APPLICATIONS OF MUON RADIOGRAPHY

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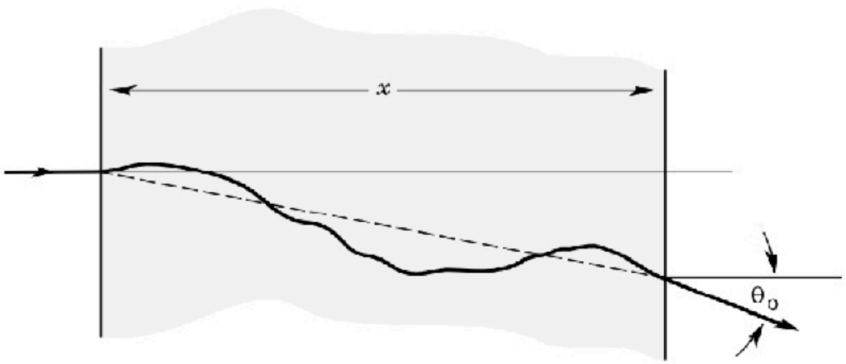
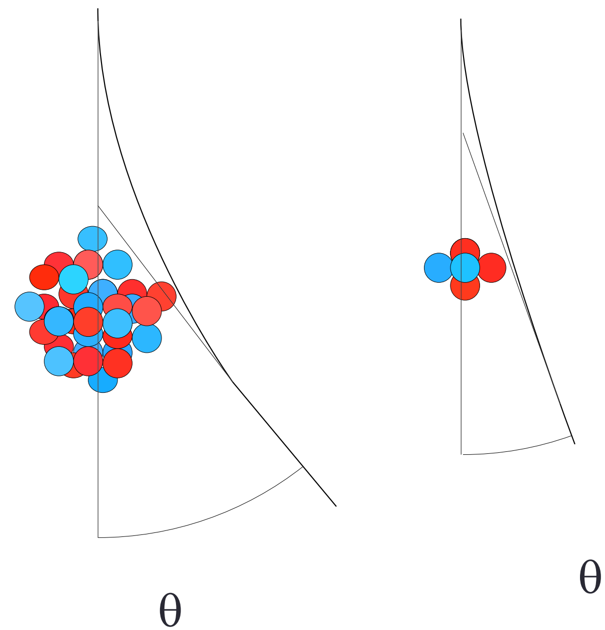
LA-UR-17-21967

Muon Multiple Coulomb Scattering

- When muons traverse matter they are deflected due to Multiple Coulomb Scattering on the nuclei.





