

ACROMASS: a portable magnetic spectrometer with particle identification capability for in-situ calibration of atmospheric muon flux models in muography

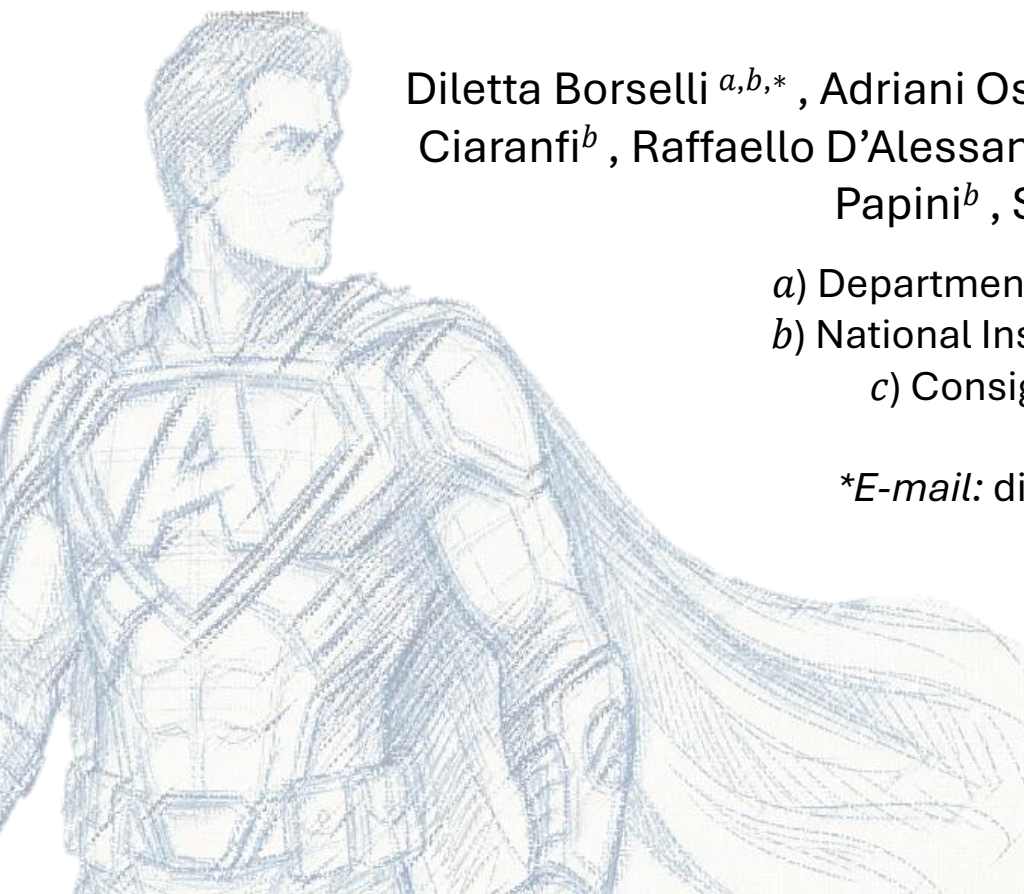
Diletta Borselli ^{a,b,*}, Adriani Oscar^{a,b}, Lorenzo Bonechi^{a,b}, Massimo Bongia^a, Carlo Cialdai,^b Roberto Ciaranfi^b, Raffaello D'Alessandro^{a,b}, Sebastiano Detti^b, Catalin Frosin^b, Nicole Orientale^a Paolo Papini^b, Sergio Bruno Ricciarini^c and Monica Scaringella^b

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c) Consiglio Nazionale delle Ricerche (CNR), Florence

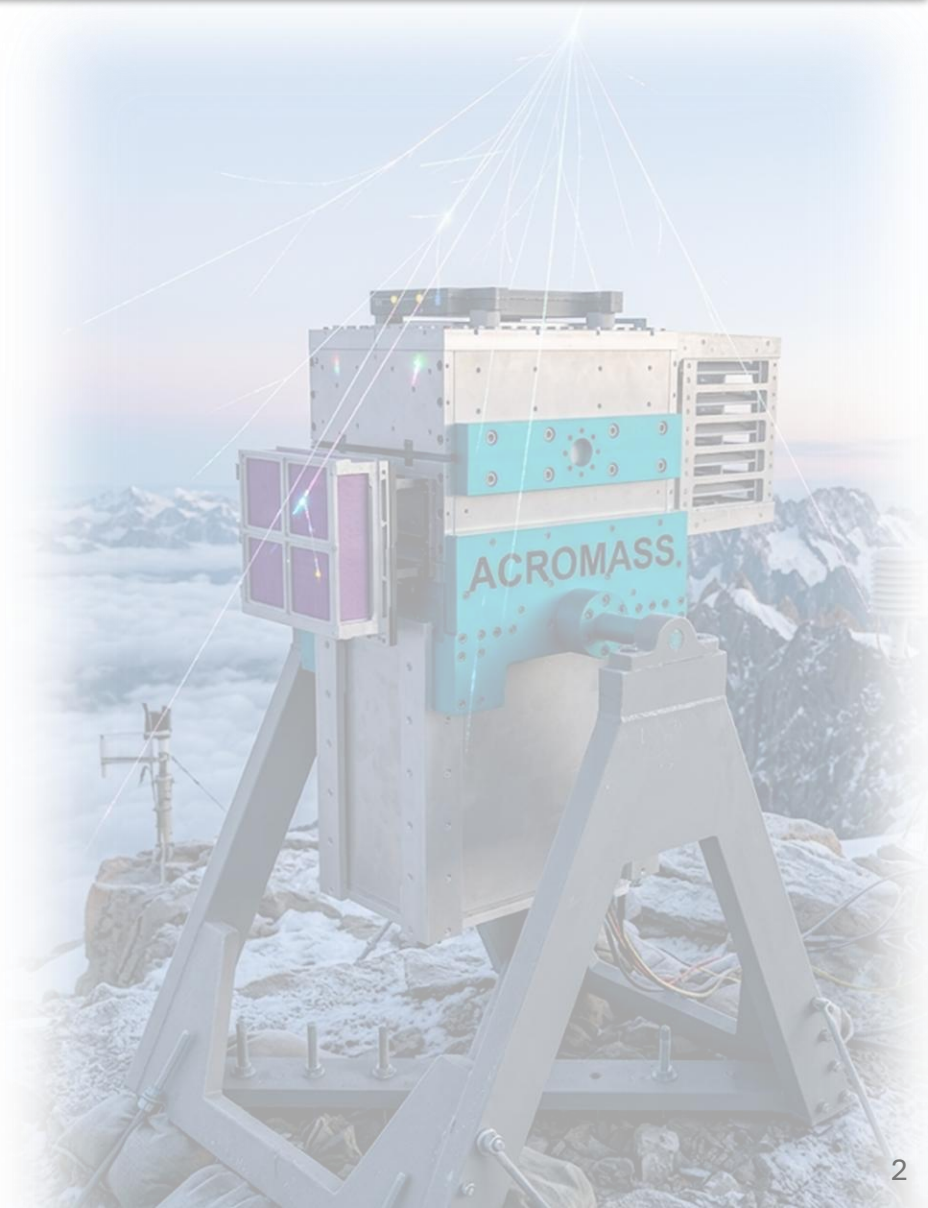
**E-mail:* diletta.borselli@fi.infn.it, diletta.borselli@unifi.it



UNIVERSITÀ
DEGLI STUDI
FIRENZE



- ACROMASS detector: Main purpose and motivation;
- Muon flux models in literature and benefits of the project;
- Detector design and structure;
- First performance estimates at the CERN PS test beam;
- Future high-altitude campaigns (> 3000 m a.s.l.).



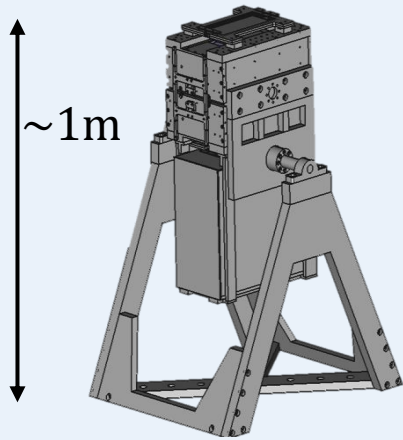
ACROMASS

Motivations and Purpose:

ACROMASS is a detector designed for precise measurements of ground-level differential muon flux $\Phi_\mu(p, \theta, \varphi)$ as a function of geographic location.

Main Purpose:

$p = 0.1 - 150 \text{ GeV}/c$
 $\theta = 0-90 \text{ [deg]}$
 $\Delta\Phi_\mu/\Phi_\mu < 5\%$
portable detector



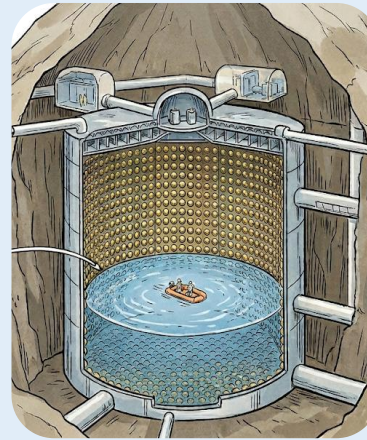
ACROMASS=The **A**tmospheric **C**osmic **R**ay **O**bservatory using a **M**agnetic **A**ltazimuth **S**ilicon **S**pectrometer (ACROMASS)

Motivations:

Neutrino Observatories:

For a precision **study of the neutrino oscillation parameters** [1-2]:

- Knowledge of the Φ_ν ($E < 1 \text{ GeV}$) is highly correlated with the Φ_μ ;
- Knowledge of $\Phi_\mu(\theta)$ between **3-4.5 km a.s.l.**

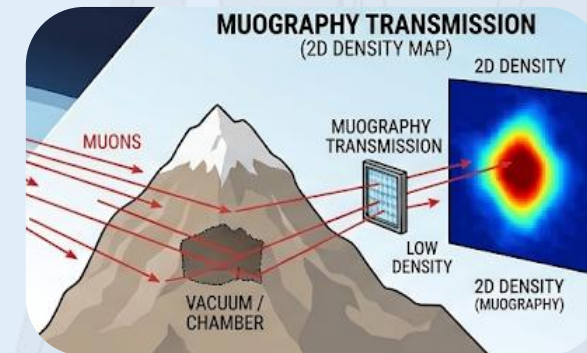


- [1] M.Honda et al., *Phys.Rev.D*100,123022(2019)
[2] M.Honda et al., *Journal of Physics: Conference Series*, 1468, 012190 (2020)

Muography:

For the implementation of a simulation:

- The **error** in the choice of the muon flux model can reach even **10-20%** [3-4].



