SIMULATIONS FOR MUON TOMOGRAPHY

Present status

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Muon tomography simulations: two parallel “frameworks”

- **MUSIC based:**
  - ✓ Computing time
  - Geometry definition
    - ✓ Materials
    - ✗ Internal structures
  - ✗ Detector issues

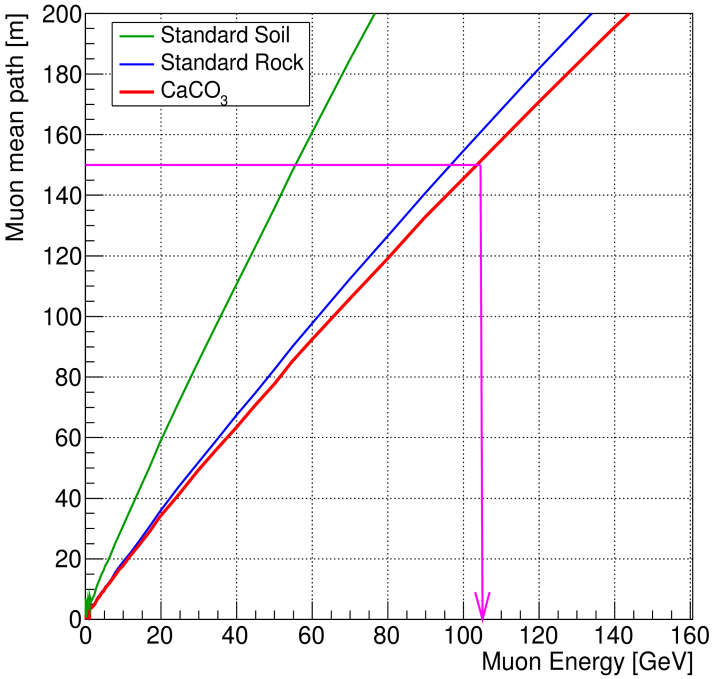
Already some studies performed

(As presented in previous meeting)

- **Geant - 4 based:**
  - Computing time (optimized using a good muon sample)
  - Geometry definition
    - ✓ Materials
    - ✓ Internal structures
  - ✓ Detector issues
    - Ideal detector for the moment
    - Possibility to implement detector features

Main results with MUSIC studies

- Dependence of the results with the ***Muon @ Surface parametrization*** considered (applicable to all further simulations)
  - Extended Gaisser parametrization:
    - As explained in ***A. Tang et al. Phys. Rev. D 74 (2006) 053007***
  - CRY generator:
    - Cosmic – ray shower library: http://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry.pdf and http://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry_physics.pdf
    - Muons generated from data tables coming from full MCNPX 2.5.0 simulations of muons.



- Muons don not cross more than ***~150 m*** of material when crossing a tumulus.
- Independently of the tumulus composition muons with energy bigger than ***~100 GeV*** would not be affected by the presence of the tumulus (furthermore, they should be considered as irreducible background).
- Is at low energy range where ***difference between models are bigger*** → It affects to the accuracy of our estimations.
- Also differences in the ***θ angular distribution*** affects the estimations.