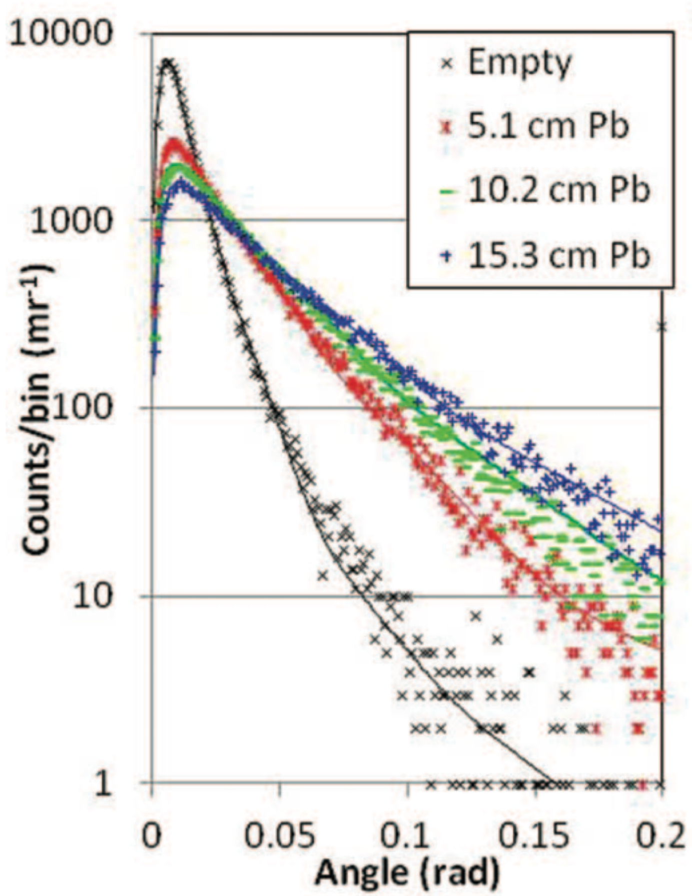
material thickness

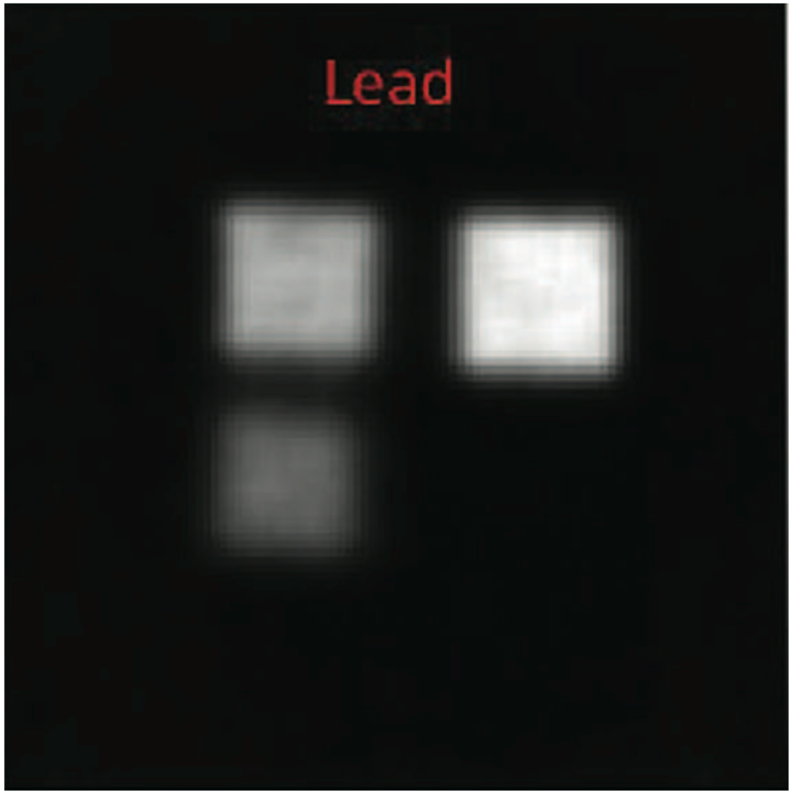
$$\frac{dN}{d\theta} = \frac{N}{2\pi\theta_0^2} e^{-\frac{\theta^2}{2\theta_0^2}} \qquad \theta_0 = \frac{14.1MeV}{pc\beta}\sqrt{\frac{l}{X_0}}$$

radiation length for material

$$\frac{1}{X_0} = \frac{Z/(Z+1)\ln(287/\sqrt{Z})}{A \cdot 716.4 g \cdot cm^{-2}}$$

Example

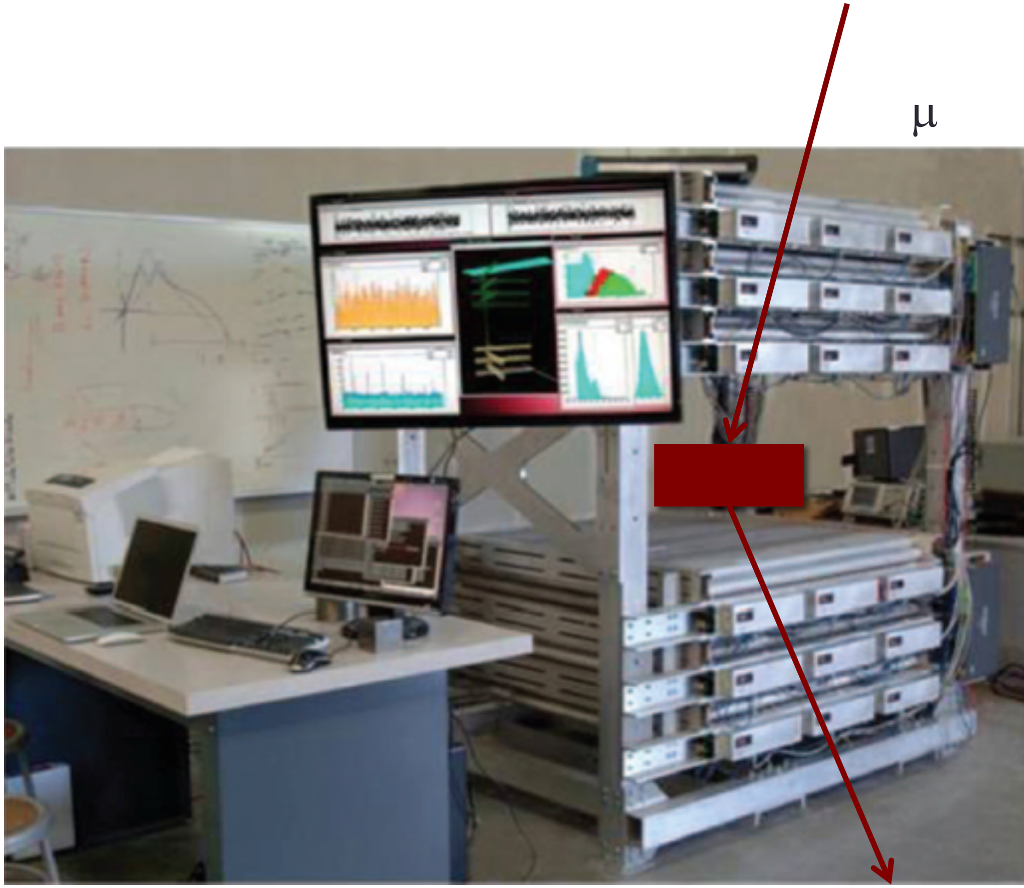




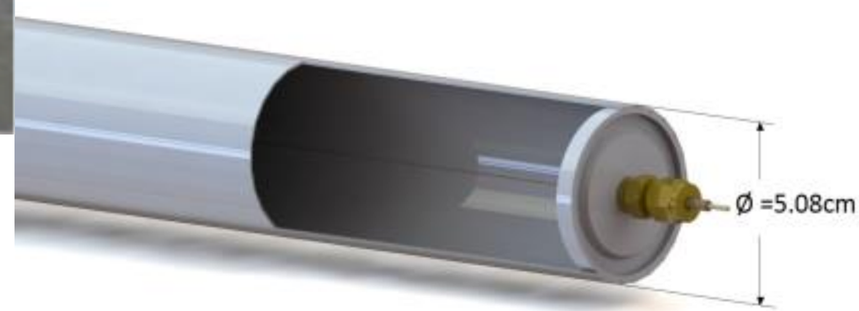
AIP Advances **2**, 042128 (2012)