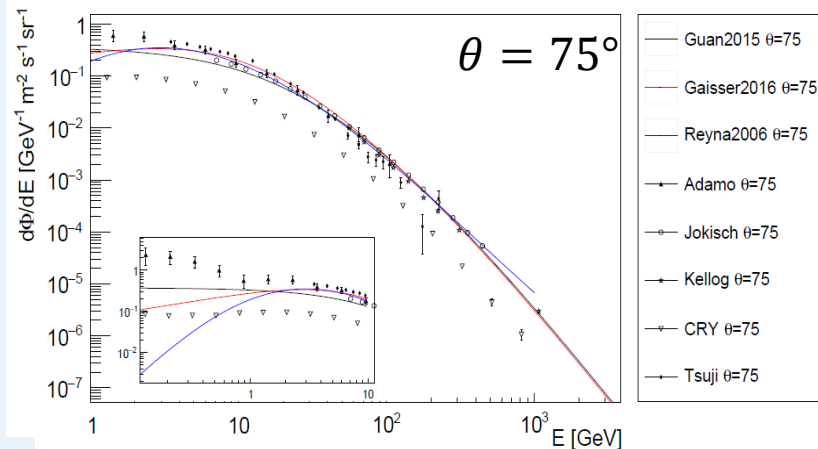
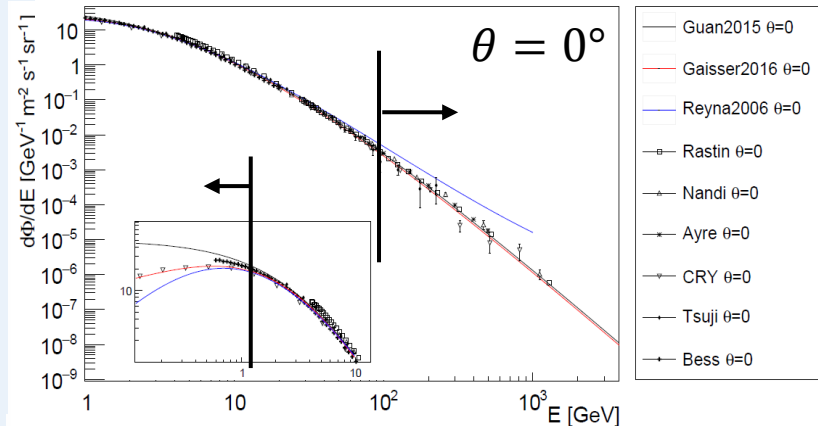
- [3] Lesparre N. et al., *Volume 183, Issue 3, December 2010, Pages 1348–1361, DOI: j.1365-246X.2010.04790.x*
[4] Lechmann A., et al., *Earth-Science Reviews*, 222, 103842, ISSN 0012-8252, (2021) DOI: j.earscirev.2021.103842.

Muon flux model:

There are **several parametric models for the differential flux of muons** at ground level, but:

- They **differ from each other** in low energies ($< 1 \text{ GeV}$) and high zenith angles ($\theta > 70^\circ$);
- **Data Fragmentation**: data varies widely due to **local differences** (location, time, altitude) and **different detectors**.

Data fit with three different parametric muon flux models:



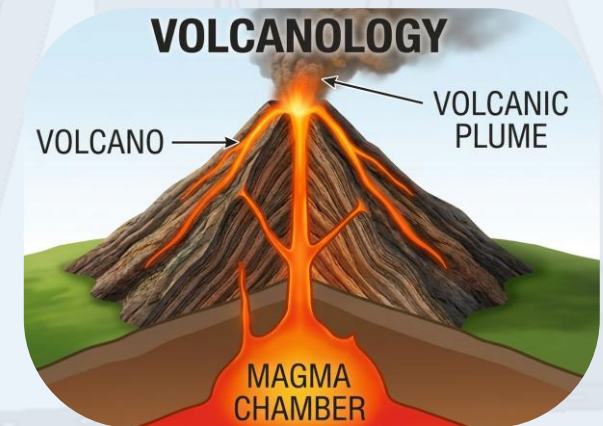
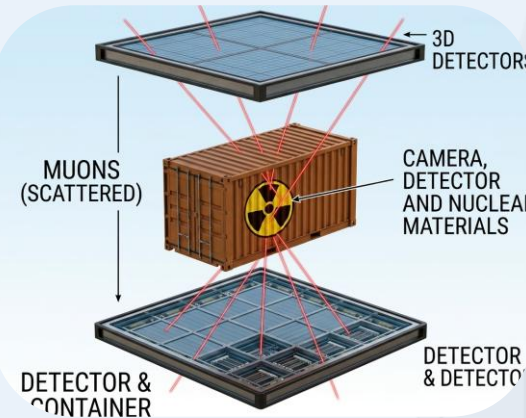
From muographic point of view:

Muon flux $< 1 \text{ GeV}$:

- ✓ Scattering muography
- ✓ small target

Muon flux $> 100 \text{ GeV}$ and $\theta > 75^\circ$:

- ✓ Volcanoes
- ✓ big targets

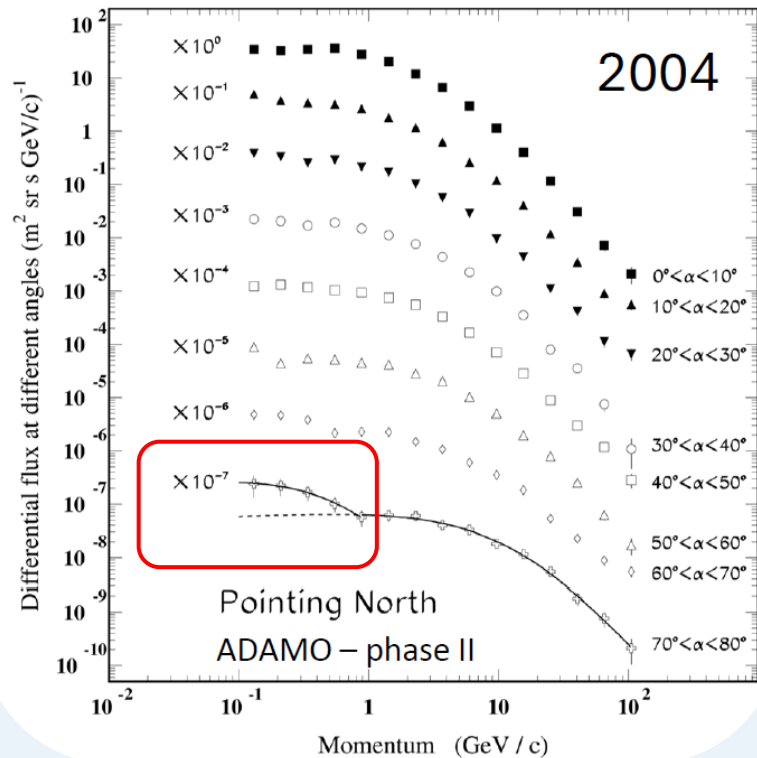


ACROMASS

Muon flux model:

- At low energy there is the effect of **electronic contamination** which must be estimated by varying the zenith angle.

29th ICRC, Pune (2005) 9, 283.286 [6]



Florence (Italy)

Lat: ($43^\circ 50' 7.80''$) N

Long: ($11^\circ 11' 46.32''$) E

ADAMO dataset currently used in EcoMug [7]
simulation based on GEANT4

[6] L. Bonechi et al., 29th International Cosmic Ray Conference 9 (2005) 283

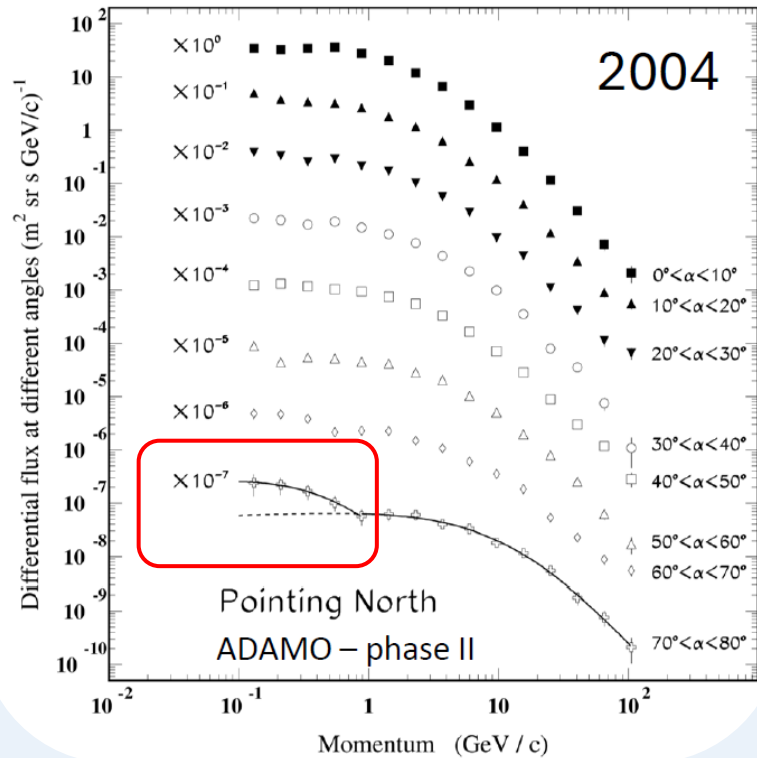
[7] D. Pagano et al., NIM A, Volume 1014, 2021, 165732, ISSN 0168-9002

ACROMASS

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From ADAMO (2000) [6]



Magnetic spectrometer

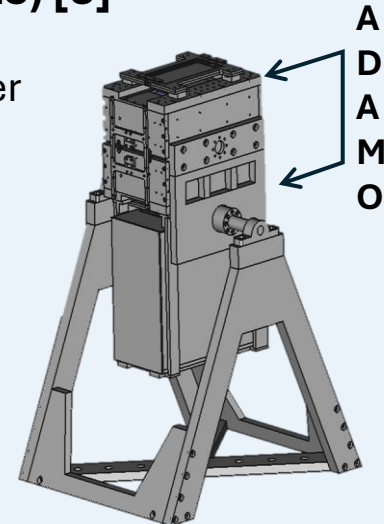


To ACROMASS (2025) [8]



