# Exploring the potential of muon radiography for blast furnace assessments: advancements in non-invasive imaging and structural analysis

16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23)

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UNIVERSITÀ DEGLI STUDI FIRENZE

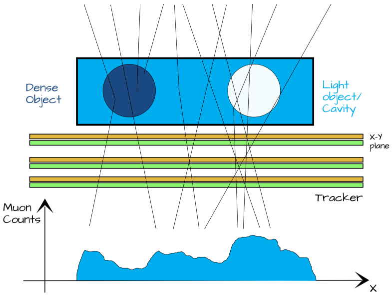
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

BLEMAB

# Outline

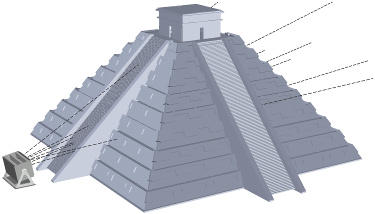
# Muon Radiography (Muography)

**Muon radiography is a technique that uses information on the absorption of cosmic ray muons to measure the thickness of the materials crossed by the muons.**



L. Bonechi et al., Reviews in Physics Volume 5, November 2020, 100038

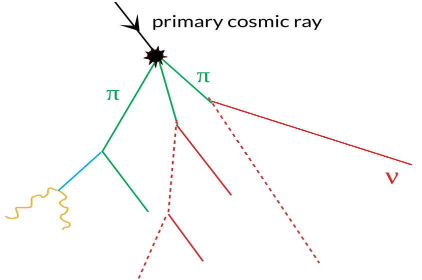
Best suited for big targets.
**Applications**: Geology, archaeology, civil engineering.

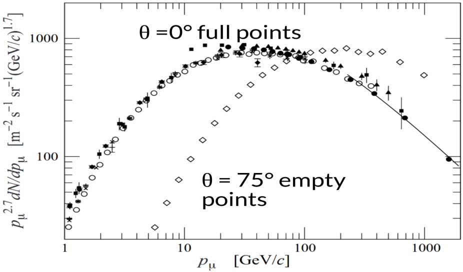


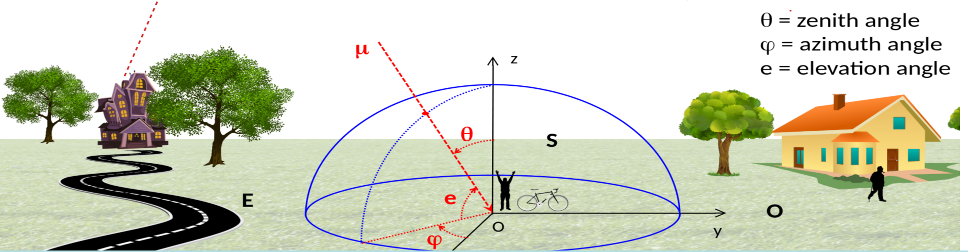
2D angular maps of average density of the object
⇒needs comparison with simulations

# The muon source

For a fixed E and polar angle $\varphi$, the flux is the highest for $\theta = 0°$ and lowest for $\theta = 90° \rightarrow \phi(\theta) = A \times cos^{n}(\theta)$ with $n \approx 2$







θ = zenith angle
φ = azimuth angle
e = elevation angle

# Image Reconstruction

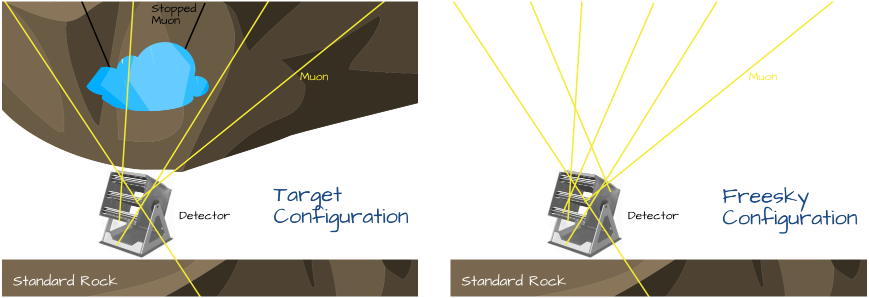
The technique to reconstruct a muographic image needs the following 4 steps (2 measurements and 2 simulations):