Three different thicknesses of lead

Our detector: the Mini Muon Tracker



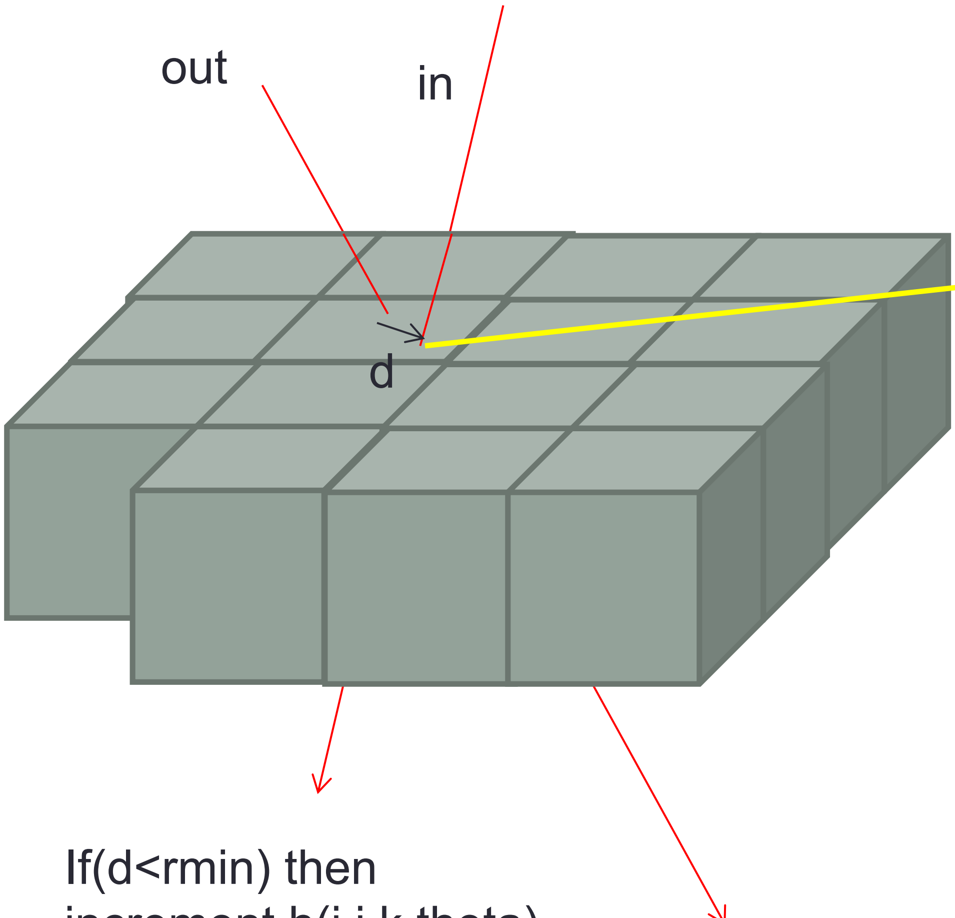
- 576 drift tubes arranged in X and Y layers
- Trackers size: 120 cm x 120 cm x 60 cm
- Trackers weight: ~800 lb/tracker
- The object of interest is placed between the trackers
- The trackers determine the trajectory of the incoming and outgoing muon, hence the scattering angle

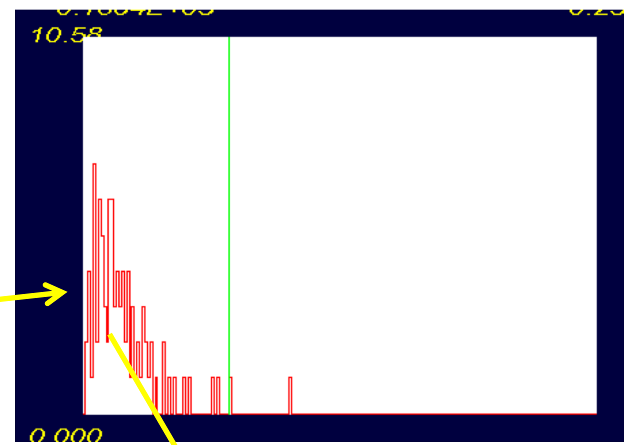


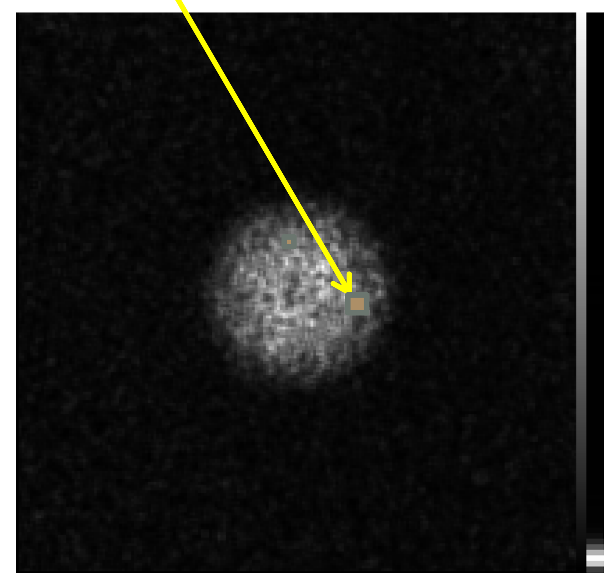
Gas mixture: 47.5% Ar, 42.5% CF_4, 7.5% C_2H_6, 2.5% He

Al tubes, gold-plated anode wire, 30-μm diameter

Generating multiple scattering images







If(d<rmin) then
increment h(i,j,k,theta)