Main results with MUSIC studies

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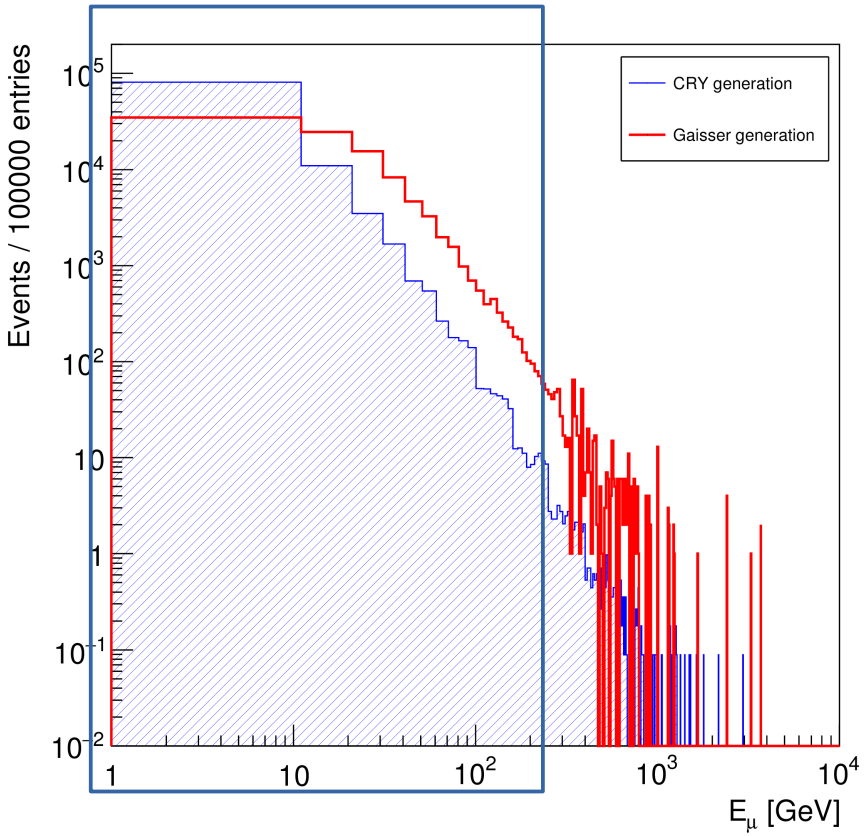
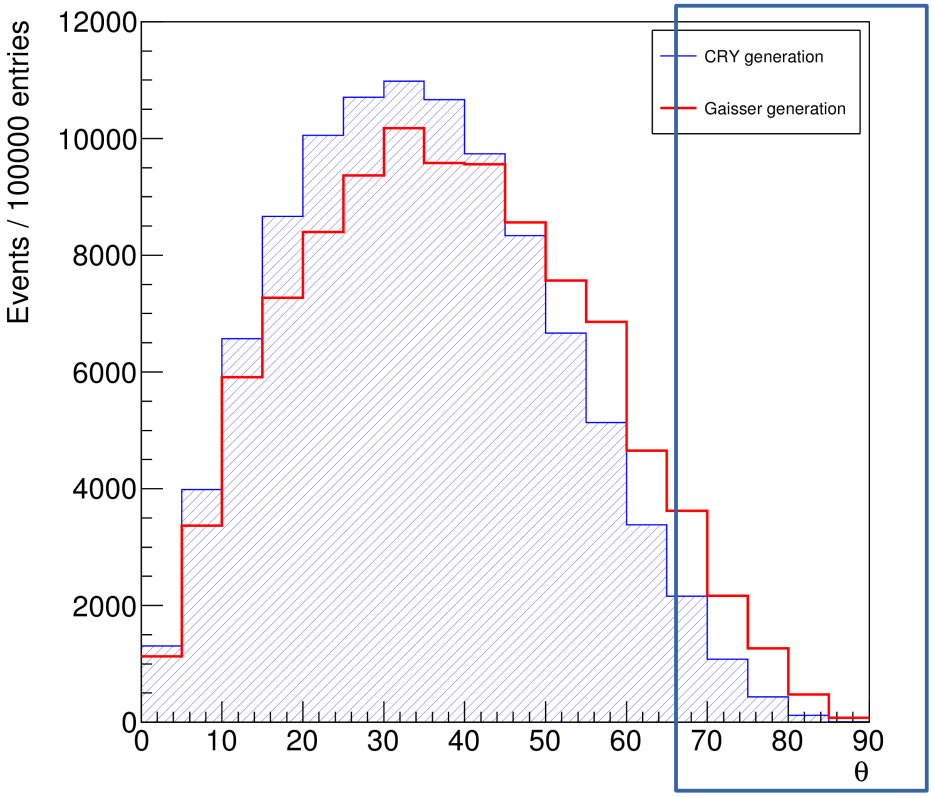


θ = 90 - α



Mean (RMS)	CRY	Gaisser
Energy [GeV]	8.4 (17.5)	27.9 (52.6)
θ [deg]	33.9 (16.0)	38.1 (17.7)

