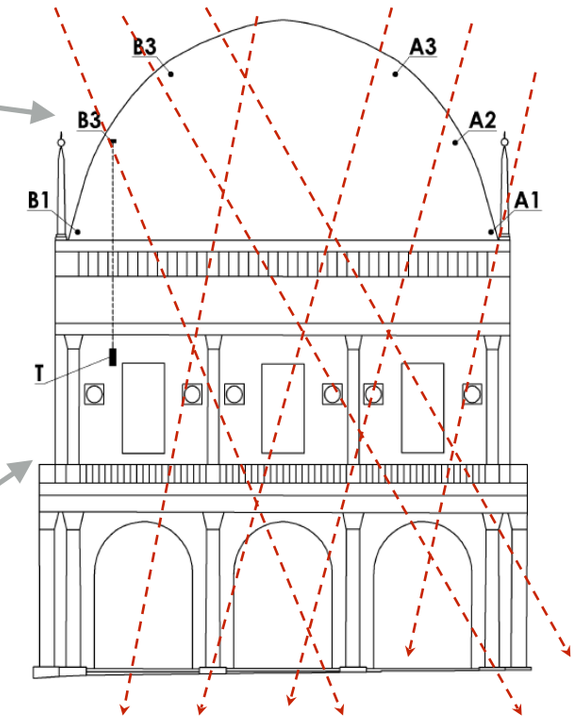
simulation of the monitoring with muons

Stability monitoring with muons: setup

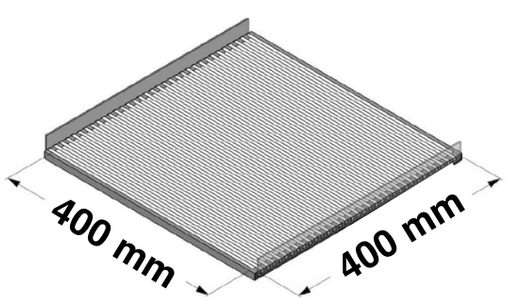


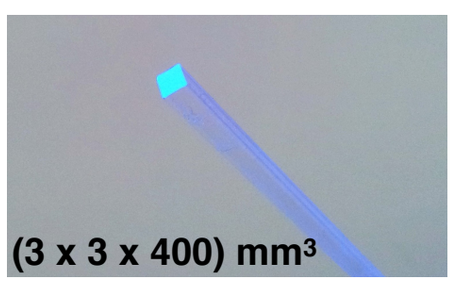
independent detectors





Proposed detector





- double layers of scintillating (3 x 3) mm² fibers
- fibers coupled to SiPMs
  - "cheap"
  - low voltage operation
  - good spatial and time resolution

necessary to correlate reconstructed events in the two independent telescopes

Stability monitoring with muons: simulation

- MC simulations performed in three different configurations:

1) $\Delta z = 350\ cm$
2) $\Delta z = 880\ cm$
3) $\Delta z = 1300\ cm$

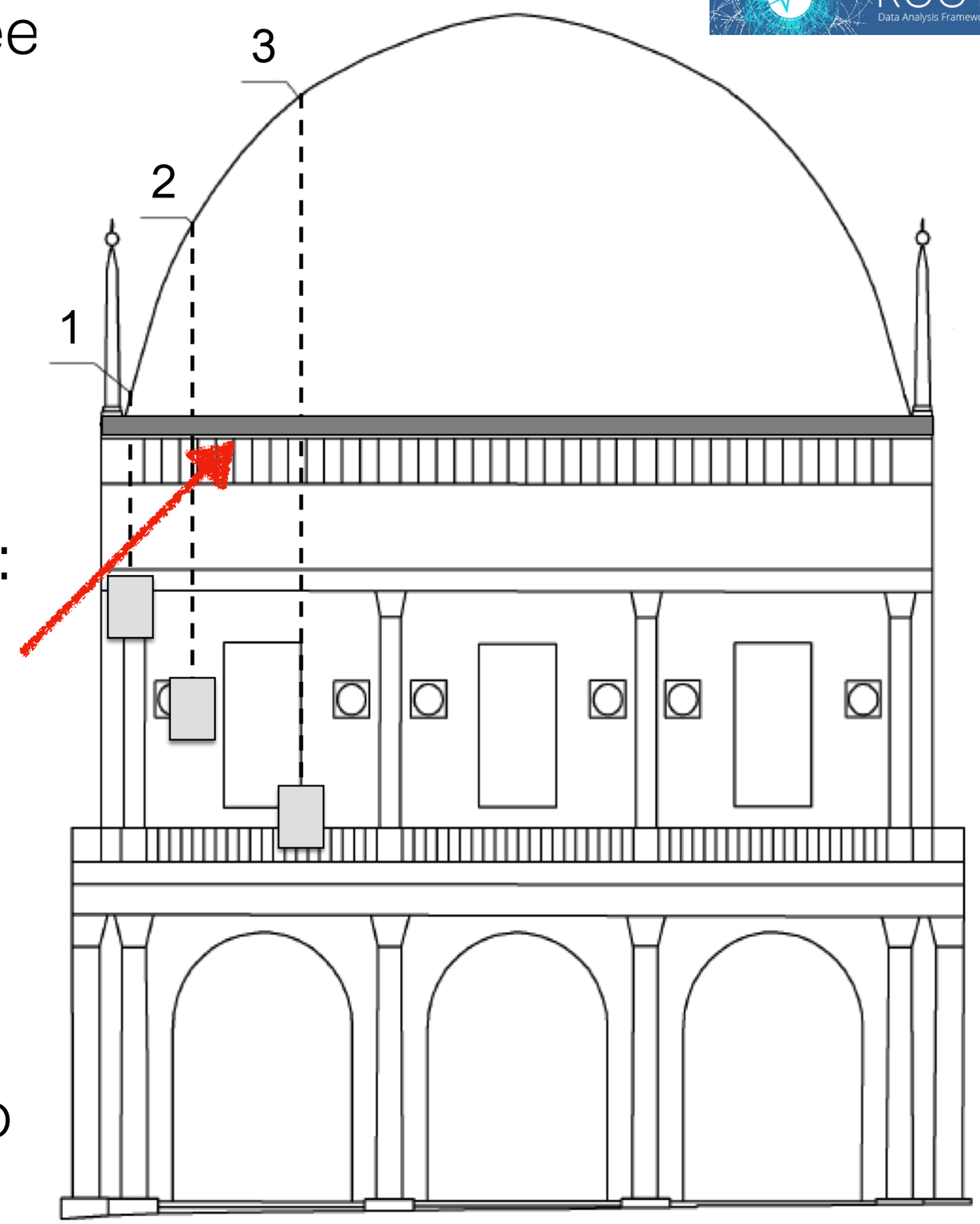
- No visibility between the detectors:

15 cm of concrete

- Realistic cosmic muon generator based on experimental data

Bonechi et al. (2005) Proc. 29th Int. Cosmic Ray Conf. vol 9 p 283

- Systematic uncertainties taken into account



Stability monitoring with muons: simulation

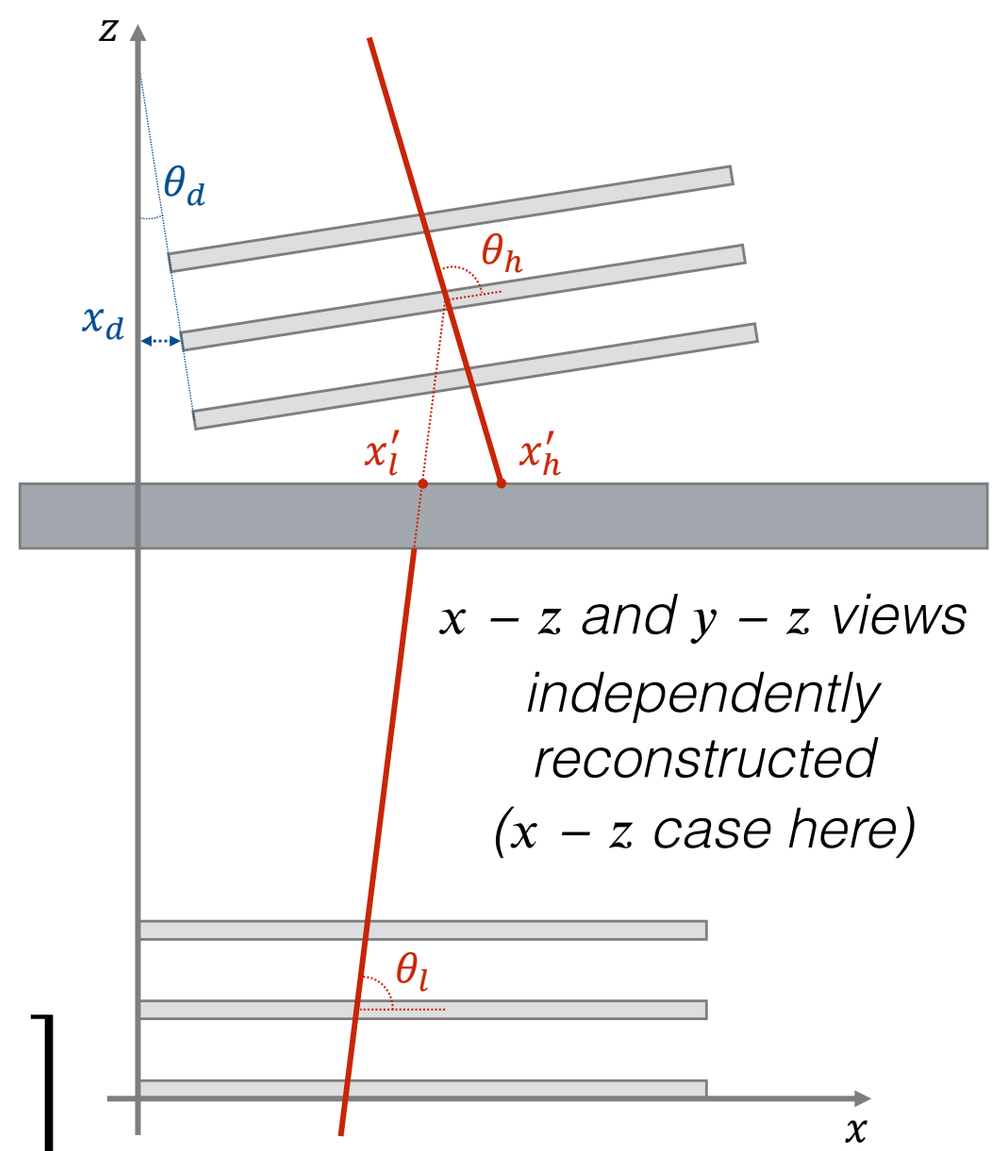
- For perfectly aligned geometry expected values $E[x_h' - x_l'] = 0$ and $E[\theta_h - \theta_l] = 0$ [time-zero (calibration) measurement]

- $x_h' - x_l'$ and $\theta_h - \theta_l$ depend on the parameters of interest x_d and θ_d

- Estimates $\hat{x}_d$ and $\hat{\theta}_d$ are extracted from a χ^2 minimization

$$\chi^2 = \sum_i \left[\frac{(x'_{h,i} - x'_{l,i})^2}{(\sigma^2_{x'_h,i} + \sigma^2_{x'_l,i})^2} + \frac{(\theta_{h,i} - \theta_{l,i})^2}{(\sigma^2_{\theta_{h,i},i} + \sigma^2_{\theta_{l,i},i})^2} \right]$$