MCS echnique developed by C. Morris’ team at LANL

IMAGING THE DOME OF SANTA MARIA DEL FIORE

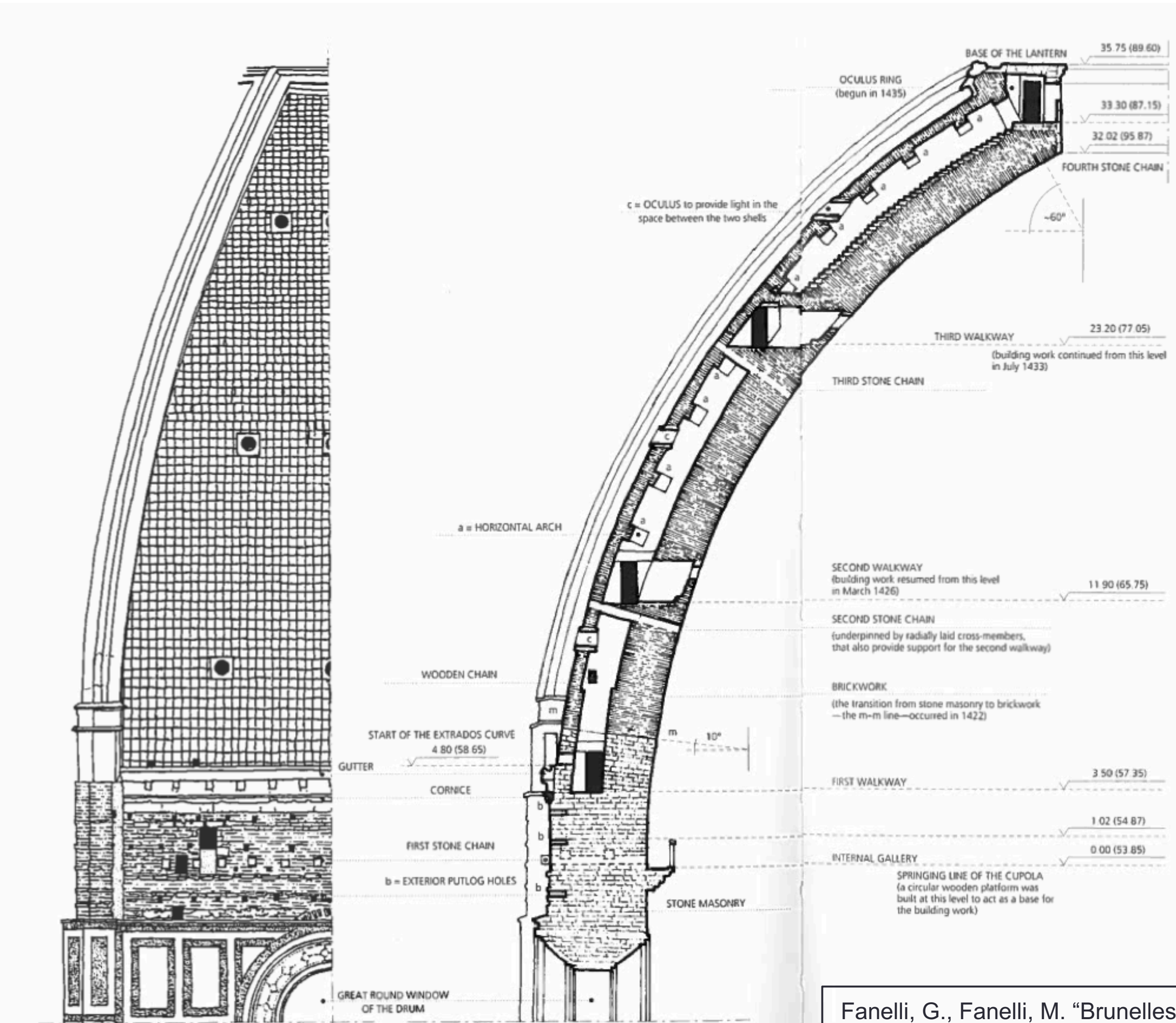
- Santa Maria del Fiore (Saint Mary of the Flower) church in Florence (Florence Cathedral)

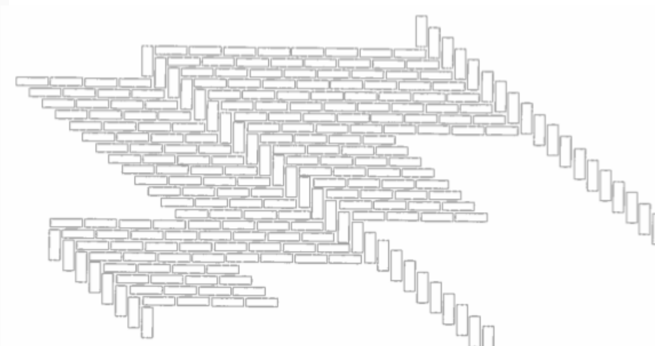
Brunelleschi's Cupola

- The church is today one of the UNESCO World Heritage sites and among the highest profile buildings in existence.
- Its Dome was built between 1420 and 1436 under the direction of Filippo Brunelleschi.
- Octagonal base: the diameter of the circle circumscribed to the octagon is 44.308 m.

