ARCHAELOGICAL STRUCTURES SCANNING BY MUON TOMOGRAPHY

Feasibility studies

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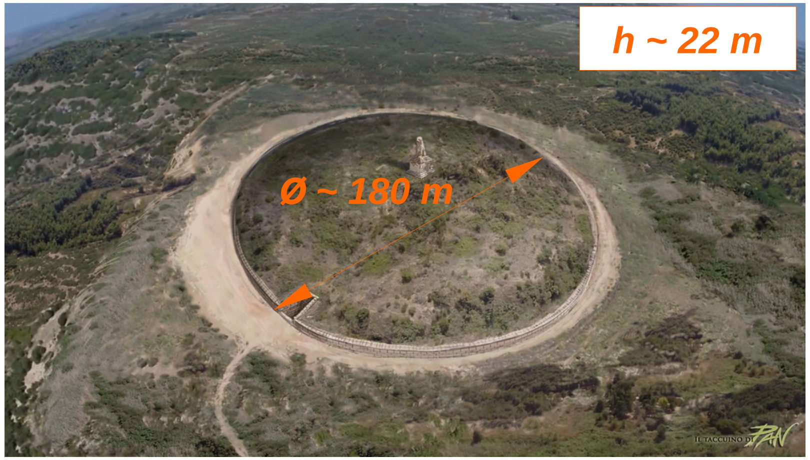
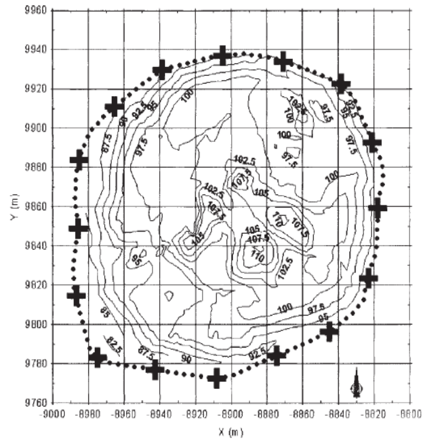
Evaluate the ***viability*** to study the internal structure (in terms of ***measurement time***) of a tumulus, using muon tomography

Precise simulations will help to the better understanding of the obtained results

Studied case: ***Kastas Amfipoli Macedonian tumulus***





Archaeological Prospection
Archaeol. Prospect. **11**, 145–158 (2004)
Published online 12 May 2004 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/arp.228

Archaeologists have already explored a corridor driving to an internal hall (~ 3 x 4 x 3 m^3), but no evidence of man-made internal structures has been found yet

Studies based on seismic tomography has already scanned the tumulus finding evidences of internal structures

Muon tomography could represent an alternative method to explore the tumulus structures (together with e.g. seismic tomography or gravimetry) in a non-destructive way

Study Definition: Geometry and Materials

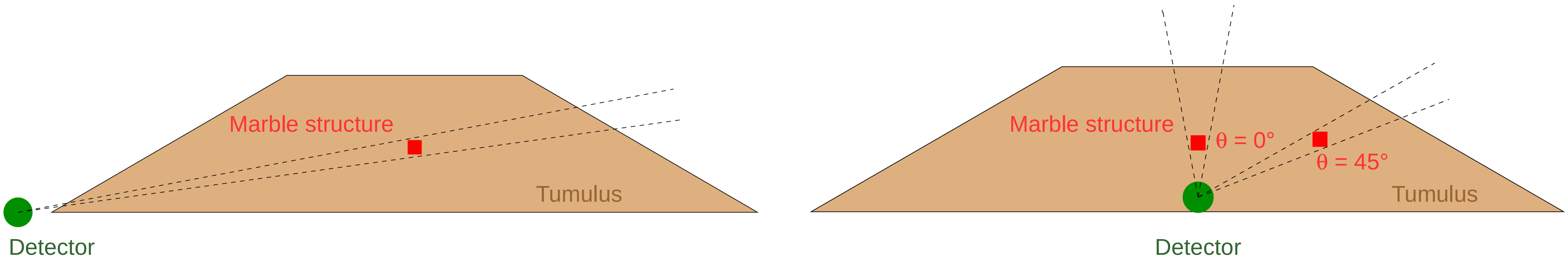
Muon tomography is based in the muon detection after crossing the studied object:

Differences on the mean density of the material traversed by muons → Differences in the detected muon rate

The measurement for different incident angles will allow to estimate the eventual position of the internal structure

Three scenarios considered:

Assuming the existence of a marble box (2 x 2 x 2 m^3) inside the tumulus, composed by standard soil



Detector on the Tumulus side (side detector) | Detector on a Tumulus internal chamber (centred detector)