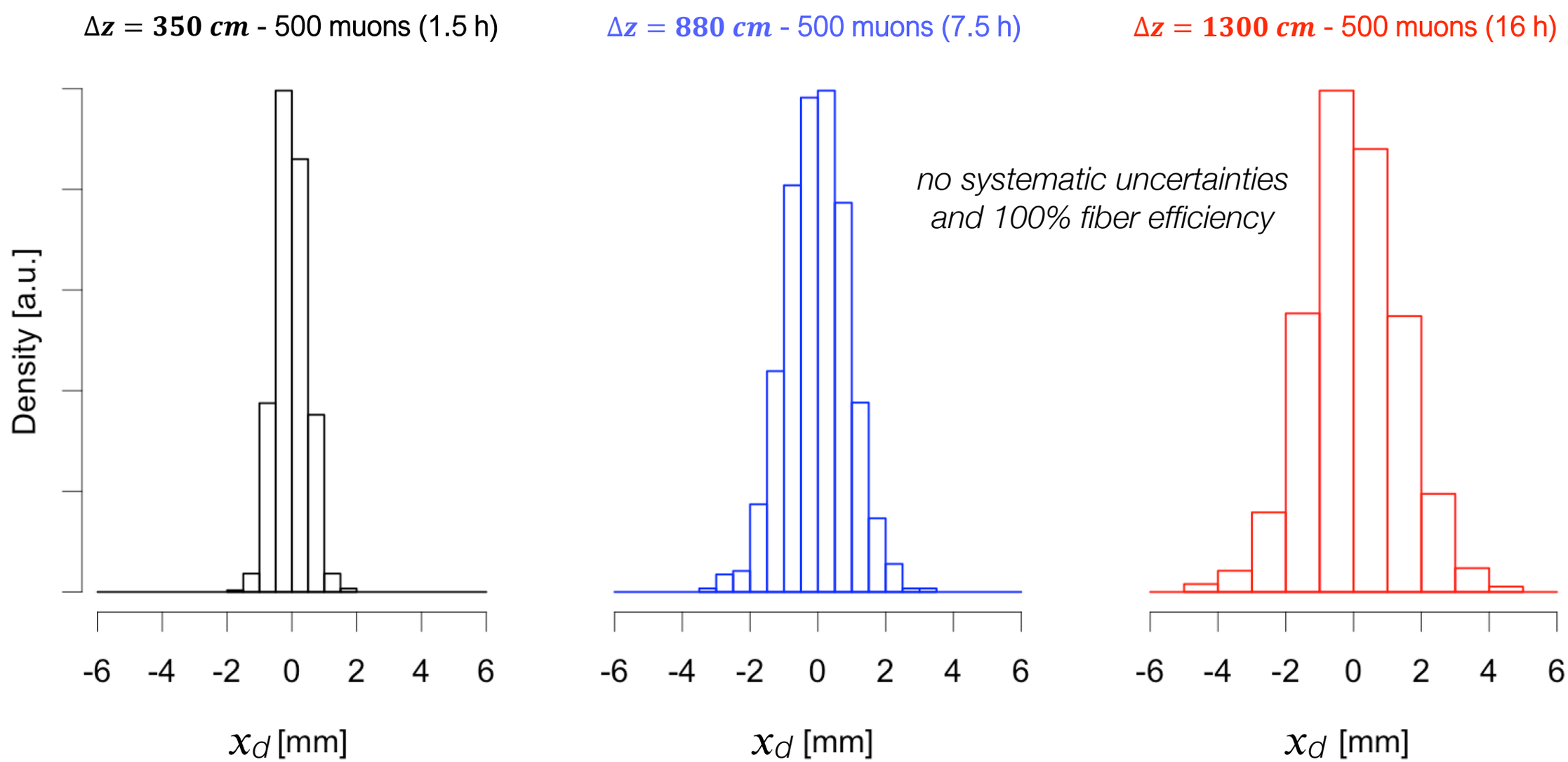
index i runs over the reconstruted muons in the data sample



-> what about the resolution?

Simulation of a specific case: MC results

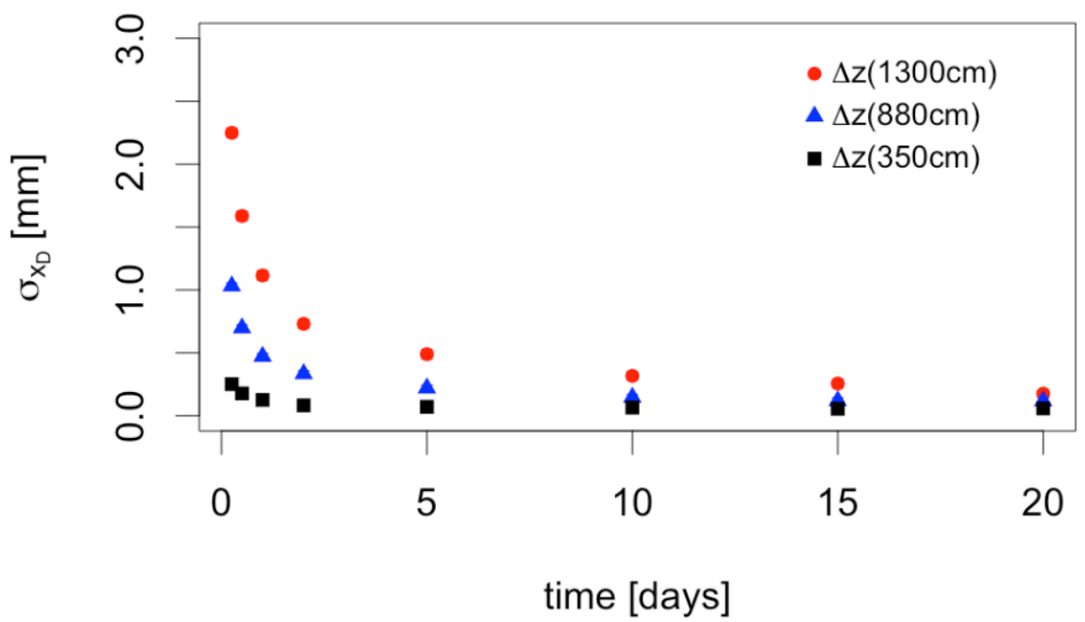
- For a given number of muons, the uncertainties on $\hat{x}_d$ and $\hat{\theta}_d$ were estimated from samples of $\hat{x}_d$ and $\hat{\theta}_d$ obtained from a large number of different MC generations