Brunelleschi’s Cupola

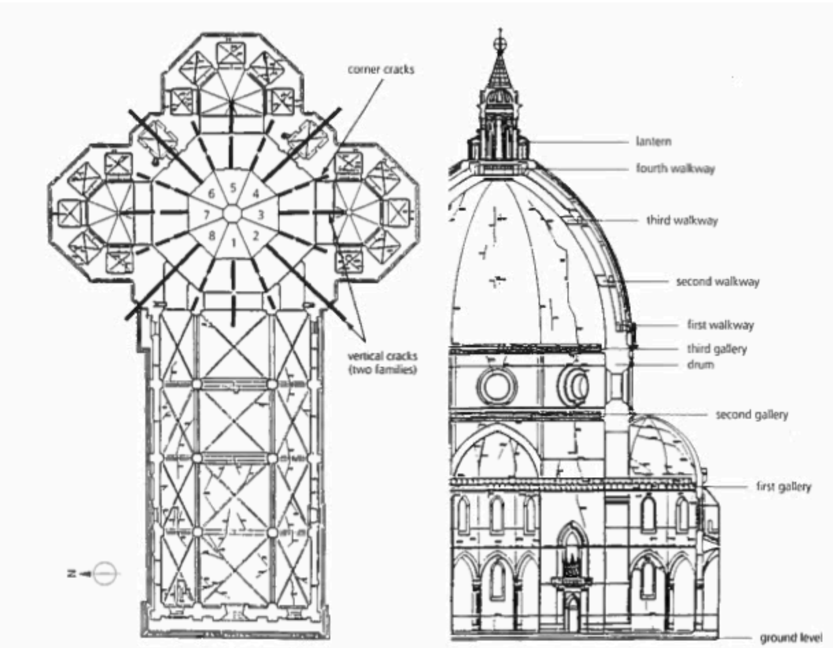
- Made of two shells, the inner one 2.25m thick at the base, the outer one 0.8m thick.
- Built out of sandstone blocks up to ~ 7m above the springing, brickwork above.
- Was built without centering (no temporary support structure)



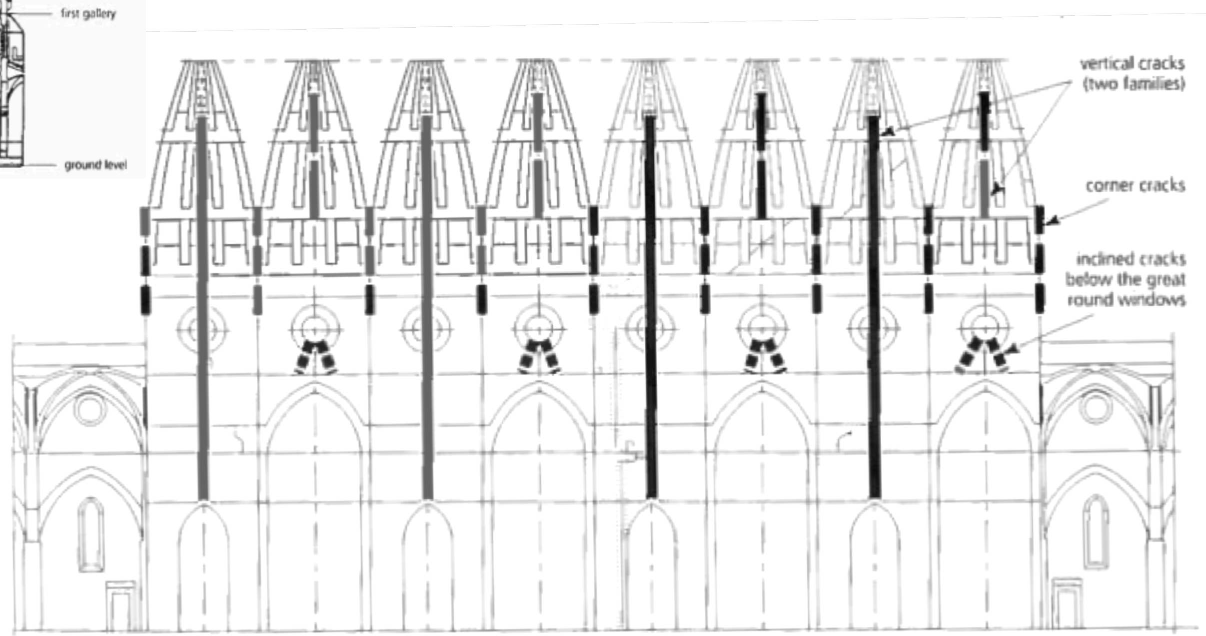


Fanelli, G., Fanelli, M. “Brunelleschi's Cupola: Past and Present of an Architectural Masterpiece”

The cracks



- The dome has been affected by cracks for centuries. They likely appeared shortly after the completion of the Cupola, they were first mentioned in 1639.
- Their width increases by 7.5 mm/century.
- The largest are up to 6-8 cm wide.
- Cracks are through both shells



Fanelli, G., Fanelli, M. "Brunelleschi's Cupola: Past and Present of an Architectural Masterpiece"

Muon tomography applied to the Cupola

- A detailed knowledge of the structure of the Cupola would benefit the finite element calculation models that are used to evaluate its behavior under static and dynamic conditions.
  - Brunelleschi purposely didn't leave drawings
- Multiple scattering muon radiography could be used to image the inside of the dome's walls.
  - Iron elements could be seen
  - The cracks' profile inside the wall could be determined, and this would shed light on how the wall itself was built.
    - Brick pattern
    - … or just the two visible brick walls filled with gravel and mortar?
    - How deeply were the cracks filled during the past centuries?