Materials defined for the study (and implemented properties for simulations):

	<Z>	<A>	ρ [g cm^{-3}]	λ [g cm^{-2}]
Standard Soil*	~12.1	~24.6	1.60	26.54
Standard Rock	11	22	2.65	26.54
Marble ($CaCO_3$)	50	100.1	2.80	24.3

* Info from http://www.engineeringtoolbox.com/earth-soil-weight-d_1349.html

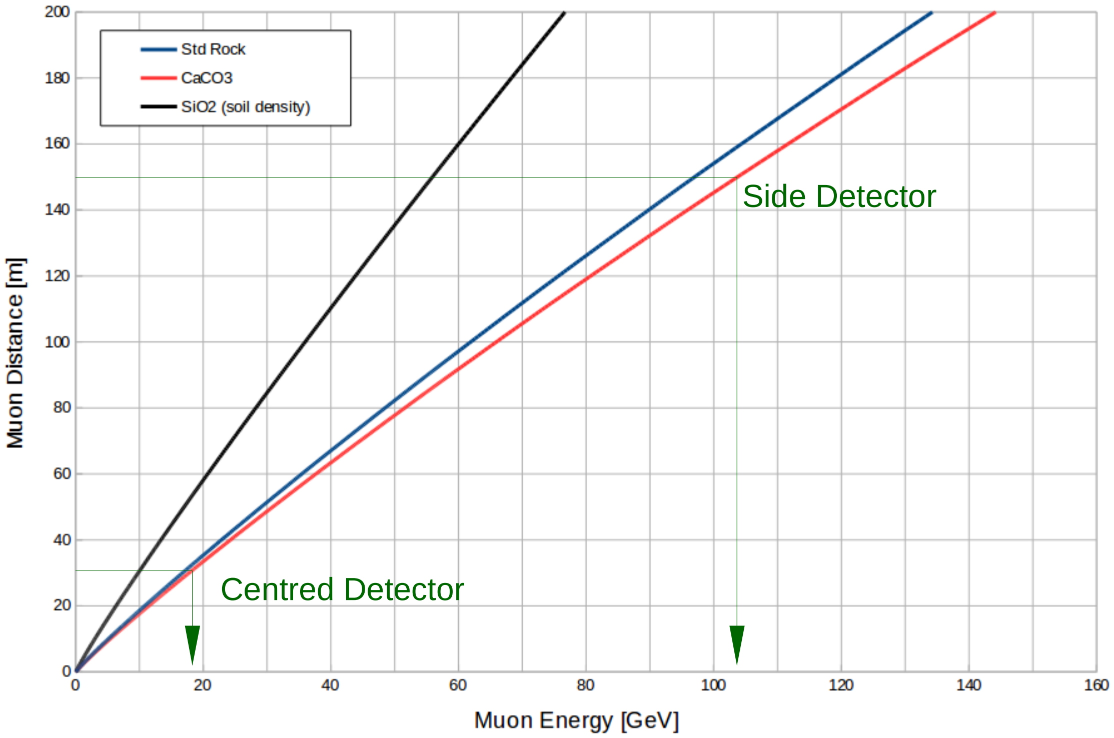
Muons suitable to be stopped during crossing the tumulus are those with ***low energy*** (high energy muons will cross the tumulus independently of the details of the tumulus composition):

Initial muon Energy and angular distributions based on two different generators

Extended ***Gaisser*** parametrization: In principle. Original parametrization works well for $E_\mu > (100 / \cos\theta)$ GeV and $\theta < 70°$

CRY generator: Based on MCNPX code and tables

Muon mean free path (from CSDA approximation) vs Muon Energy for different materials



Study Definition: Muon input

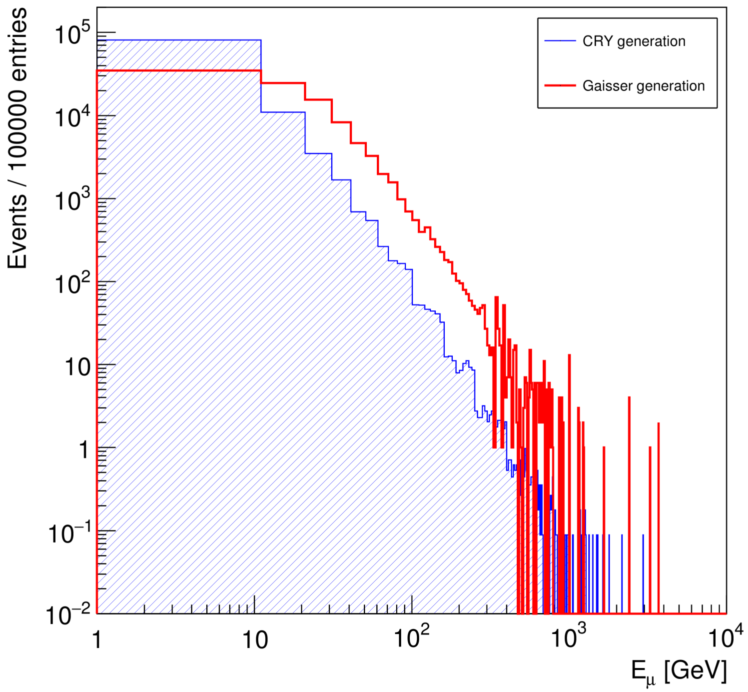
Muons suitable to be stopped during crossing the tumulus are those with ***low energy*** (high energy muons will cross the tumulus independently of the details of the tumulus composition):