- Magnetic spectrometer
- Time of Flight
- Calorimeter

PID!!
Particle
Identification

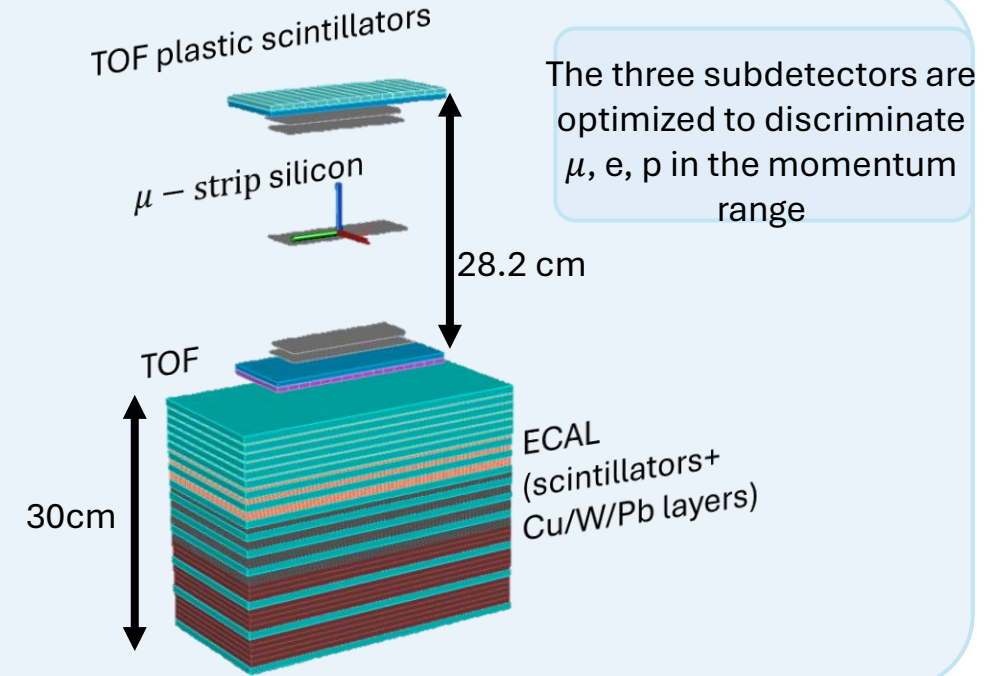
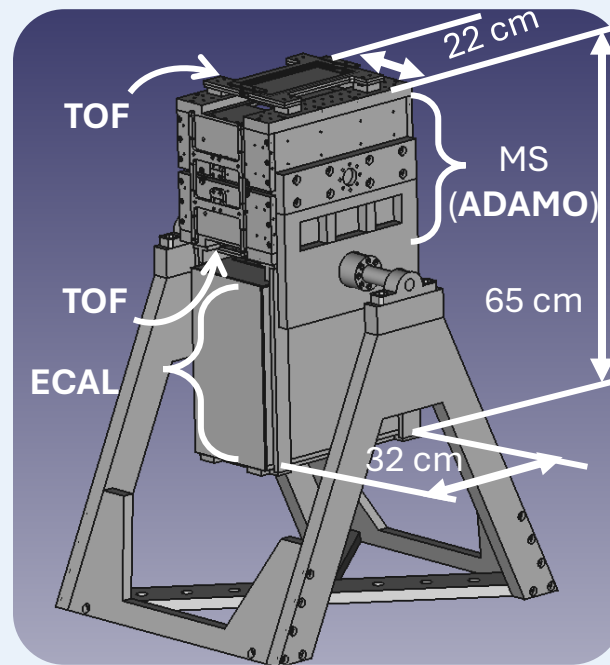
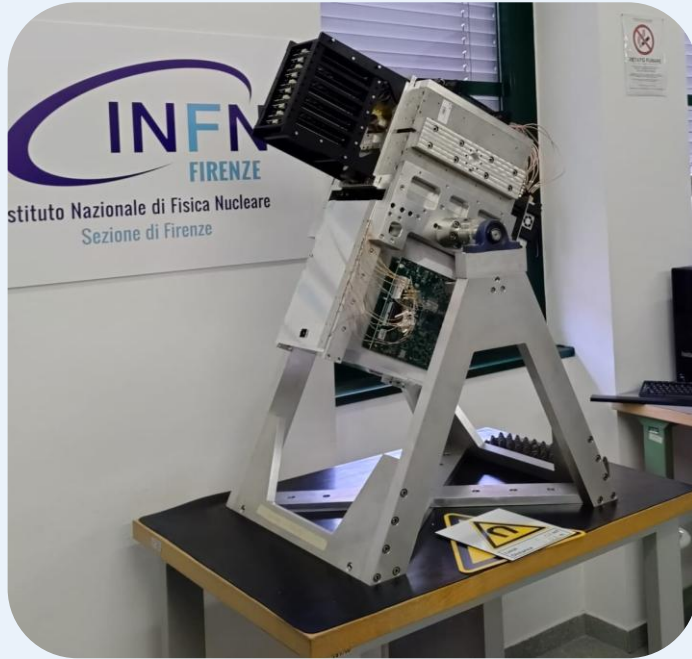


[8] Bonechi L., et al. PoS ICRC2025 (2025), 992,
DOI: 10.22323/1.501.0992

ACROMASS

The detector: global structure

Assembled in 2025 at INFN Florence



Main Characteristics	ACROMASS detector
Geometrical Factor G_F	6.7 cm ² sr
MDR (Maximum Detection Rigidity)	250 GV/c
Momentum range	(0.1 – 150) GeV/c
Angular Range θ	(0-90) ^o
Mass	approximately 180 kg

Estimated time for $\Delta\Phi_\mu/\Phi_\mu < 5\%$ in the lowest energy bin

Vertical $0^\circ < \theta < 10^\circ \rightarrow \Delta t \cong 3$ days

Intermediate $40^\circ < \theta < 50^\circ \rightarrow \Delta t \cong 8$ days

Horizontal $70^\circ < \theta < 80^\circ \rightarrow \Delta t \cong 60$ days

The three subdetector:

The magnetic spectrometer (ADAMO structure)

It is the prototype of the Magnetic spectrometer of PAMELA satellite experiment.

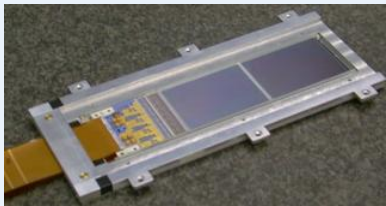
Tracker:

- 5 double sided μ -strip silicon (5x7)cm;
- Spatial resolution of $\sigma_x = 3\mu\text{m}$.

Magnet:

- permanent magnet of NdFeB,
- Residual magnetization: 1.2 T,
- $\bar{B} \sim 0.4 \text{ T}$

Double sided μ -strip silicon (5x7) cm²



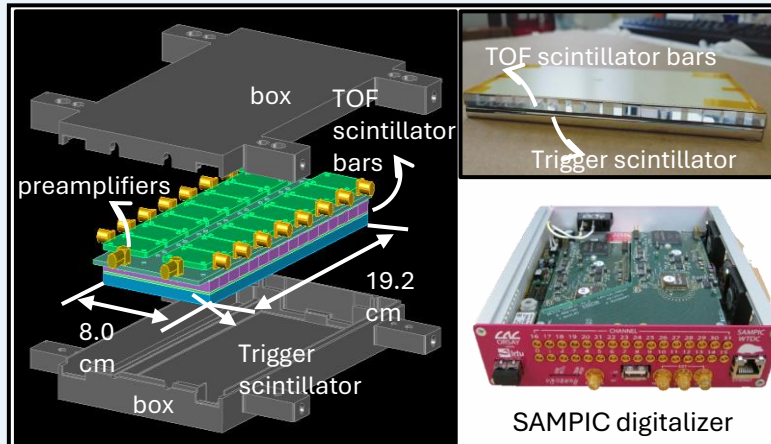
Magnetic spectrometer

Time of Flight

- **Two fast plastic scintillators** (EJ-232-Q-(0.5% Benzophenone) ELJEN Technology):
- segmented bar of (5x12x80) mm³;
- light sensors: **SiPMs** (Onsemi J-Series 30035 model) (4x4) mm²;
- SAMPIC digitalizer 32 channels, 6.4 Gs/s [9]

[9] D. Breton et al, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2016) 51–60.

Time resolution estimated about 100ps [10]



[10] Borselli et al., PoS, 2025, ICRC2025, 200, 10.22323/1.501.0200

Electromagnetic Calorimeter

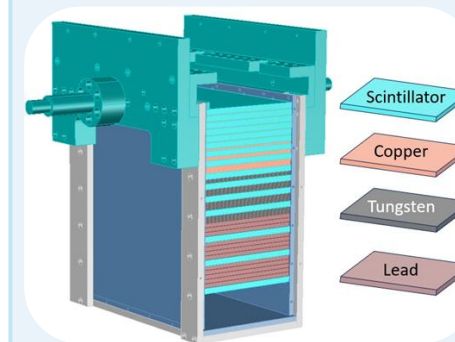
Sampling calorimeter with $\cong 22 X_0$:

Active layers:

- 16 plastic scintillators with (8x150x300) mm³
- Light sensors: ADVANSID NUV SiPM (4x4) mm²
- Electronics: custom board

Passive:

- Copper
- Tungsten
- Lead

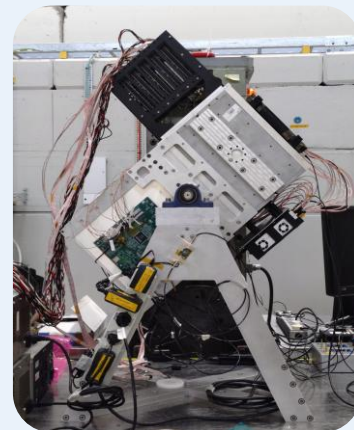
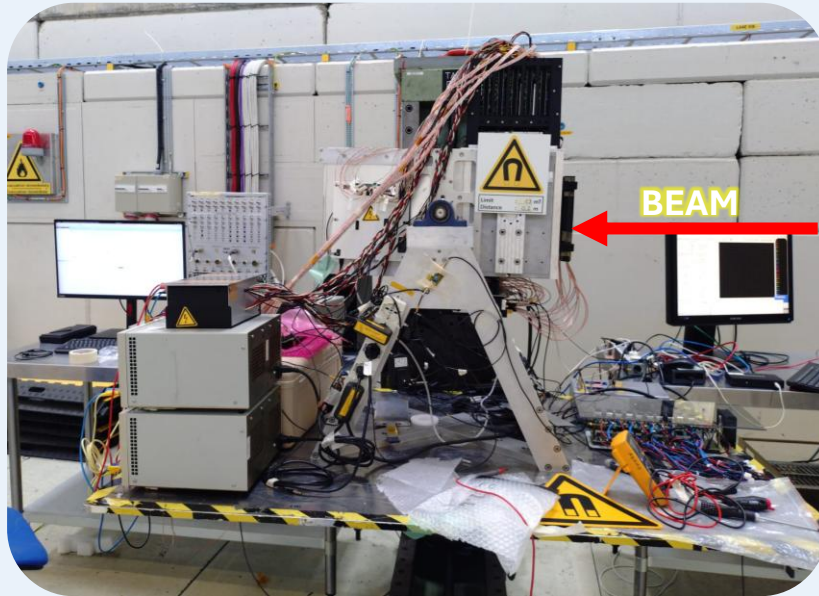
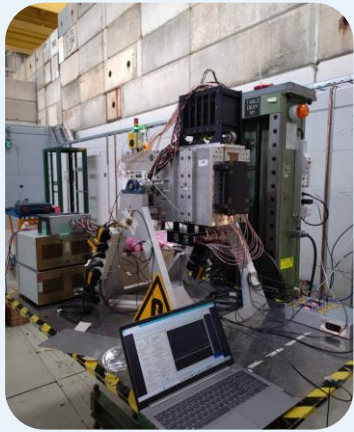


ACROMASS

Test Beam at PS and SPS (CERN):

2 Test Beam at **PS CERN**

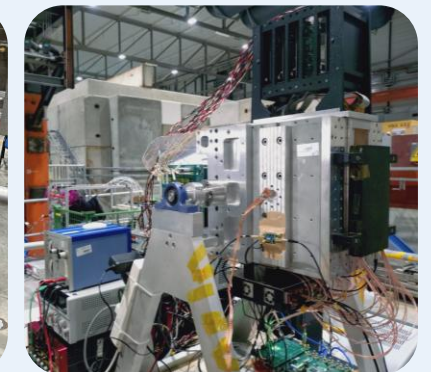
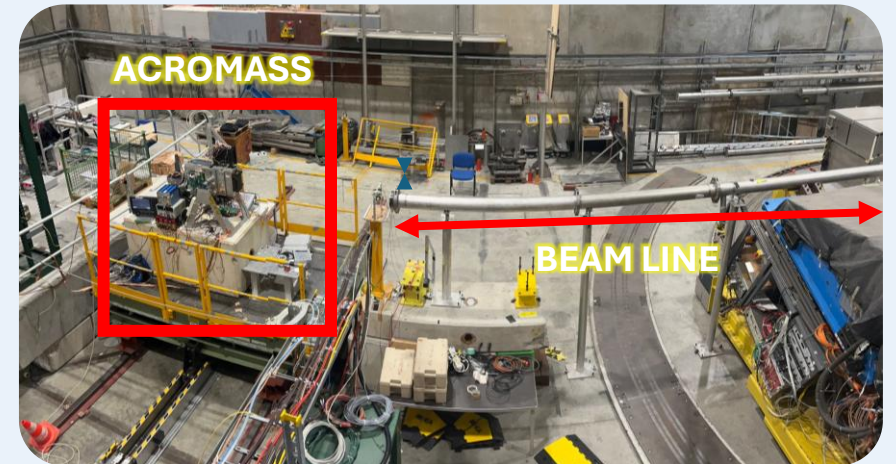
- September 2025
- April – May 2026



Particle	Beam momentum (GeV/c)
e^- , e^+ , Hadrons (pos, neg)	0.1, 0.2, 0.3, 0.5, 0.7, 1, 3, 5
Mixed	10
μ^- , μ^+	1, 2, 5, 10, 12

1 Test Beam at **SPS CERN**

- October 2025

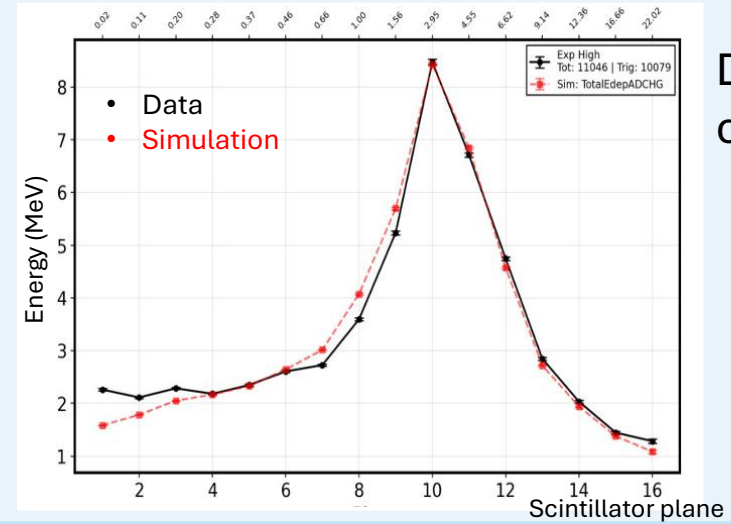
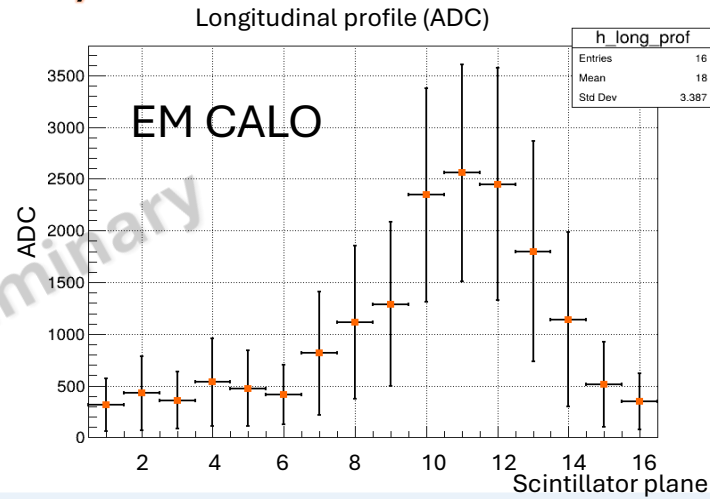
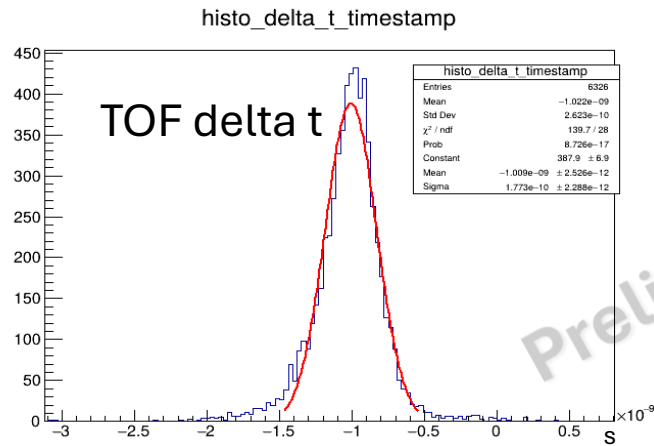


Particle	Beam momentum (GeV/c)
e^- , e^+	10, 20, 50
Hadrons (pos), μ^+	50, 100, 200

ACROMASS

Some preliminary results at PS, TOF and EM CALO:

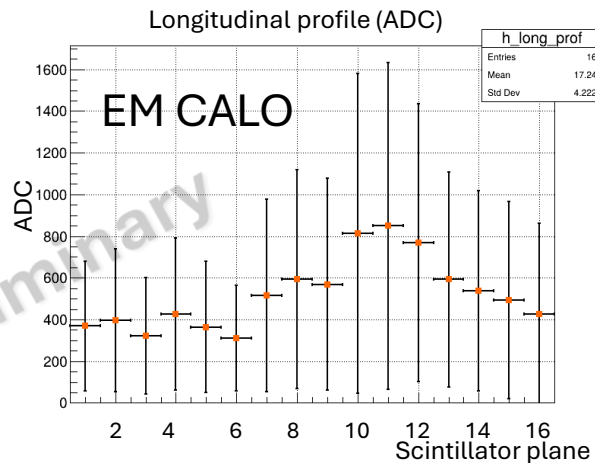
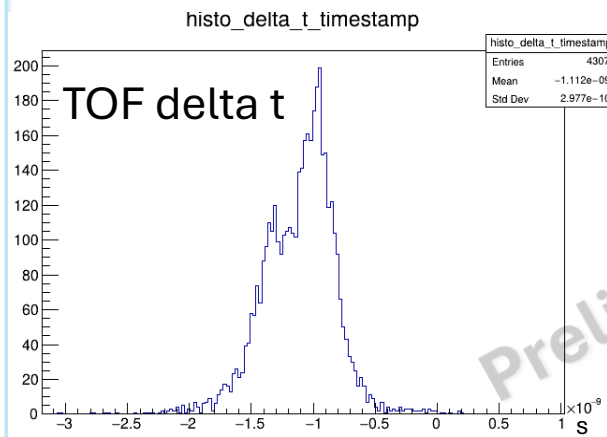
e^- 1GeV/c



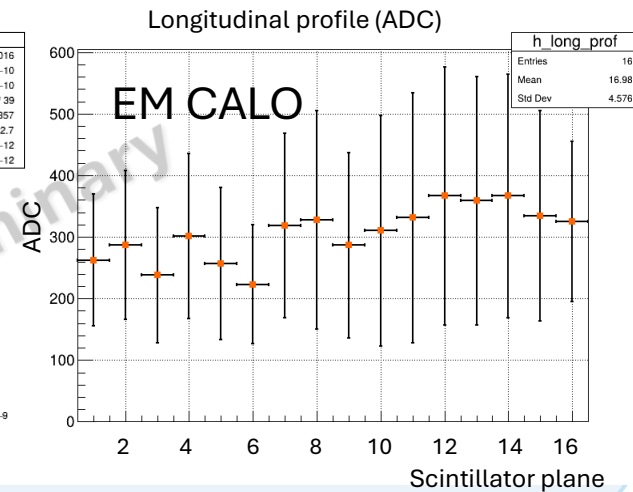
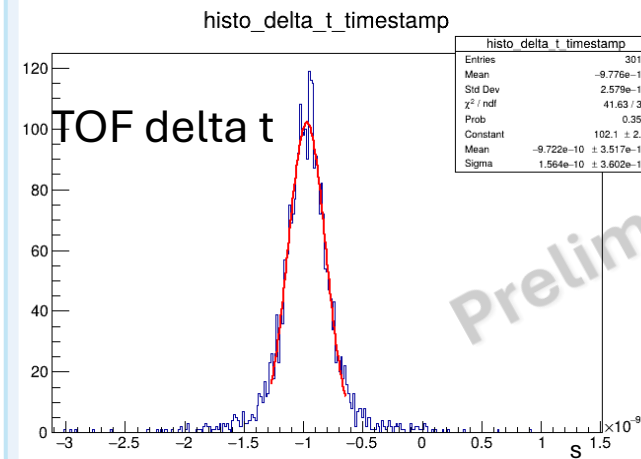
Data-simulation comparison

