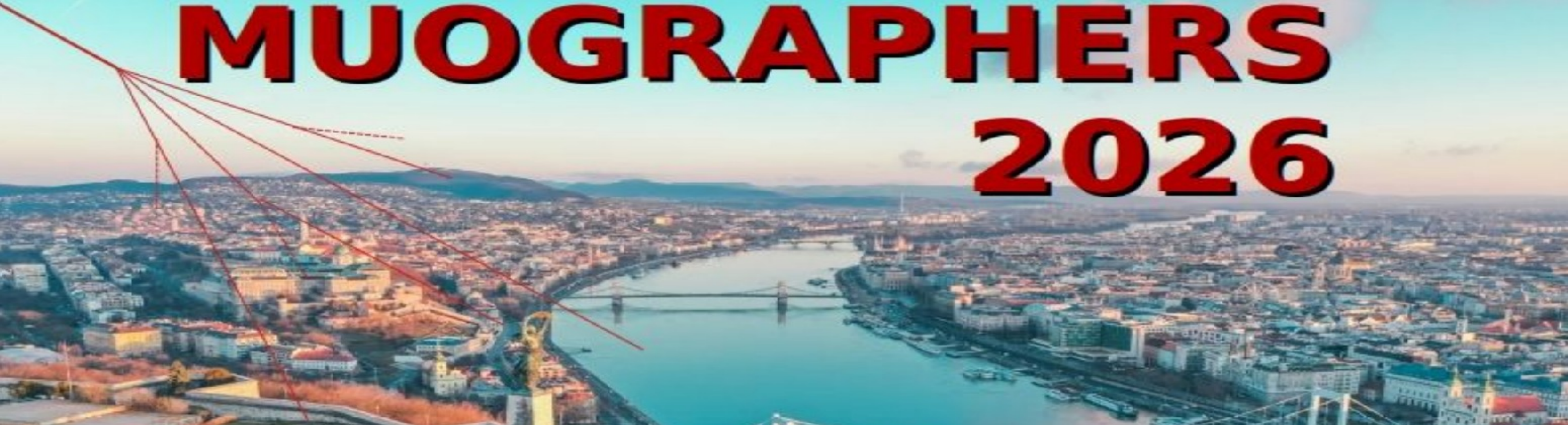

Rotational Muon Detector: Development and Proof-of-Concept for Muography Applications

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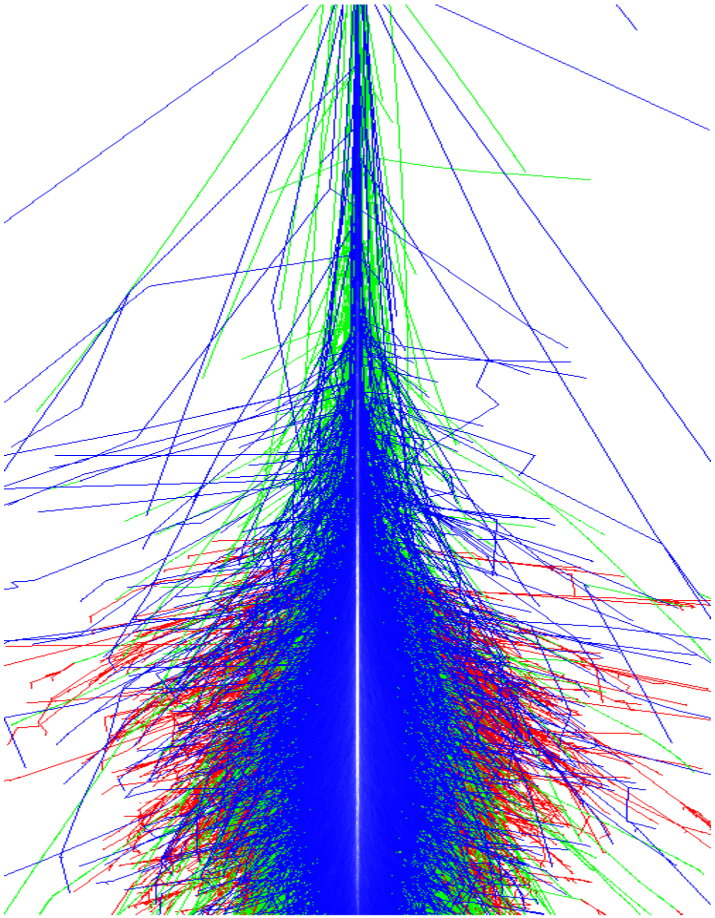
CONICET

Comisión Nacional de Energía Atómica

Instituto de Tecnologías en Detección y Astropartículas

universidad de buenos aires - exactas departamento de física

Outline



- Introduction
- Muon detection experience

  Idea: rotational counter
- Prototype + first simulations
- Prototype + data
- Conclusions and perspectives

Introduction

Background: LAGO + MuTe + AMIGA + **MATe**

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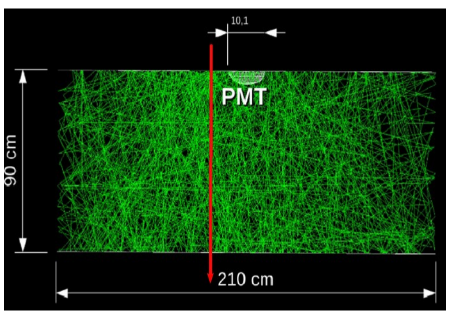
MuTe
The Muon Telescope

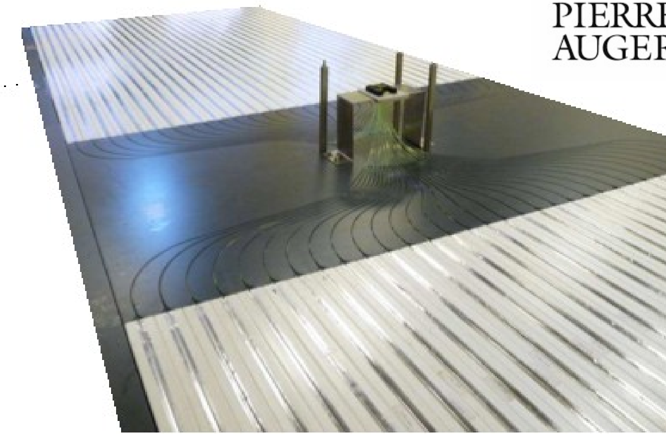
AMIGA project
Pierre Auger Observatory

OBSERVATORIO PIERRE AUGER



LAGO Collaboration

Colombia



CNEA - Argentina

In previous experiments and studies, we used detectors composed of scintillating materials, PMTs, and SiPMs; in all cases, we simulated using CORSIKA and Geant4.