Initial muon Energy and angular distributions based on two different generators

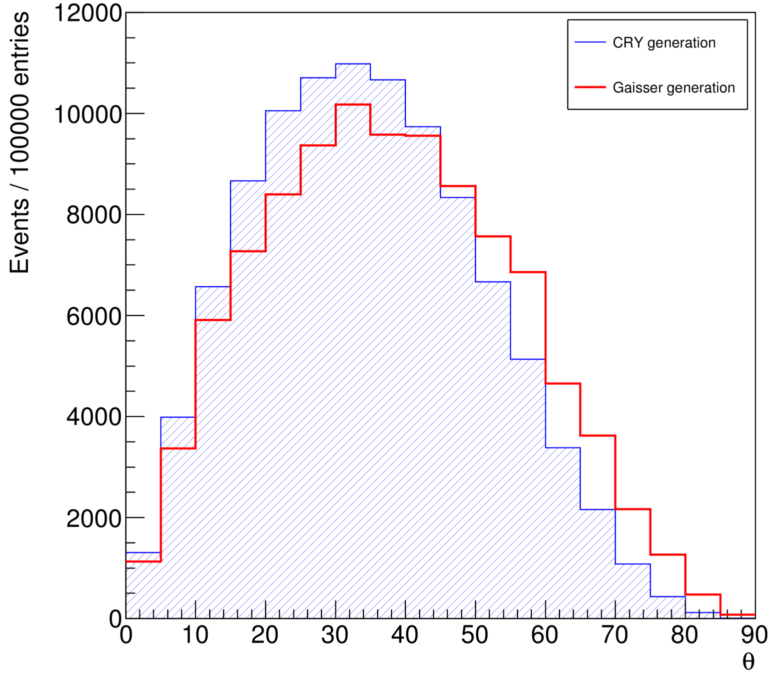
Extended ***Gaisser*** parametrization: In principle. Original parametrization works well for $E_\mu > (100 / \cos\theta)$ GeV and $\theta < 70°$

CRY generator: Based on MCNPX code and tables

Muon Energy spectrum at surface



Muon incident zenith angle distribution at surface



CRY generator has higher percentage of low energy muons and slight different angular distribution with respect to the extended Gaisser parametrization → ***What is the impact on the simulation results (cross - check)***

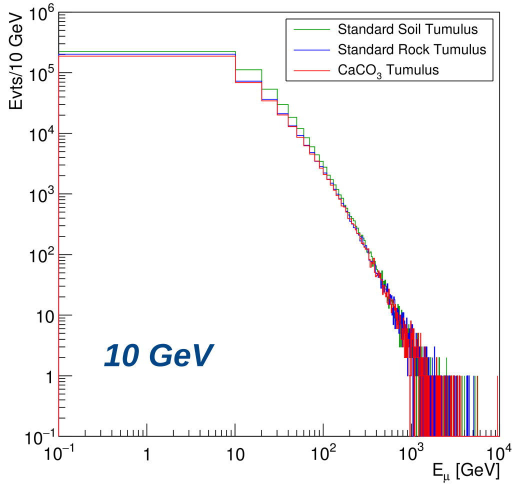
Simulation results: CRY input with different thresholds

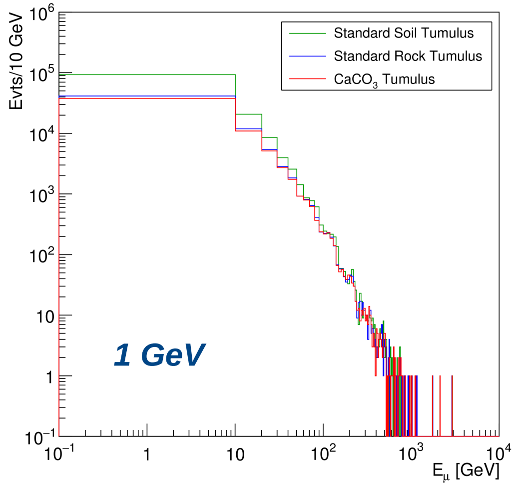
For each simulation configuration (detector position and tumulus material) two parameters are computed