[10] Grossini A., Master Thesis, University of Florence, April 2026

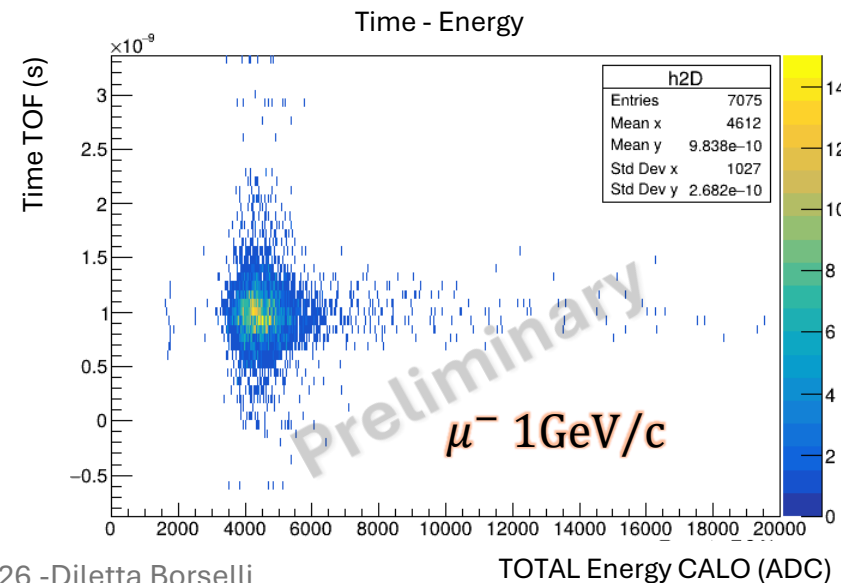
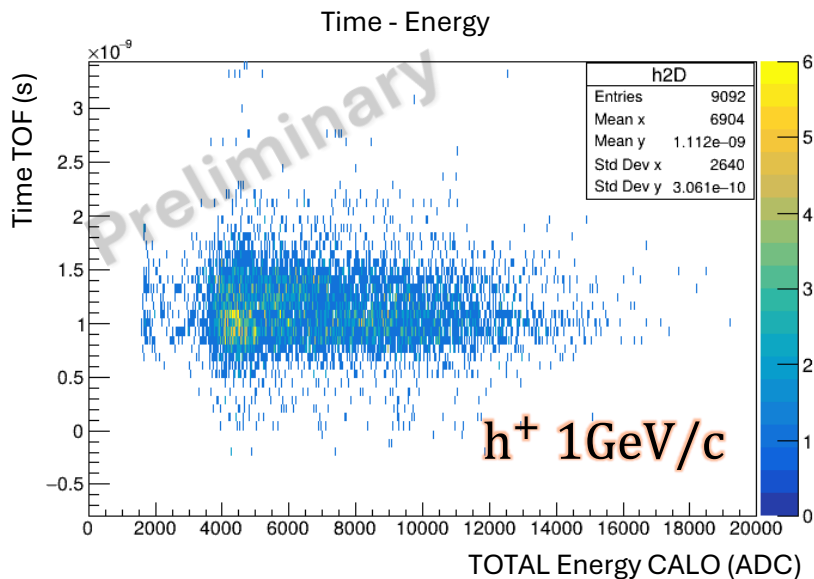
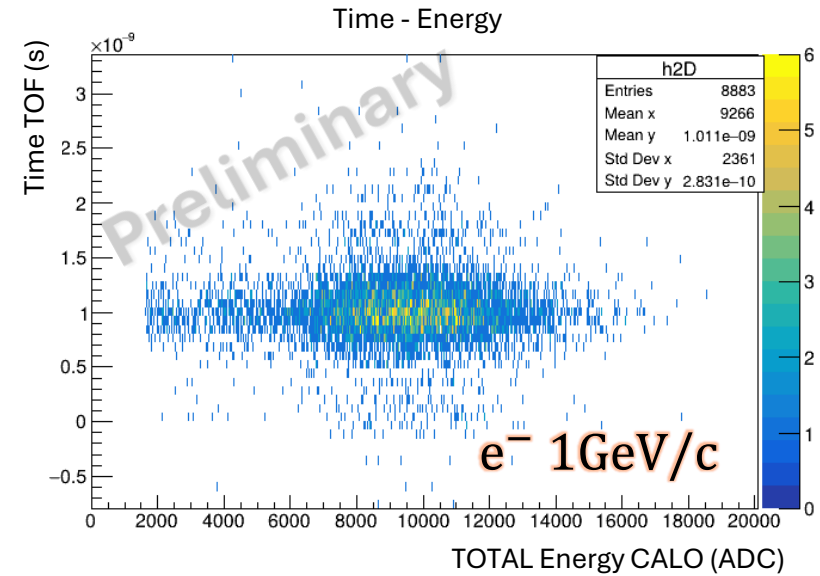
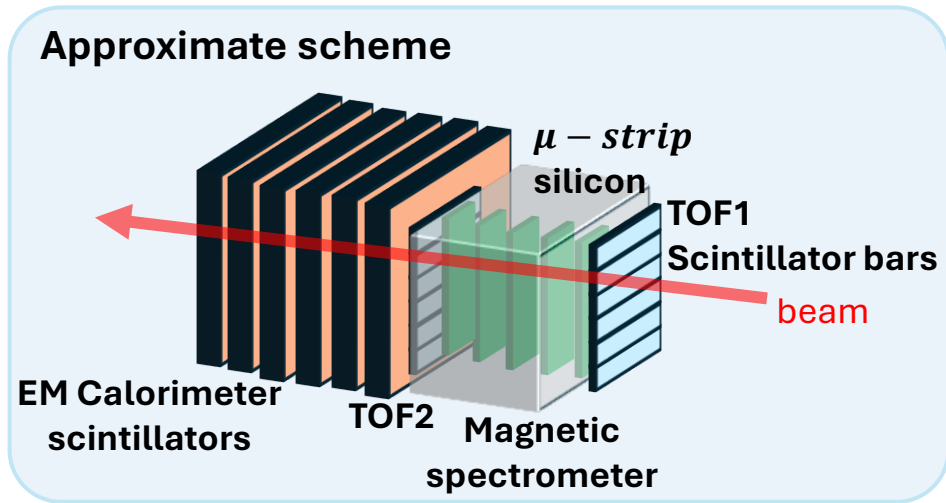
Hadrons pos 1GeV/c



μ^- 1GeV/c



Some preliminary results at PS, TOF and EM CALO:

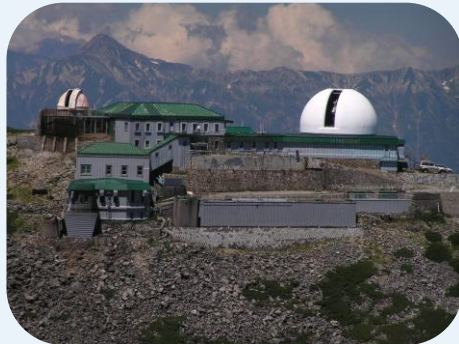


The total energy releases in the calorimeter is consistent with the particle type

Preparation of high-altitude measurements and conclusions:

The following measures are foreseen at altitude:

- Testa Grigia research station of CNR (Italy), 3480 m a.s.l
- Piccolo Cervino (Italy), 3883 m a.s.l
- Expression of interest from Norikura Solar Observatory (Japan) 2770 m a.s.l.



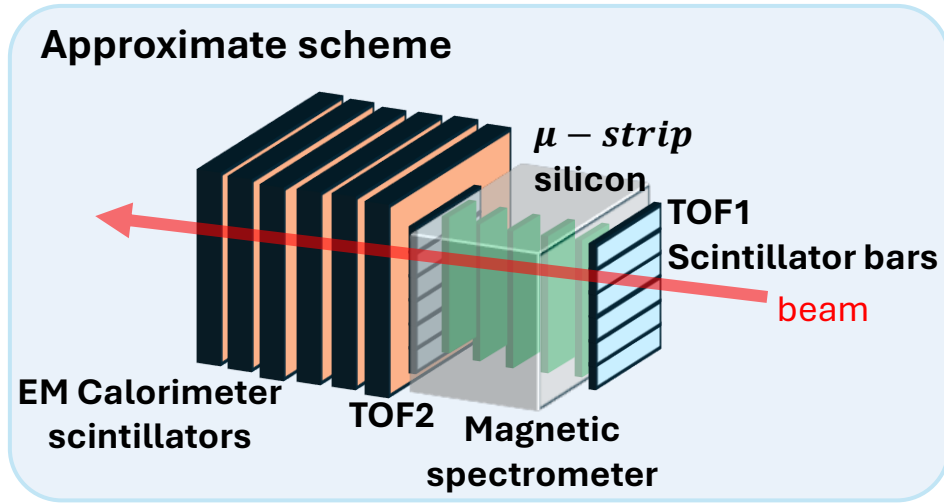
Conclusions:

- ACROMASS was assembled in 2025 with the aim of making measurements of differential cosmic ray fluxes at ground level;
- We did some beam tests to calibrate the instrument;
- We will analyze the data acquired during the beam tests with all three detectors;
- In the next months we will acquire the muon flux in Florence;
- We can start high-altitude measurements at the end of 2026



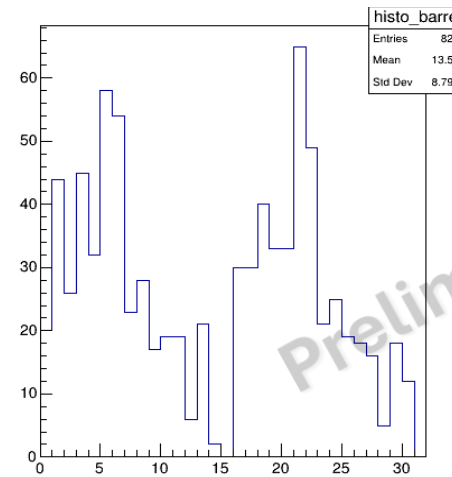
BACKUP

Some preliminary results at PS, MONITORING TOF and ECAL :