Partially filled segment of a crack

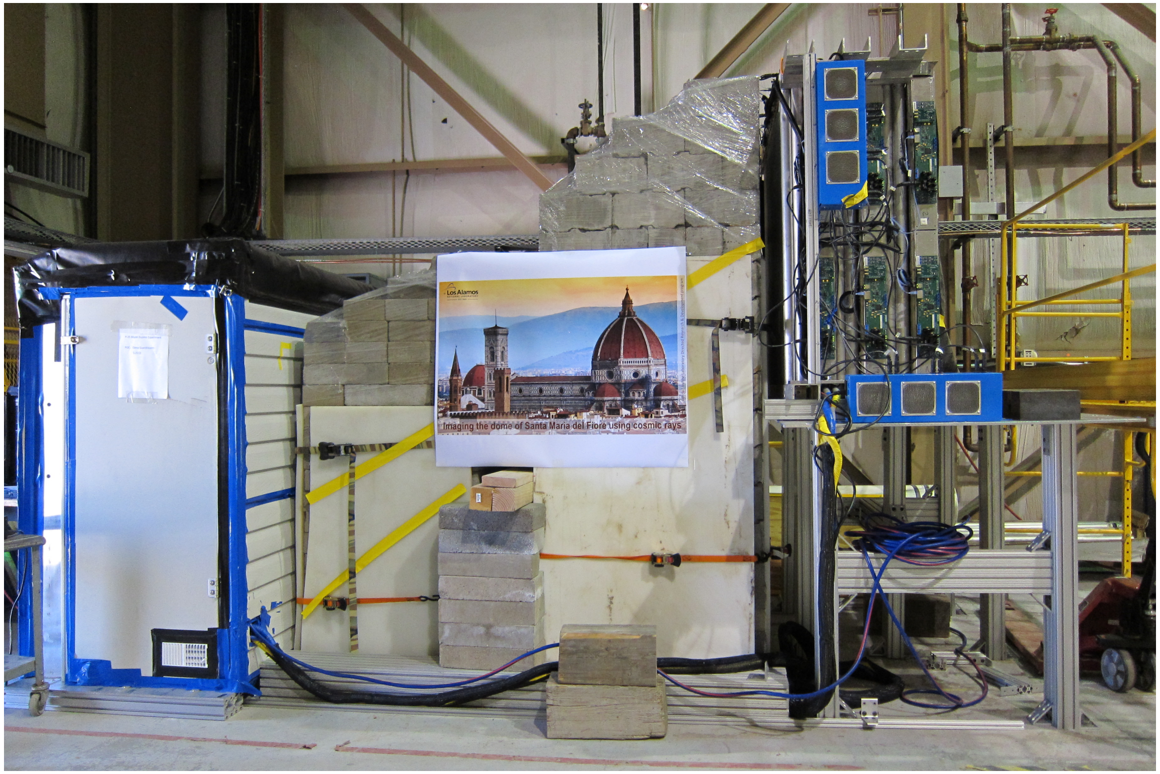
Demonstration measurement at LANL

- Demonstration measurement at LANL, during summer 2015.
- Built a concrete wall having the same thickness, in radiation lengths, as the inner (and thicker) wall of the Dome, placed three iron bars inside it.
- The cross sections of the bars are square/rectangular.
- Their dimensions were:
- 4.76 cm x 5 cm
- 2 cm x 3 cm (the bars in the Cupola wall are believed to be this size)
- 10 cm x 10 cm.

The mock-up wall after its completion, with the students who built it.

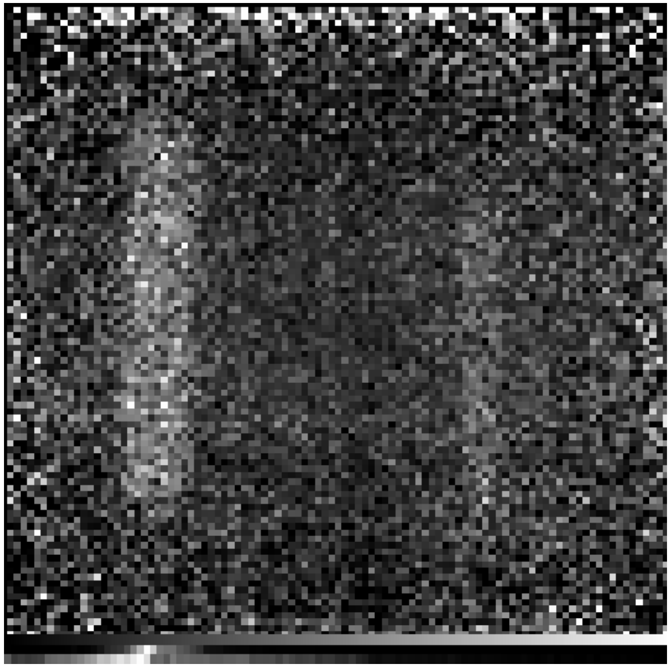
The iron bars inside the wall

Our muon trackers around the wall

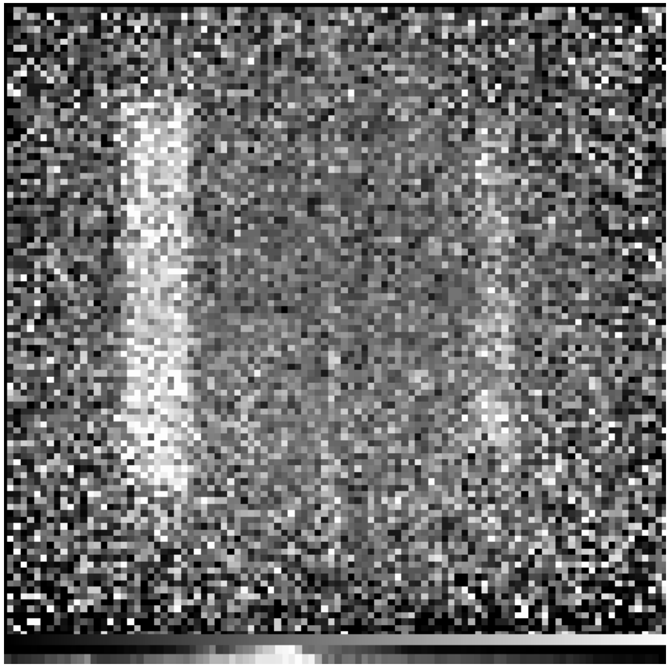


The two muon trackers have been deployed on two opposite sides of the wall and are taking data.