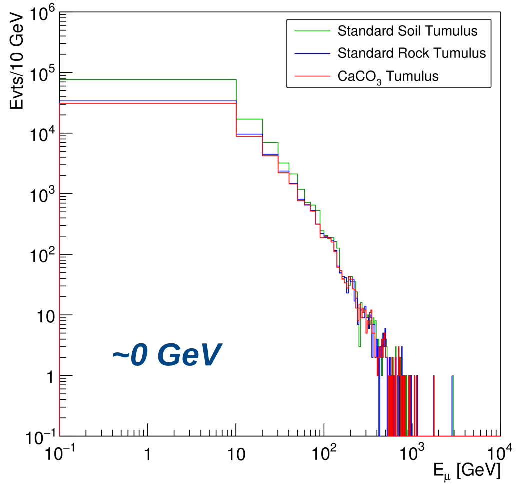
Detection Probability = Muons reaching the detector / Simulated muons (considering 100 % detection efficiency)

Normalization to Soil Tumulus case: δ_{Soil} = Detected events (Material) / Detected Events (Soil)

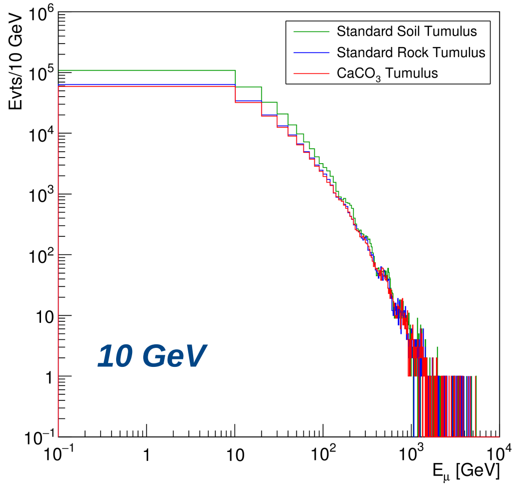
Centred Detector

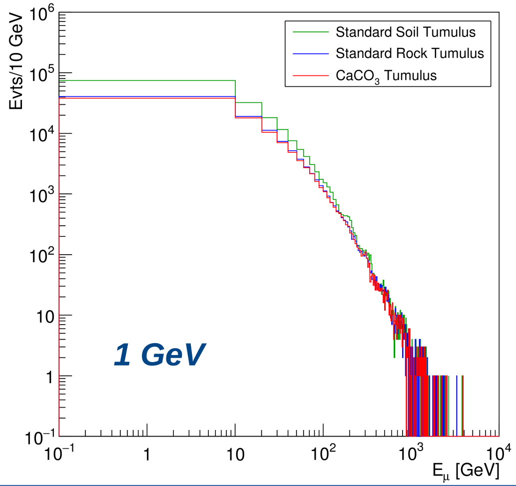


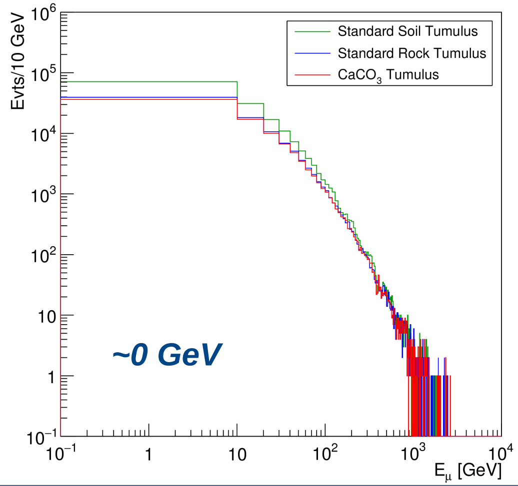




Side Detector







Simulation results: CRY input with different thresholds

For each simulation configuration (detector position and tumulus material) two parameters are computed

Detection Probability = Muons reaching the detector / Simulated muons (considering 100 % detection efficiency)

Normalization to Soil Tumulus case: δ_{Soil} = Detected events (Material) / Detected Events (Soil)

