Monitoring systems with cosmic ray muons

Germano Bonomi

University of Brescia and INFN Pavia

SUMMARY

- A different idea for cosmic ray muons
- A “study” case
- Future developments
- Conclusions

Our group is mostly involved in data analysis and Monte Carlo simulations

We are also working on a project for a compact and easy-to-use detector based on scintillator fibers for muon tomography applications

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

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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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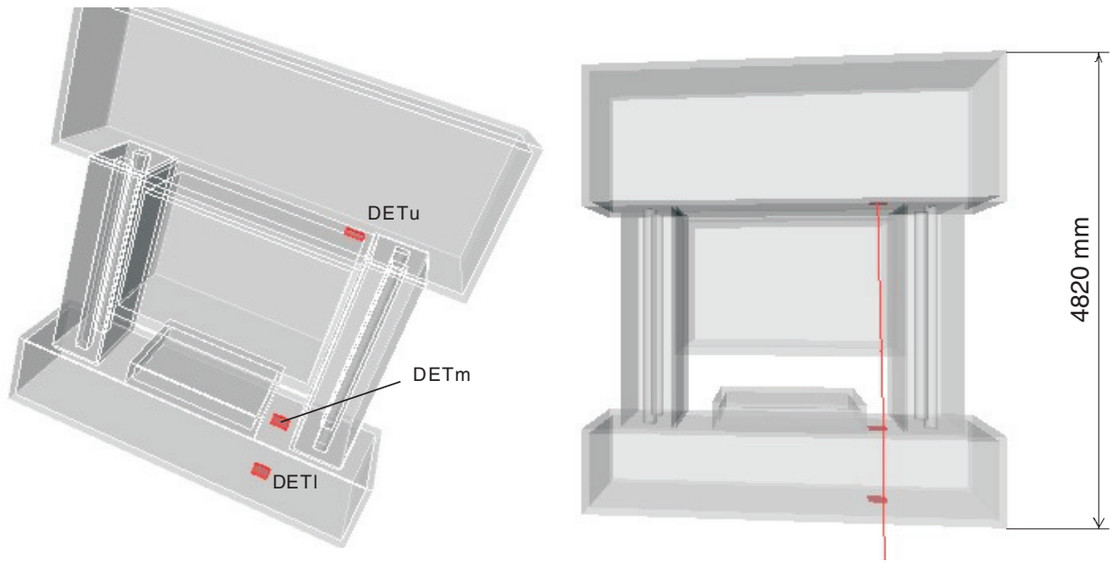


Figure 1. Pictures of the simulated configuration for the structure of the industrial press and the detectors, crossed by a cosmic ray. The upper (DETu), middle (DETm) and lower (DETl) detectors constitute the detection system, called telescope. They are mechanically connected to the parts of the structure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

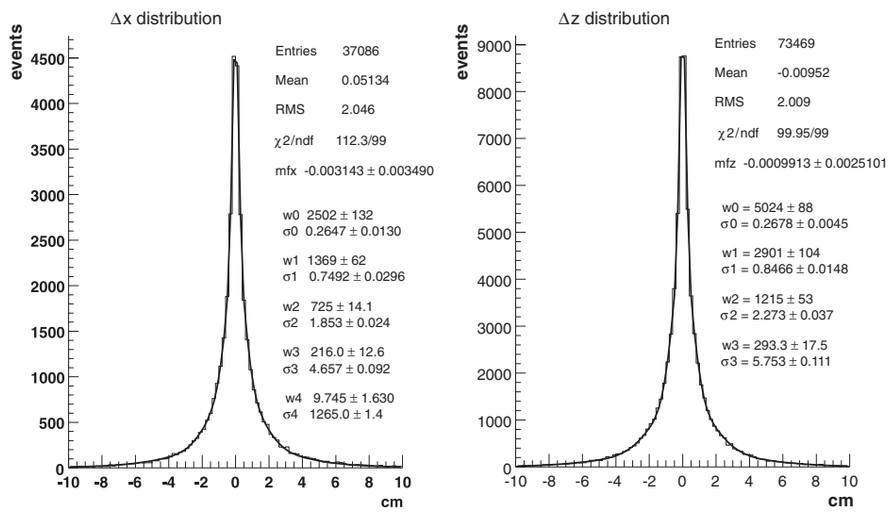


Figure 4. In these two figures the best-fit functions are superimposed on their respective Monte Carlo distributions for Δx and Δz statistical variables. Moreover the reduced χ^2 values, the best-fit function mean values (m_{f_x} and m_{f_z}) and the values of the (σ_i, w_i) parameters are reported.

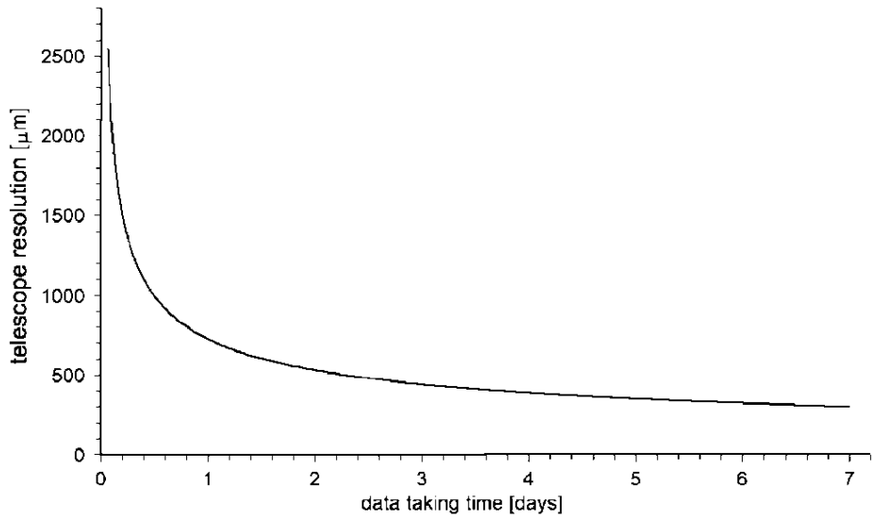
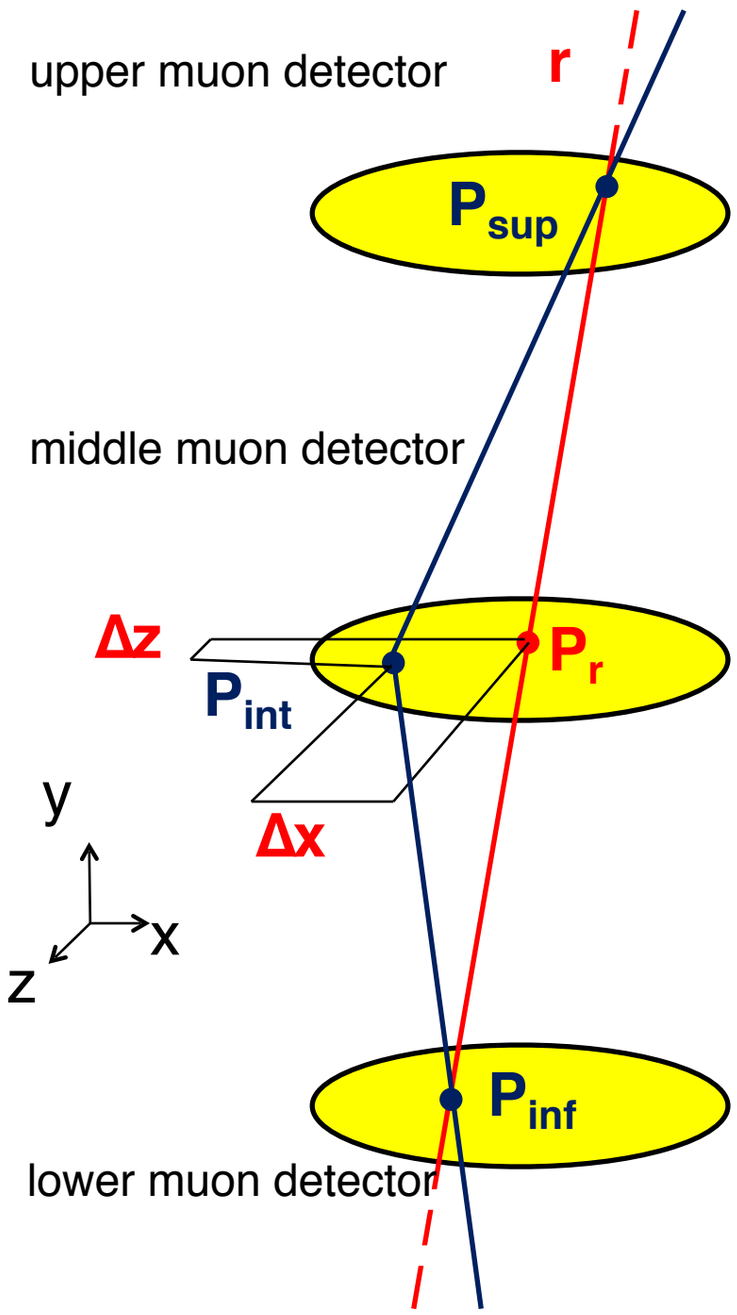


Figure 9. Resolution of the measurement system as a function of the data-taking time calculated for the considered geometry and supposing a calibration data taking of 1 week.

A different idea: stability systems with cosmic ray muons

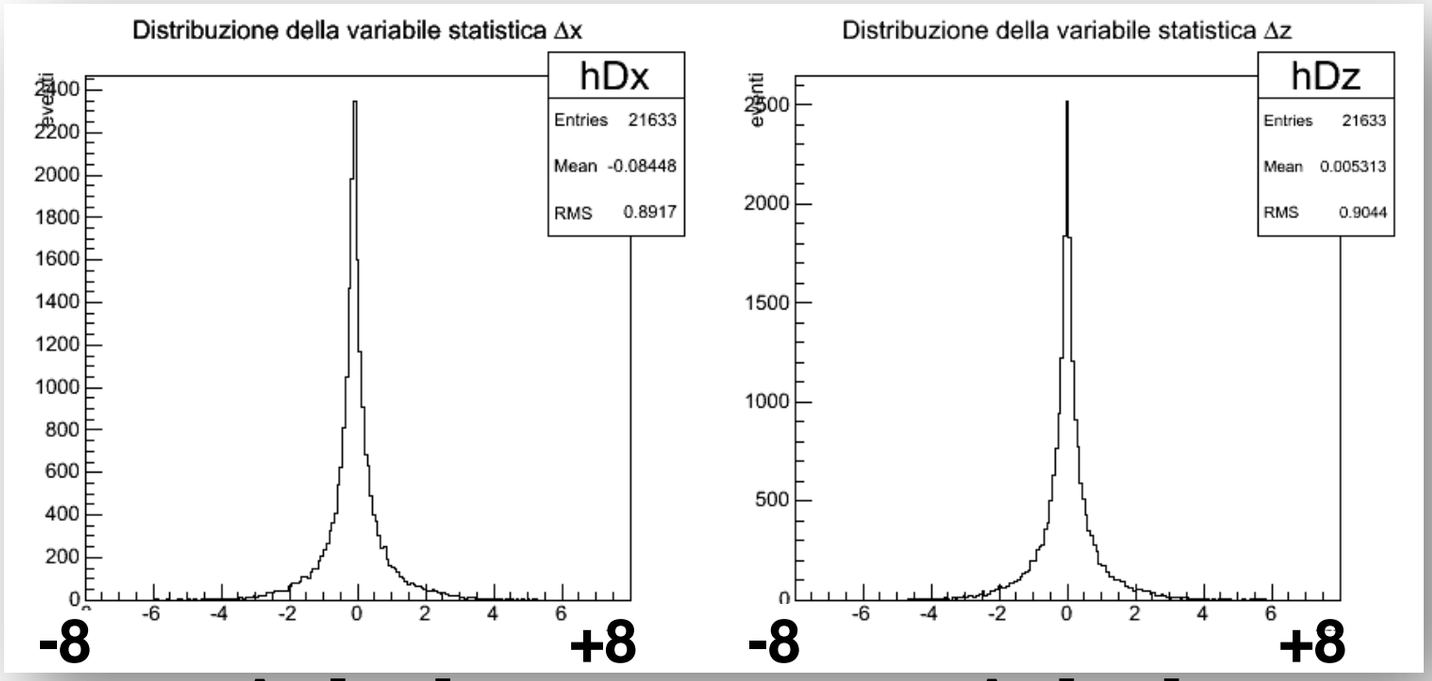


Statistical variables

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

and their distributions

position of the middle detector with respect to the other two (assuming "perfect" vertical alignment)