Demonstration measurement at LANL



Data



Simulation

~1 month data taking
All three bars can be seen
They were already visible after 17 days of data taking

Approval from the Opera del Duomo

- Results presented in Florence on 8/31/15 to a team composed of professors and researchers from the universities of Parma and Florence, and to the president of the Opera del Duomo
- Results very positively received and we had the approval to proceed from the Opera del Duomo.
- I also visited the Cupola with some experts to determine where the detectors could be deployed and what specifications they should meet
- We agreed to aim for a measurement in the rib vault number 6 of the dome (number 1 is the one aligned with the central nave of the church, then they are numbered clock wise when looking up from the floor), above the internal gallery and below the lowest oculus.
- One tracker inside the dome, the other in the space between shells

We will focus on this region

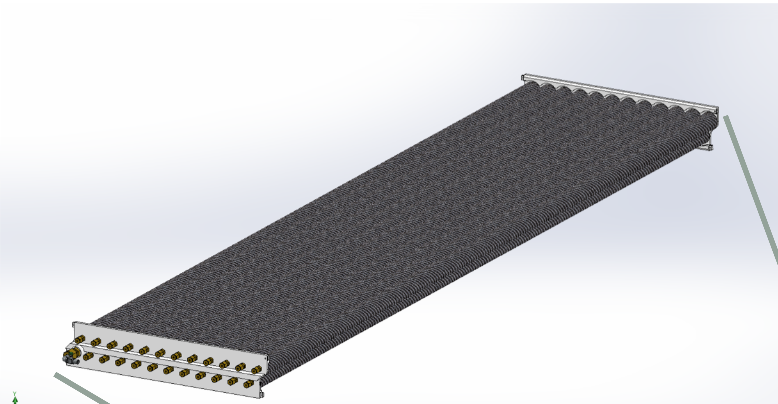
Lightweight detectors

- Need lightweight, modular detectors to be carried up narrow spiral staircases and to be hanged against the wall of the church

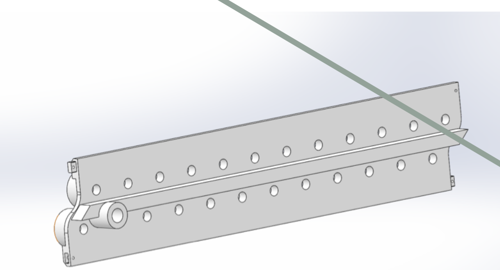
➔Carbon fiber drift tubes with conductive plastic endcaps

- 1 inch diameter tubes to reduce the overall thickness of each tracker to 1 ft
- 24 channel modules that can be carried independently and assembled into a detector in situ
- Detector construction funded by LANL LDRD program

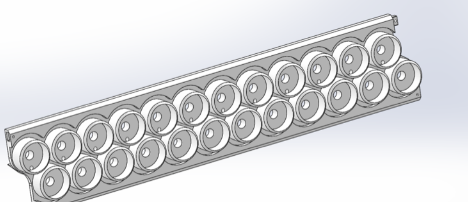
Detector model



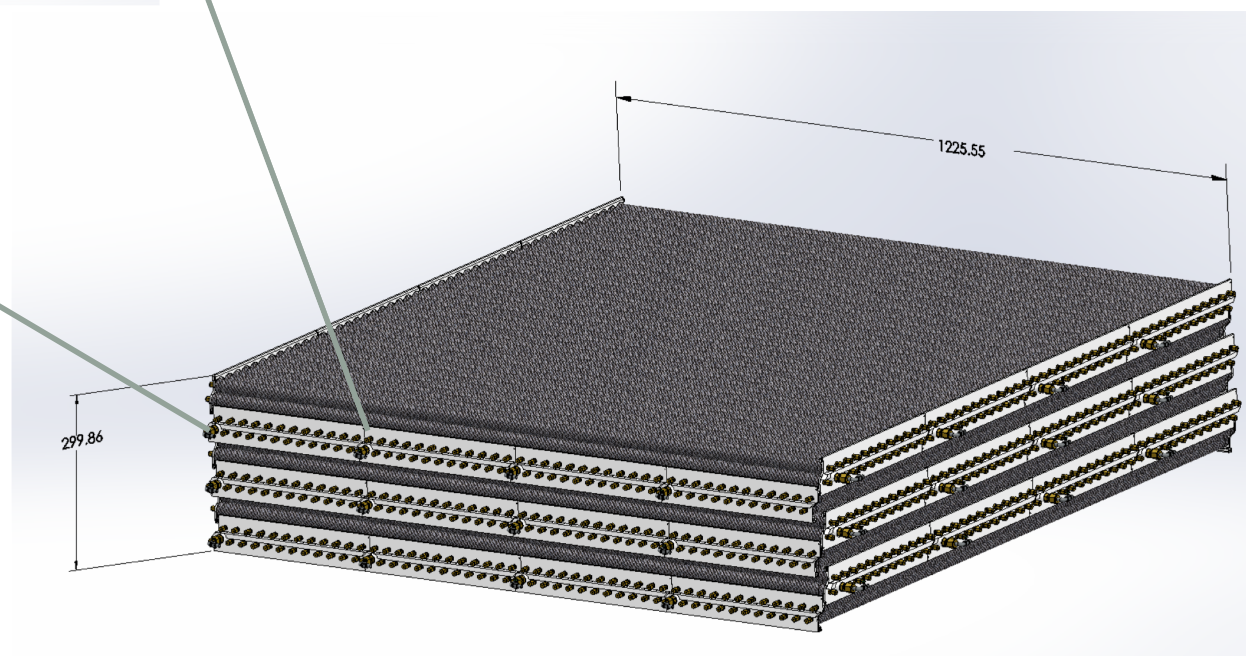
- 24 modules in each tracker
- Gas manifold 3D printed in the endcap
- Endcaps printed using Selective laser Sintering (SLS) from conductive plastic