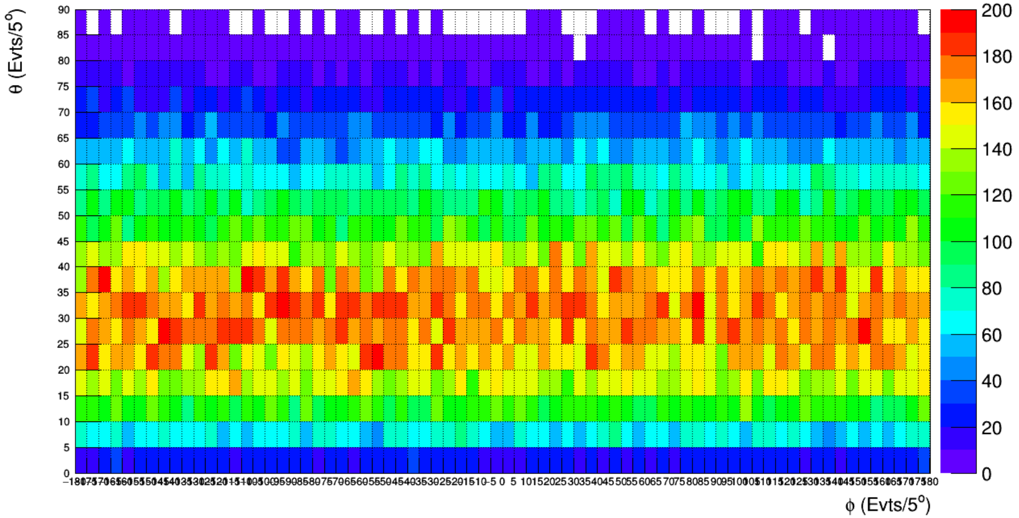
1 GeV	**Centred Detector**		**Side Detector**	
	Detection Probability (%)	δ_{Soil}	**Detection Probability (%)**	δ_{Soil}
Standard Soil	26.93	1	34.31	1
Standard Rock	13.55	0.50	20.81	0.61
$CaCO_3$	12.49	0.46	19.60	0.57

~0 GeV	**Centred Detector**		**Side Detector**	
	Detection Probability (%)	δ_{Soil}	**Detection Probability (%)**	δ_{Soil}
Standard Soil	22.20	1	32.76	1
Standard Rock	11.15	0.50	19.96	0.61
$CaCO_3$	10.30	0.46	18.76	0.57

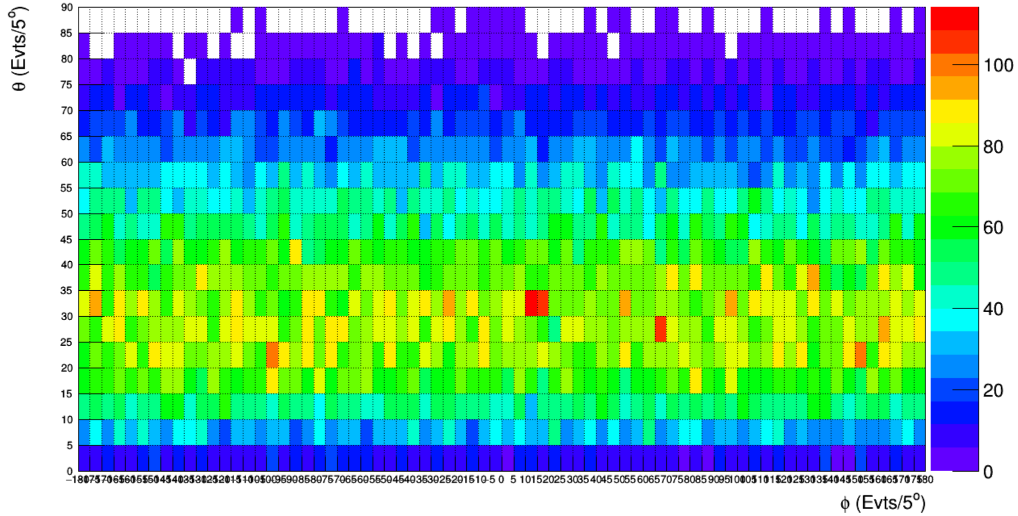
Simulation results: CRY input with different thresholds