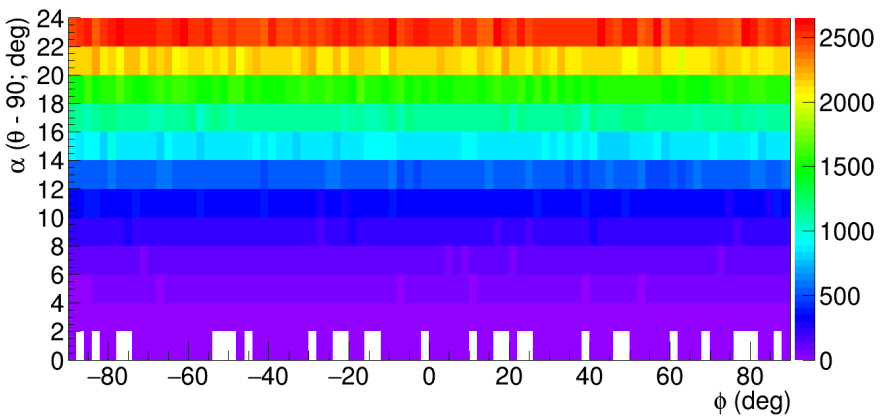
Events with E < 200 GeV and θ > 70°

→ CRY: 1.4 %

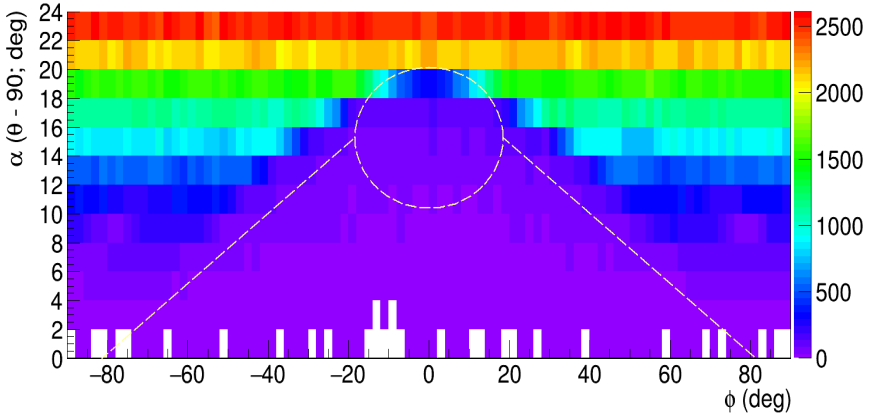
→ Gaisser: 3.6 %

Main results with MUSIC studies

- Detector on the tumulus side (180 m bottom Ø ; 60 m top Ø; 22 m height)
- 2° x 2° angular resolution assumed
- Muon angular distribution after ~2 days measurement



Open air measurement (no tumulus)

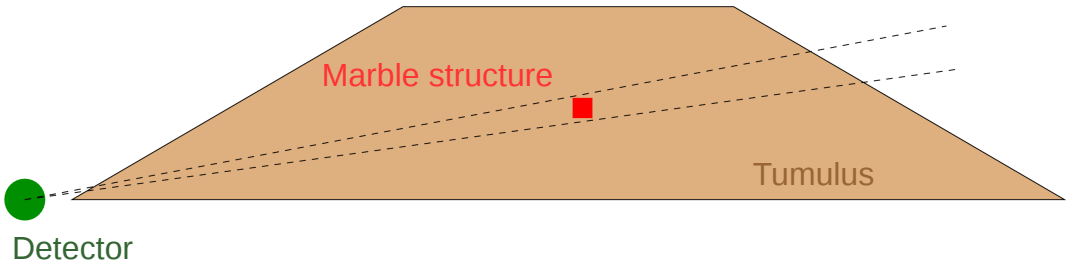


Measurement with “homogeneous” tumulus

- Tumulus shape identifiable
- In present MUSIC- based framework is difficult to define internal “structures” inside the tumulus
- However, based on simulation of different composition tumulus, some results about muon rate difference can be obtained analytically

Main results with MUSIC studies

		L_{marble} [m]	$L_{Tumulus}$ [m]	δR_{μ} [s^{-1}]	ϕ_{μ} [$cm^{-2}s^{-1}$]	$\delta\mu$ [day^{-1}]
CRY	***Side Detector***	2	140	$5.86\ 10^{-3}$	$3.41\ 10^{-9}$	***0.02***
	Centred Detector ($\theta = 0°$)	2	22	$3.18\ 10^{-2}$	$3.60\ 10^{-5}$	***989.10***
	Centred Detector ($\theta = 45°$)	2	35	$2.00\ 10^{-2}$	$1.63\ 10^{-5}$	***281.66***
Gaisser	***Side Detector***	2	140	$2.86\ 10^{-3}$	$3.86\ 10^{-8}$	***0.10***
	Centred Detector ($\theta = 0°$)	2	22	$2.36\ 10^{-2}$	$3.59\ 10^{-5}$	***732.01***
	Centred Detector ($\theta = 45°$)	2	35	$1.49\ 10^{-2}$	$2.03\ 10^{-5}$	***261.33***