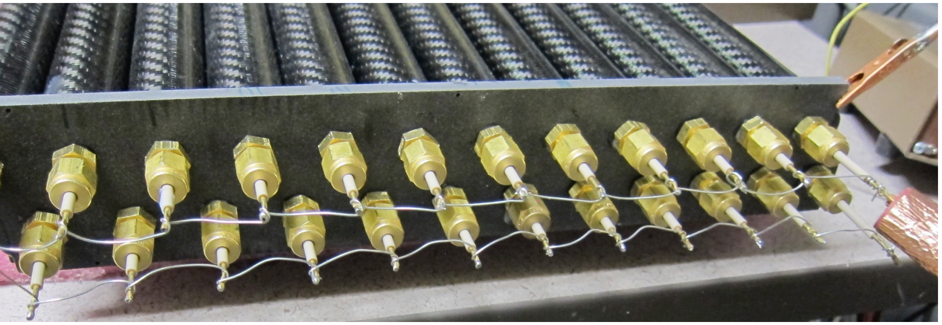
Gas side endcap - back



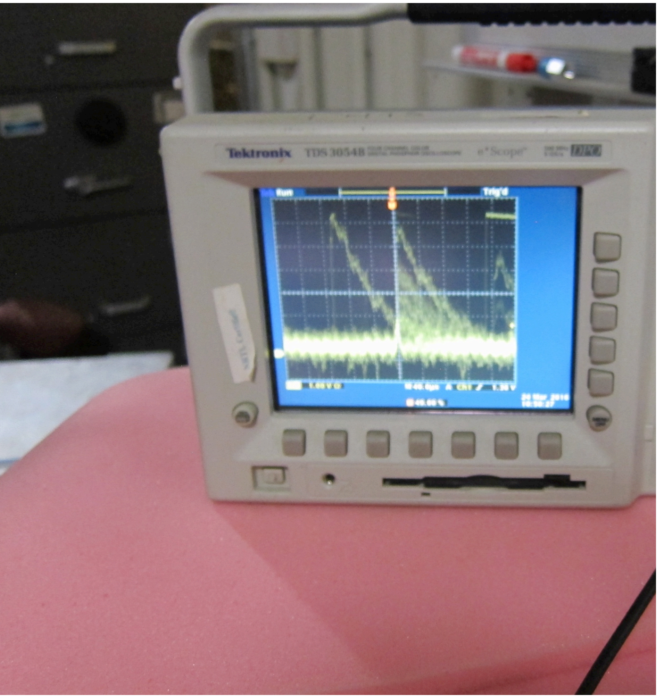
Gas side endcap - front

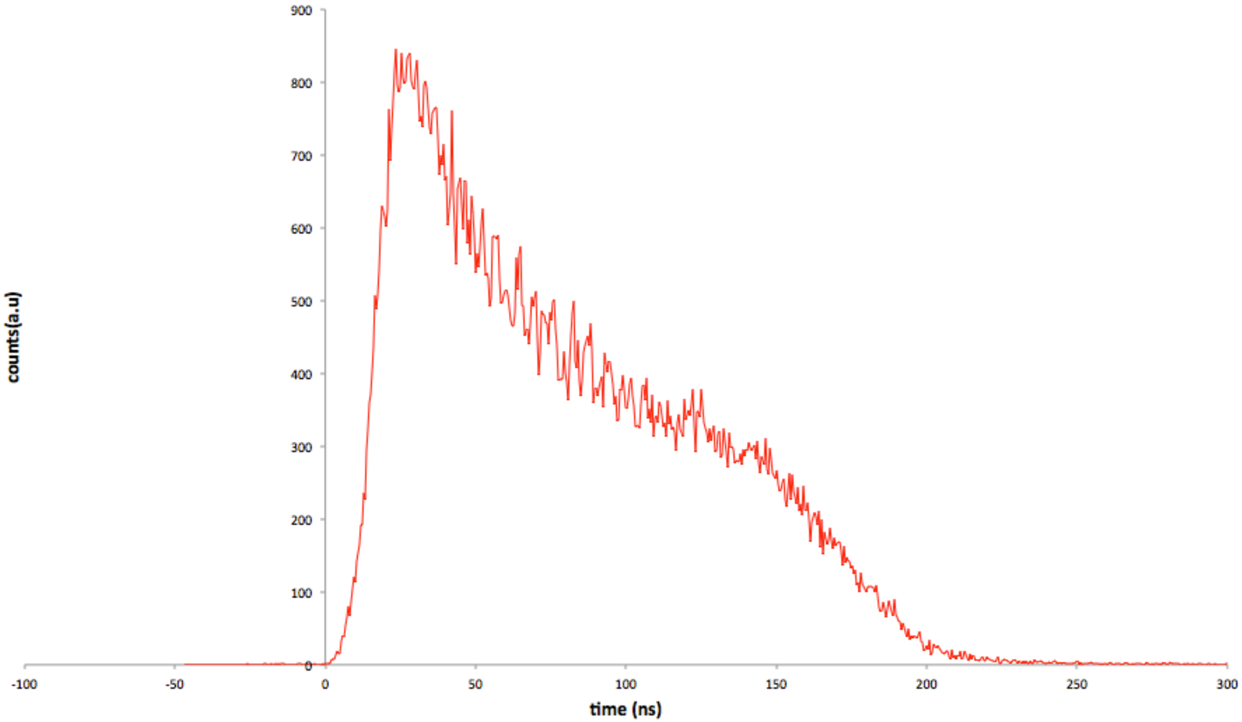


First prototype



Drift time spectrum for V=2200 V





Detector construction

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THE END