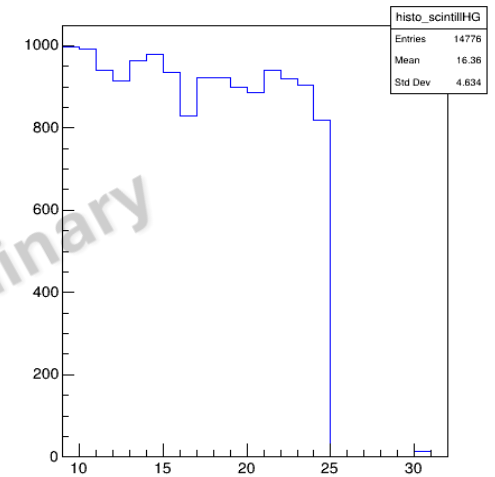


μ^+ 1 GeV/c

TOF: bars above threshold

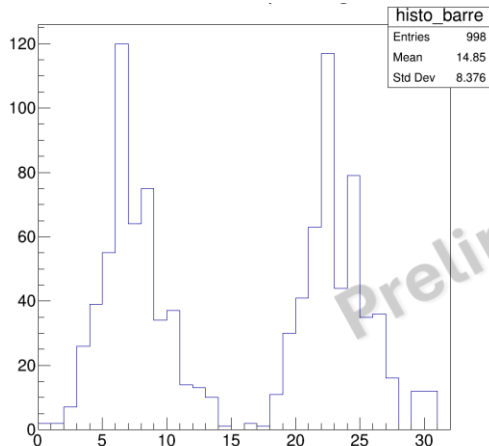


CALO: channel above threshold

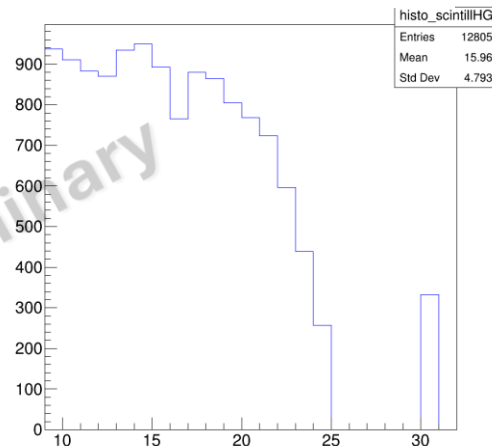


h^+ 1 GeV/c

TOF: bars above threshold

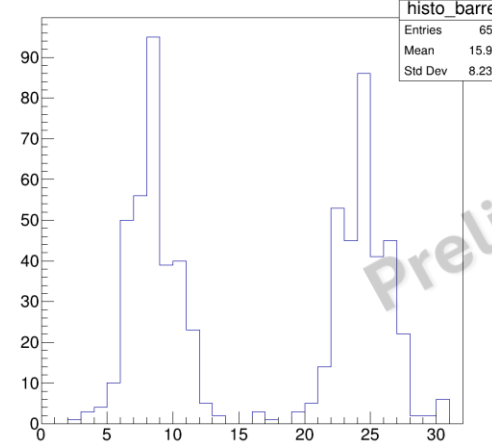


CALO: channel above threshold

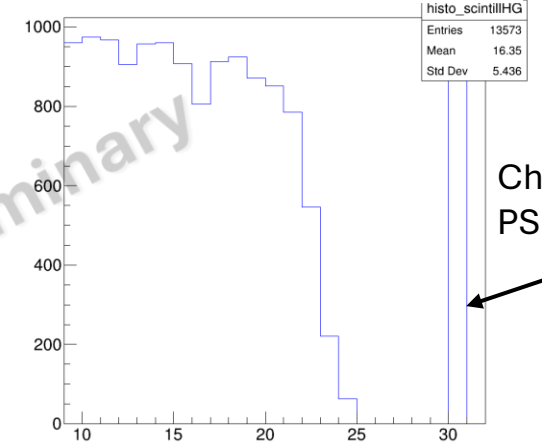


e^+ 1 GeV/c

TOF: bars above threshold



CALO: channel above threshold



Cherenkov PS detector

Muon flux model:

Gaisser

$$\Phi_{\text{Gaisser1990}} = 0.14 \left(\frac{E_\mu}{\text{GeV}} \right)^{-2.7} \left[\frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850}} \right] \quad (1)$$

This model is valid at high energies where muon decay and Earth's curvature are negligible.

To extend the validity to lower energies and larger zenith angles, Gaisser (2016) introduced a suppression factor S_μ , leading to:

$$\Phi_{\text{Gaisser2016}} = f \cdot S_\mu(E_\mu) \cdot \Phi_{\text{Gaisser1990}} \quad (2)$$

$$S_\mu(E_\mu) = \left(\frac{\Lambda_N \cos \theta}{X_0} \right)^{p_1} \left(\frac{E_\mu}{E_\mu + \frac{2}{\cos \theta}} \right)^{p_1 + \gamma + 1} \Gamma(p_1 + 1) \quad (3)$$

where: $\Lambda_N = 136.8 - 7.8 \log_{10}(E_\mu)$, X_0 = vertical atmospheric depth, and $p_1 = \frac{1}{E_\mu \cos \theta + 2}$.

Guan

The semi-empirical model of Guan suggests a modified parametrization that can overcome the shortcomings of Gaisser 1990 equation.

$$\Phi_{\text{Guan}} = 0.14 \left[\frac{E_\mu}{\text{GeV}} \left(1 + \frac{a \text{ GeV}}{E_\mu (\cos \theta^*)^b} \right) \right]^{-2.7} \left[\frac{1}{1 + \frac{1.1 E_\mu \cos \theta^*}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta^*}{850 \text{ GeV}}} \right] \quad (4)$$

$$\cos \theta^* = \sqrt{\frac{(\cos \theta)^2 + P_1^2 + P_2 (\cos \theta)^{P_3} + P_4 (\cos \theta)^{P_5}}{1 + P_1^2 + P_2 + P_4}} \quad (5)$$

with $a = 3.64$, $b = 1.29$ (fit from literature), and curvature parameters P_1 to P_5 .

Bugalev - Reyna

The Bugaev model includes muon production from three-body kaon decays and describes the vertical flux as:

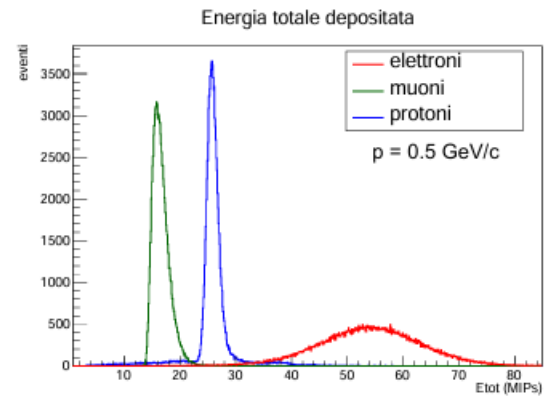
$$\Phi_{\text{Bugaev}} = c_1 p^{-(c_5 y^3 + c_4 y^2 + c_3 y + c_2)} \quad \text{with } y = \log_{10}(p) \quad (6)$$

where p is the muon momentum at sea level, and c_1 - c_5 are fit parameters. Reyna (2006) extended this model to all zenith angles by scaling:

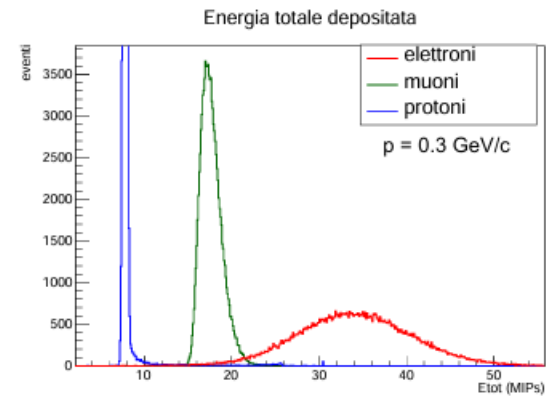
$$\Phi_{\text{Reyna}} = \cos^3(\theta) \Phi_{\text{Bugaev}}(p \cos \theta) \quad (7)$$

This angular correction exploits the empirical scaling of data with $p \cos \theta$, assuming similarity across zenith angles. Coefficients vary by momentum range; the model is valid for $1 \text{ GeV}/c < p < 1000 \text{ GeV}/c$, as higher-order terms vanish at high momentum.

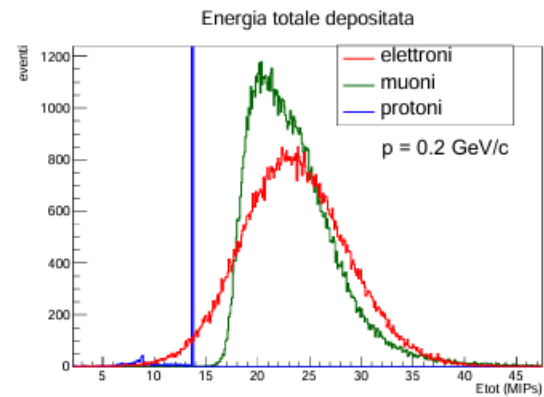
Simulations



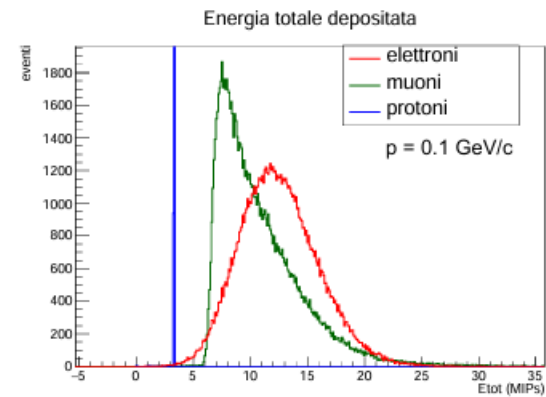
(a)



(b)