Angular distribution of the detected events: Centred Detector

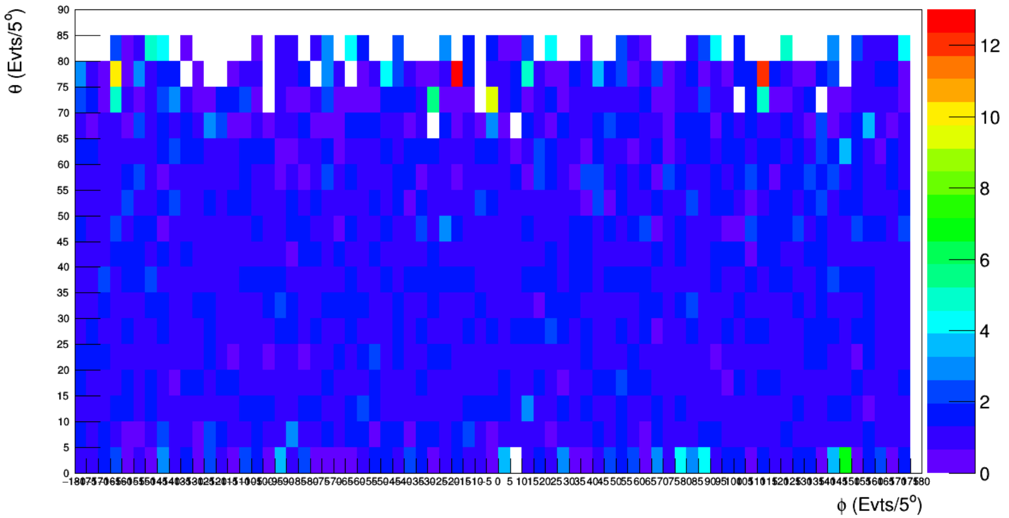
Standard Soil



$CaCO_3$



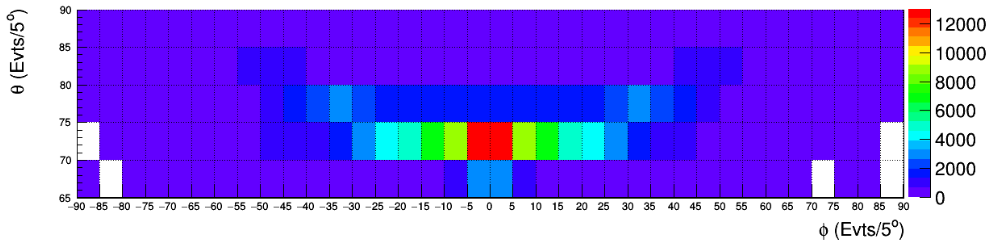
(Standard Soil – $CaCO_3$)/$CaCO_3$



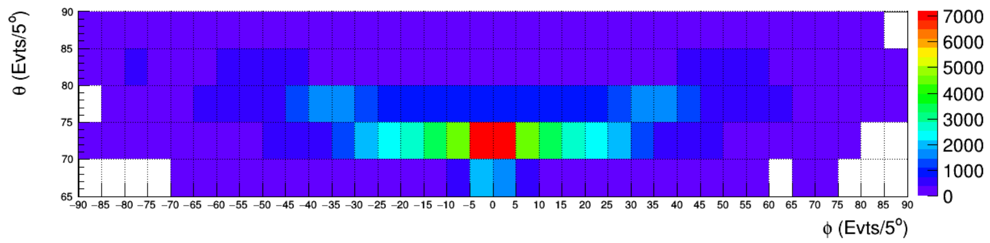
Simulation results: CRY input with different thresholds

Angular distribution of the detected events: Side Detector

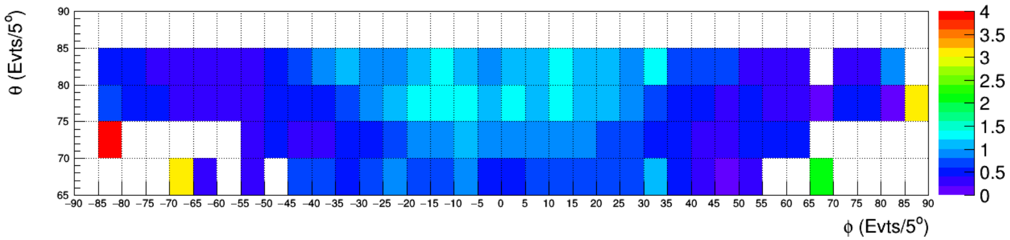
Standard Soil



$CaCO_3$



(Standard Soil – $CaCO_3$)/$CaCO_3$



Simulation results: CRY input with different thresholds

Parameter to evaluate → Minimum measurement time Δt:

The required time to significantly detect the muon rate variation (as defined in ***Geophysical Journal International 183 (2010) 1348 – 1361***)

$$\Delta t > \frac{1}{T_{Det} (\delta R_\mu)^2 \phi_\mu}$$

- T_{Det}: Detector acceptance (100 cm^2 sr considered)
- δR_μ: Muon rate variation; $\delta R_\mu = \frac{L_{marble}}{L_{tumulus}} (1 - \delta_{soil})$
- ϕ_μ: Detected muon flux (for the considered solid angle and geometry)