MATe **Muon Andes Telescope**

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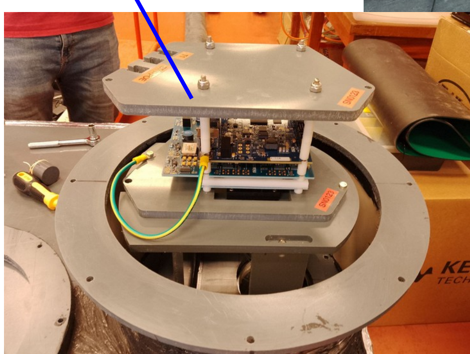
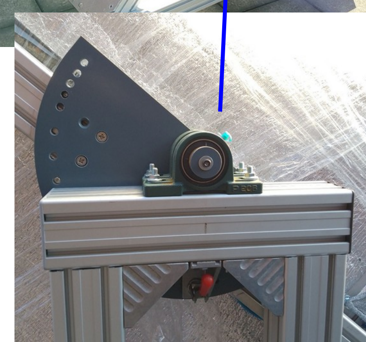
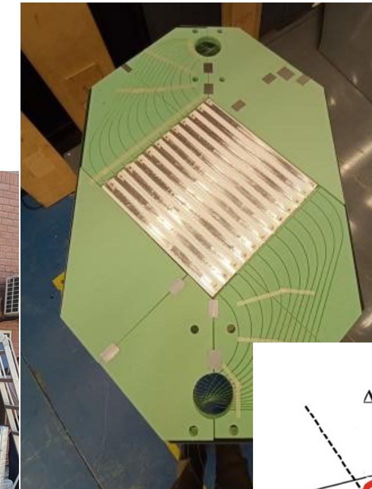
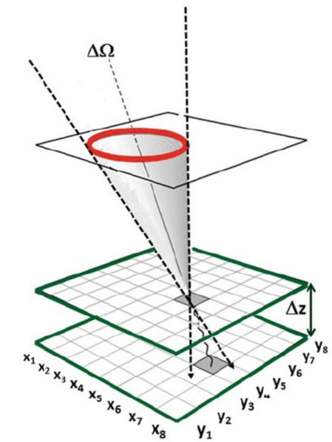
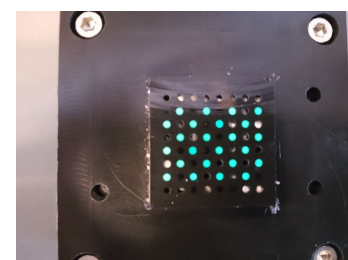
64-channel readout electronics











Swiss Army knife **Our muon counting system**

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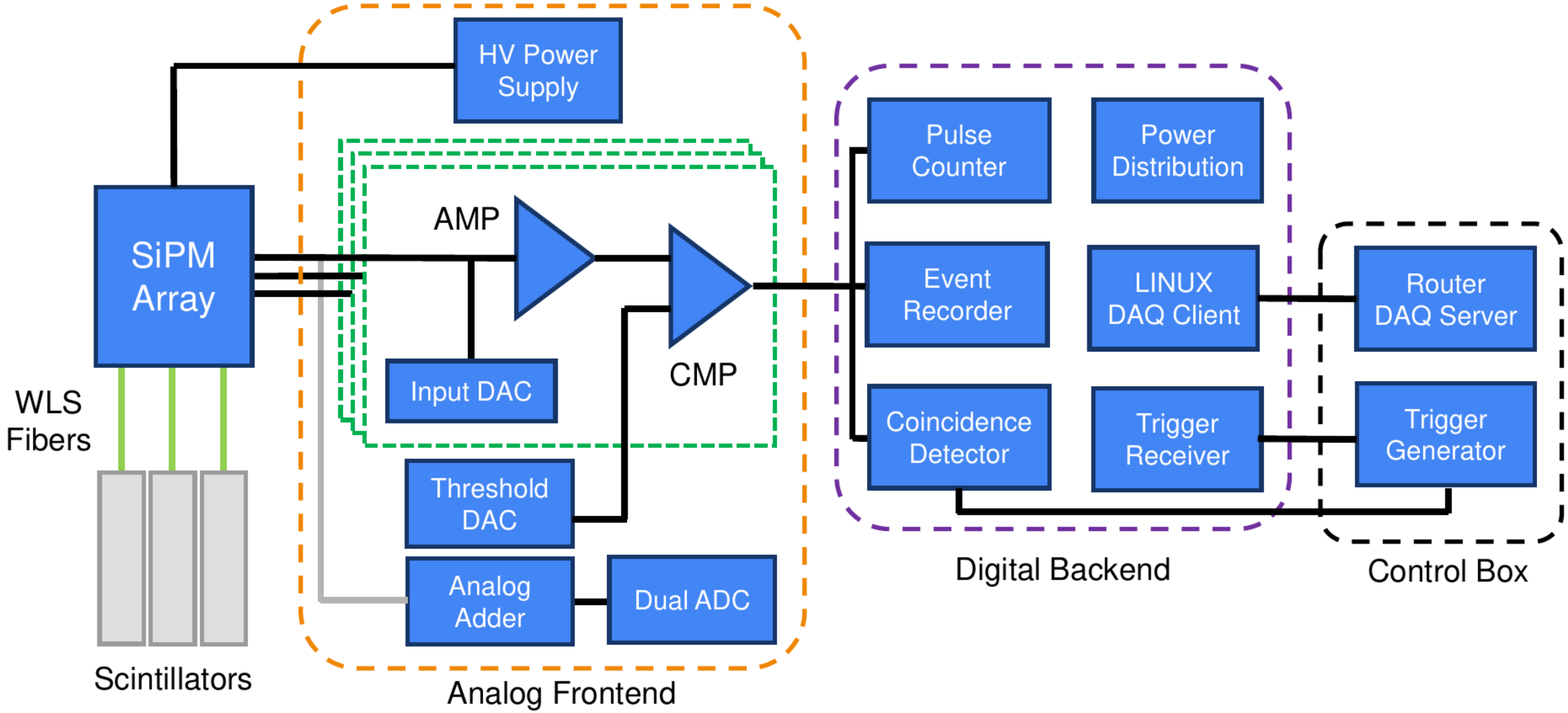
Muon telescopes, tomography, many geometries = counter and integrator modes



