Simulation of a cosmic muon telescope

Advanced Topics in Computational Physics

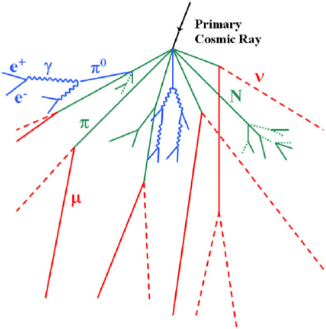
Guilherme Gaspar, Mariana Ribeiro, Sebastião Fonseca

Departamento de Física
Instituto Superior Técnico - ULisboa

04/2023

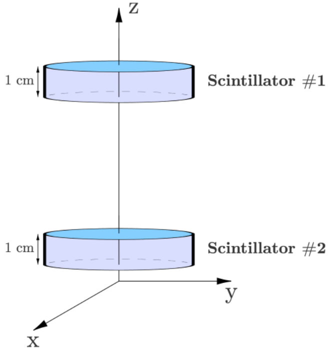
Introduction

- Cosmic muons are created when cosmic rays collide with air molecules in the Earth's atmosphere, creating a particle cascade.
- Muons lose energy while propagating through a medium and this energy is converted to photons, which can then be detected.
- In order to measure the muon flux at surface level, a muon telescope is used, consisting of two plastic scintillator disks that have SiPM devices on the lateral wall which allow for detection of scintillation photons.
- To find the optimal configuration we ran a simulation of the muon telescope.



Simulation Characteristics

- Implemented in C++, using ROOT package
- Two scintillator disks ($R = 5$ cm, $h = 1$ cm)
- Variable distance d between scintillators
- N SiPM devices placed symmetrically along the lateral wall of the scintillators
- Thickness of the air gap, $t_{air} = 0.1cm$ and aluminium foil, $t_{al} = 0.0016cm$



Defining the Geometry using ROOT package

- Define the volumes according to the geometry the telescope
- Define the materials to be used in the simulation: Scintillator plastic, vacuum and aluminium
- Fill each volume with its respective material and build the telescope

Generating and propagating cosmic muons

- Generate position assuming a uniform distribution in first scintillator plane
- Generate muon's momentum and zenith angle using a 2D accept-reject method according to:

$$I(p_\mu, \theta) = \cos^3(\theta) I_\mathrm{v}(p_\mu \cos\theta), \tag{1}$$

- Calculate energy loss while propagating the muon using Bethe-Block formula:

$$\boxed{-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \frac{nz^2}{\beta^2} \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 ln\left[\left(\frac{2m_e c^2 \beta^2}{I(1-\beta^2)} \right) - \beta^2 \right]} \tag{2}$$

- Generate photons from energy lost according to Poisson distribution with expected value:

$$N_{photons\_generated} = \Delta E / 100eV \tag{3}$$

Generating and propagating photons

- Generate isotropic photons, with energies according to energy spectrum of scintillator, obtained from Spline3 interpolation of manufacter data
- Propagate photons: check for absorption, reflections and losses in aluminium
- Check if photons are detected by one SiPM device and, if so, convert to signal through detector's efficiency (also using Spline3 interpolation)

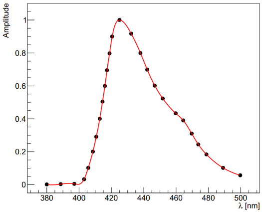


Figure: Generated photon wavelength spectrum.

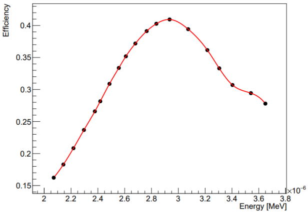


Figure: Detector efficiency as a function of photon energy.