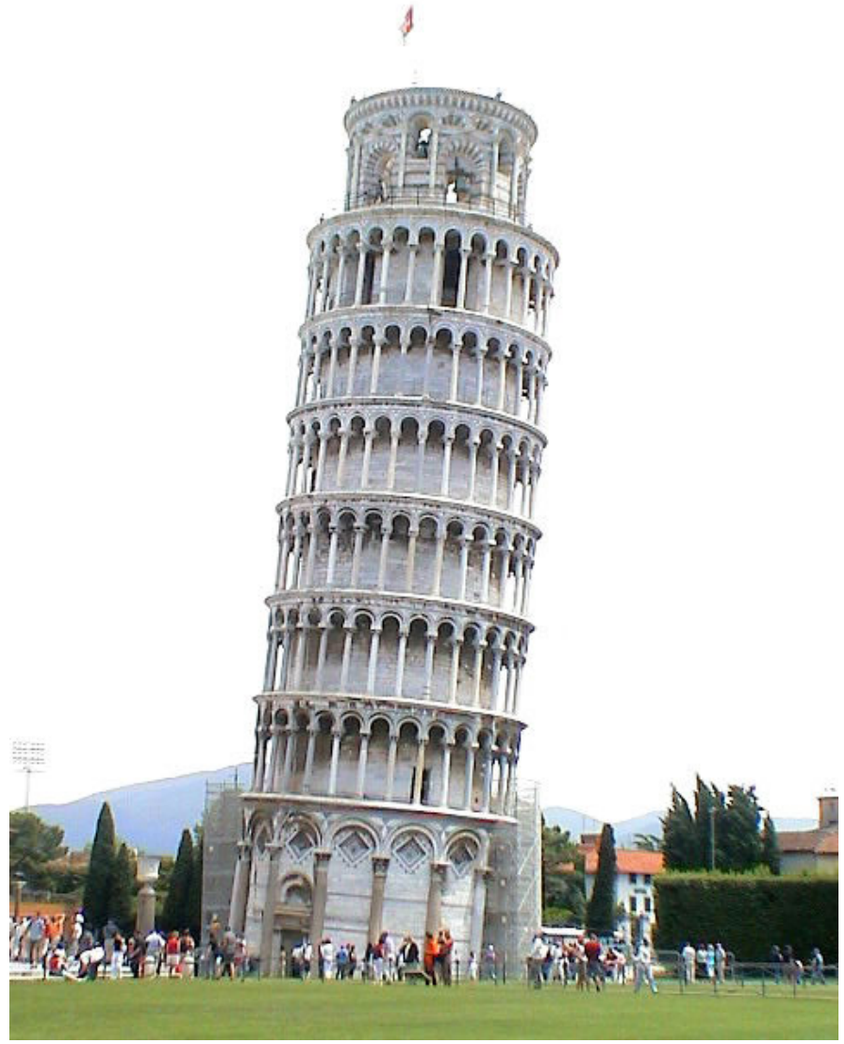
The "mean" of the distribution gives the relative position of the middle detector with respect to the other two. Once "measured" this position at a given time defined as t = 0 [through a calibration campaign] it is the possible to monitor it as a function of time to detect relative displacements

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

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

A different idea: stability systems with cosmic ray muons

- stability monitoring of “vertical structures” (towers, pillars, skyscrapers, historical buildings, etc.) is often fundamental



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
👎 low rate of cosmic muons → (relatively) long data taking

Simulation of a specific case: Palazzo della Loggia in Brescia

MONSTER&CO PROJECT (2013-14)

MONitoraggio di STrutture Edili mediante Raggi Cosmici
A project financed by the Dipartimento di Ingegneria Meccanica e Industriale, Università di Brescia

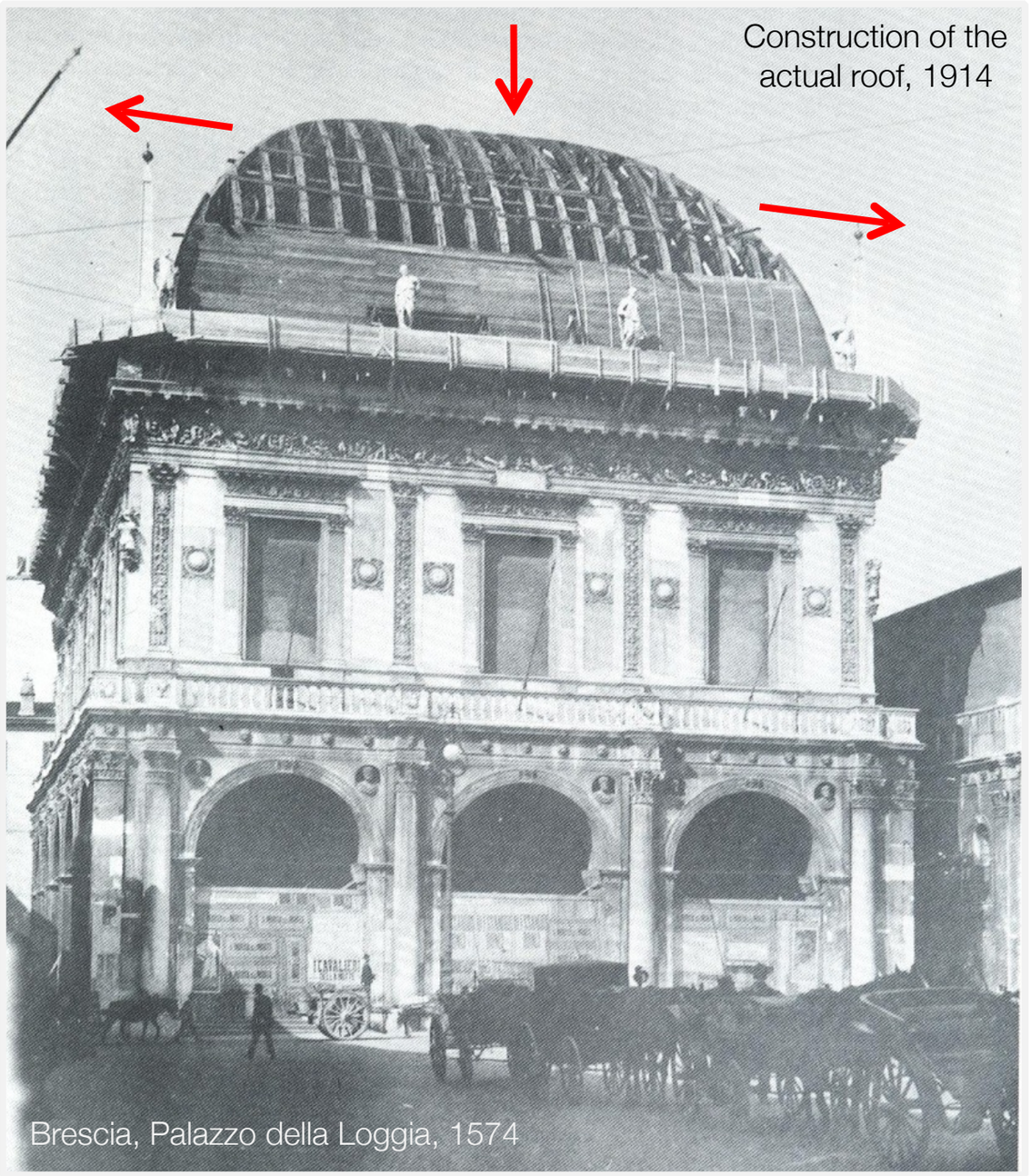
Brescia, Palazzo della Loggia, 1574

A. Donzella[1], A. Zenoni[1], G. Baronio[1], I. Bodini[1], G. Bonomi[1], D. Cambiaghi[1], M. Lancini[1], M. Subieta[1],D. Vetturi[1], V. Villa[1], C. Riccardi[2], P. Vitulo[2], G. Zumerle[3]

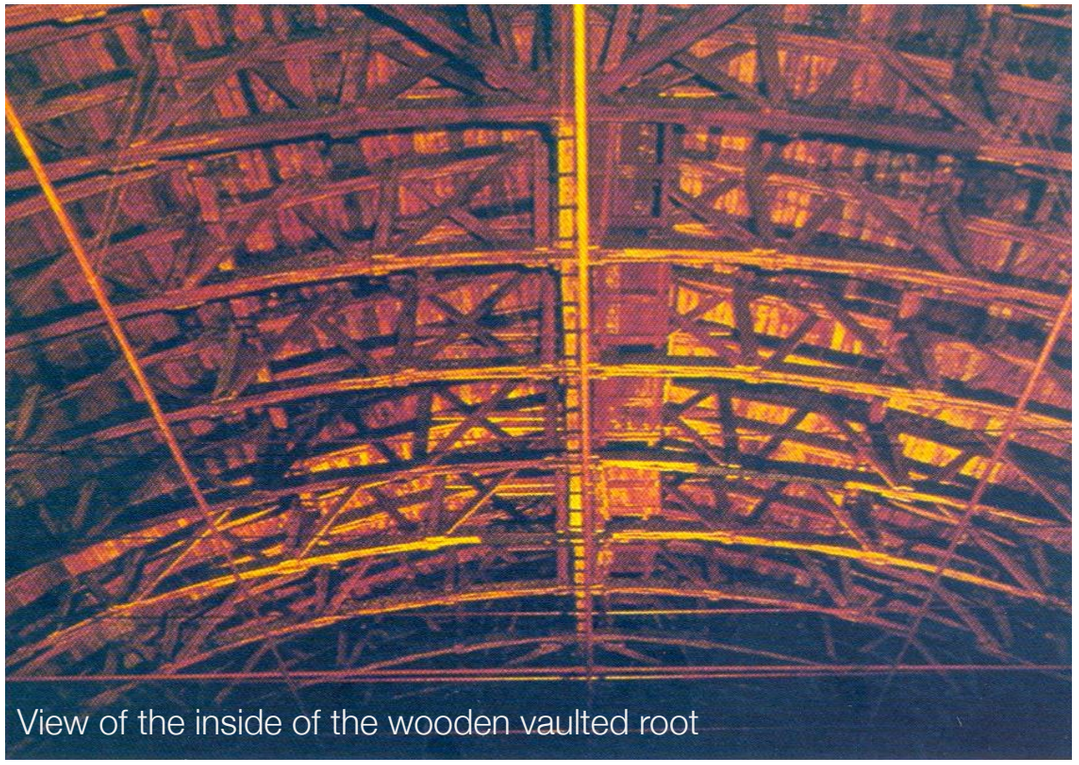
[1] Dipartimento di Ingegneria Meccanica e Industriale, University of Brescia
[2] Dipartimento di Fisica, University of Pavia
[3] Dipartimento di Fisica e Astronomia, University of Padova