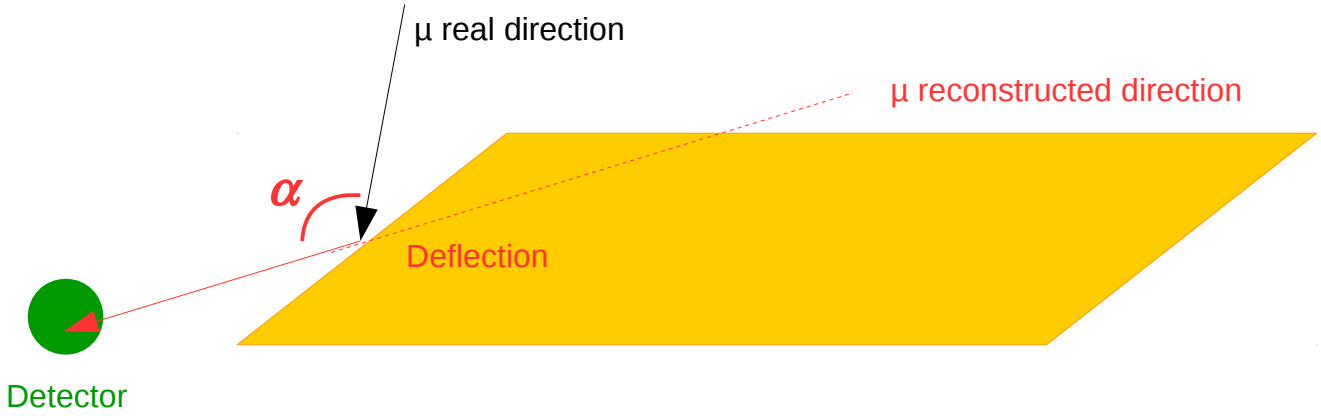
- Comparing the rate w/wo the presence of a ***2x2x2 m^3 marble box*** in the tumulus (at ***$\alpha \sim 5°$***)
- The muon rate difference is ***less than 1 muon per day***
- However depending on the model there is a ***factor 5 variation***

Conclusions and next steps

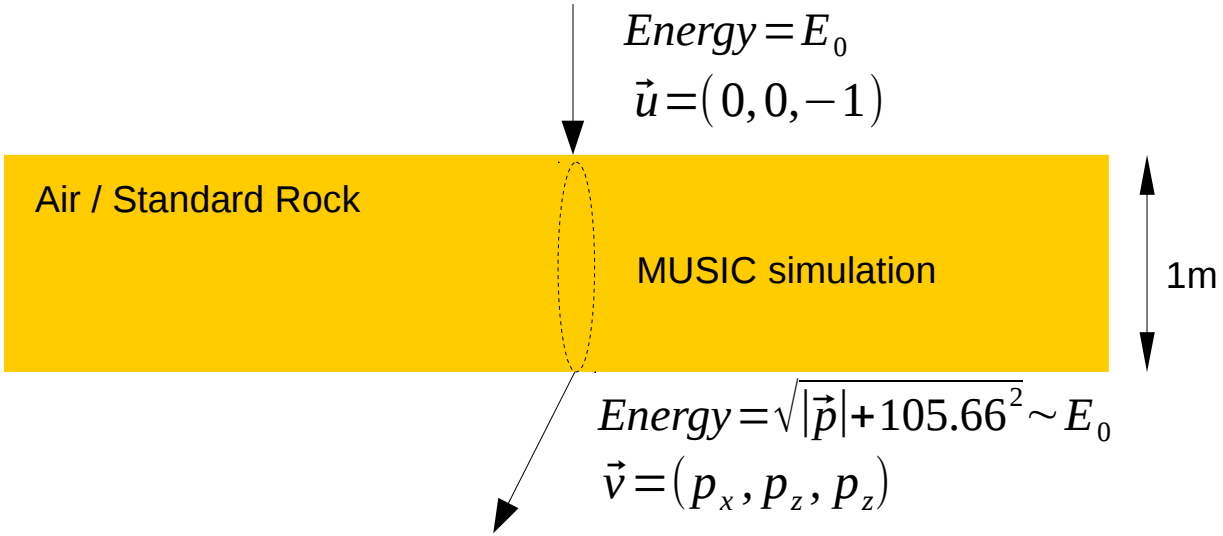
- Conclusion from MUSIC results
  - Estimation of the measurement time is highly dependent on the muon @ surface parametrization used
    - This problem will be present at Geant – 4 simulations too
  - MUSIC simulation have provided all the possible information considering their limitations
  - However Geant – 4 simulations will provide:
    - Cross-check of these results
    - More accuracy on the geometry definition
    - Possibility to include detector issues
  - *A good first example to perform with Geant – 4 could be the same done with MUSIC (using both muon generator)*
  - *It is necessary to estimate / simulate possible backgrounds*
    - *One of them could be deflected muons*

Muon deflection @ air / object surface

- Deflected muons on air close to the tumulus/volcano or in their surface can contaminate the muon angular distribution:

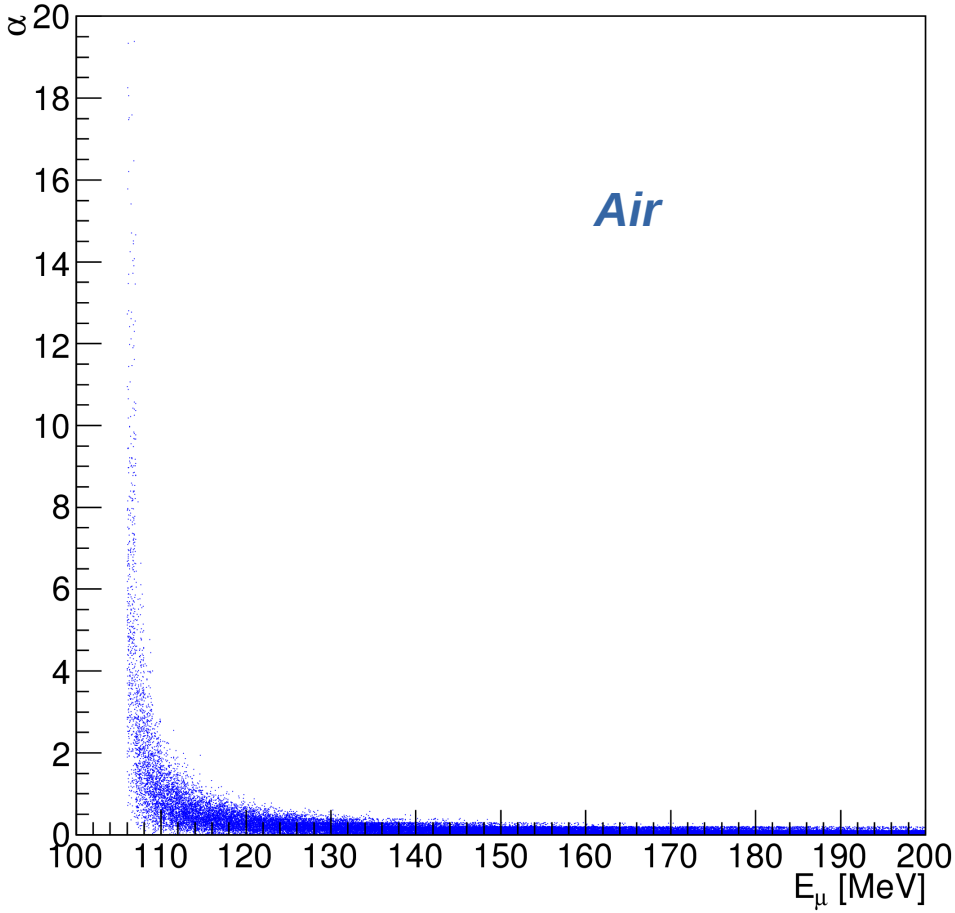


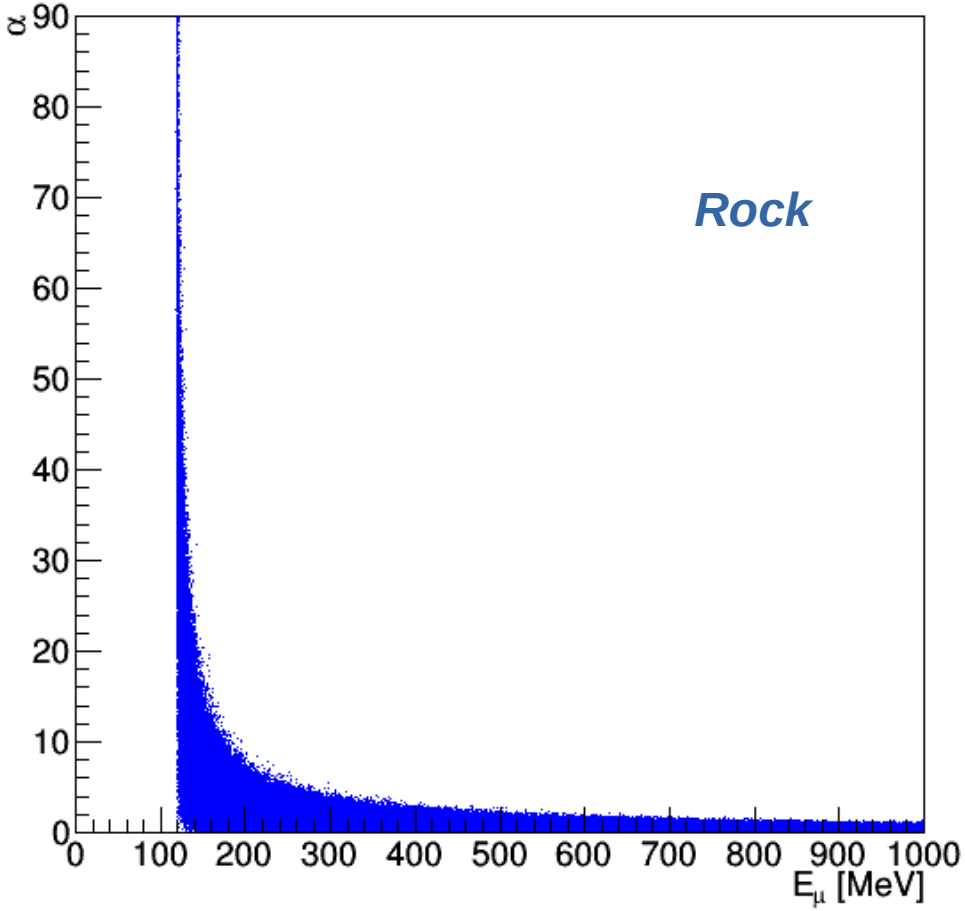
- Study to evaluate this effect:



$$\cos(\alpha) = \frac{\vec{u}\,\vec{v}}{|\vec{u}||\vec{v}|}$$ (α = Deflection angle)