Idea: rotational counter

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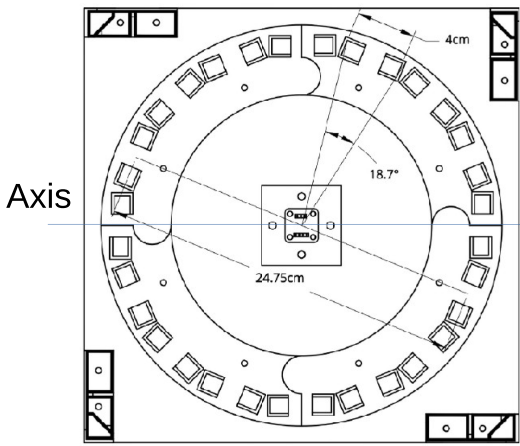

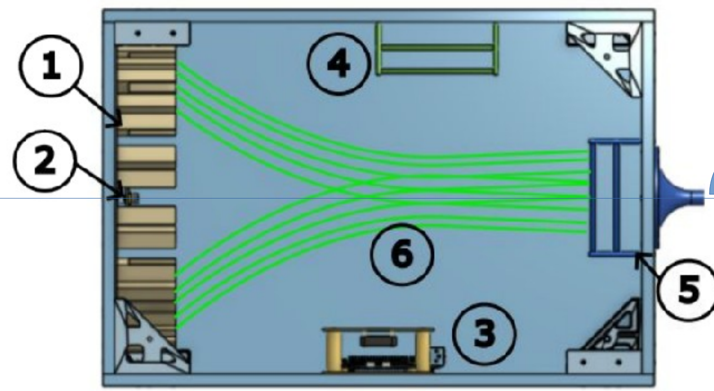

Interior of the detector

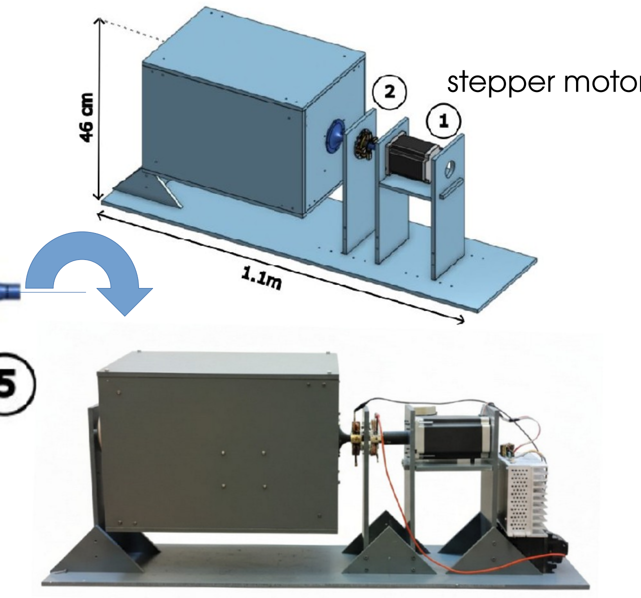

Fig 1. The scintillators (1) generate light guided by optical fibers (6) towards the SiPM electronics (5); an encoder (2) measures the angle at which the detector is oriented, while the FPGA (4) combines this data with coincidences in the SiPM, and the Raspberry Pi (3) stores it.

Fig 2. The rotation of the system is handled by a stepper motor (1) that ensures controlled and precise movement, while the carbon brushes (2) allow continuous transmission of the electrical signal (24V).

Idea: rotational prototype

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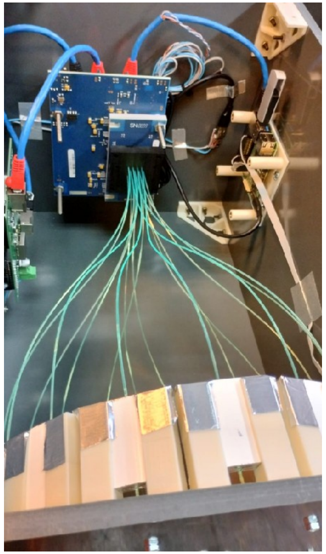