Simulation of a specific case: Palazzo della Loggia in Brescia

Palazzo della Loggia: the roof has stability issues



Brescia, Palazzo della Loggia, 1574



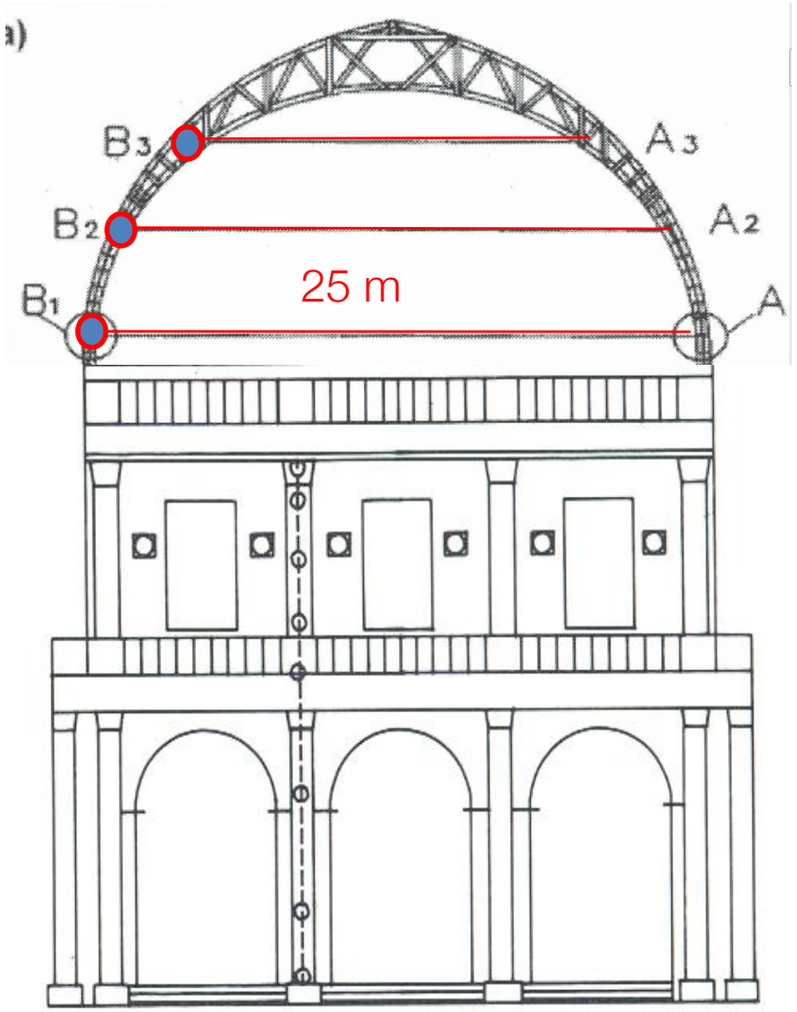
View of the inside of the wooden vaulted root

Details of a joint

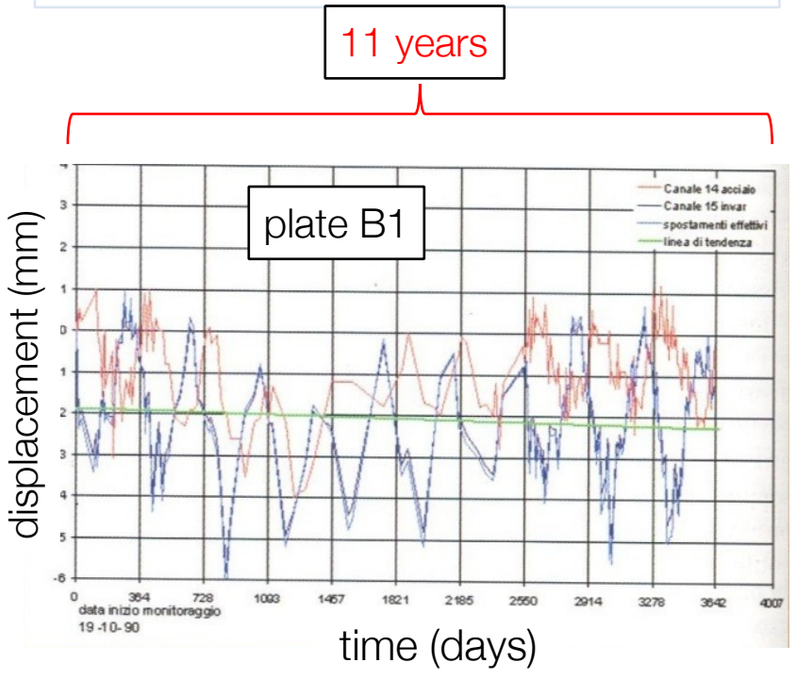
Studies reported here have been performed by the
"Centro di studio e ricerca per la conservazione ed il recupero dei beni architettonici ed ambientali"
Dipartimento di Ingegneria Civile, University of Brescia

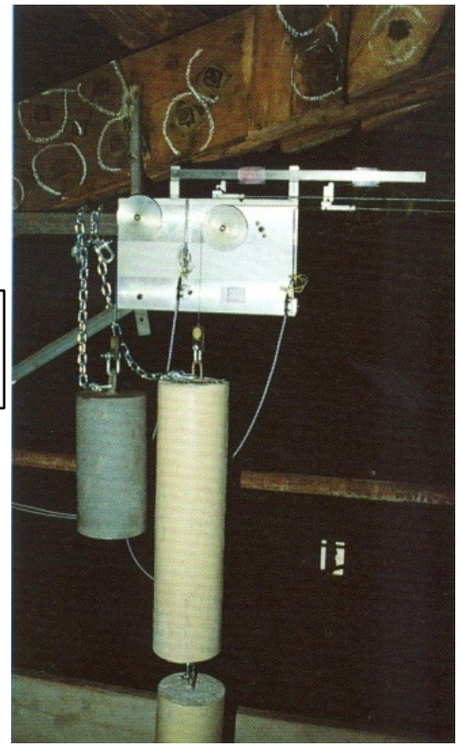
Simulation of a specific case: Palazzo della Loggia in Brescia

Palazzo della Loggia: the monitoring campaign of the "Palazzo" (1999-2001)

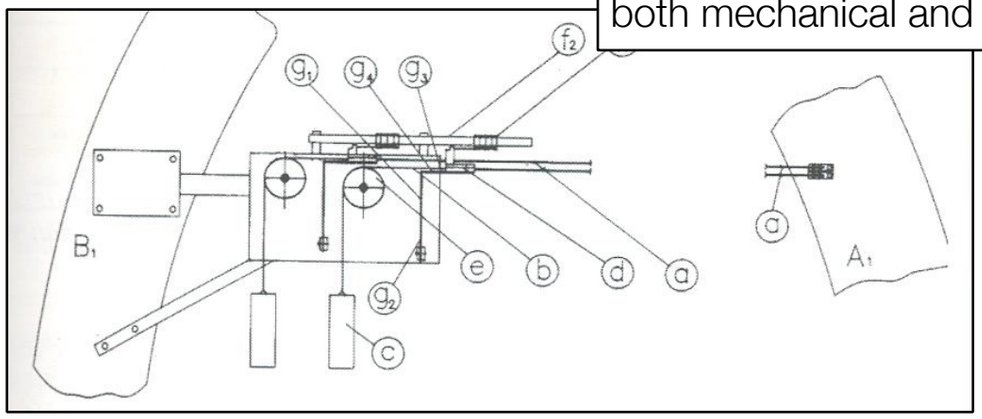


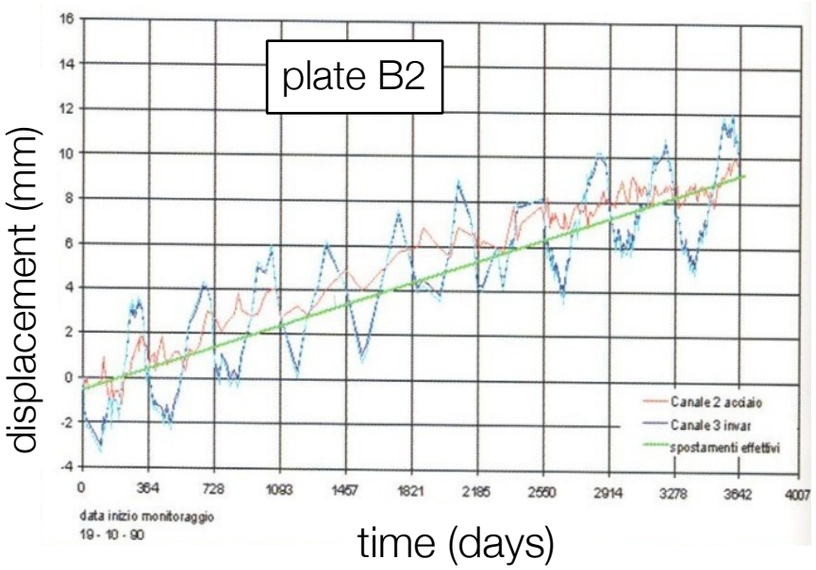
Sensors consisted in a couple of wires of invar (nickel-iron alloy) and steel to compensate for thermic variations





Measurement of elongation both mechanical and electronic





Simulation of a specific case: simulation tools

Geant 4

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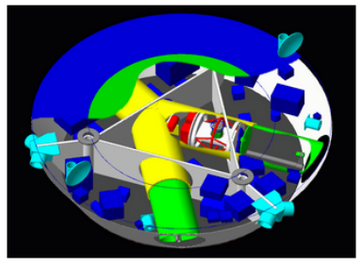
Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The two main reference papers for Geant4 are published in *Nuclear Instruments and Methods in Physics Research* A 506 (2003) 250-303, and *IEEE Transactions on Nuclear Science* 53 No. 1 (2006) 270-278.

Applications

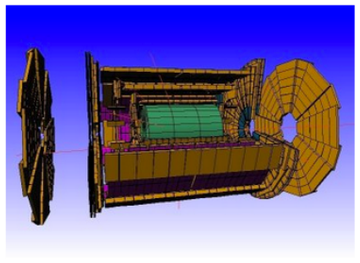
A sampling of applications, technology transfer and other uses of Geant4

User Support



Getting started, guides and information for users and developers

Publications



Validation of Geant4, results from experiments and publications

Collaboration

Who we are: collaborating institutions, members, organization and legal information

News

- *20 March 2014* - **Patch-03** to **release 9.6** is available from the source archive area.
- *19 March 2014* - 2014 planned developments.
- *28 February 2014* - **Patch-01** to **release 10.0** is available from the download area.

Events

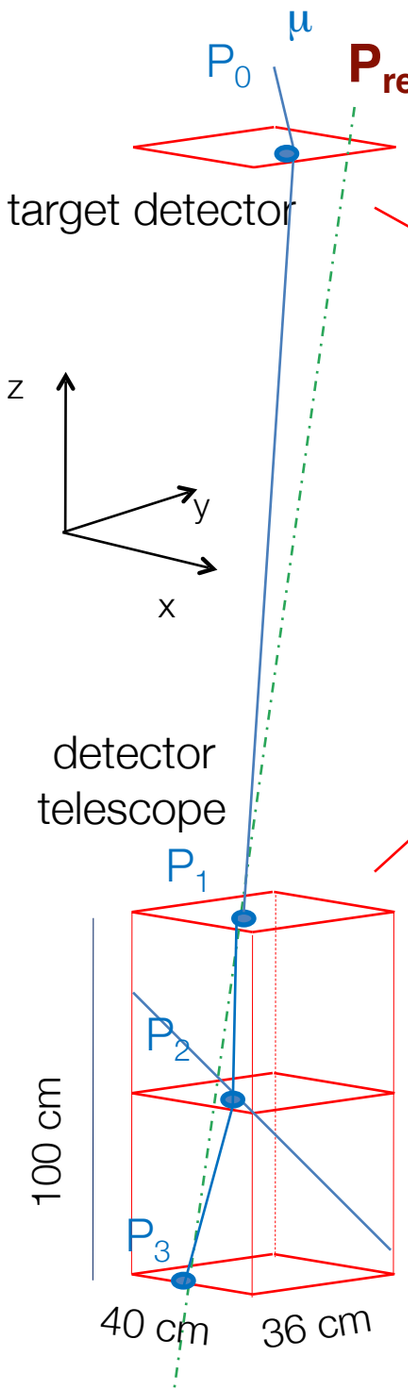
- Geant4 Course at the 11th Seminar for Nuclear, Sub-nuclear and Applied Physics, Porto Conte, Alghero (Italy), **25-30 May 2014**.
- 10th Geant4 Space Users Workshop, at NASA/MSFC, Huntsville, Alabama (USA), **27-29 May 2014**.
- International Workshop on Monte Carlo Techniques in Medical Physics, Quebec City (Canada), **17-20 June 2014**.
- 19th Geant4 Collaboration Meeting, Okinawa (Japan), **29 September - 4 October 2014**.
- **Past events**