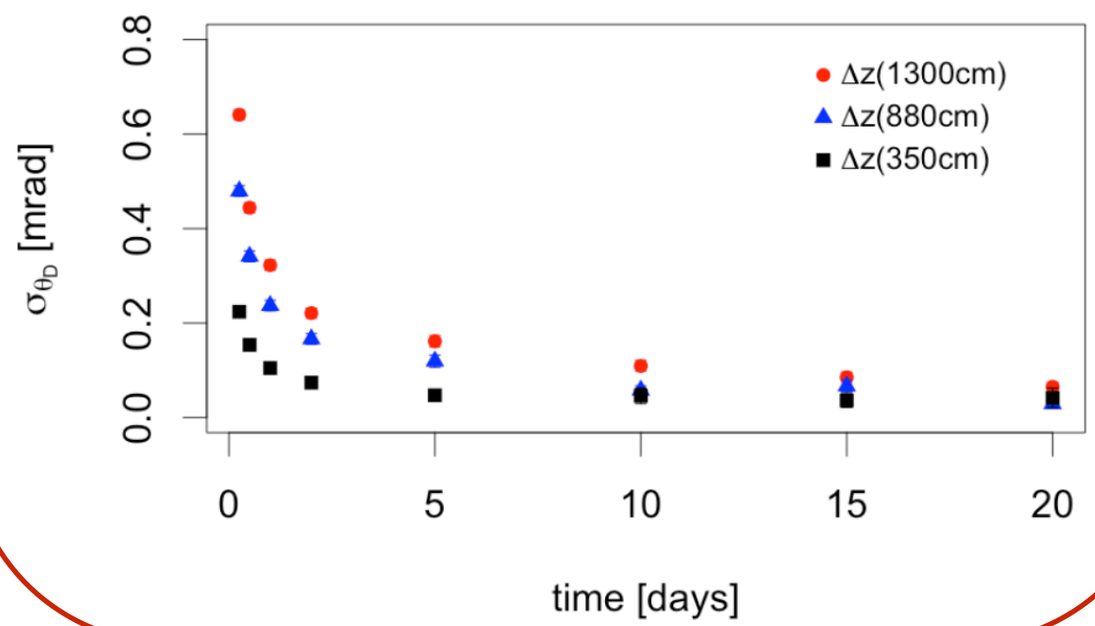


- As the lower telescope and the upper telescope are perfectly aligned in the simulation, the distributions are symmetric and centered at zero. The width of the distributions is due both to the resolution of the telescopes and to the multiple scattering suffered by the muon trajectories
- Given the same statistics, the standard deviation depends on the distance between the telescopes: the closer the two telescopes, the better the accuracy

Simulation of a specific case: MC results

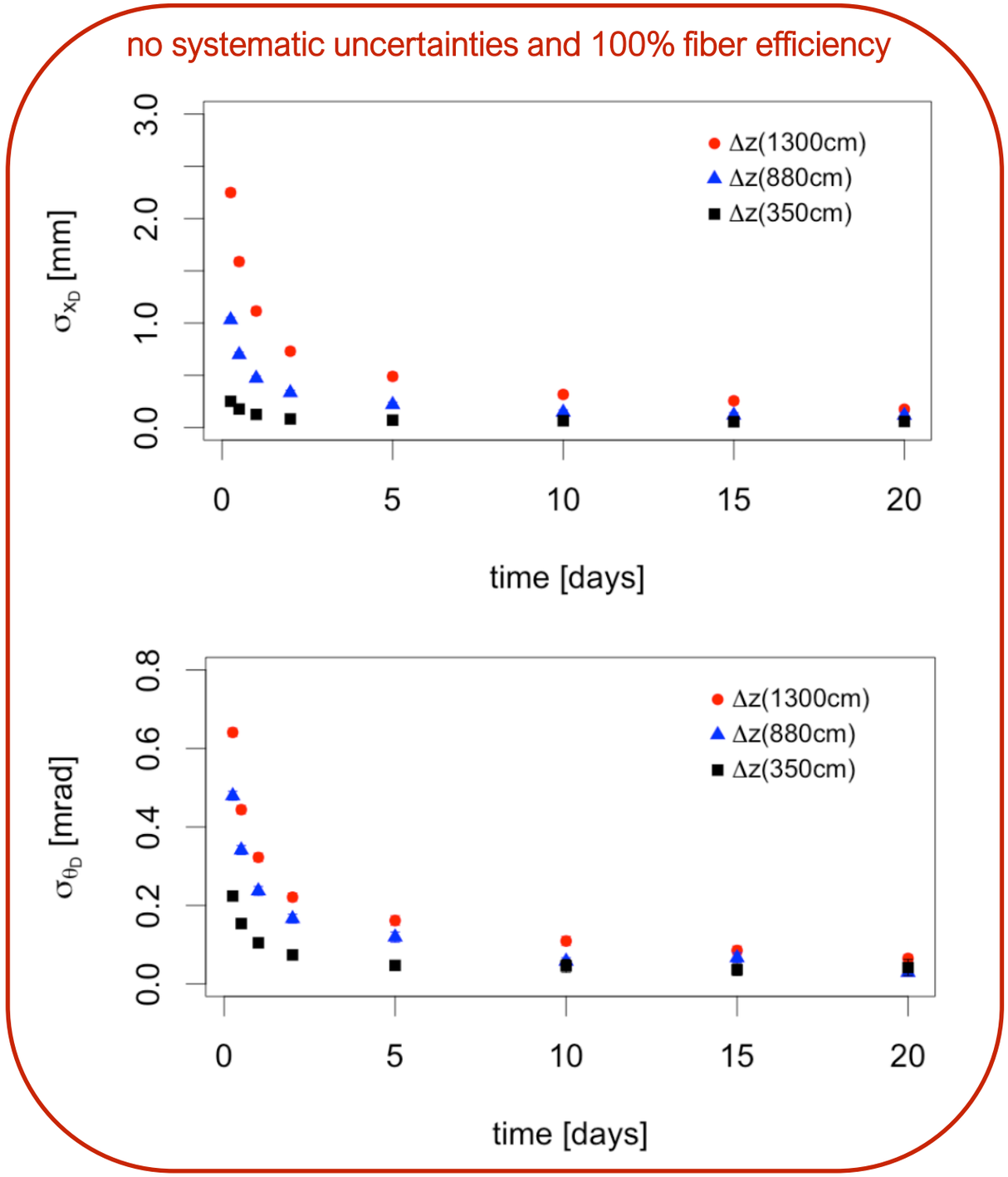
no systematic uncertainties and 100% fiber efficiency