1 GeV	**L_{marble} [m]**	**$L_{tumulus}$ [m]**	**Distance Det - Marble [m]**	**δR_μ**	**ϕ_μ [cm^{-2} s^{-1}]**	**Δt [days]**
Side Detector	2	140	91	$6.12\ 10^{-3}$	$2.68\ 10^{-9}$	**> 1 year**
Centred Detector (θ = 0°)	2	22	11	$4.87\ 10^{-2}$	$5.73\ 10^{-5}$	**1**
Centred Detector (θ = 45°)	2	35	16	$3.06\ 10^{-2}$	$1.80\ 10^{-5}$	**7**

~0 GeV	**L_{marble} [m]**	**$L_{tumulus}$ [m]**	**Distance Det - Marble [m]**	**δR_μ**	**ϕ_μ [cm^{-2} s^{-1}]**	**Δt [days]**
Side Detector	2	140	91	$6.10\ 10^{-3}$	$2.65\ 10^{-9}$	**> 1 year**
Centred Detector (θ = 0°)	2	22	11	$4.87\ 10^{-2}$	$6.08\ 10^{-5}$	**1**
Centred Detector (θ = 45°)	2	35	16	$3.06\ 10^{-2}$	$1.75\ 10^{-5}$	**7**

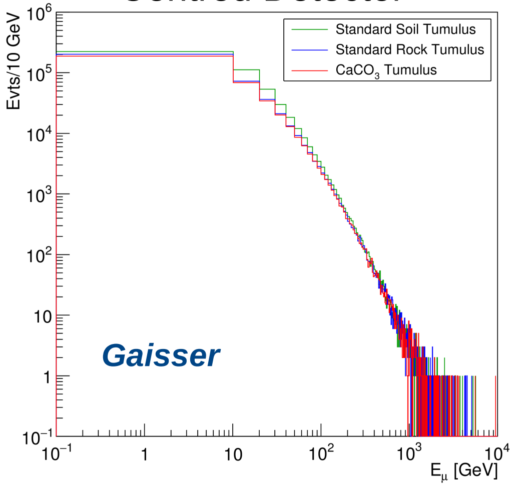
Simulation results: 10 GeV Threshold Comparison (***cross -check***)

For each simulation configuration (detector position and tumulus material) two parameters are computed

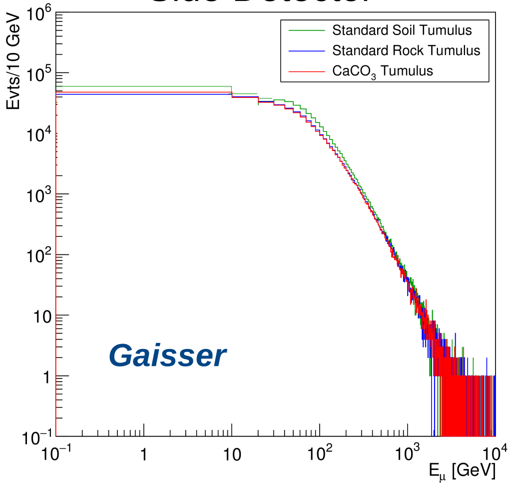
Detection Probability = Muons reaching the detector / Simulated muons (considering 100 % detection efficiency)

Normalization to Soil Tumulus case: δ_{Soil} = Detected events (Material) / Detected Events (Soil)

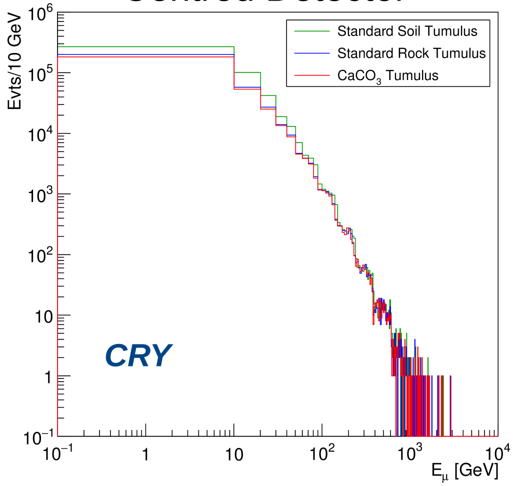
Centred Detector



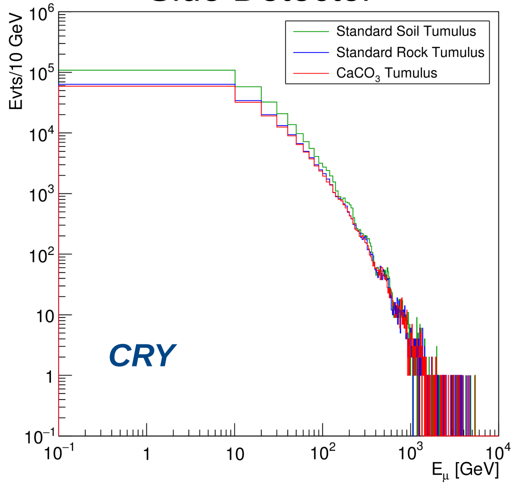
Side Detector



Centred Detector



Side Detector



Simulation results: 10 GeV Threshold Comparison (***cross -check***)