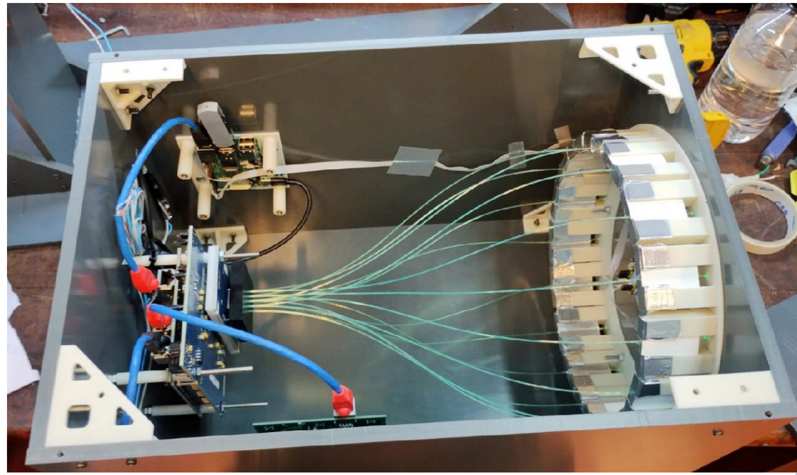

Interior of the detector

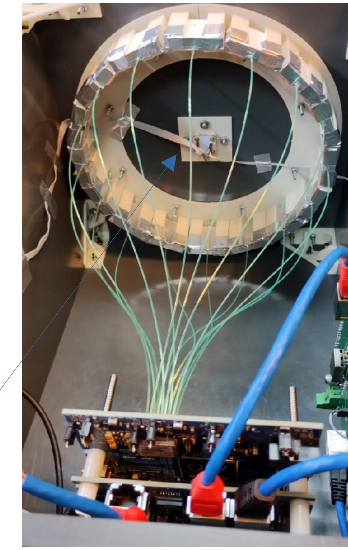

Fig 3. 1- The AS5600 encoder has a 12-bit resolution, equivalent to 4096 discrete positions per revolution, meaning a step size of 360°/4096 ≈ 0.088° per step.

2- Rotation improves the statistical precision of the reconstructed spectrum (more data, more orientations, better fit of the global distribution)

See how it rotates

Idea: rotational prototype

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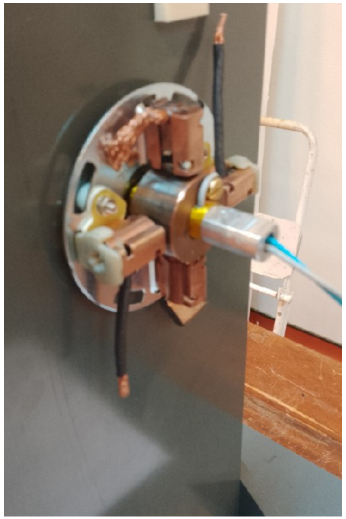
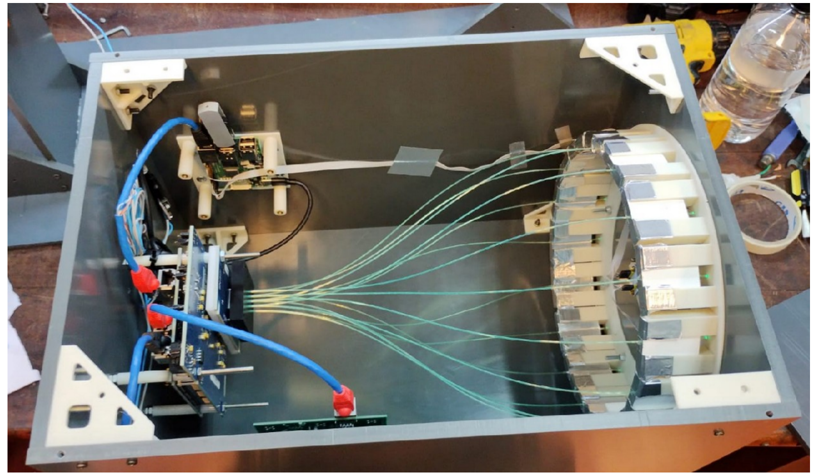




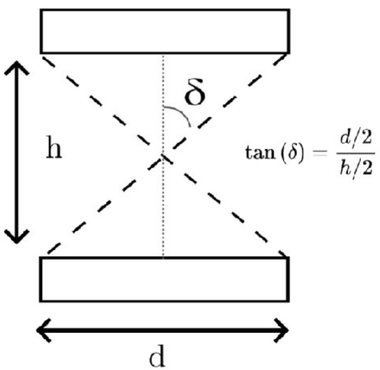
Interior of the detector

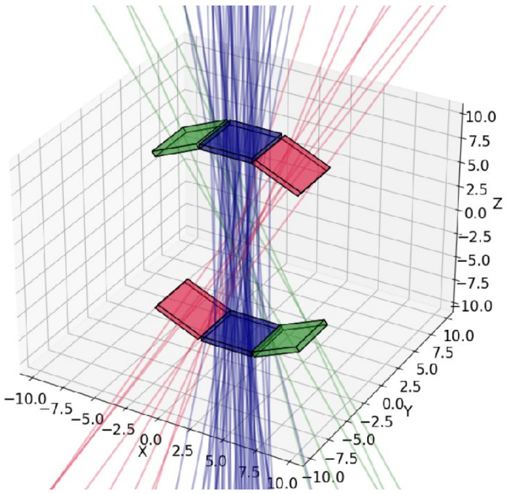
Fig 4. 1- The AS5600 encoder has a 12-bit resolution, equivalent to 4096 discrete positions per revolution, meaning a step size of 360°/4096 ≈ 0.088° per step.

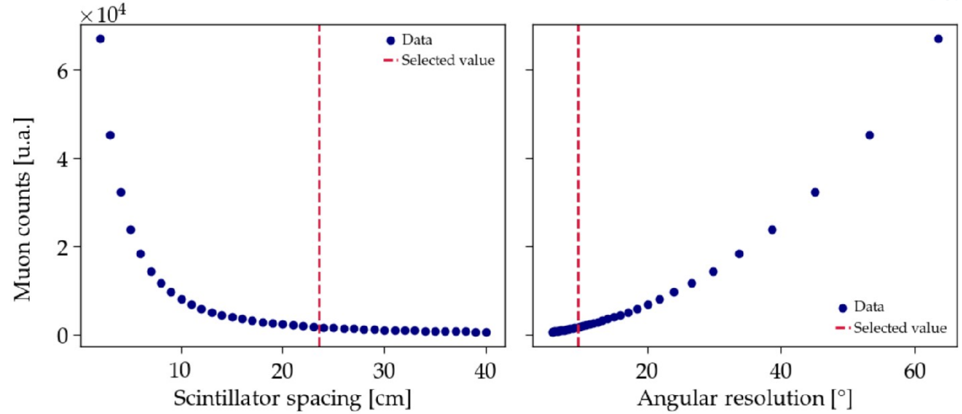
2- Rotation improves the statistical precision of the reconstructed spectrum (more data, more orientations, better fit of the global distribution)