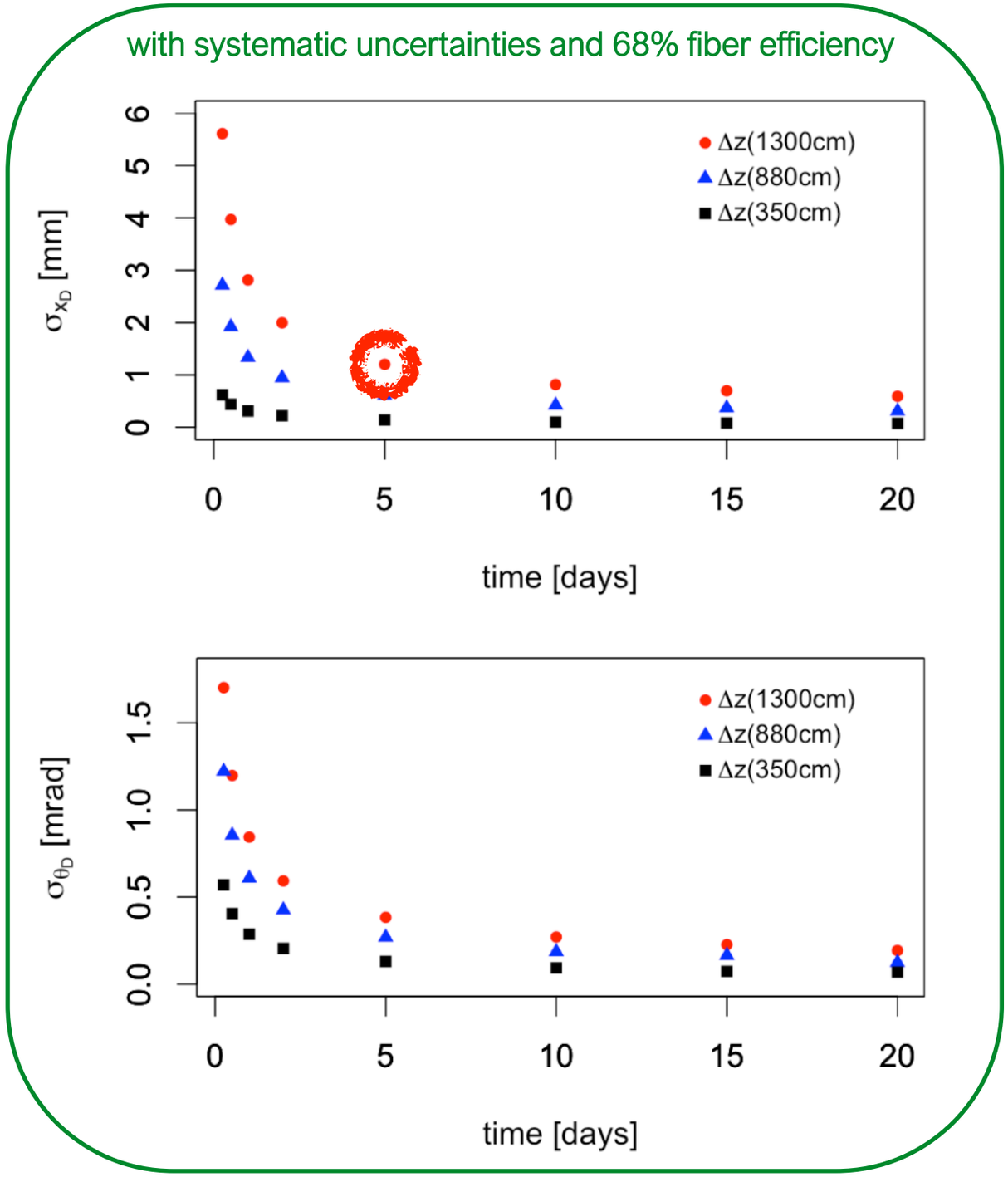




Simulation of a specific case: MC results

Systematic uncertainties related to geometrical tolerances in the detectors and to their relative positioning were taken into account





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https://doi.org/10.1088/1361-6501/ab00d7

Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study

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Abstract

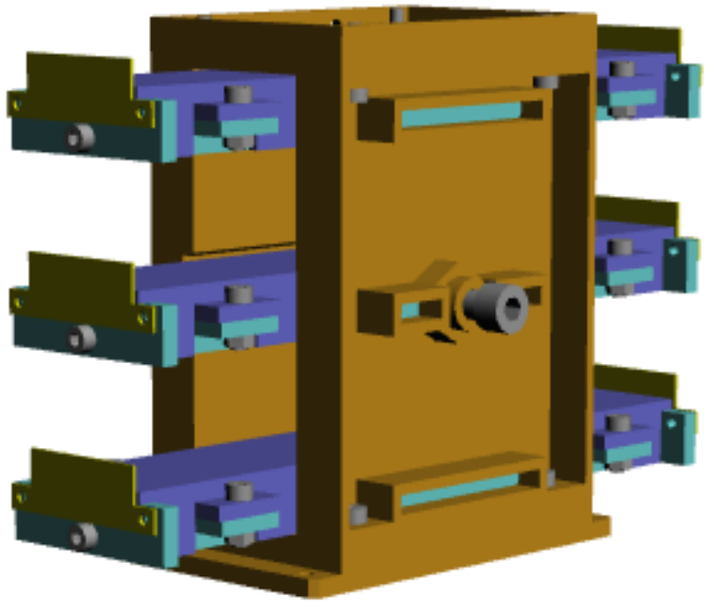
A cosmic ray muon detection system is proposed for stability monitoring in the field of civil engineering, in particular for the static monitoring of historical buildings, where conservation constraints are severe and the time evolution of the deformation phenomena under study may be of the order of months or years. The stability monitoring of the wooden vaulted roof of the *Palazzo della Loggia*, located in the town of Brescia, Italy, has been considered as a case study. The feasibility, as well as the performance and limitations of a stability monitoring system based on cosmic ray tracking have been studied by Monte Carlo simulations. A study of possible systematic uncertainties is presented along with a realistic design for the construction of a measurement system prototype.

A SMALL SCALE (toy) PROTOTYPE

Small scale prototype: design

Design

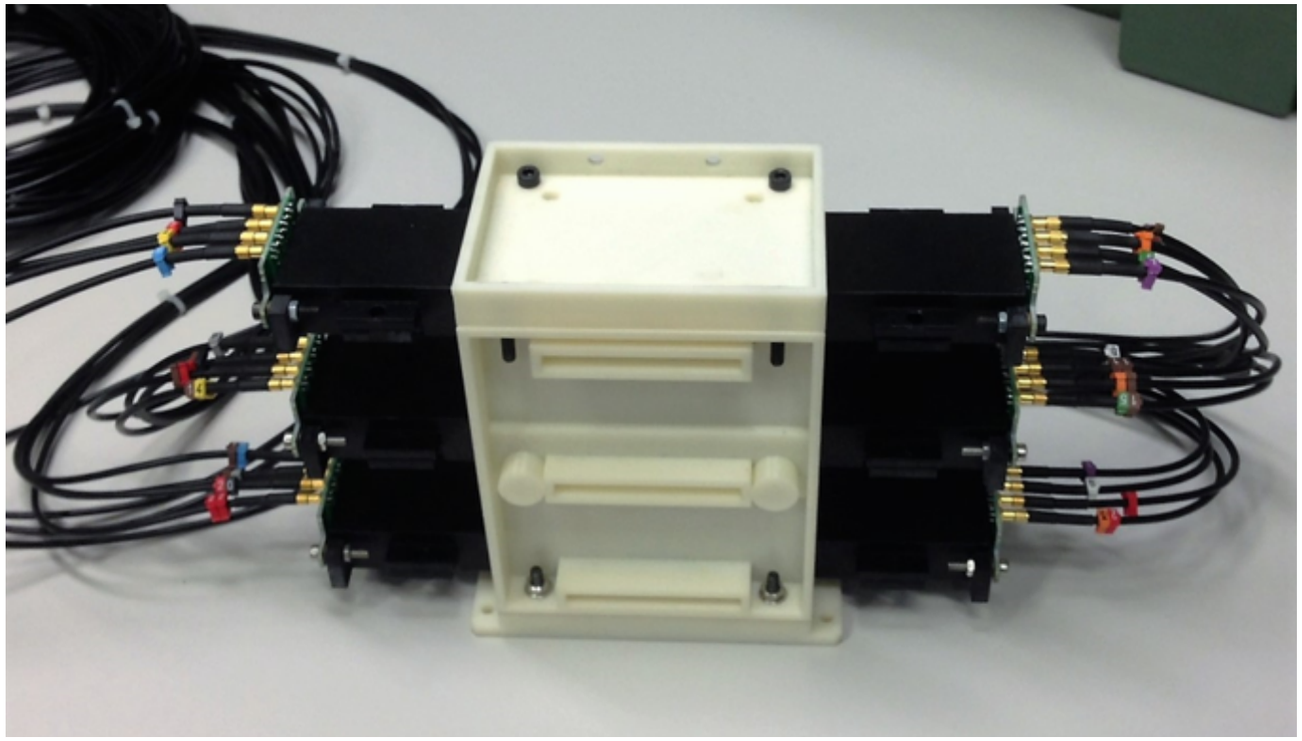
- As a proof of principle a small-scale detection system, consisting of one telescope and a single layer, was designed and created