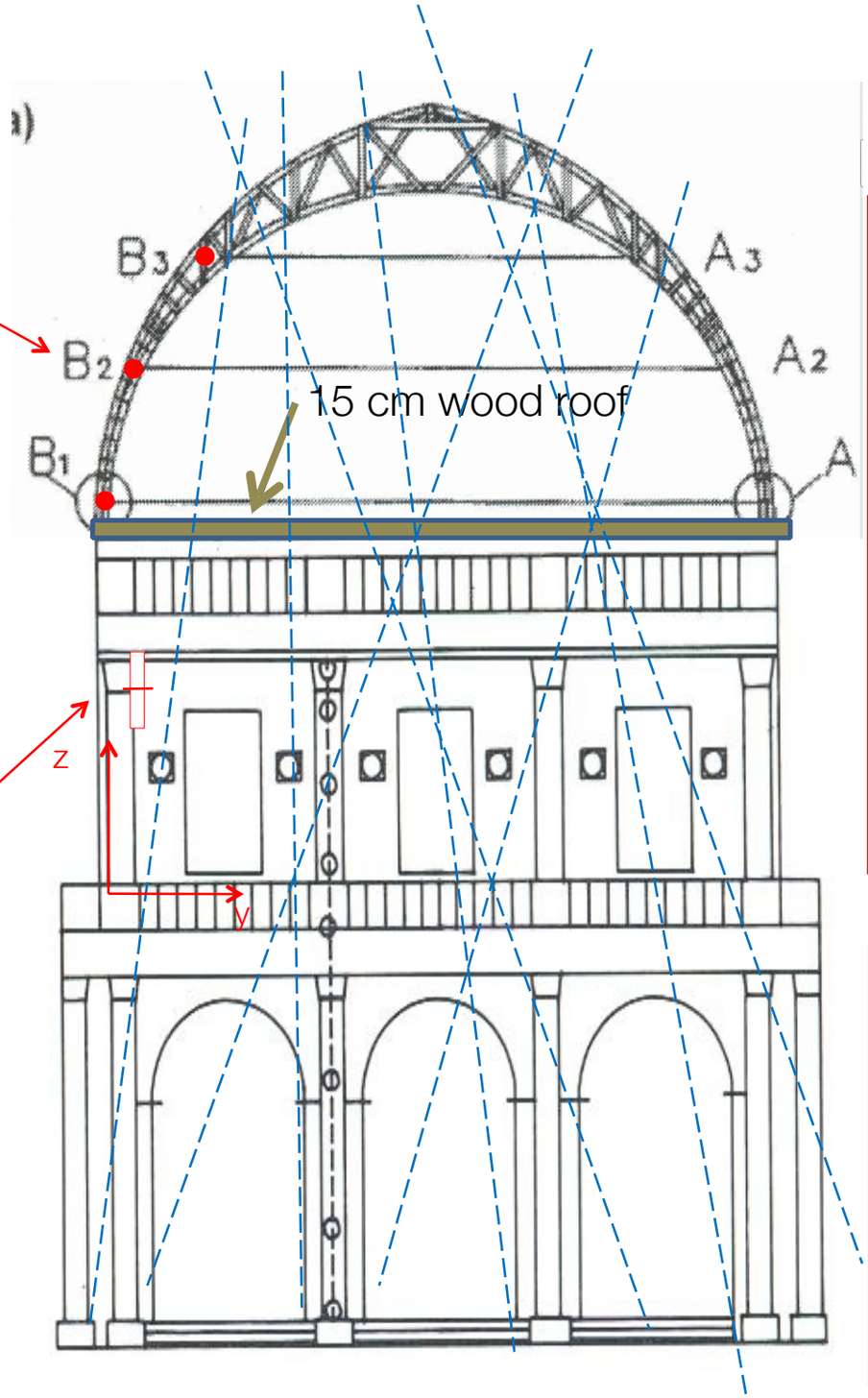
Geant4 is monte-carlo simulation toolkit – http://geant4.web.cern.ch/geant4

- Simulates radiation interactions with matter
- GEometry ANd Tracking
- HEP background
- C++ based / Object orientated

Simulation of a specific case: basic idea

Simulation: it 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)





210000 muoni/s

Why evaluating 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

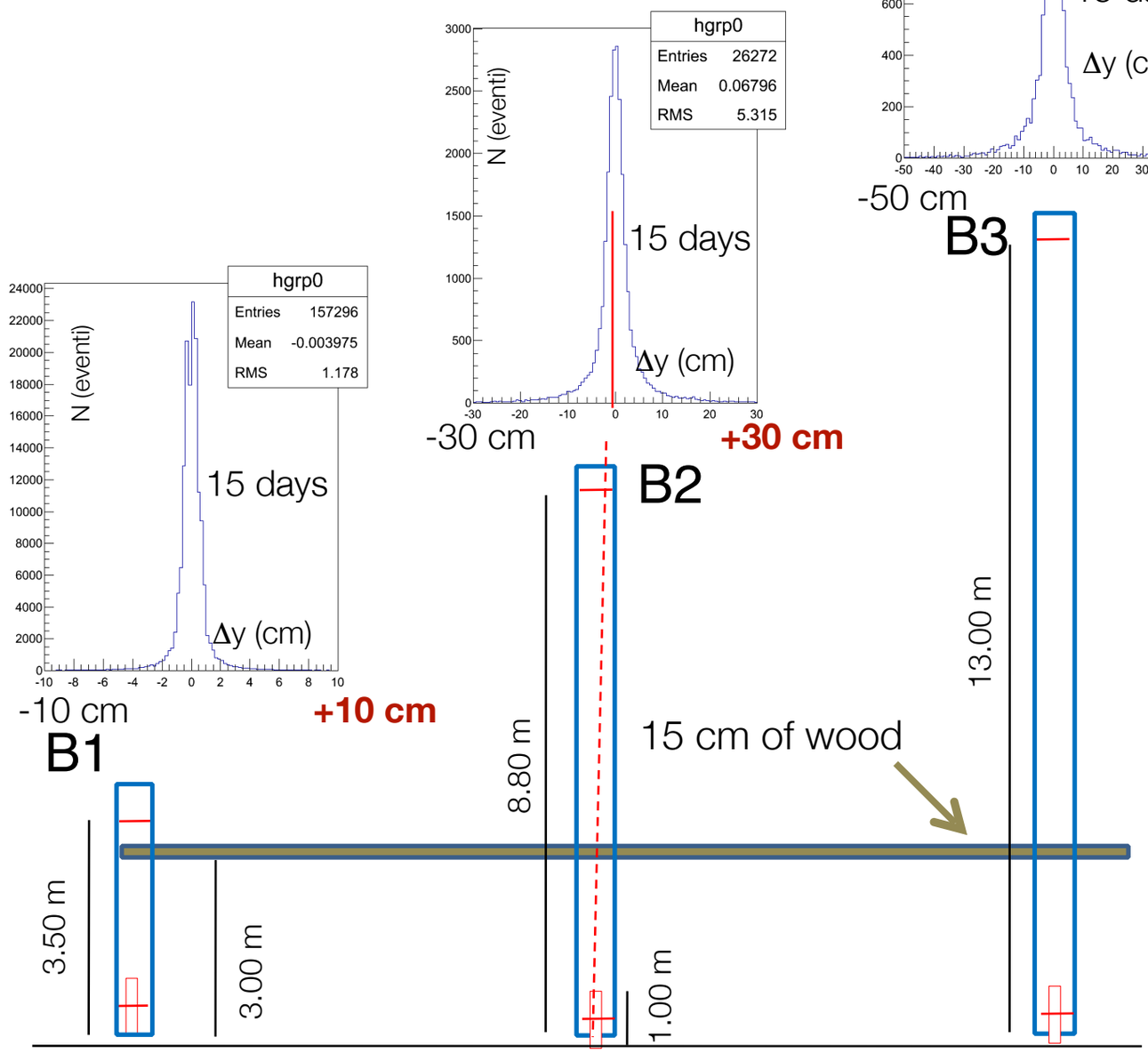
✓ the presence of statistical deviations requires the usage of distributions

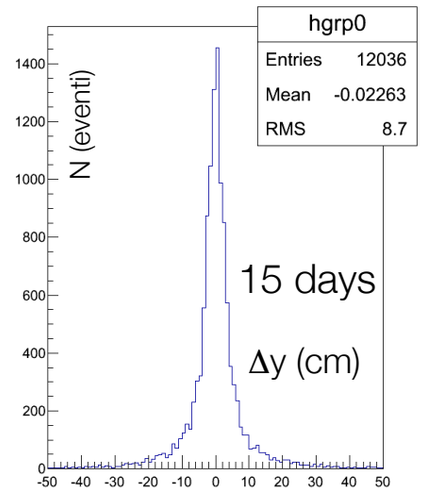
✓ the need to accumulate enough statistics and thus wait the required time

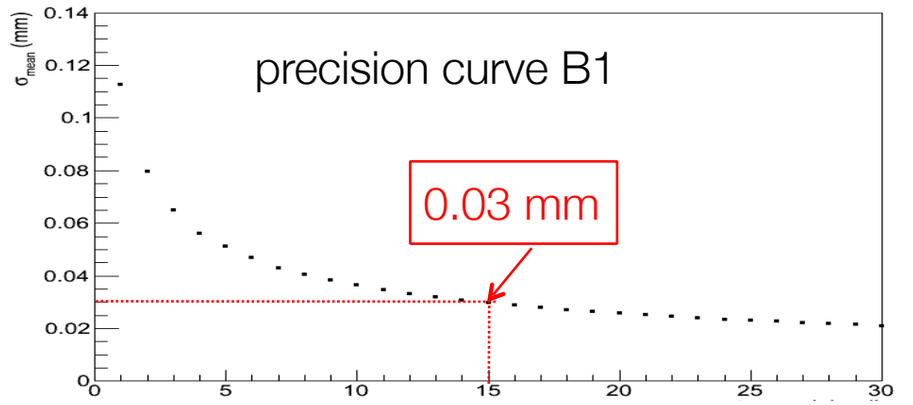
Simulation of a specific case: Palazzo della Loggia in Brescia

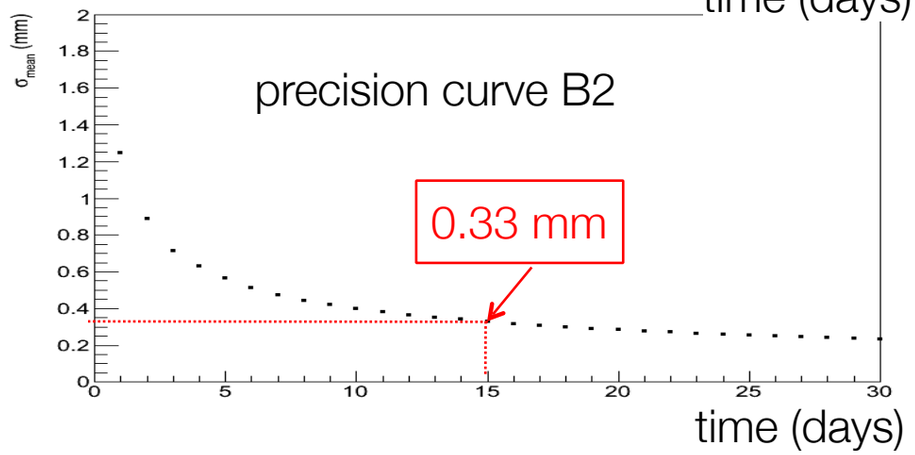
Displacement resolution as a function of time

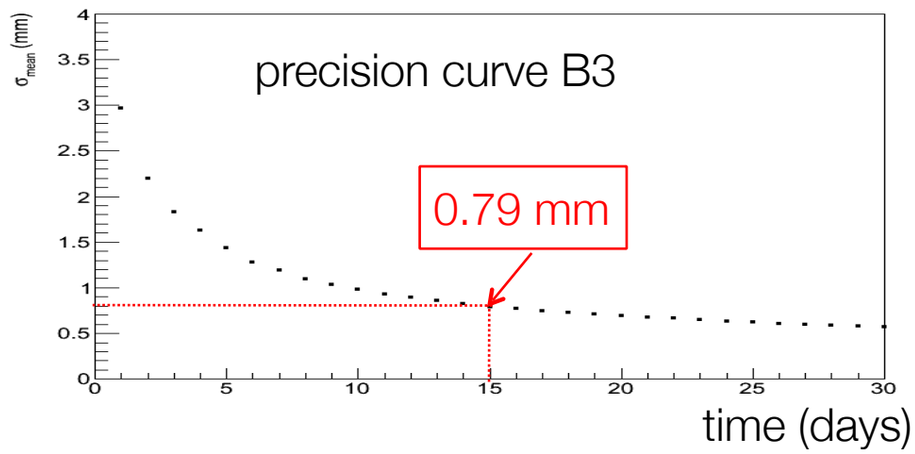
difference between the coordinate measured in the target detector and that obtained with the extrapolation based on the detector telescope measurement
(31.7 million muons crossing the "target")