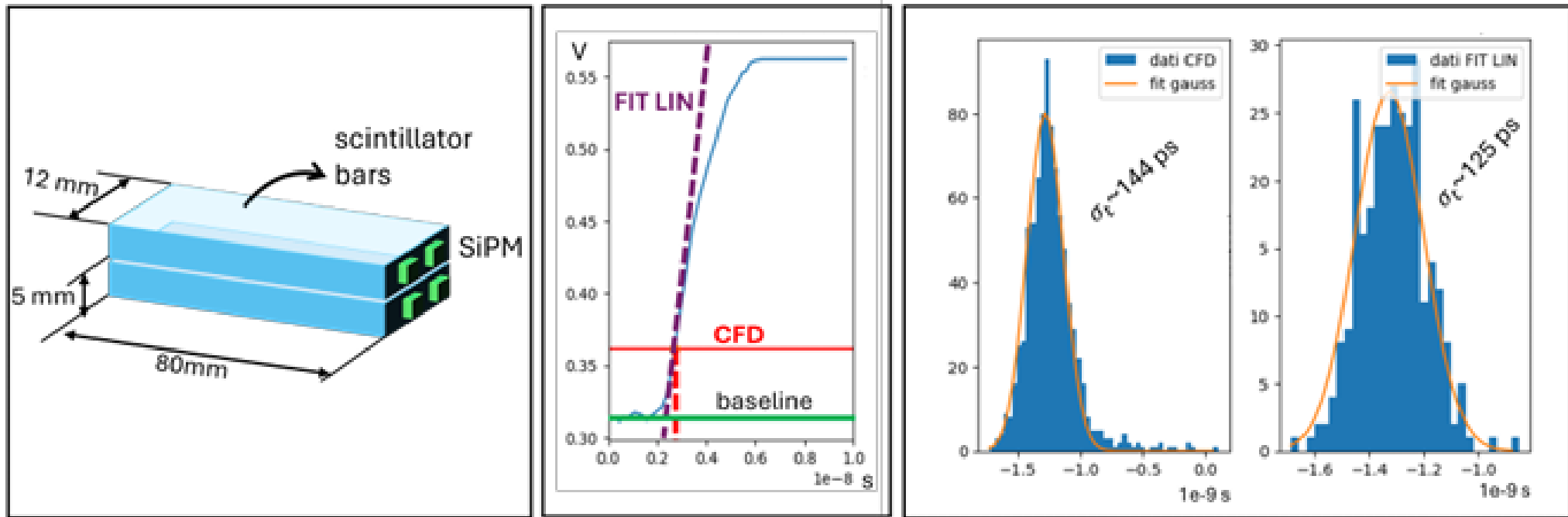
(c)



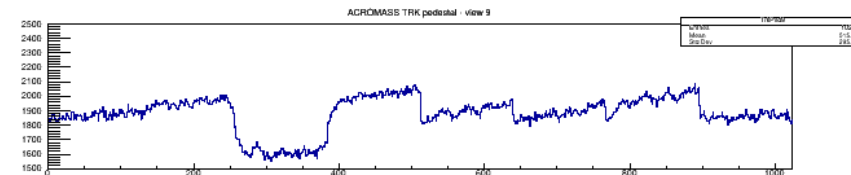
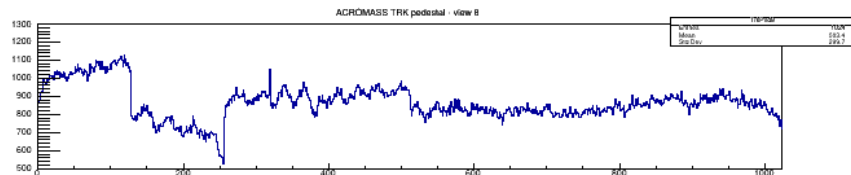
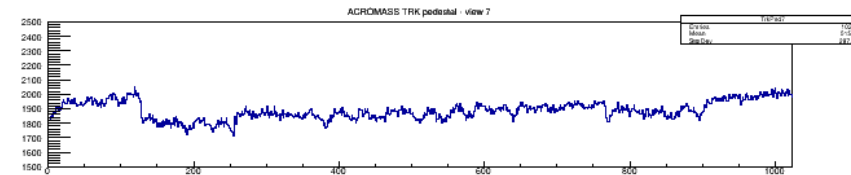
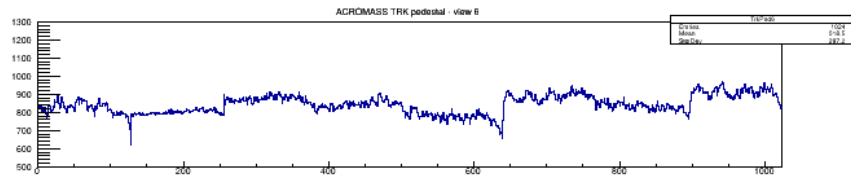
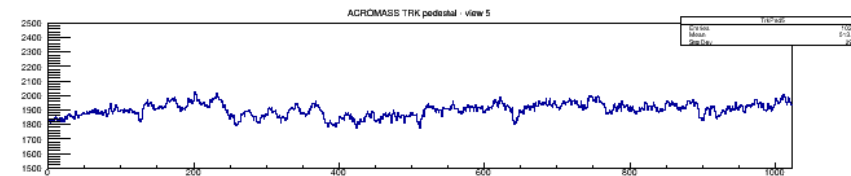
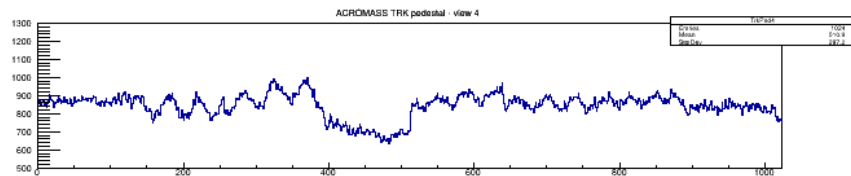
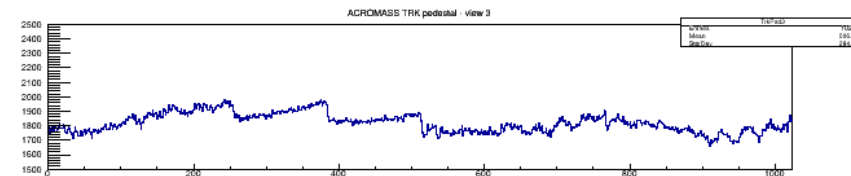
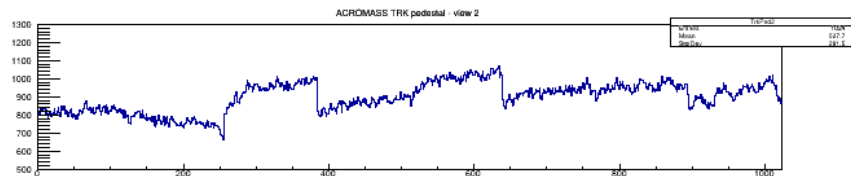
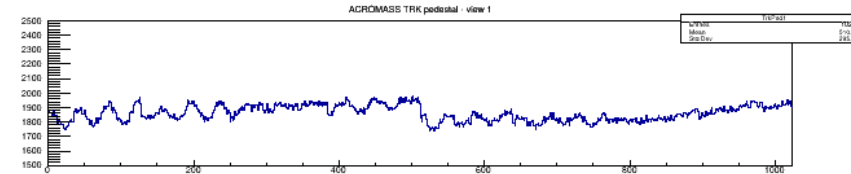
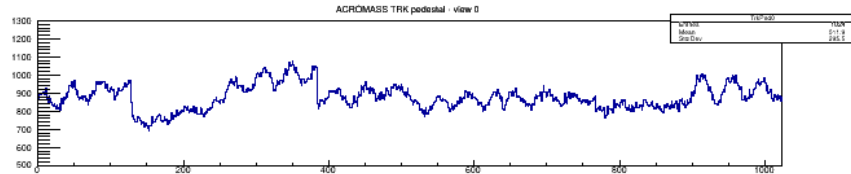
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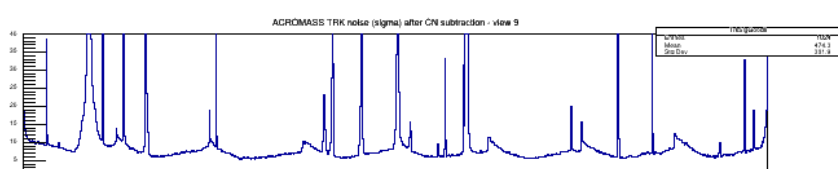
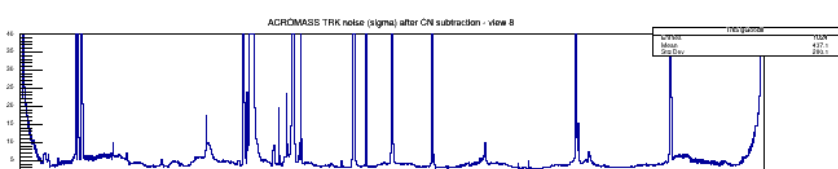
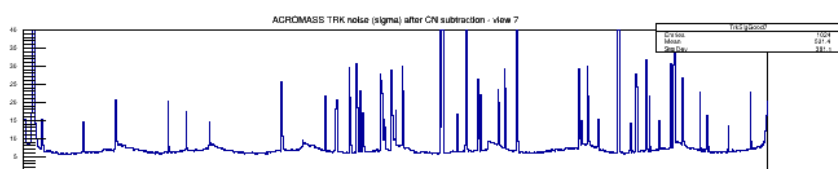
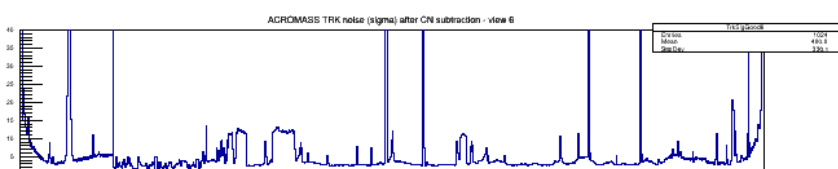
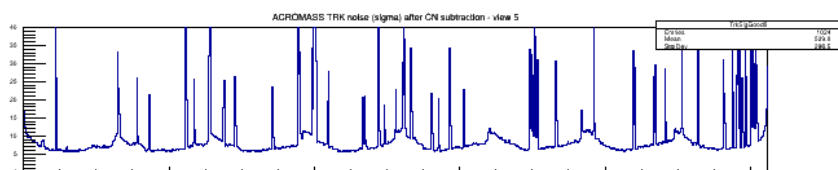
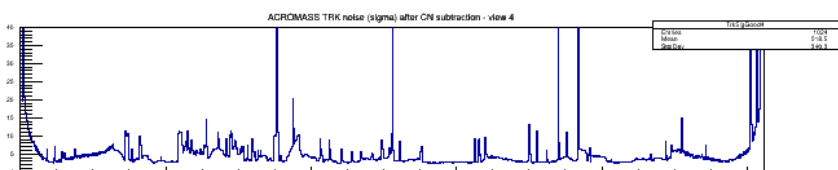
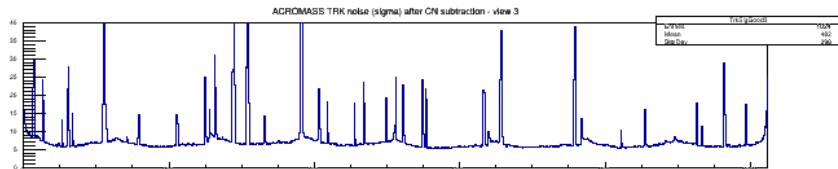
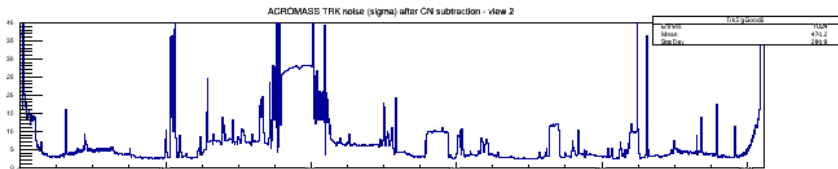
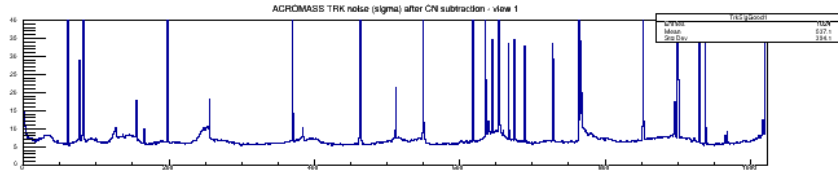
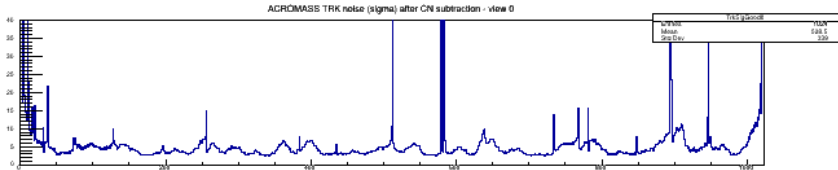
[11] Scordamaglia S.V., Master Thesis,
University of Florence, 2021