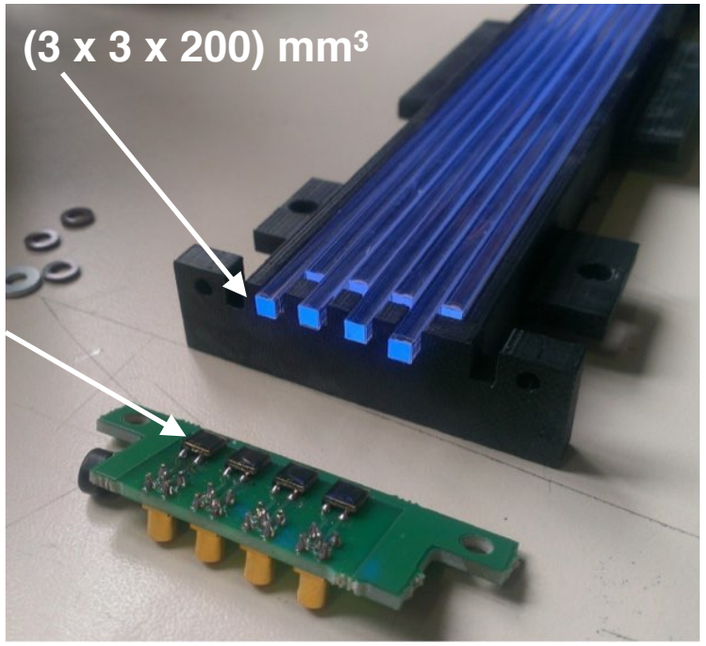


all the mechanical supports (ABS) created with a 3D printer

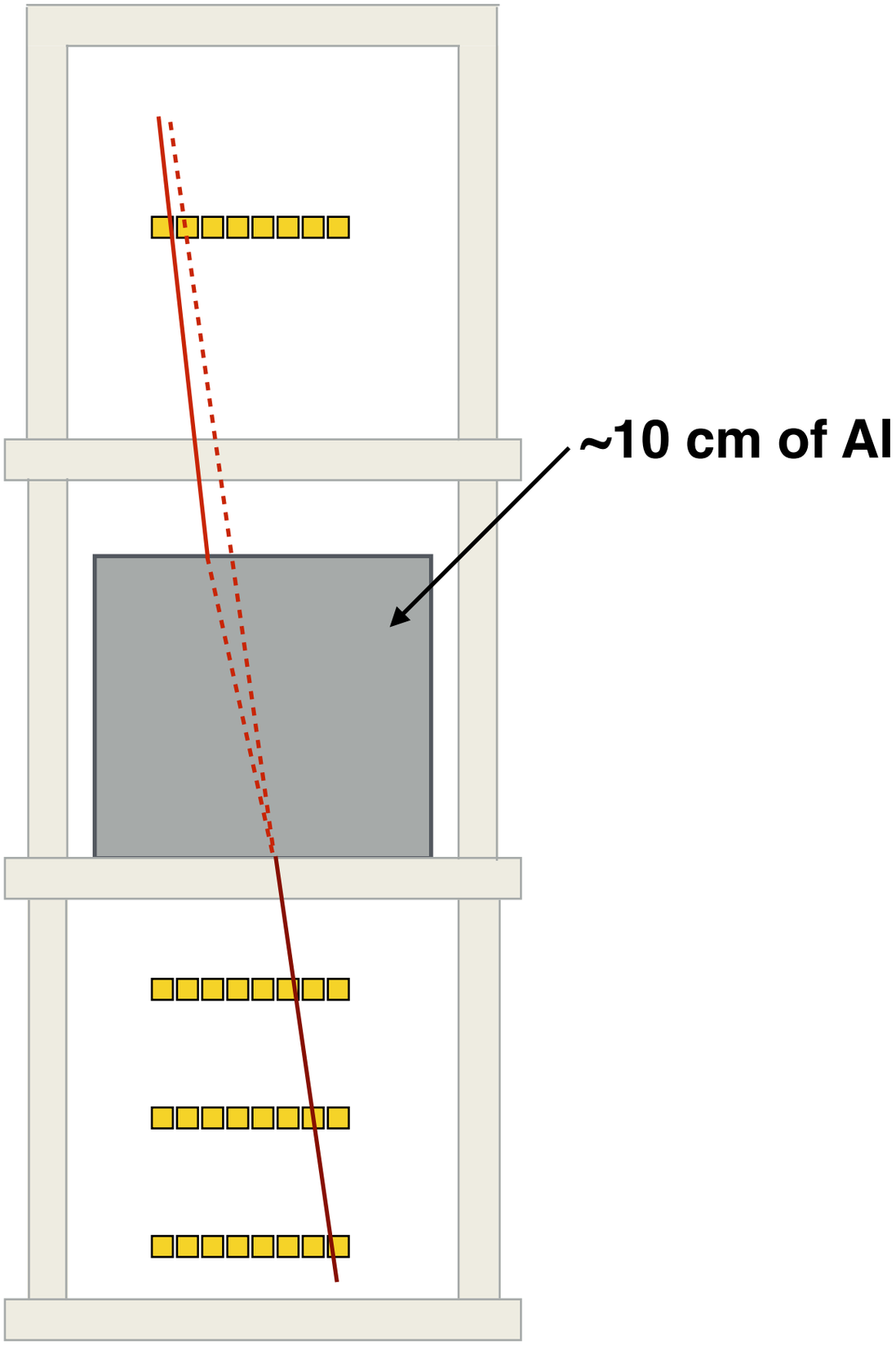
each layers composed by 8 scintillating fibers (BCF-10 from Saint-Gobain)