Modes of operation of the program

- **-Draw n:** Propagates and draws the tracks of a muon and *n* photons generated.
- **-Ang:** Propagates muons through both detectors and stores it's azimuthal angle and impact point for each detector.
- **-Geo:** Propagates muons through both detectors, storing number of accepted muons, total muons generated and distance between scintillators.
- **-Map n:** Propagates muons and photons until they hit the scintillator surface for the first time. Stores photons' radial position and height in the scintillator lateral wall.
- **-Disk:** Propagates muons with varying impact point and saves the detector efficiency on the top scintillator, the impact point and the number of SiPMs used.
- **-Det n:** Program that stores the number of photons generated and detected in the specified scintillator, allowing for an estimation of the number of photons detected per muon.

Multi-threading

- Implemented with the *thread* library of C++
- One *TGeoNavigator* per thread that allows for parallelization of the propagation of muons

Thread Count	1	2	3	4	5	6	8
Running Time (s)	3879.76	1957.28	1265.96	993.10	788.57	745.39	594.77
Speedup (%)	0	98.22	206.47	290.67	391.99	420.55	552.31

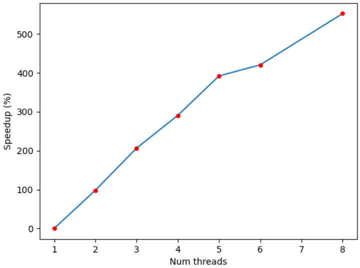


Figure: Speedup as a function of the number of threads

-Draw Mode

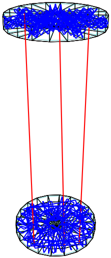


Figure: Visualization of the tracks of 3 muons and 2 photons per muon

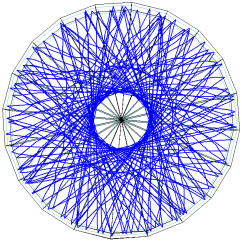


Figure: Top view of photon propagation.

-Ang Mode

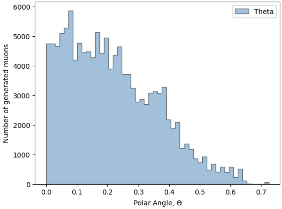


Figure: Histogram for polar angle distribution of the generated muons (distance between scintillators = 10 cm).

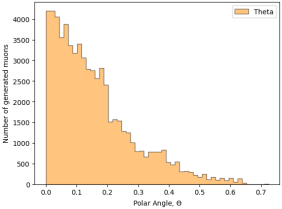


Figure: Histogram for polar angle distribution of the generated muons (distance between scintillators = 25 cm).

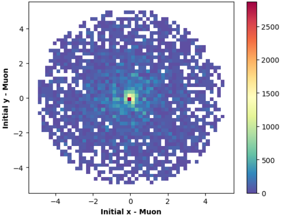


Figure: 2D histogram for impact point distribution of the generated muons (distance between scintillators = 10 cm).

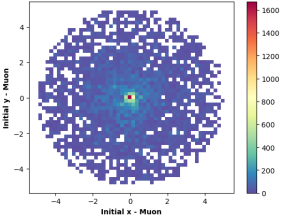


Figure: 2D histogram for impact point distribution of the generated muons (distance between scintillators = 25 cm).

-Geo Mode

Monte Carlo simulations of 3000 accepted muons, for 50 distances from 1 to 50 cm.

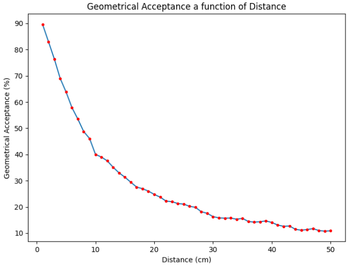


Figure: Geometrical Acceptance of the Muon Telescope as a Function of Distance

When there's a bigger distance between the scintillators the muons generated with lower inclination don't reach the second scintillator and escape the telescope.