1. **Target measurement:** object to investigate between source and detector
2. **Freesky measurement:** measurement of the flux without the object
3. **Target simulation:** same setup as target measurement but we assume a certain density for the object
4. **Freesky simulation:** freesky simulation with a muon generator and detector

# Image Reconstruction

For every observation direction (zenith $\theta$ and polar $\varphi$) we **measure**:

- $N_{m,tar}(\theta,\varphi)$ e $N_{m,freesky}(\theta,\varphi)$: number of tracks detected in the two configuration
- $t_{tar}$ e $t_{freesky}$: acquisition times in the two configurations



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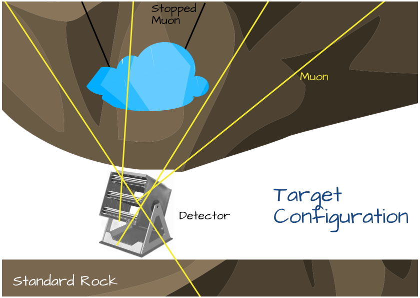
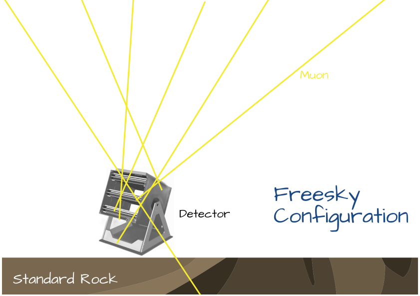




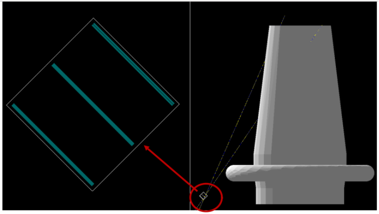
$$T_m(\theta,\varphi) = \frac{\Phi_{m,tar}(\theta,\varphi)}{\Phi_{m,freesky}(\theta,\varphi)} = \frac{N_{m,tar}(\theta,\varphi)}{N_{m,freesky}(\theta,\varphi)} \times \frac{t_{freesky}}{t_{tar}} \tag{1}$$

# Image Reconstruction

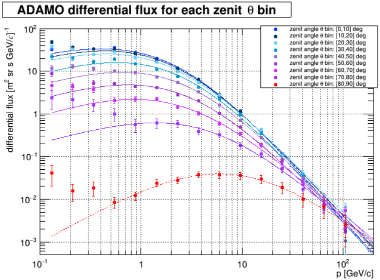
What we need for the simulation:

- **target geometry** → digital model of terrain(**DTM**) or **CAD**
- **muon source** → differential flux as a function of $p$ and zenith angle $\theta$ (measured in Florence)

Geometry

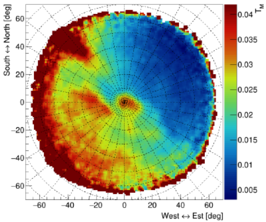


Flux

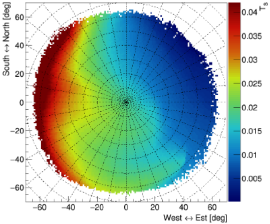


# Image Reconstruction

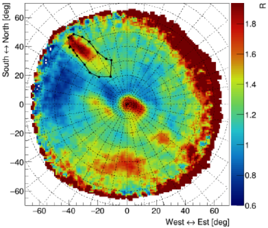
*see D. Borselli et.al., Scientific Reports volume 12, 22329 (2022)*



$T_m$



$T_{sim}$ ($\rho = 3$ g/cm $^{-3}$)



R ($\rho = 3$ g/cm $^{-3}$)