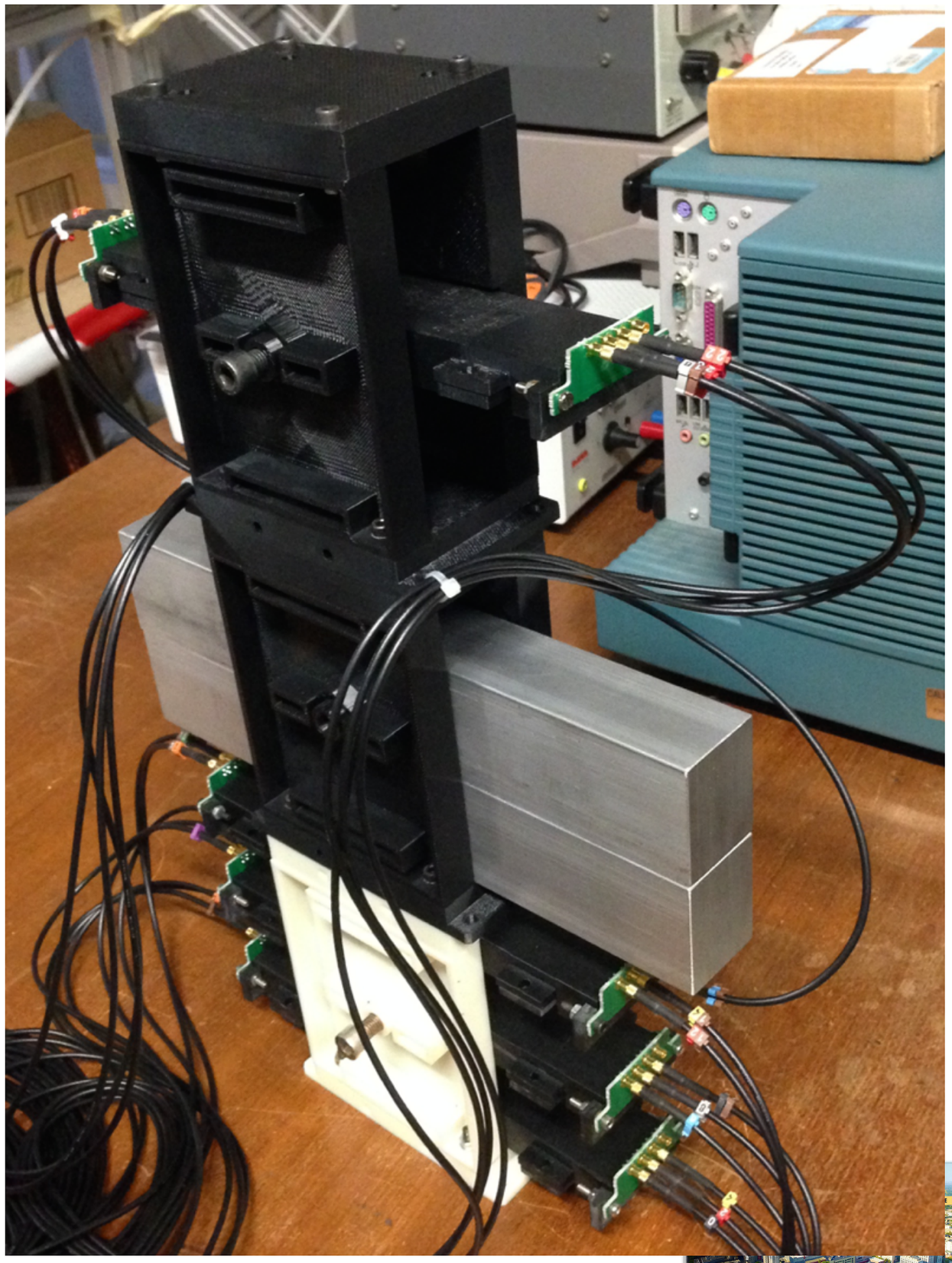
signals from SiPMs amplified with a (custom made) three stages amplification