-Disk Mode

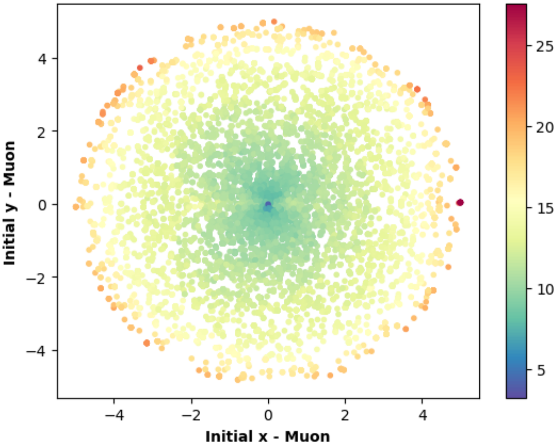
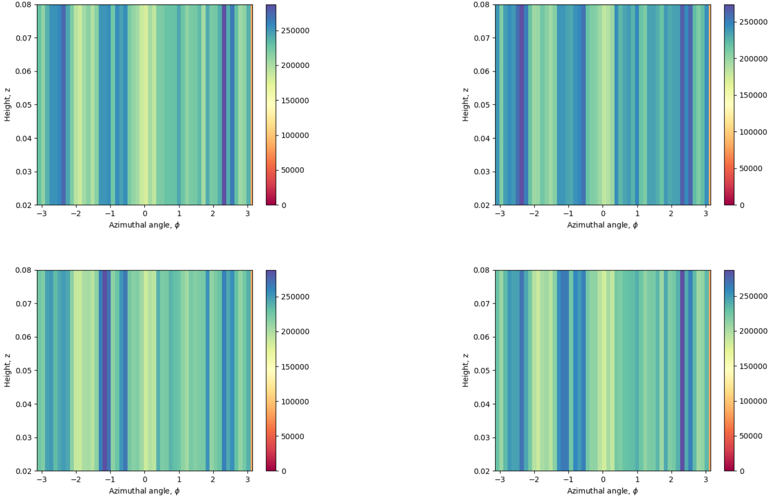


Figure: Detector efficiency as a function of the muon impact point.



In these 2D histograms each event corresponds to a photon that hits the lateral surface of the top scintillator, for a distance of 10 cm between the two scintillators.

-Det Mode

Simulation of 1000 muons propagating in the first scintillator for different number of SiPMs in scintillator #1

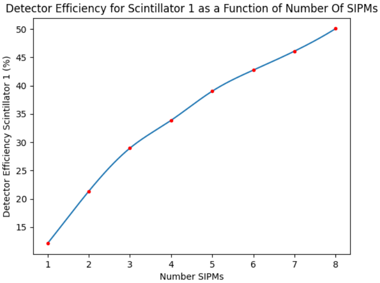


Figure: Detector Efficiency (%) as a Function of Number of SIPMs

As expected, the detector efficiency increases, as there are more areas of detection of the photons.

Some important results

	distance 25 cm		distance 10 cm	
	Top Scintillator	Bottom Scintillator	Top Scintillator	Bottom Scintillator
Number of photons per muon	3206	3934	3298	4056
Number of photons per muon per SiPM area	68	55	66	54

Table: Table with the number of photons that, on average, reach the lateral surface per muon for each scintillator and distance combination, and the corresponding estimate of photons per SiPM area per muon.

	distance 25 cm		distance 10 cm	
	Top Scintillator	Bottom Scintillator	Top Scintillator	Bottom Scintillator
Number of accepted muons	2000	1000	2000	3000
Number of detected photons	3256	3581	3392	3550
Detection efficiency	12.1 %	13.5 %	12.2 %	13.4 %

Table: Average number of photons detected in the SiPM for each scintillator and each distance between scintillators. The table also shows the telescope detection efficiency for each scintillator (fraction of emitted photons that is detected).

Conclusions

- We were able to fully implement the muon telescope, the propagation of particles and detection of photons.
- There is still room for improvement:
  - Parallelize the photons for faster single muon propagation.
  - Calculate the number of detected photons with the SiPM devices located in different areas, mainly the ones showing bigger discrepancies on the heat maps.
  - Convert the number of detected photons to eletric current values.
  - Analyse the detected signal per SiPM, for different numbers of SiPMs per scintillator.
  - Analyse the difference in the detected signal between different SiPMs on the same scintillator, for different impact points.

Thank you!