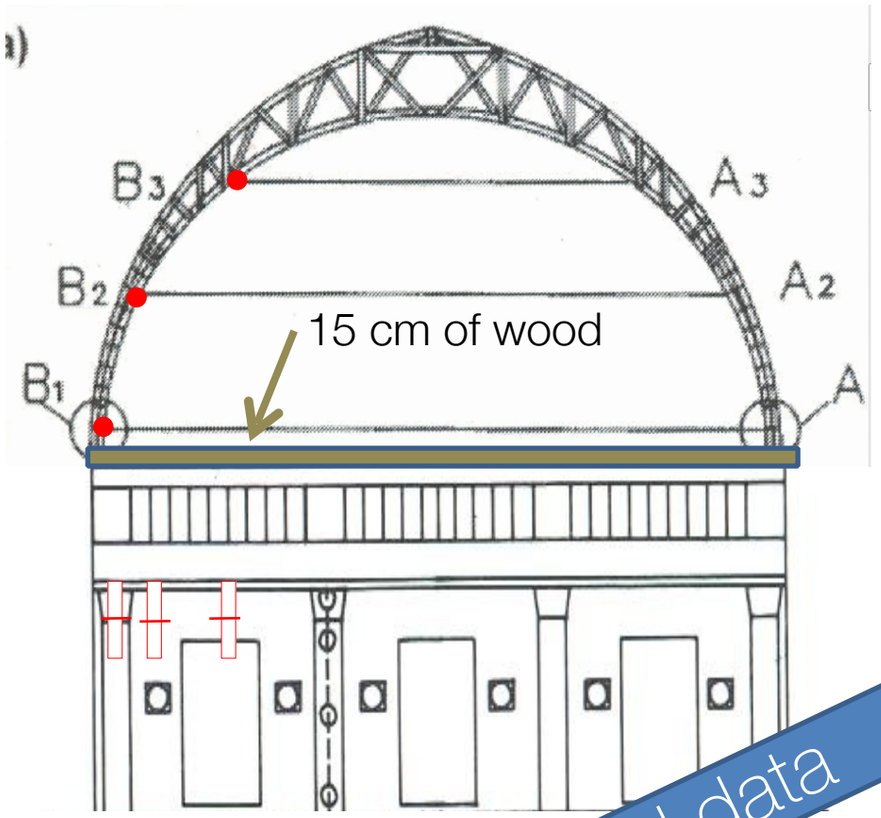




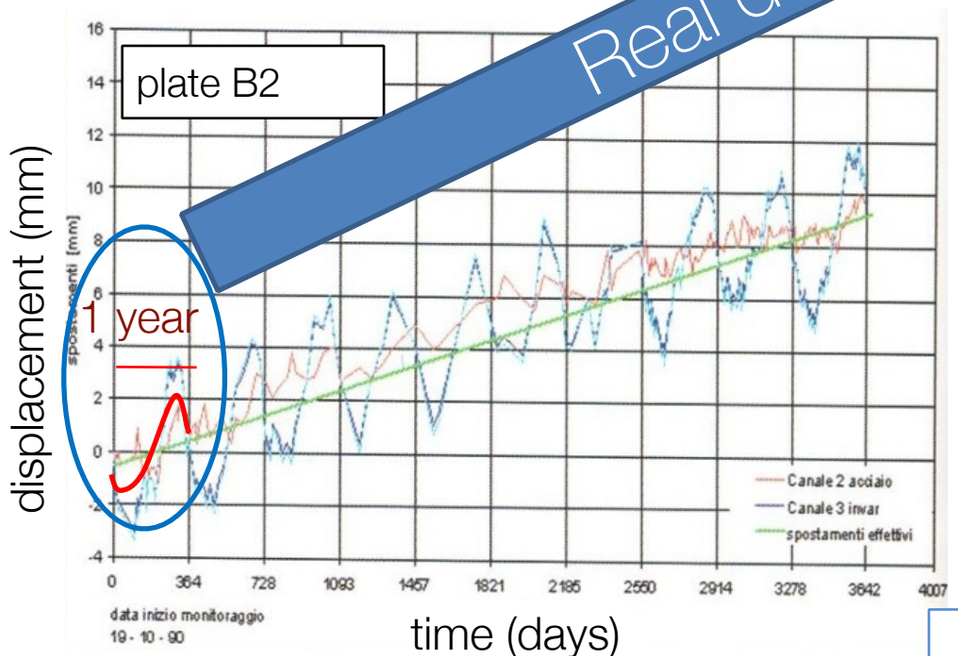
uncertainty on the mean $\sigma_{mean} = \sigma_{distr}/\sqrt{N}$

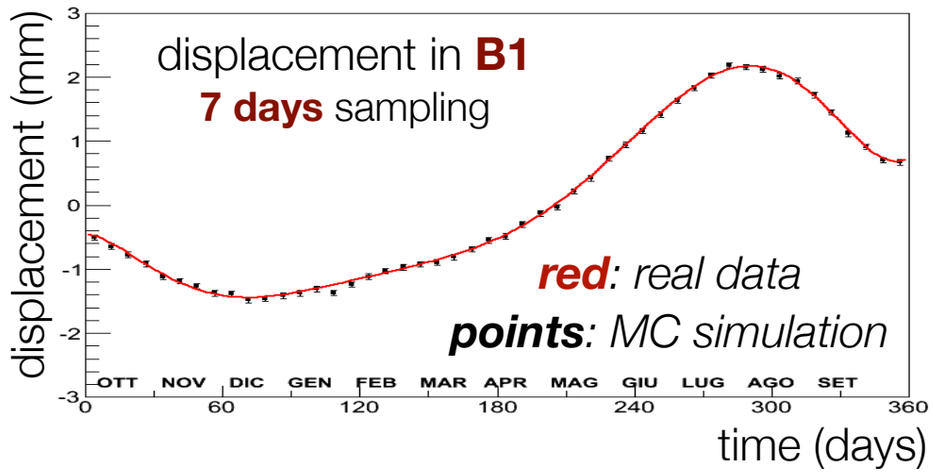
Simulation of a specific case: Palazzo della Loggia in Brescia

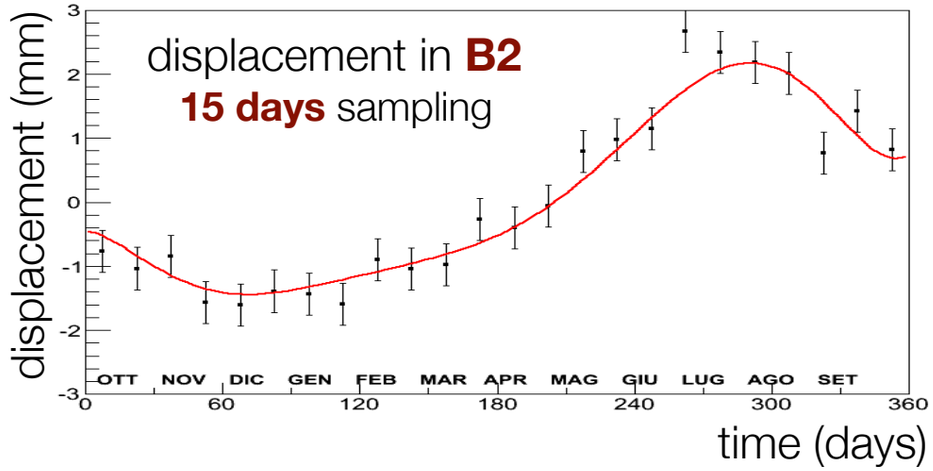
Simulation of the seasonal displacement

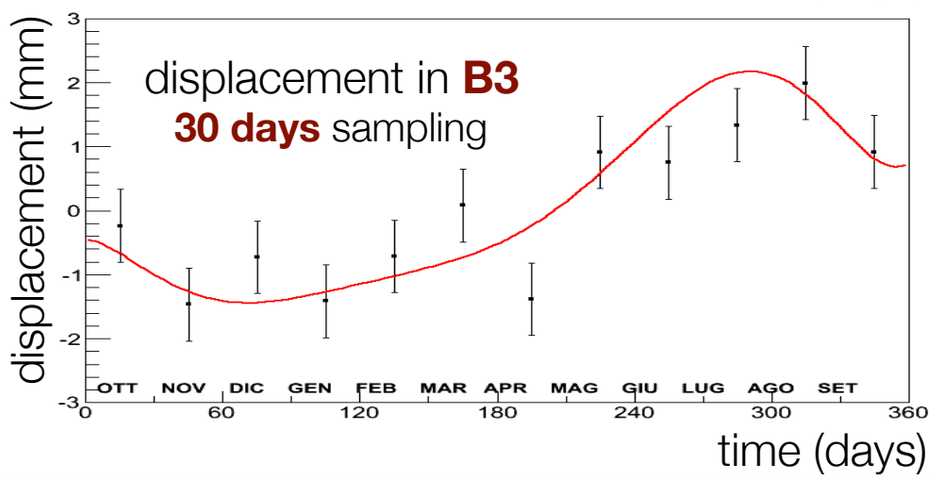


Real data



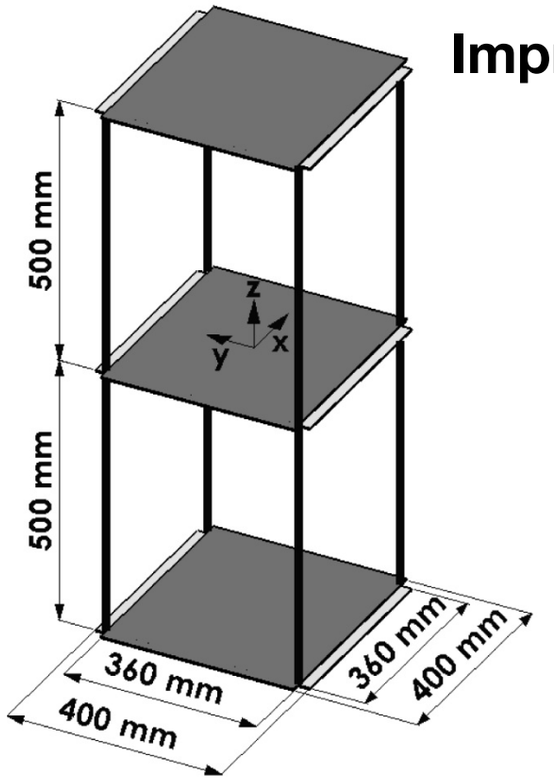






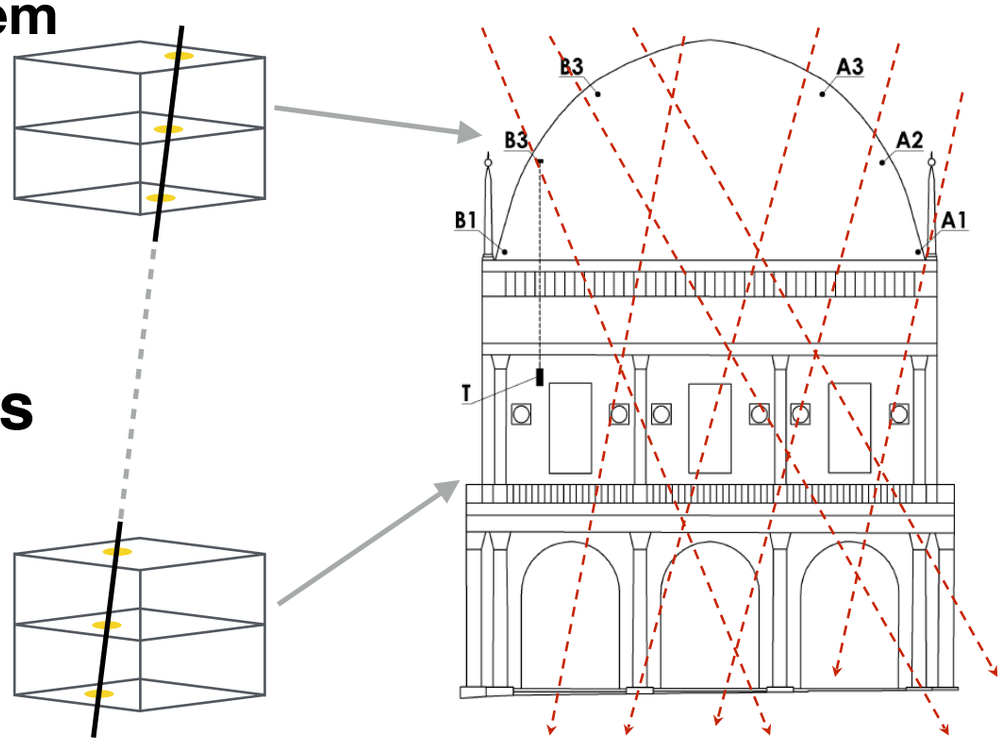
a more refined statistical analysis (a function to fit the data instead of using the mean of the distribution) can improve the resolution, if required