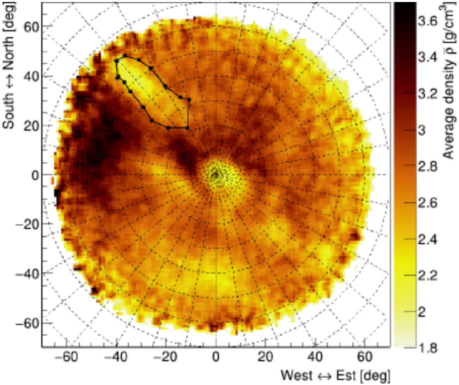
Relative transmission:

$$R(\theta, \varphi, \rho) = \frac{T_m(\theta, \varphi)}{T_{sim}(\theta, \varphi, \rho)} \tag{2}$$

For a line of sight ($\theta$,$\varphi$):

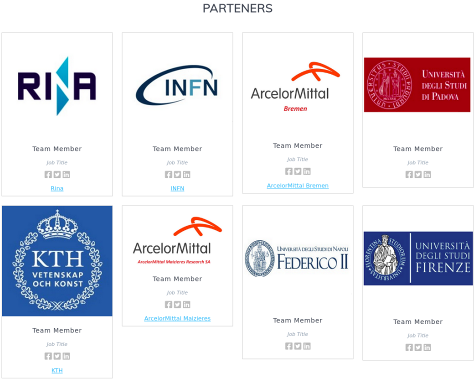
- $R(\theta, \varphi, \rho) = 1$: the simulated density matches the measured one
- $R(\theta, \varphi, \rho) > 1$ the mean measured density is lower than the simulation (**cavity?**)
- $R(\theta, \varphi, \rho) < 1$ the mean measured density is higher than the simulation(**high density object?**)

# Image Reconstruction



By repeating the simulation with different density hypothesis, we can built a polar density map where for each bin ($\theta$,$\varphi$) we choose $\rho$ in order to have $R(\theta, \varphi, \rho) \approx 1$

# **BL**ast furnace stack density **E**stimation through on-line **M**uons **AB**sorption measurements (https://www.blemab.eu)



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- Imaging of Blast Furnaces with muography
- European Project (HORIZON 2020)

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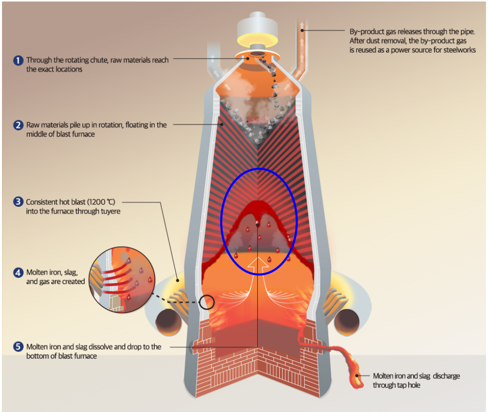

- Imaging of Blast Furnaces with muography
- European Project (HORIZON 2020)
- Study of the cohesive zone to optimize the iron production
- Possible on-line monitoring
- Comparison with multi-probe measures and standard blast furnace models

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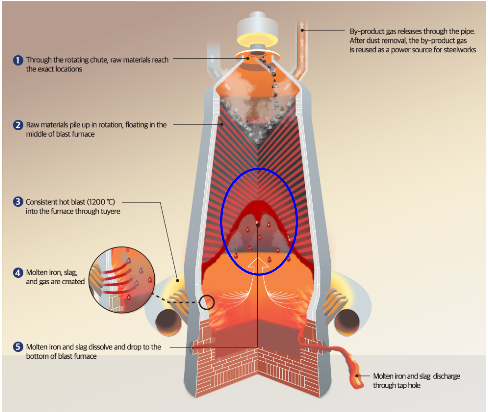