See how it rotates

Prototype + model + first simulations







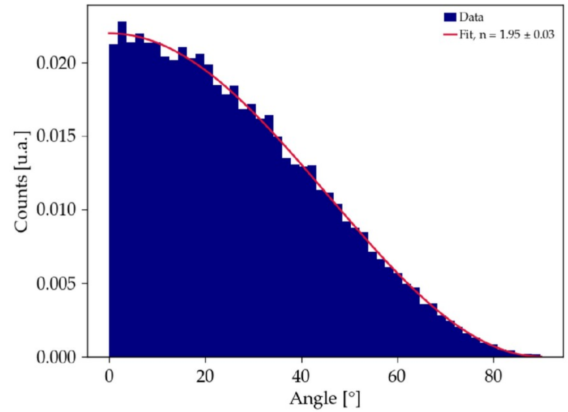


Fig 5. First, generate synthetic data, then produce models and understand the geometry. The results are shown in the figure. A $\cos^2(\theta)$ fit was performed, obtaining n = 1.95 ± 0.03. A Kolmogorov test was applied to compare with a $\cos^2(\theta)$ distribution, yielding a p-value of 0.08, which does not reject the hypothesis at a significance level of 0.05.

Prototype + data + results

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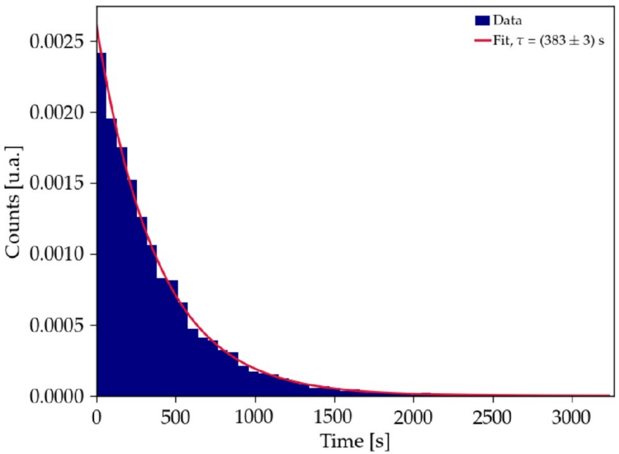

Inter-arrival times: exponentially distributed (Poisson process)

Bayes' theorem

$$P(x \mid D) = \frac{P(D \mid x) \cdot P(x)}{P(D)}$$

Mixture model

$$P(y_i \mid x) = \lambda \cdot P_1(y_i \mid n, \phi) + (1 - \lambda) \cdot P_2(y_i)$$

Muon signal distribution $P_1(\theta \mid n, \phi) = A \cdot |\cos(\theta + \phi)|^n$

Parameter	Prior
n	$\mathcal{N}(\mu = 2,\ \sigma = 1), \quad n \geq 0$
ϕ	$\mathcal{N}(\mu = \phi_0,\ \sigma = 0{,}5)$
λ	$\mathrm{Beta}(\alpha = 5,\ \beta = 2), \quad \lambda \in [0, 1]$

The angular data was modeled as a mixture of two distributions: the muon signal $|\cos(\theta+\varphi)|^n$ and a uniform noise background, combined through a mixing coefficient λ. Bayesian inference via PyStan was used to recover the three parameters (n, φ, λ) from each scintillator pair separately, using physically motivated priors. Once the phases were obtained, all pairs were aligned and the inference was repeated on the full dataset, successfully separating the muon signal from the background noise

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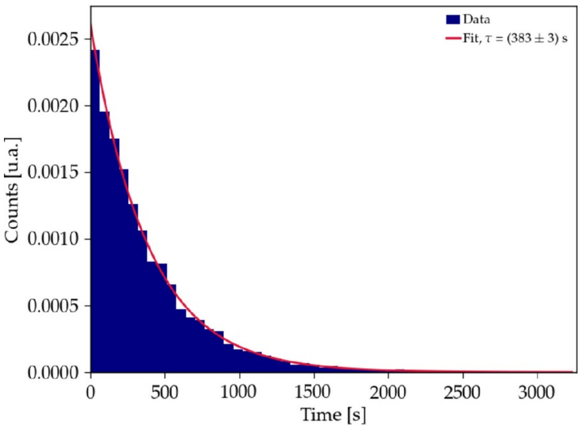
Prototype + data + results



Inter-arrival times: exponentially distributed (Poisson process)