Muon deflection @ air / object surface



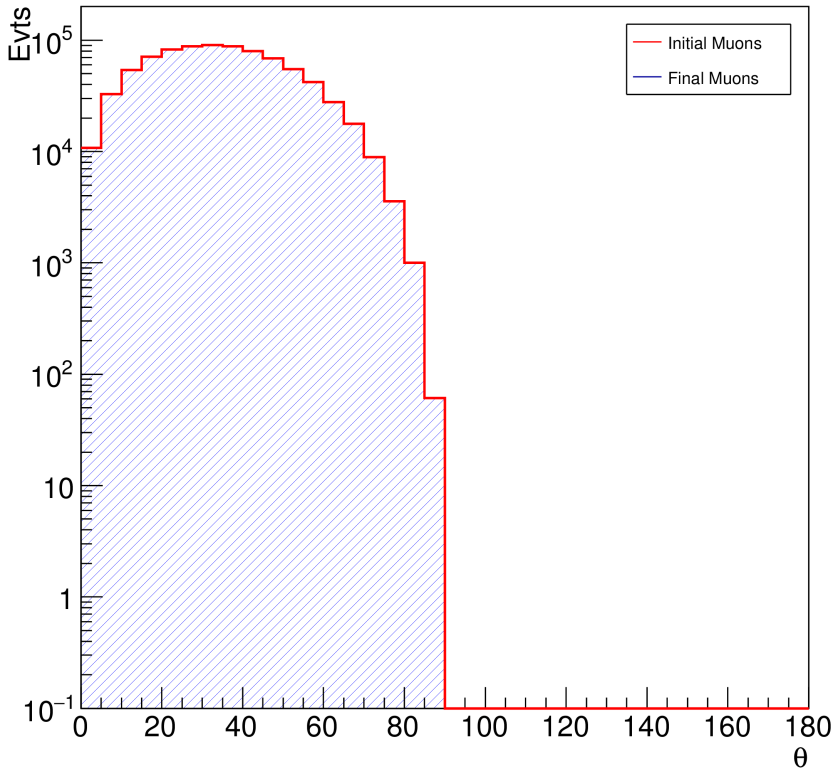


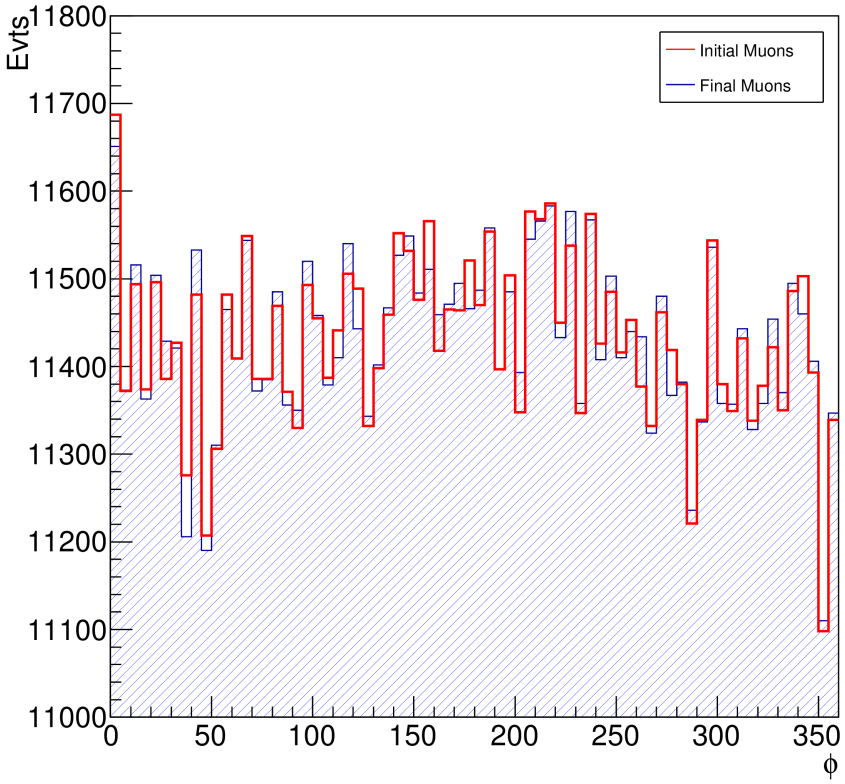
- Low energy muons (p ~ 0) can deflect up to 20°
- Deflection for E_μ > 170 MeV almost negligible