- Imaging of Blast Furnaces with muography
- European Project (HORIZON 2020)
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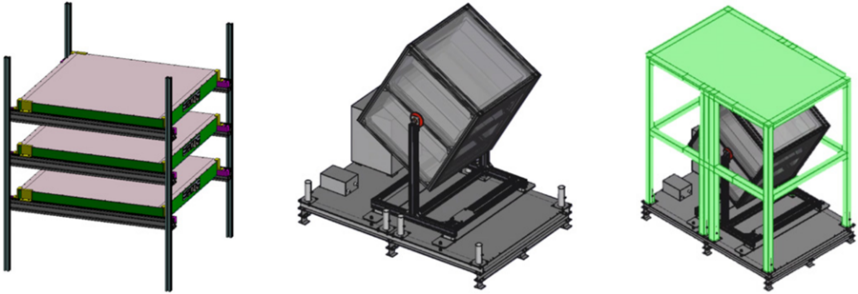
- Comparison with multi-probe measures and standard blast furnace models

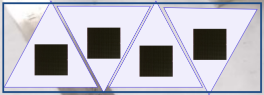
- It is estimated that steel production is responsible for 7-10% of all $CO_2$ emissions.

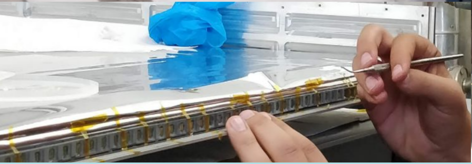
# The BLEMAB tracker

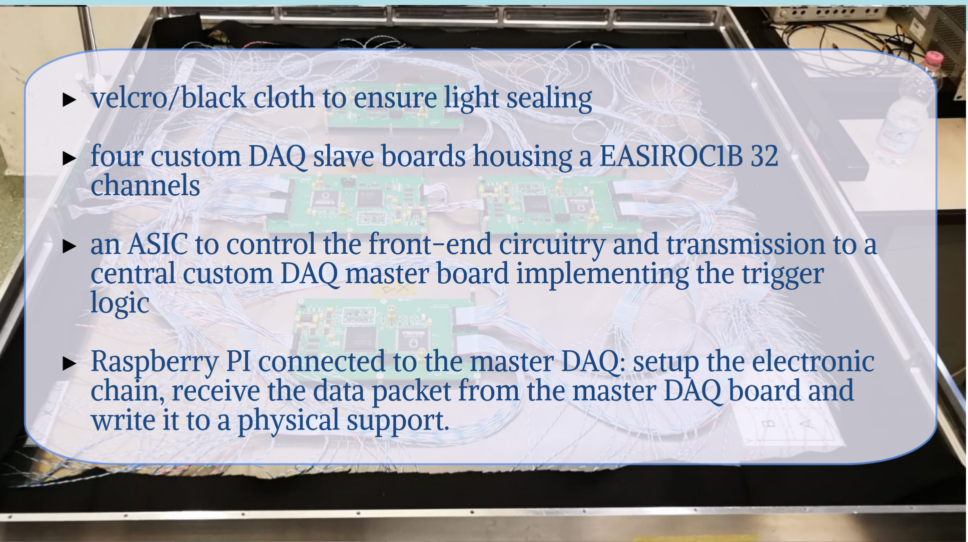


- 3 XY tracking planes. Each plane is composed of 63 scintillating bars.
- Protection box with orientation and mechanical support.
- Housing with cooling system.

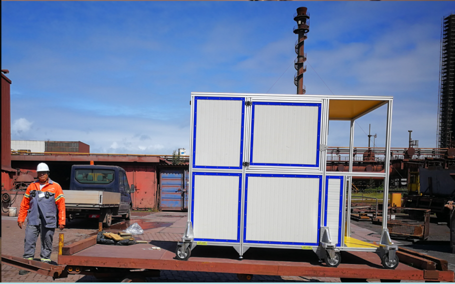
- Triangular shape 80 cm long from SCIONIX
- Each bar has a pair of 4x4 mm2 SiPM with the same working voltage (V=40–42 V)
- Aluminized mylar to cover the bars
- Mounted in Florence at the INFN