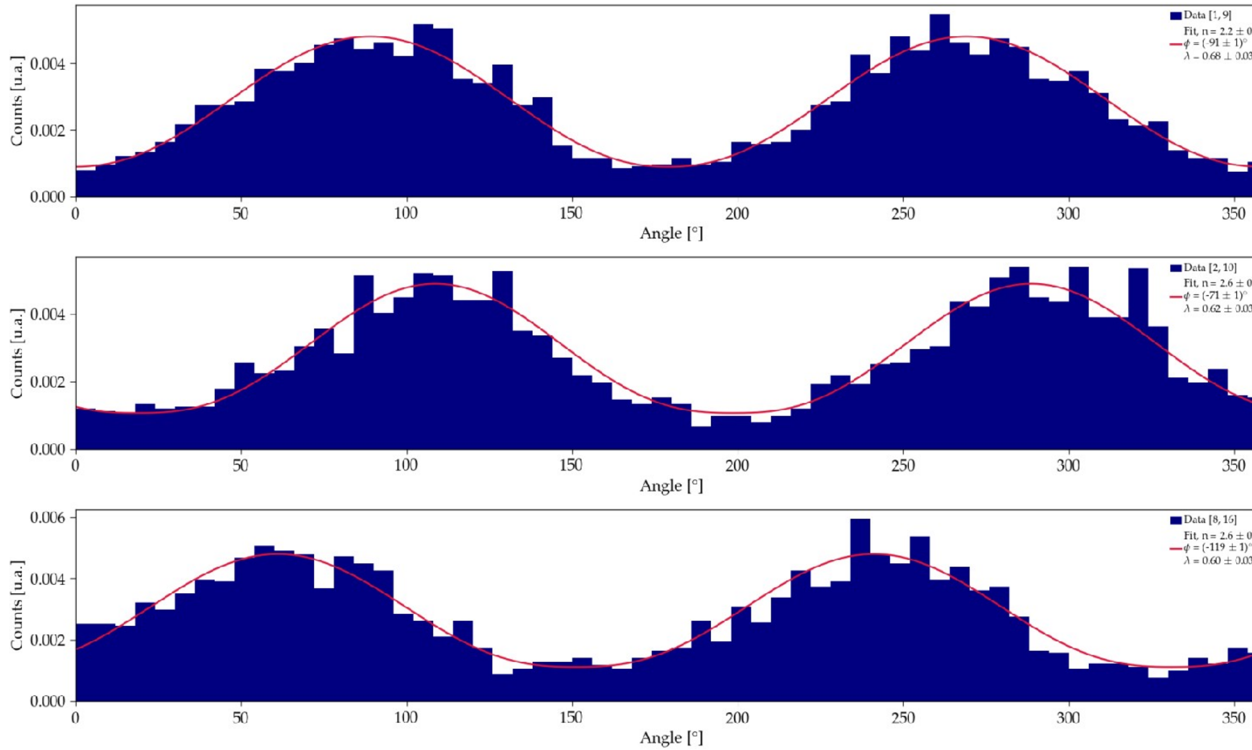


Fig 6. Histograms of the angular values measured by the encoder for coincidences between each pair of opposite scintillators. In red, the distribution functions of a mixture between a uniform distribution and a $|\cos^n(\theta)|$ distribution

Prototype + data + results

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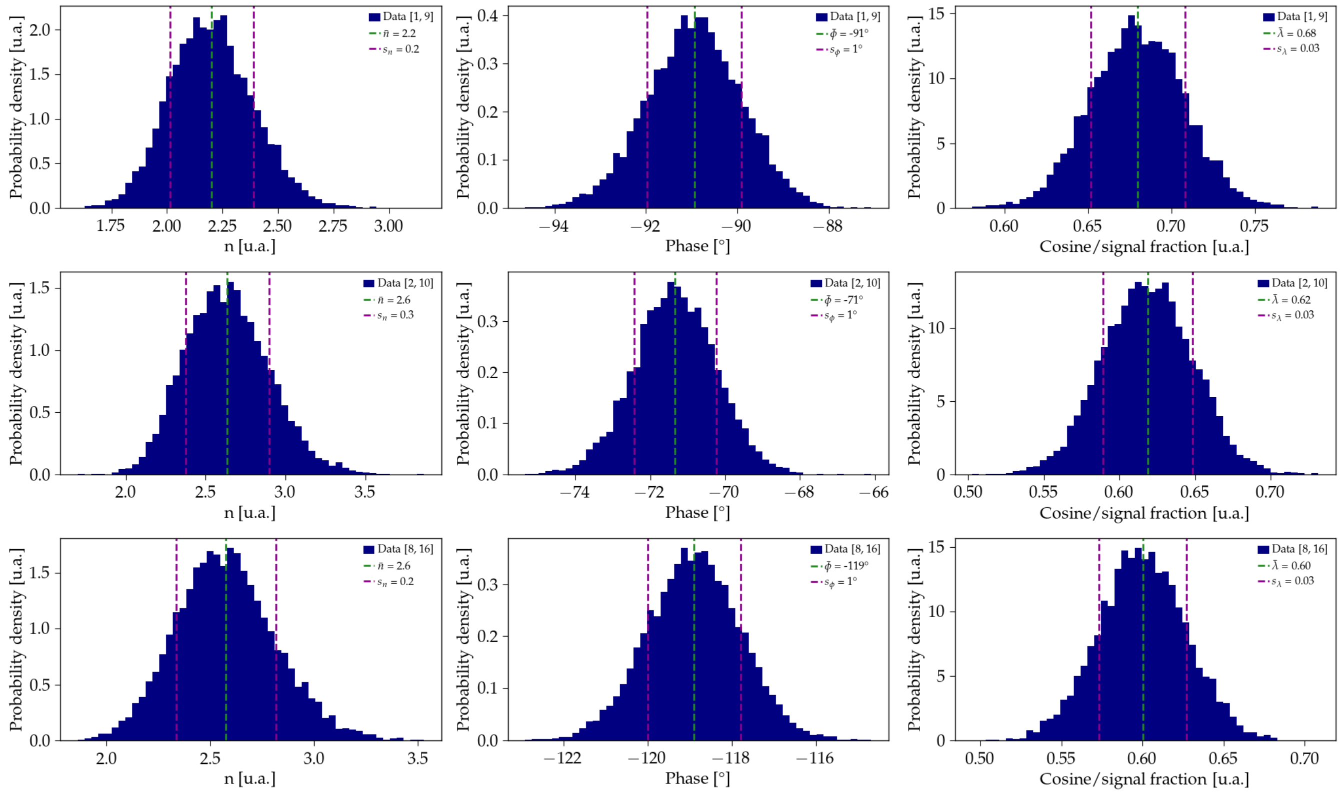


Fig 7, Histograms of the posterior distributions of the parameters n (left), φ (center) and λ (right) obtained with Bayesian inference. Each row corresponds to a pair of opposite scintillators. The green dashed lines correspond to the mean of each parameter. The violet dashed lines enclose the values within one standard deviation from the mean