- Big deflection for low energy muons
- Deflection for Eμ > 1 GeV almost negligible

Muon deflection @ air / object surface

- Check that the deflection for $E_\mu > 1$ GeV is almost negligible (***from CRY muon spectrum and angular distributions***)
  - Study of angular distributions of muons before and after crossing 1 m of rock
  - Direct comparison of the angles





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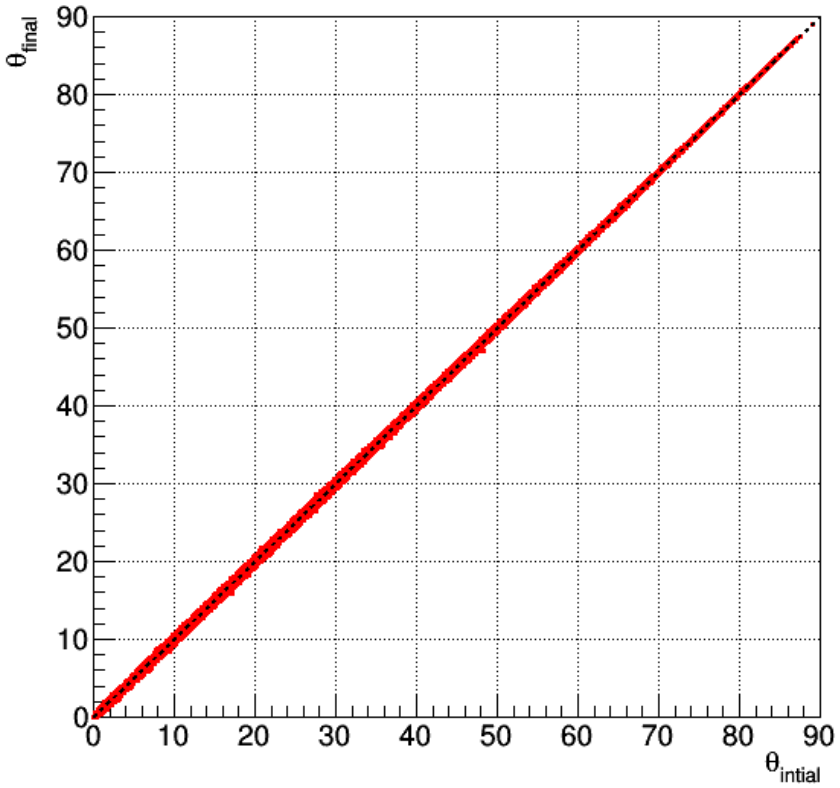