Simulation of a specific case: possible improvements

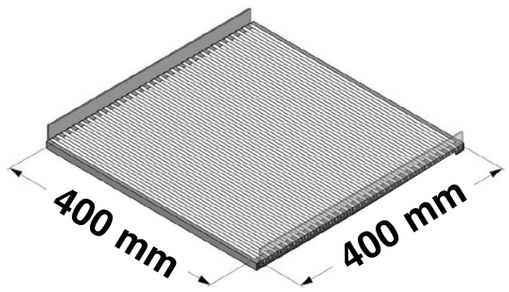


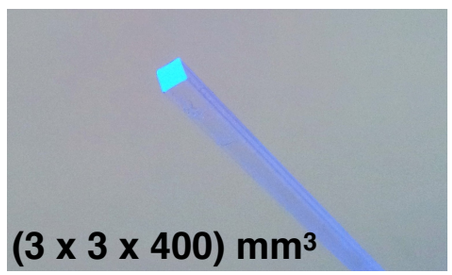
Improving the monitoring system

<u>independent</u> detectors



Proposed detector



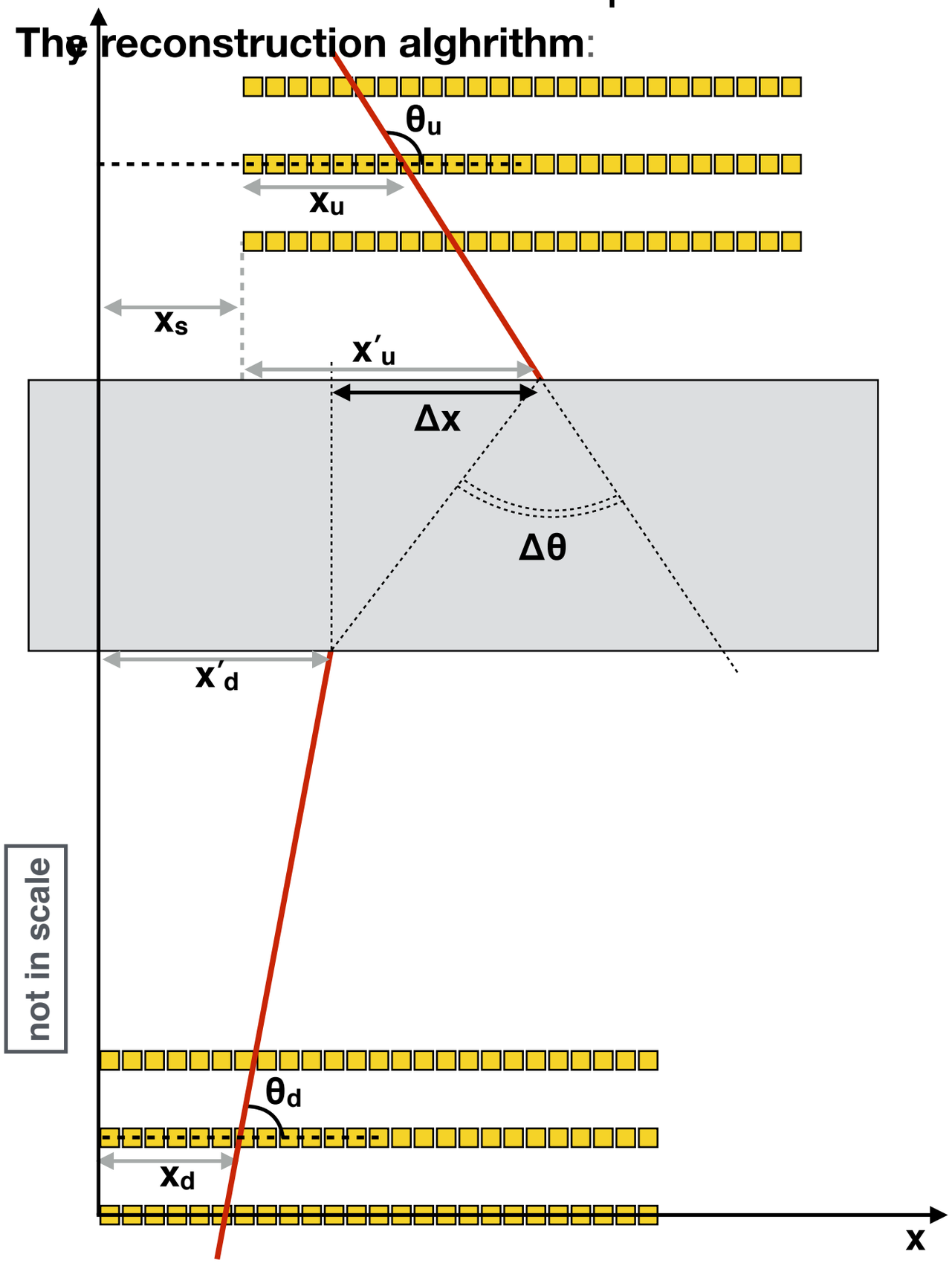


- double layers of scintillating (3 x 3) mm² fibers
- fibers coupled to SiPMs
  - “cheap”
  - low voltage operation
  - good spatial and <u>time resolution</u>

necessary to correlate reconstructed events in the two independent telescopes

Simulation of a specific case: possible improvements

The reconstruction alghrithm:



- $x'_d = x_s + x'_u + \Delta x(x_s)$
- $\theta_d = \theta_u + \Delta\theta(x_s)$
- x_s independent of the event
- Given x_s, $\forall$ event i : $\Delta x_i, \Delta\theta_i$ determined by $x_{u,i}, \theta_{u,i}, x_{d,i}, \theta_{d,i}$
- Estimate $\hat{x_s}$ from χ^2 minimization:

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

A possible detector design

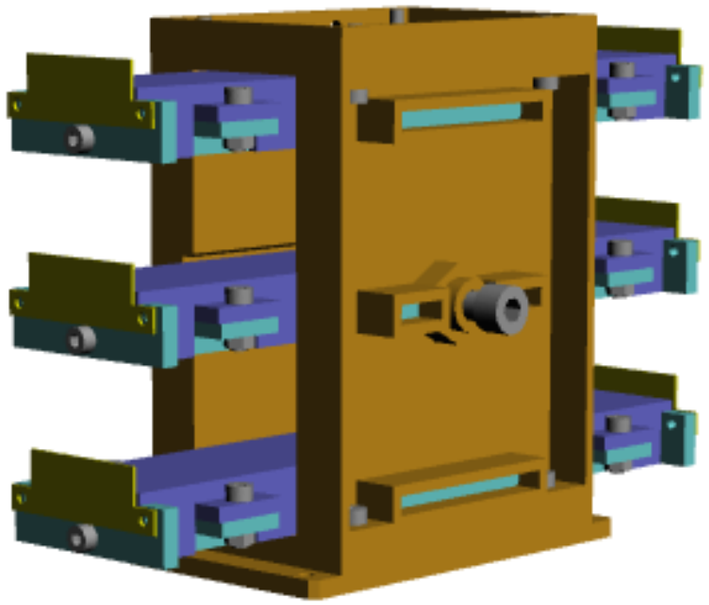
Design and development of a small-scale prototype

in collaboration with University of Pavia (P. Vitulo group)

A possible detector design: a small-scale detector prototype

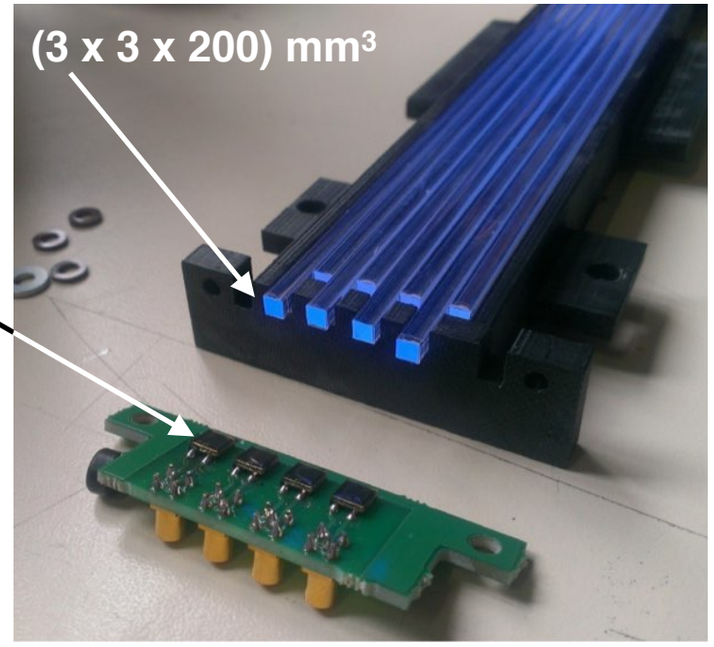
Design

- two hodoscopes (“telescopes”in the following) composed by three detecting layers



- all the mechanical supports (ABS) created with a 3D printer
- each layers composed by 8 scintillating fibers (BCF-10 from Saint-Gobain)
- each fiber coupled to a SiPM (SiPM3S-P from AdvanSiD)

Effective Active Area	3×3	mm^2
Cell Size	50×50	μm^2
Cells number	3600	–
Spectral response range	$350 \div 900$	nm
Peak sensitivity wavelength	390	nm
Photon Detection Efficiency	33	%
Breakdown Voltage	27 ± 2	V
Dark Count	$100 \times 10^3 \div 300 \times 10^3$	Cps/mm^2
Gain	4×10^6	–