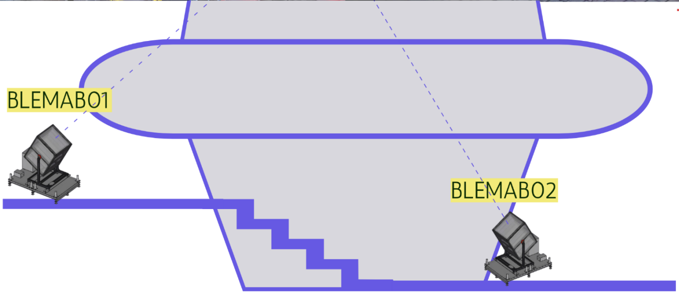




- velcro/black cloth to ensure light sealing
- four custom DAQ slave boards housing a EASIROC1B 32 channels
- an ASIC to control the front-end circuitry and transmission to a central custom DAQ master board implementing the trigger logic
- Raspberry PI connected to the master DAQ: setup the electronic chain, receive the data packet from the master DAQ board and write it to a physical support.

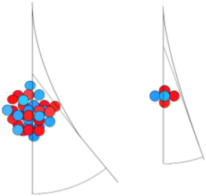



BLEMAB01
BLEMAB02
Subzone 1


BLEMAB01
BLEMAB02

1. Introduction to muography
   - Muon Radiography
   - Image Reconstruction
2. The BLEMAB project & Detector
   - BLEMAB
   - Design and Performance
   - Installation
3. Results
   - Multiple Scattering Effects
   - Preliminary Map
4. Conclusions

# MS as possible background for muography?

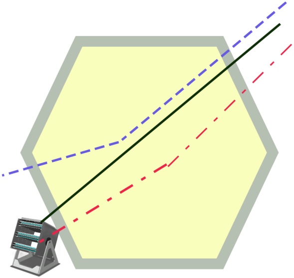


The sigma of the deflection distribution is approximately :

$$\sigma(\theta) = \frac{13.6MeV/c}{\beta cp}\sqrt{\left(\frac{l}{X_0}\right)}$$

*For the case of an "underground" measurement in- and out-scattering usually cancel each other out and do affect measurements only through a "blurring" effect.*

*A. Lechmann Earth-Science Reviews 222 (2021) 103842*



Straight Muons

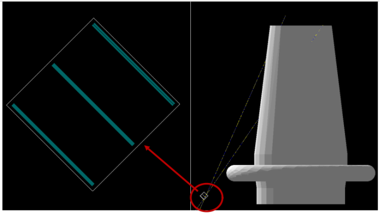
In-Scattering Muons

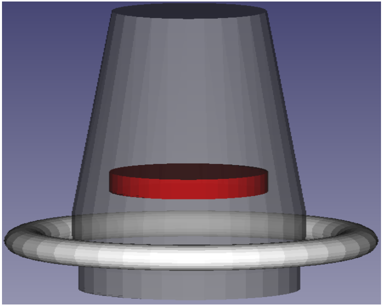
Out-Scattering Muons

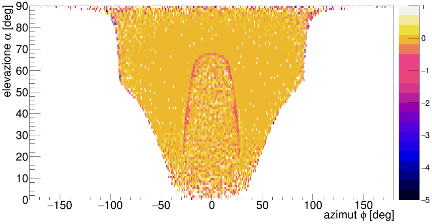
*In the case of a muon flux measurement near an object with portions of the freesky directly seen by the detector, the situation is different. There might be an imbalance between in-and out-scattering muons due to a non symmetric configuration.* ***For example, one can observe a too high muon flux around the edges .***

## GEANT4 simulation:

- 45 degrees pointing at the furnace
- Detector 15 m away from furnace $0.3 < p < 500$ GeV/c over the full $\theta$ and $\phi$ phase space
- Furnace:
  1. Torus → $SiO_2$, 2.65 g/cm$^3$
  2. Central structure → Fe, 7.87 g/cm$^3$
  3. Cohesive zone → Fe, 3.94 g/cm$^3$ (red plate)
- Different configurations:
  1. Full Fe geometry of furnace
  2. Low density region corresponding to cohesive zone

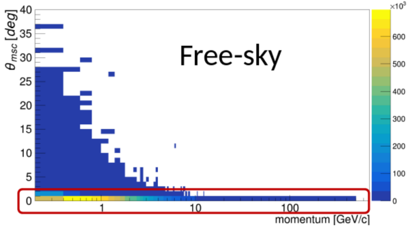




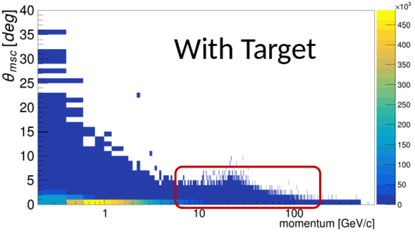


Difference between generation and detection angle normalized to the generation muon counts.