Prototype + data + results

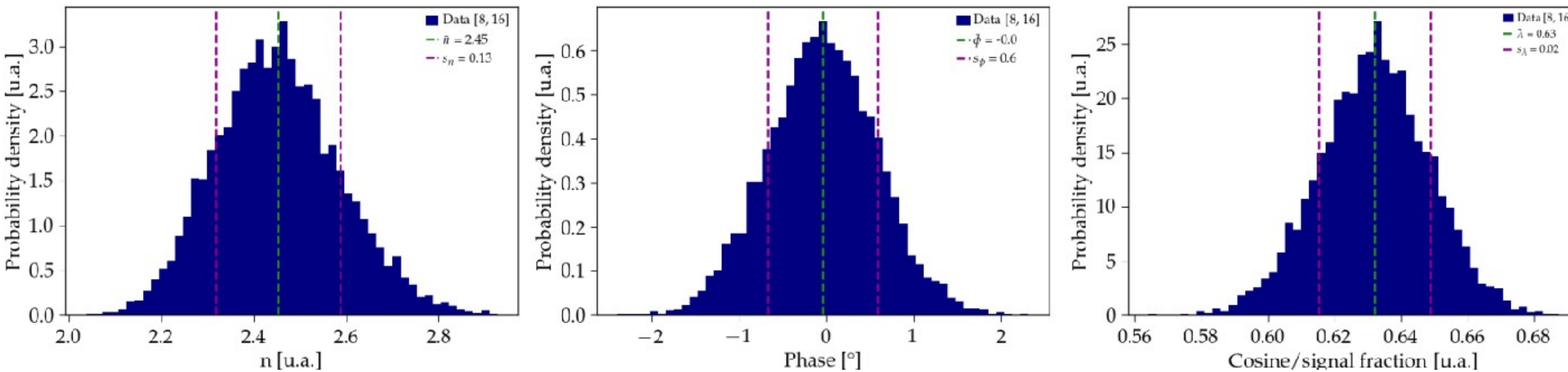
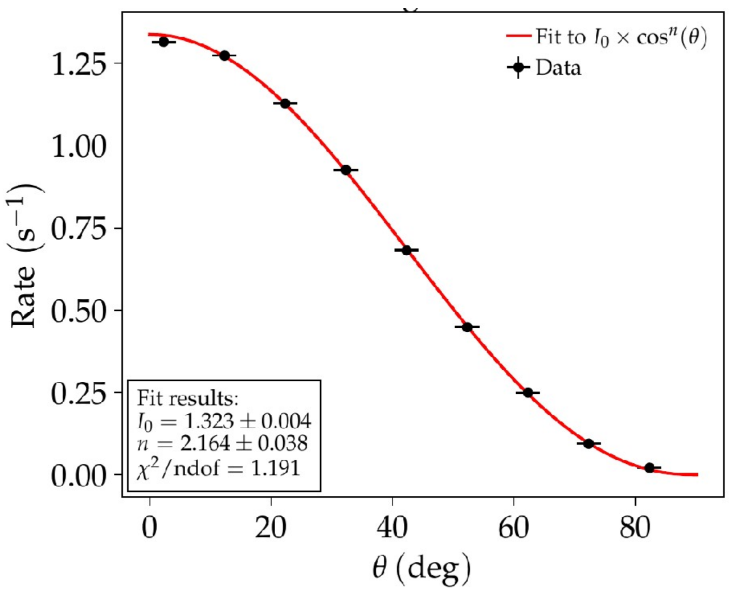


Fig 8, Histograms of the posterior distributions of the parameters n (left), φ (center) and λ (right) obtained with Bayesian inference for all pairs combined with their phases centered at 0°. The green lines correspond to the mean of each parameter and the violet lines enclose the values within one standard deviation from the mean.

Prototype + data + results



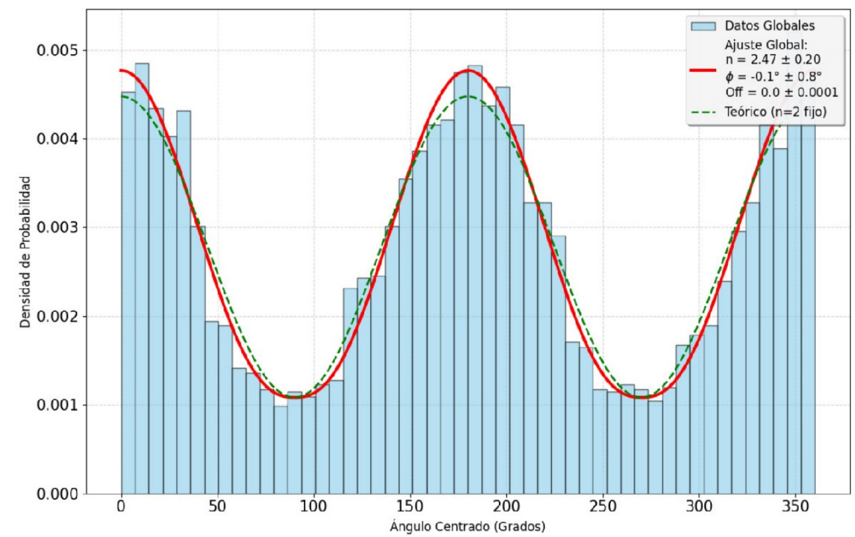
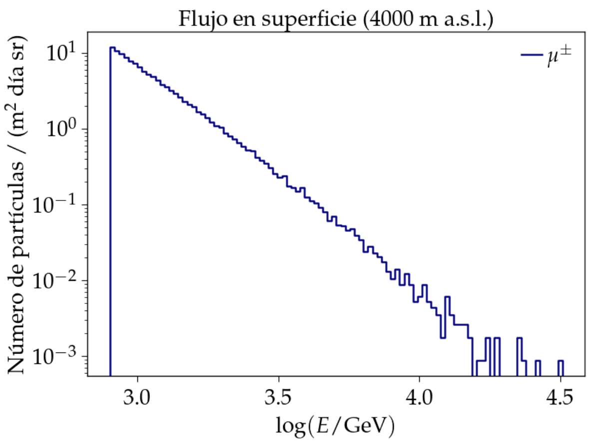