TOF time resolution:



The system measured time resolution is approximately $\sigma_t \sim 144$ ps for the CFD method which corresponds to a resolution on the single bar of $\sigma_t/\sqrt{2} \sim 101$ ps. In the case of linear fit, an improvement in resolution of approximately $\sigma_t/\sqrt{2} \sim 88$ ps (figure 3, right) is obtained.



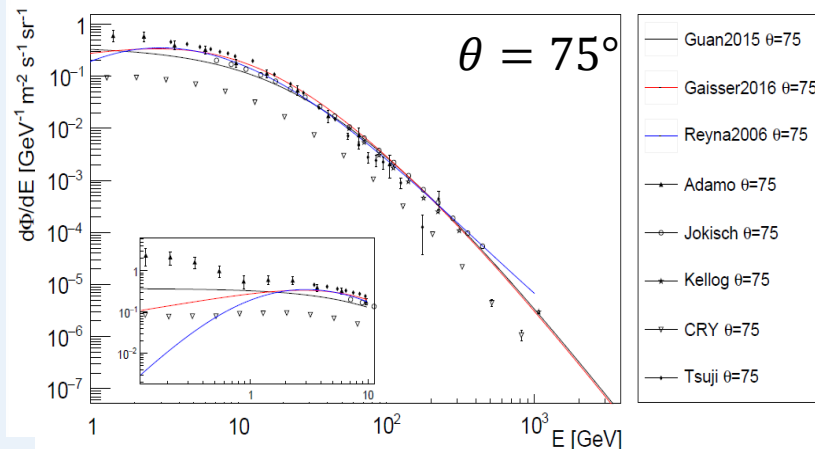
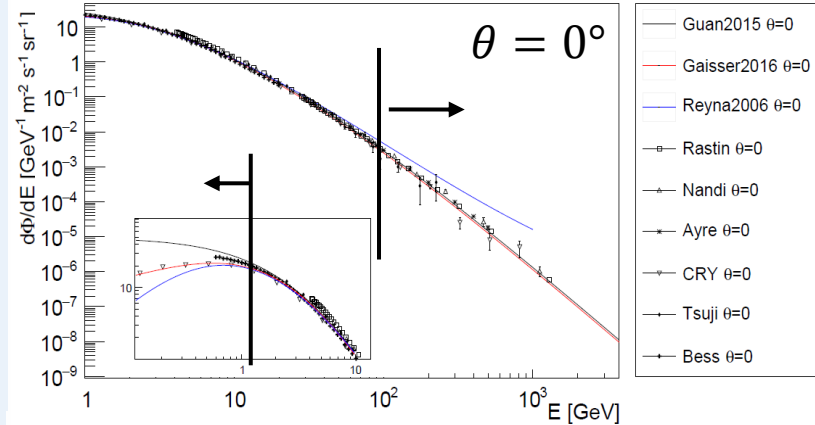


Muon flux model:

There are **several parametric models for the differential flux of muons** at ground level, but:

- They differ from each other in low energies (< 1 GeV) and high zenith angles ($\theta > 70^\circ$)
- Data Fragmentation: data varies widely due to local differences (location, time, altitude) and different detectors

Data fit with three different parametric muon flux models:



- Guan 2015
- Gaisser 2016
- Reyna 2006

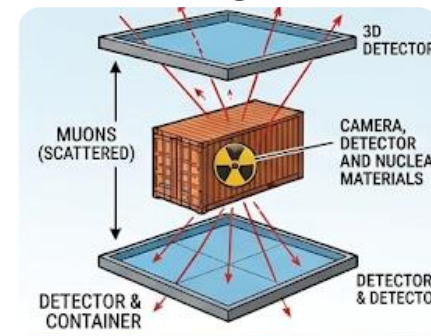
Data Fragmentation

No.	Authors	Year	Altitude (m)	Energy(GeV)	Zenith angle (deg)
1	Achard <i>et al.</i>	2004	450	20-3000	0-58
2	Bonechi <i>et al.</i>	2004	50	0.13-105	0-80
3	Kremer <i>et al.</i>	1999	360	0.25-100	0-20
4	Allkofer <i>et al.</i>	1985	5	11-8000	78-90
5	Green <i>et al.</i>	1979	100	2.5-250	55-90
6	Jokisch <i>et al.</i>	1979	10	1-1000	68-82
7	Kellog <i>et al.</i>	1978	10	55-1000	19-41, 64-86

[5] C. Frosin et al., 2025 J. Phys. G: Nucl. Part. Phys. 52 035002

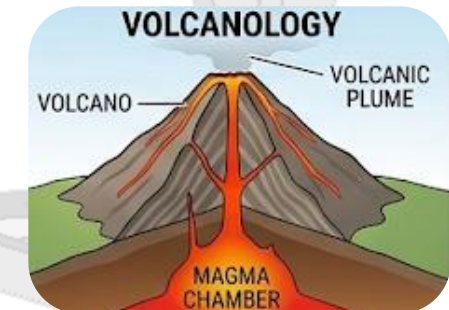
Muon flux < 1 GeV:

- ✓ Scattering muography
- ✓ small target



Muon flux > 100 GeV and $\theta > 75^\circ$:

- ✓ Volcanoes
- ✓ big targets

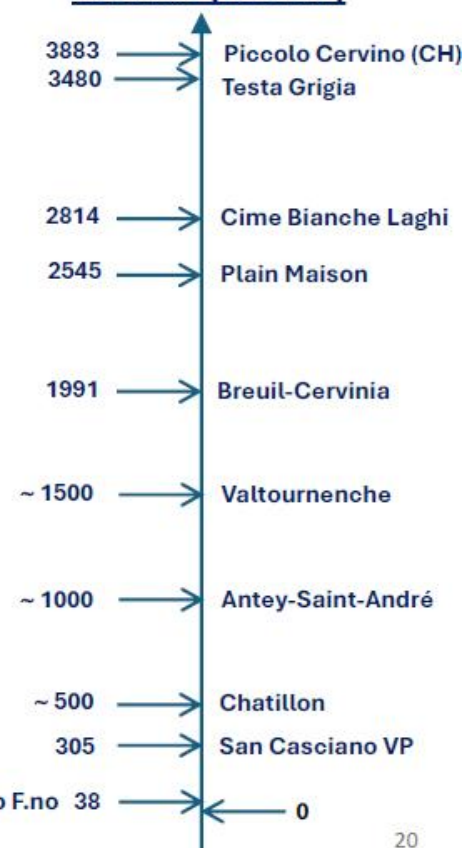




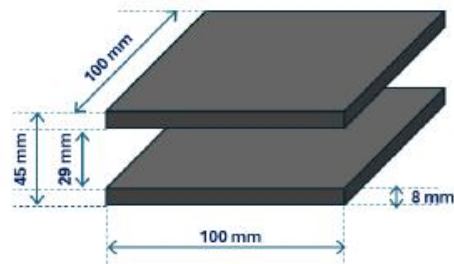
Very preliminary study at different altitudes



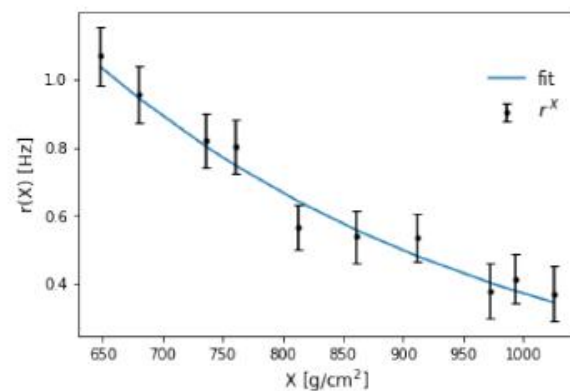
Altitude (m a.s.l.)



- Compact test apparatus
 - (CRMC = Cosmic Ray Muon Counter)
- Plastic scintillators with custom coincidence circuit



16 July 2025



ICRC 39th - The ACROMASS project

Dr. Chiara Volpato
 Master's Thesis
 University of Florence
 2023-2024
 (in Italian)