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Normalization to Soil Tumulus case: δ_{Soil} = Detected events (Material) / Detected Events (Soil)

Gaisser	Centred Detector		Side Detector	
	Detection Probability (%)	δ_{Soil}	**Detection Probability (%)**	δ_{Soil}
Standard Soil	97.77	1	97.74	1
Standard Rock	77.35	0.79	81.10	0.83
$CaCO_3$	72.64	0.74	78.20	0.80

CRY	Centred Detector		Side Detector	
	Detection Probability (%)	δ_{Soil}	**Detection Probability (%)**	δ_{Soil}
Standard Soil	94.28	1	59.87	1
Standard Rock	65.97	0.70	37.50	0.63
$CaCO_3$	61.11	0.65	35.40	0.59

- Higher δ_{Soil} differences
- Lower Detection probabilities
- Bigger differences for Side Detector case

Simulation results: 10 GeV Threshold Comparison (***cross -check***)

Parameter to evaluate → Minimum measurement time ***Δt***:

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- T_{Det}: Detector acceptance (100 cm^2 sr considered)
- δR_μ: Muon rate variation; $\delta R_\mu = \frac{L_{marble}}{L_{tumulus}} (1 - \delta_{soil})$
- ϕ_μ: Detected muon flux (for the considered solid angle and geometry)

Gaisser	L_{marble} [m]	$L_{tumulus}$ [m]	Distance Det - Marble [m]	δR_μ	ϕ_μ [cm^{-2} s^{-1}]	Δt [days]
Side Detector	2	140	91	$2.86\ 10^{-3}$	$3.77\ 10^{-8}$	**> 1 year**
Centred Detector (θ = 0°)	2	22	11	$2.34\ 10^{-2}$	$3.51\ 10^{-5}$	**6**
Centred Detector (θ = 45°)	2	35	16	$1.47\ 10^{-2}$	$1.98\ 10^{-5}$	**27**

CRY	L_{marble} [m]	$L_{tumulus}$ [m]	Distance Det - Marble [m]	δR_μ	ϕ_μ [cm^{-2} s^{-1}]	Δt [days]
Side Detector	2	140	91	$5.84\ 10^{-3}$	$3.41\ 10^{-9}$	**> 1 year**
Centred Detector (θ = 0°)	2	22	11	$3.20\ 10^{-2}$	$3.00\ 10^{-5}$	**4**
Centred Detector (θ = 45°)	2	35	16	$2.01\ 10^{-2}$	$1.36\ 10^{-5}$	**21**

Simulation results: 10 GeV Threshold Comparison

Gaisser	L_{marble} [m]	$L_{tumulus}$ [m]	Distance Det - Marble [m]	δR_μ	ϕ_μ [cm^{-2} s^{-1}]	Δt [days]
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- Different models induce correlated differences in δR_μ and detected muon flux ϕ_μ
  - More low energy muons (CRY) → Bigger detection differences (δR_μ) but less flux over 10 GeV
  - As a result, the ***time measurements are compatible for both models***
- However, better determination of the expected muon flux is necessary, specially for small solid angles (as in the Side Detector case)

Summary & Prospects

- ***SUMMARY***
  - Scanning of a tumulus (based on Amfipoli one) by muon tomography has been simulated
    - MUSIC software for muon propagation
    - CRY and extended Gaisser parametrization for initial muon distribution → Critical issue at low energies
    - It seems that both parametrization give equivalent results (at least for 10 GeV threshold)
  - Three particular scenarios has been considered
    - ***2 with the detector placed in an internal hall → Short term measurements***
    - 1 with the detector at tumulus side → Too long measurements to extract conclusions
  - Initial muon flux determination has important uncertainties nowadays
- ***POSSIBLE IMPROVEMENTS***
  - Study of other muon generators as simulation input
  - Determination of the initial muon flux
  - If a measurement will be performed, more accurate geometry definition can be done for more accurate simulations
    - Some of these simulations already done for other experiments (eg Double - Chooz)

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