A possible detector design: a small-scale detector prototype

Design

- two hodoscopes (“telescopes”in the following)
  com

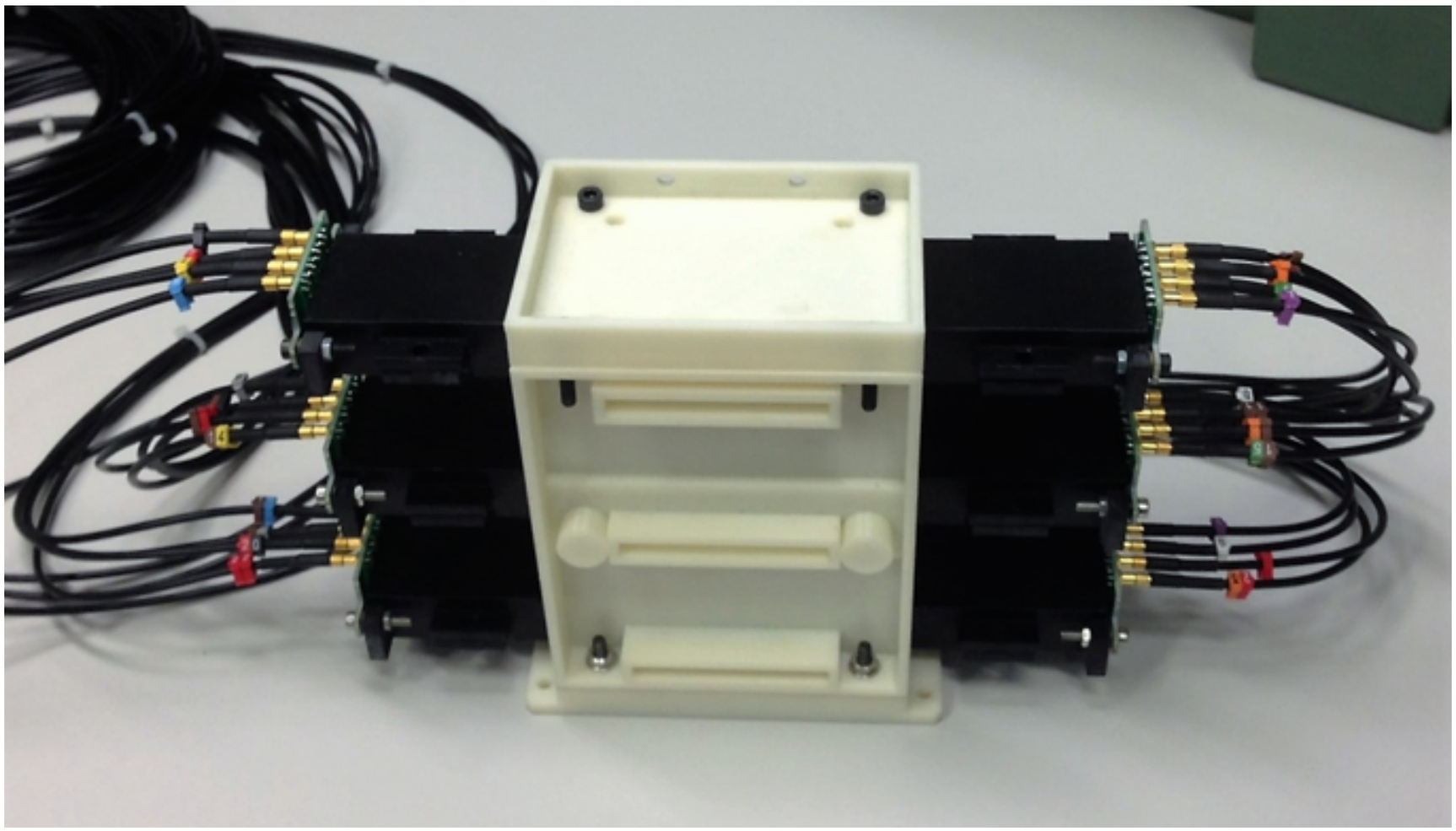
- all r

- eac
  (BC

- eac

Effe
Cel
Cel
Spe
Pea
Pho
Bre
Dar
Gain

the final telescope



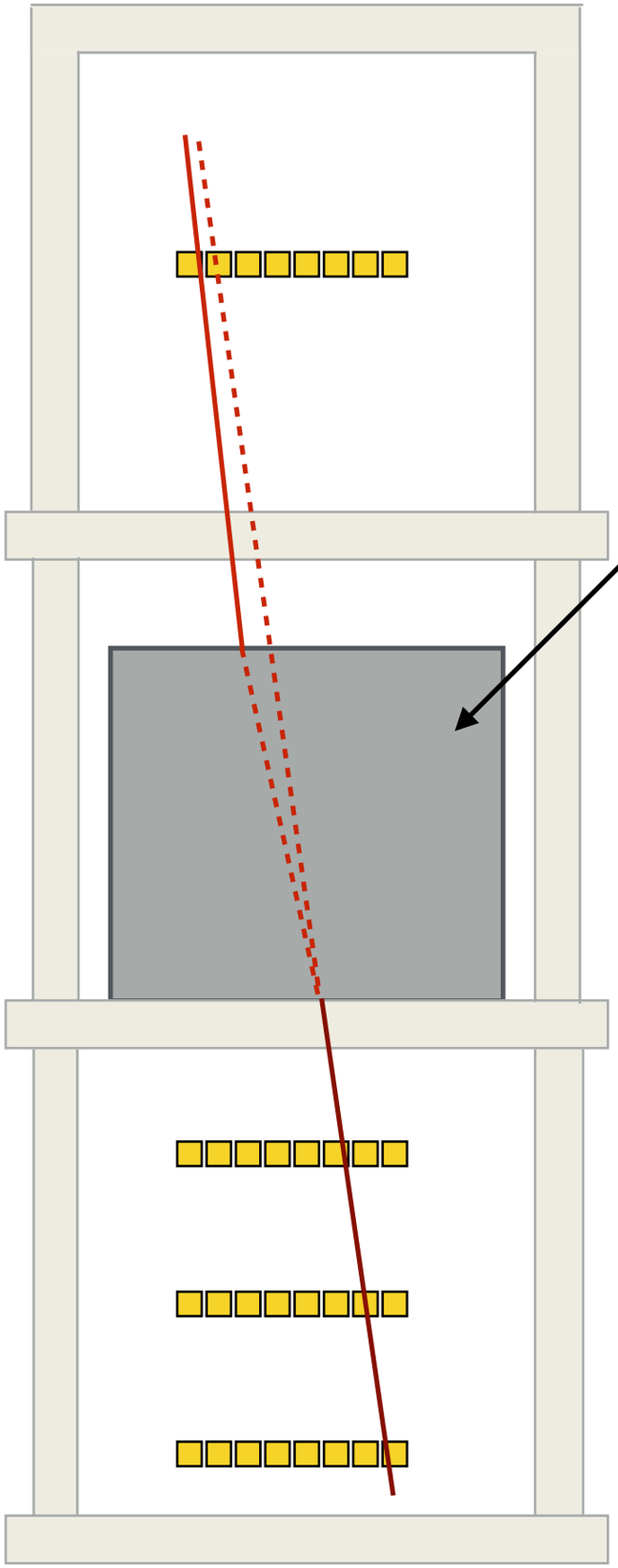
- signals from SiPMs amplified with a (custom made*) three stages amplification module, based on 3 AD8009 amplifiers (10 dB gain)

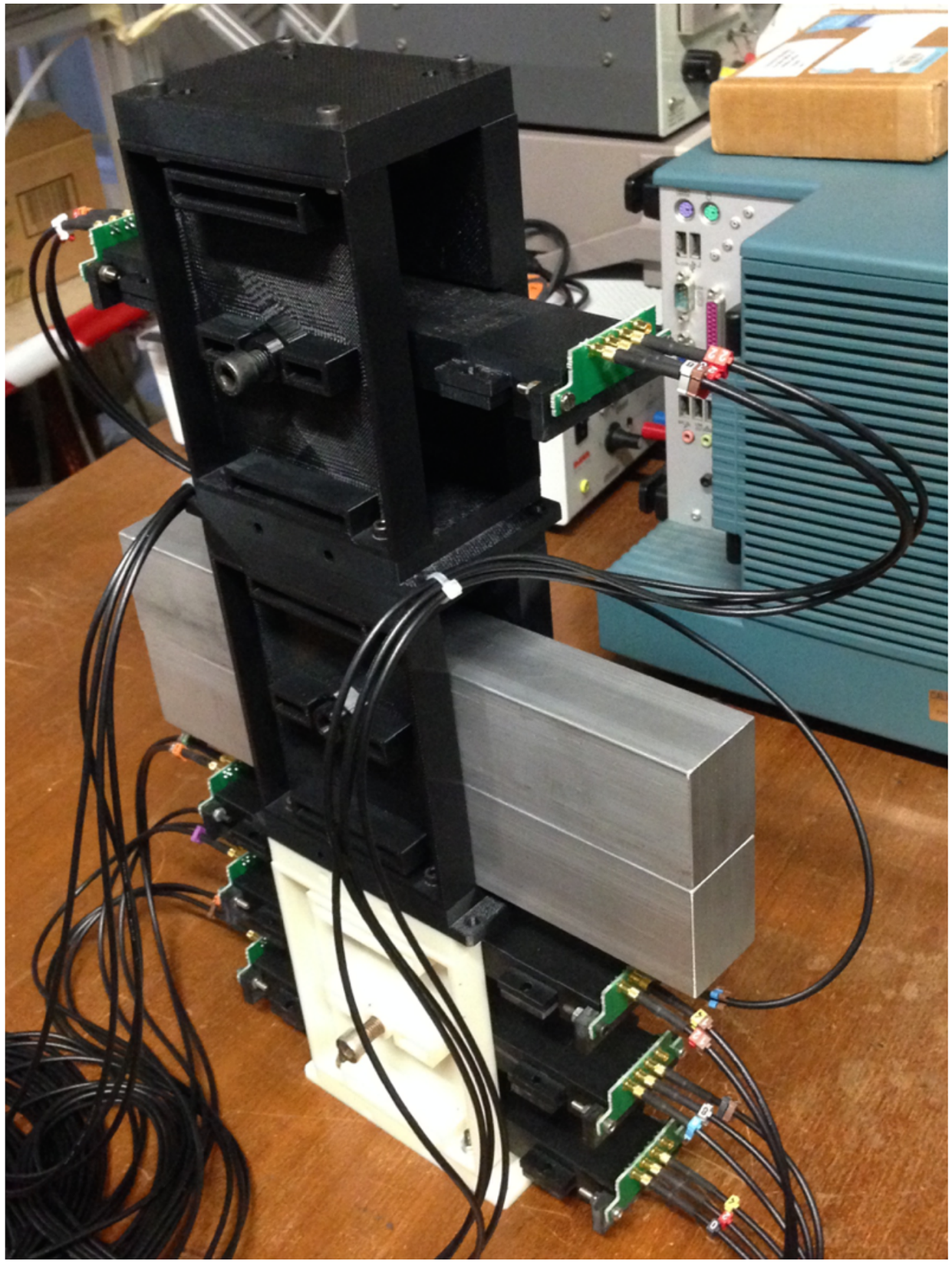
*carried out at the University of Pavia

A possible detector design: a small-scale detector prototype

Data and MC comparison for the small-scale prototype

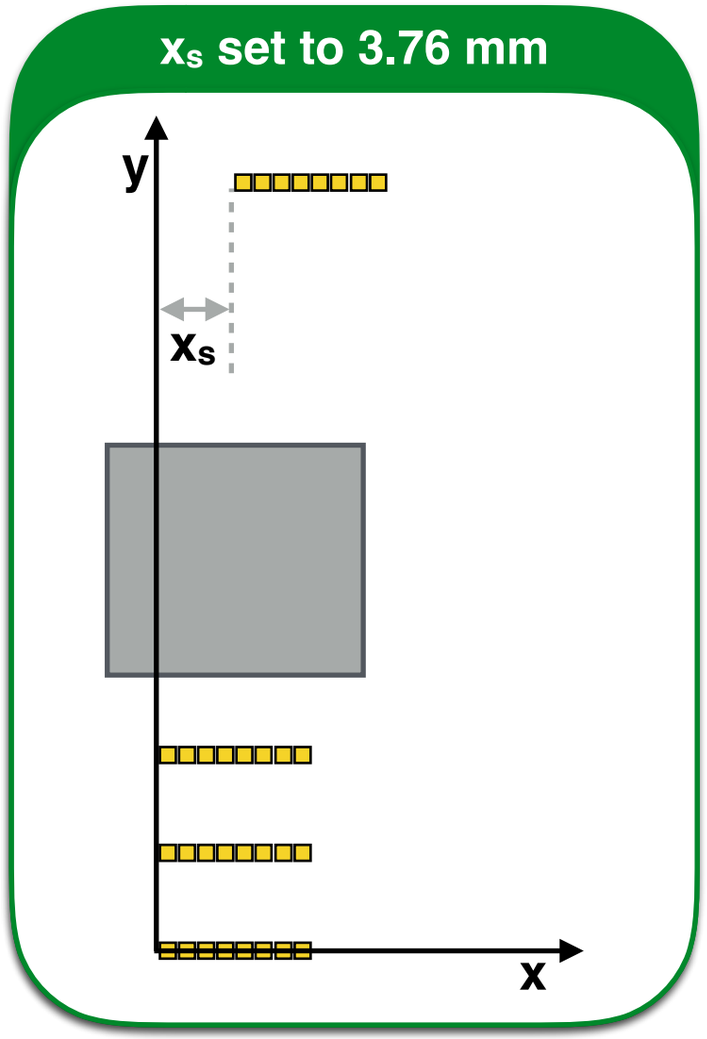
A possible detector design: experimental setup