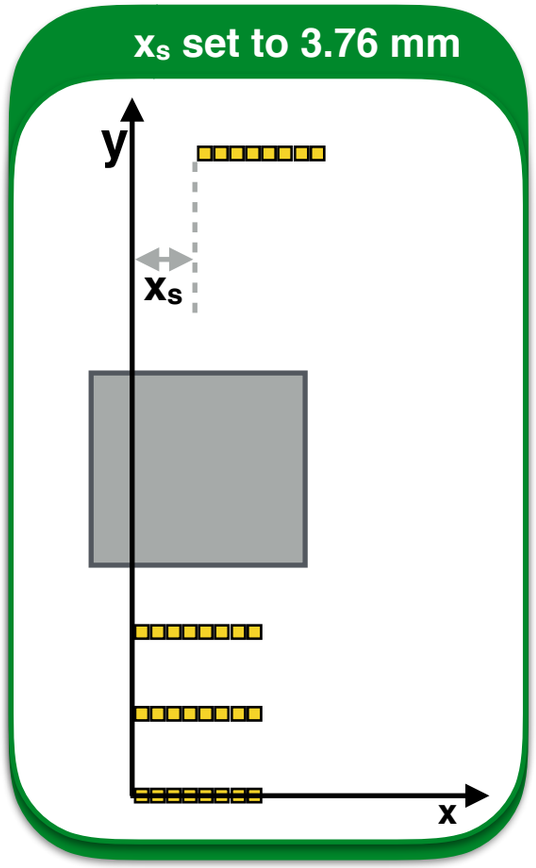


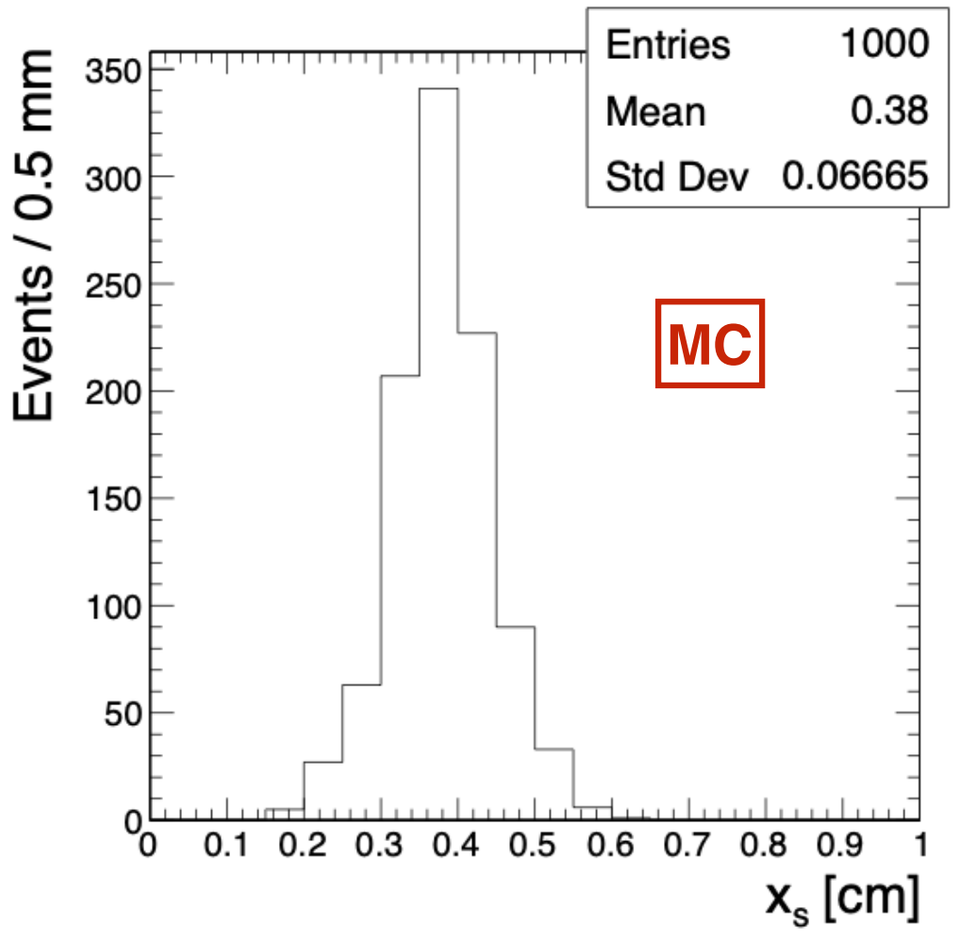
Small scale prototype: setup



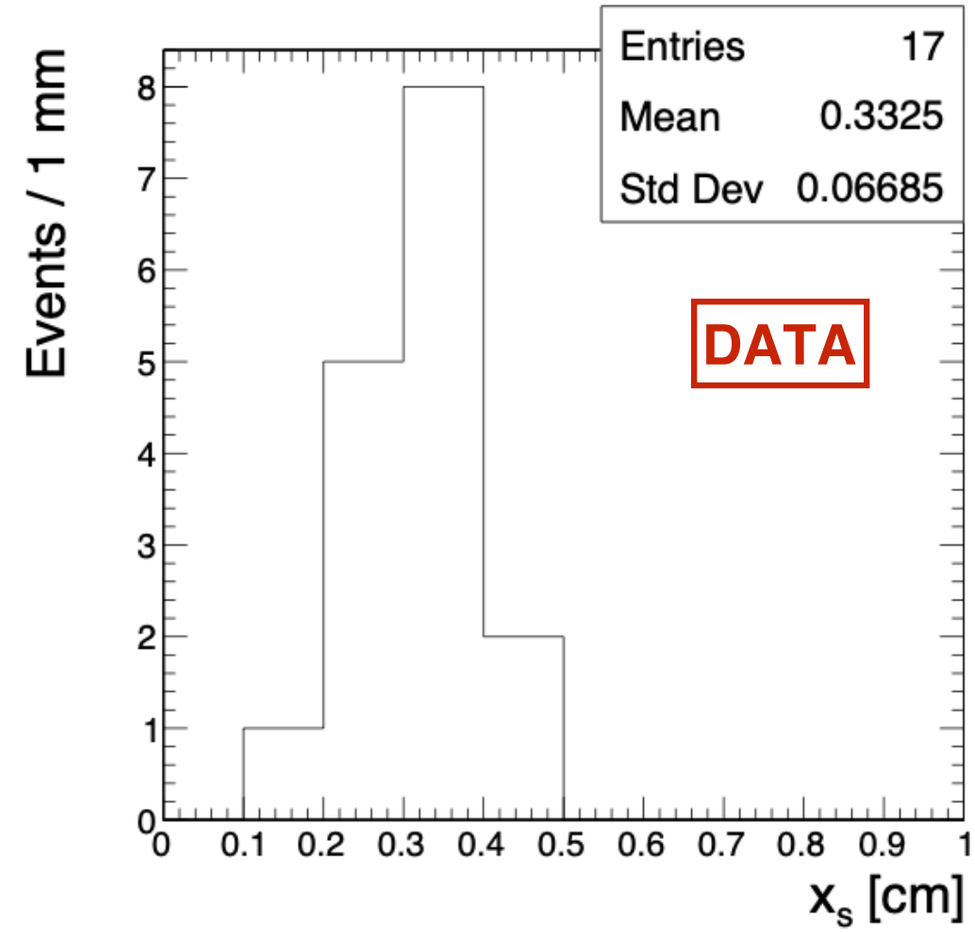


Small scale prototype: results





1000 samples of 100 events each



17 samples of 100 events each

The system proved to be capable to detect a relative displacement and the Monte Carlo to be reliable in estimating the resolution of the system

CONCLUSIONS

Conclusions

- A technique and a suitable detector for the stability monitoring of (historical) buildings, using cosmic ray muons, have been studied
- The technique was applied to a realistic scenario, using the “Palazzo della Loggia” in Brescia a case study
- Three different geometrical configurations (from Δz = 350 to 1300 cm) were considered
- MC results showed that resolutions smaller than 1 mm could be achieved with one week of data taking
- As a proof of principle, we also developed a small-scale detector prototype based on the same technology of the proposed detector
- We are now designing a specific SiPM readout board and we would like to build an easy-to-use detector for cosmic ray muons applications

THANK YOU FOR YOUR ATTENTION