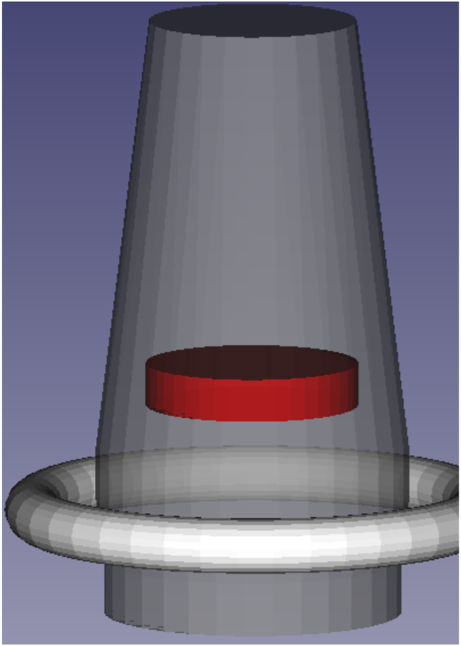
$$\theta_{msc} = arccos\frac{\overrightarrow{p_{det}} \cdot \overrightarrow{p_{gen}}}{|\overrightarrow{p_{det}}| \cdot |\overrightarrow{p_{gen}}|}$$



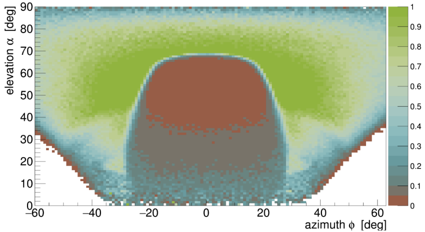
Muons detected but have undergone multiple scattering → (1.60%±0.01%) Both Detector and Target contributions



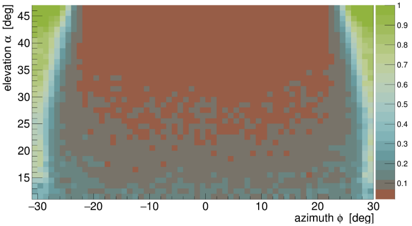
Muons lost because of multiple scattering → (4.76%±0.04%)



$$T_{sim}(\theta,\varphi) = \frac{\Phi_{sim,tar}(\theta,\varphi)}{\Phi_{sim,freesky}(\theta,\varphi)} = \frac{N_{sim,tar}(\theta,\varphi)}{N_{sim,freesky}(\theta,\varphi)} \times \frac{t_{freesky}}{t_{tar}}$$



Increase of flux (13%±1%) with respect to the uniform density Fe (7.87 g/cm$^3$) case in the cohesive region.



## Summary

- ✓ Optimization of Blast furnace operation through muography is an exciting and promising task to perform.
- ✓ The results can benefit both the steel production by improving the modelization of the internal structure and the environment indirectly.
- ✓ We estimated throughout a first GEANT4 simplified simulation the possible effects of MS on the muographic measurement

## Future Prospects

- ★ Installation concluded at the end of August and measurements are ongoing at the moment
- ★ Improve the simulations by including more and more complex geometries inside the CAD to faithfully reproduce the measuring setup
- ★ Final goal is to provide a characterization of the cohesive region in terms of location, density and 3D shape.

**The Florence group**: Vitaliano Ciulli, Lorenzo Villiani, Catalin Frosin, Raffaello D'Alessandro, Lorenzo Bonechi, Roberto Ciaranfi, Sandro Gonzi, Diletta Borselli, Andrea Paccagnella, Tommaso Beni and Rosa Petrini