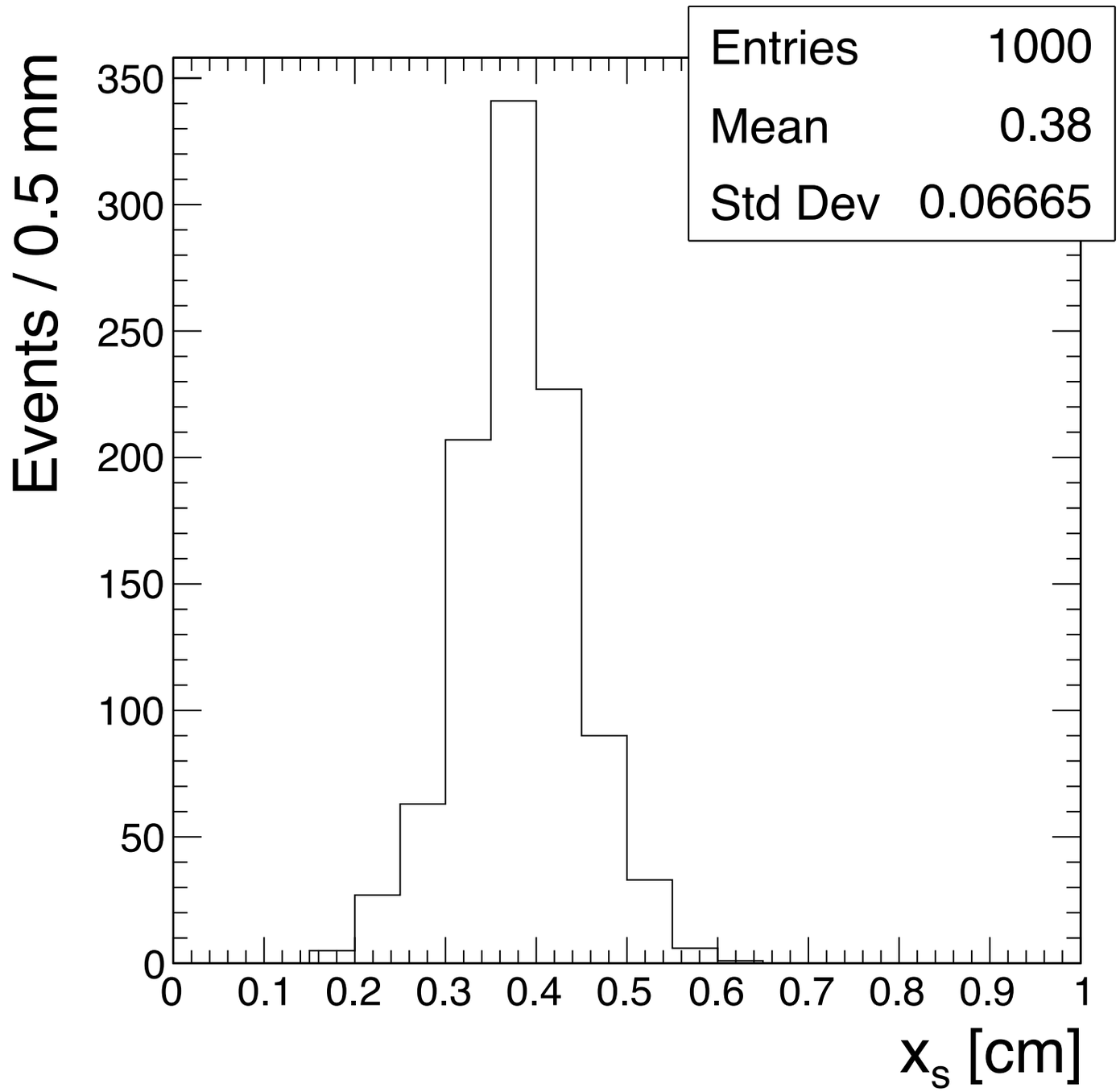




A possible detector design: experimental setup

MC





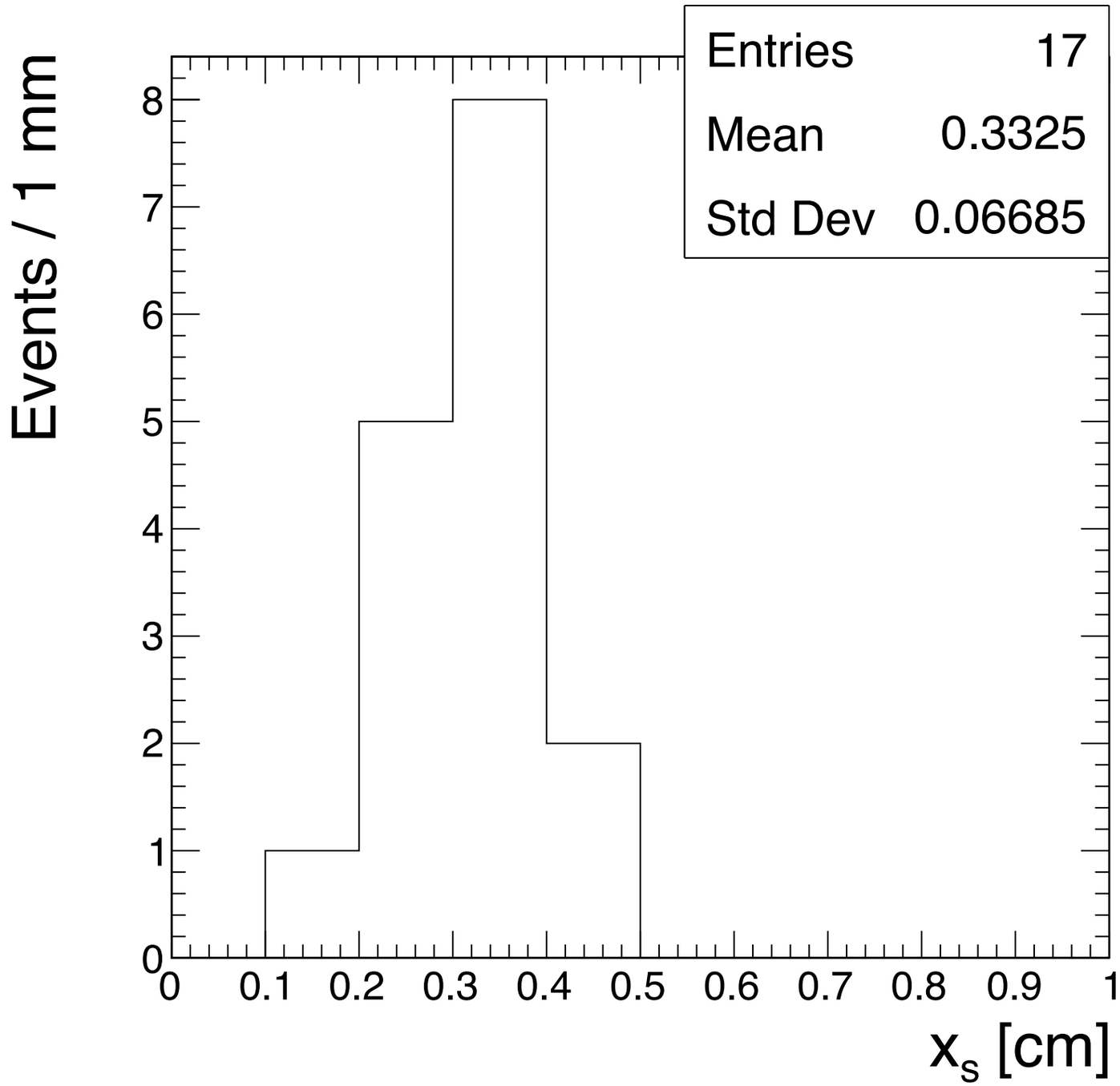
- **detector misalignment**
- **detector noise**
- **detector cross-talk**

1000 samples of 100 events each (~2 days)

with systematic uncertainties

A possible detector design: experimental setup

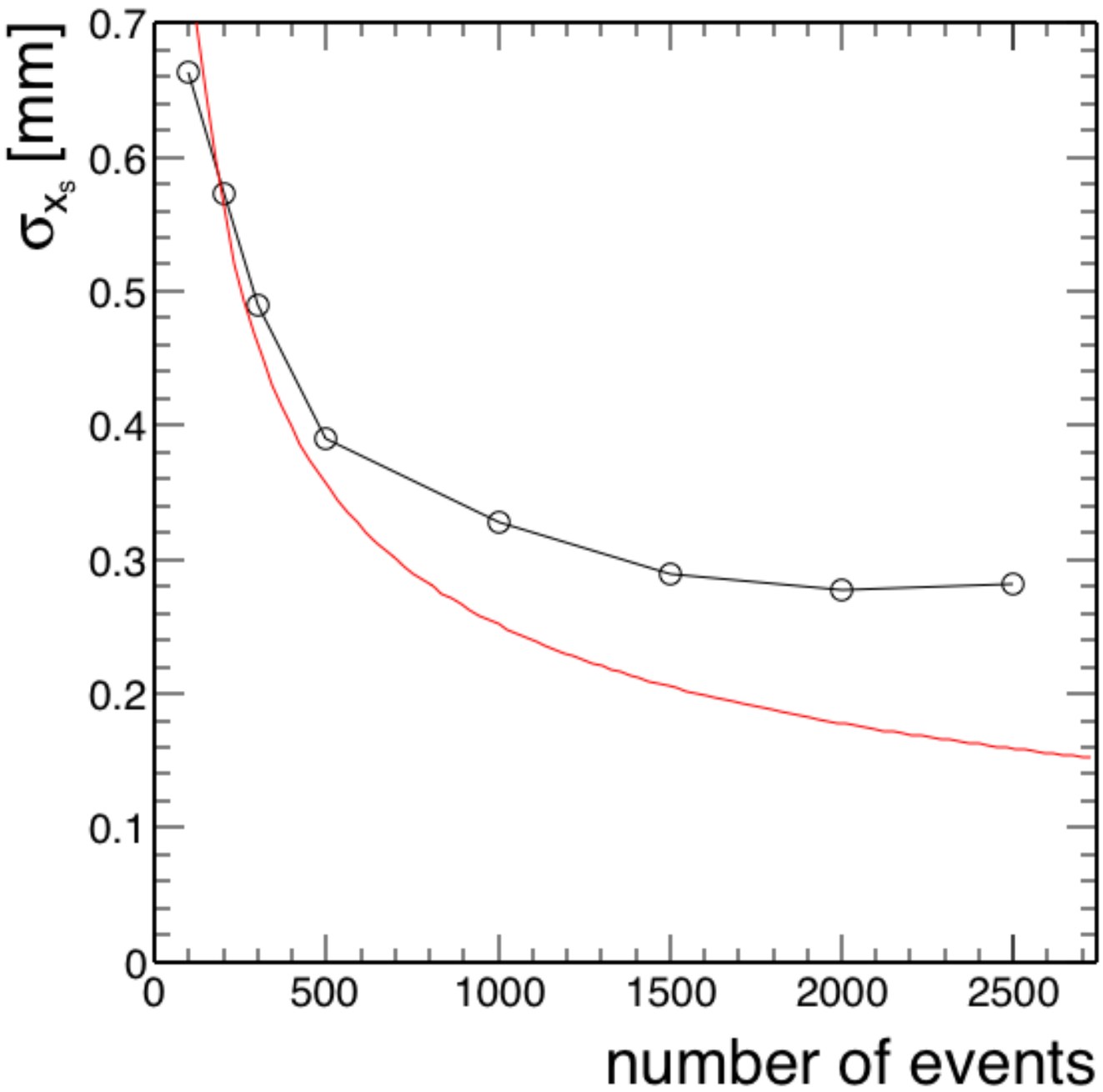
DATA



17 samples of 100 events each (~2 days)

A possible detector design: experimental setup

MC



resolutions computed with 500 samples

with systematic uncertainties

PRIN-2017 proposal to build a real-scale prototype

MIUR.AOODGRIC.REGISTRO_PRIN2017.0002291.28-03-2018

Ministero dell'Istruzione dell'Università e della Ricerca

Dipartimento per la formazione superiore e per la Ricerca

Direzione Generale per il Coordinamento, la promozione e la valorizzazione della Ricerca

PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE – Bando 2017

Prot. 2017XM82N2

PART A

1. Action line

Main line/Linea Principale

2. Research project title

Cosmic Rays as Stability Probes of Historical Buildings (CosPHi)

PRIN-2017 proposal to build a real-scale prototype

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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

- 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