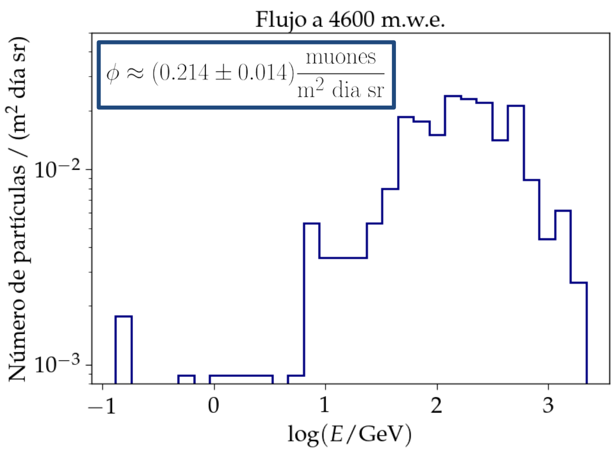
Fig 9. On the left we observe the zenith angle distribution measured with a MATe muon telescope with n = 2.164 ± 0.038, and on the right the reconstructed fit using the rotational telescope. In this case n = 2.47± 0.20 is estimated, due to the fact that measurements were taken two floors below ground level.

Future work: Take measurements of objects and determine their thickness using the profile (flux)

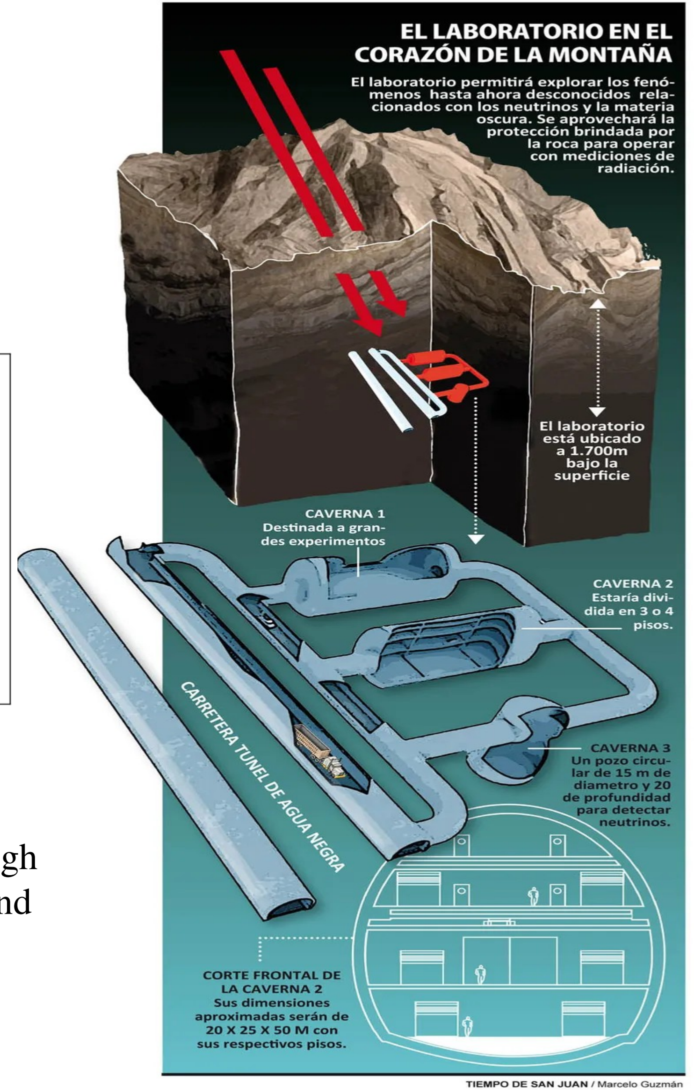
Motivation : It could happen soon $\rightarrow$ Opportunity!

ANDES Underground Laboratory (flux before and after the rock volume)





Simulation using Geant4 through Meiga: the surface flux is transported through the volume of material (rock) and attenuated, resulting in a muon spectrum and an induced background at approximately 1750 m depth.



Conclusions

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- 1. Instrumentation and operation : A compact rotating muon telescope was built and successfully operated, allowing measurements in multiple directions despite partial detector failures.

- 2. Data analysis and validation: Statistical analysis (Kolmogorov tests and Bayesian modeling) enabled the separation of signal and background and confirmed the consistency of the data.

- 3. Physical result and interpretation: An exponent of $n=2.47\pm0.20$ was obtained, showing a deviation from the reference value, likely due to environmental effects. (two floors below ground level).

- 4. Rotation improves the statistical precision of the reconstructed spectrum (more data, more orientations, better fit of the global distribution), but it does not improve the angular resolution per event. To improve the latter, the detector geometry must be changed: greater separation between scintillators, smaller pixels, or additional detector planes (layers).

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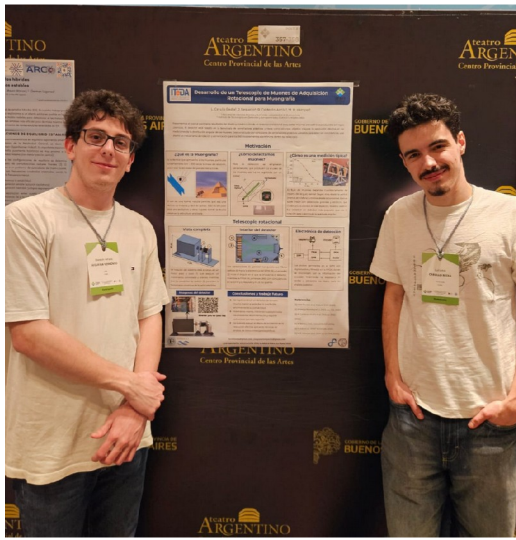
¡Thank you for your attention!



¡Gracias totales!

Backup slides

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