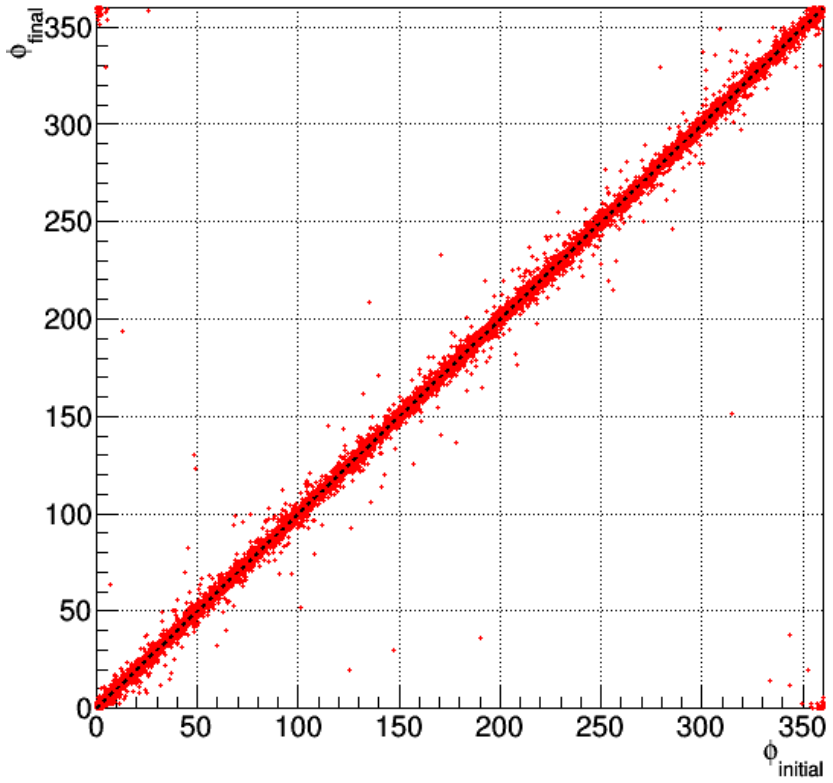
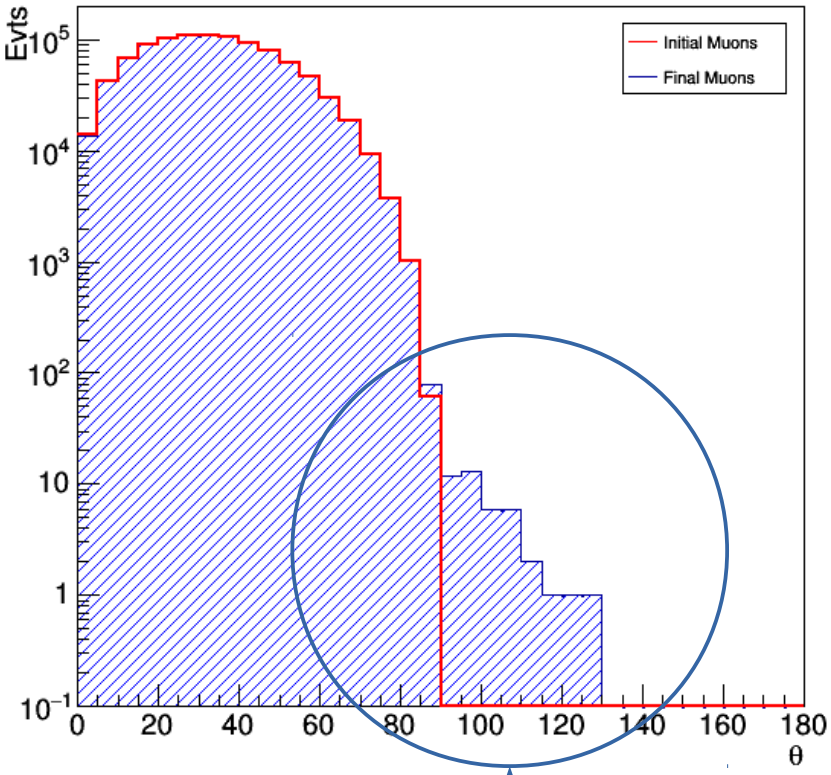
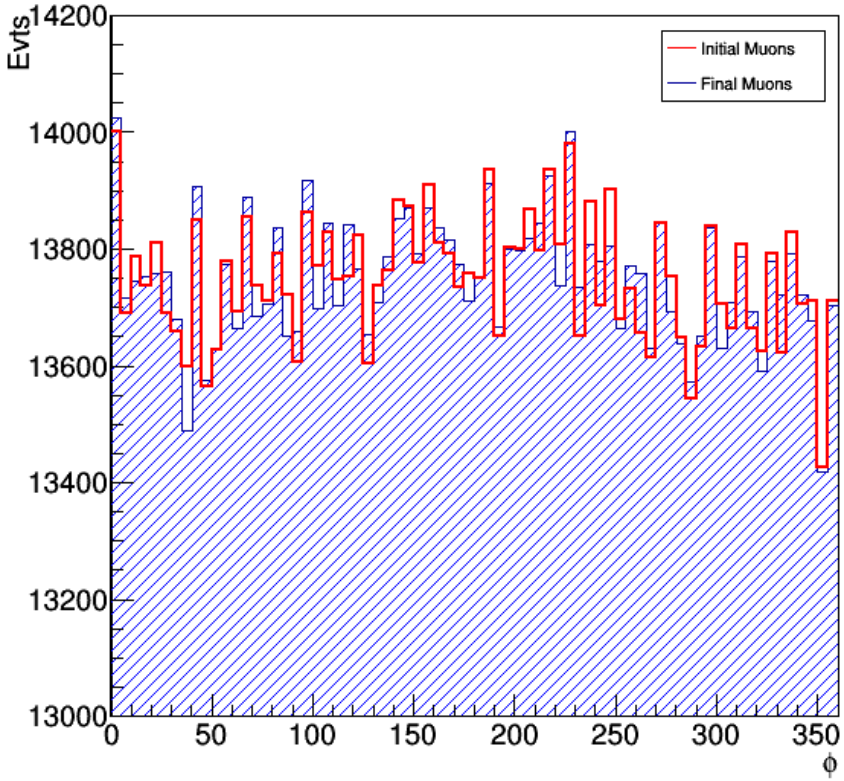




Muon deflection @ air / object surface

- What happens if we include ***energies lower than 1 GeV***?





Muons trend to deflect to more horizontal directions even upwards

Muon deflection @ air / object surface

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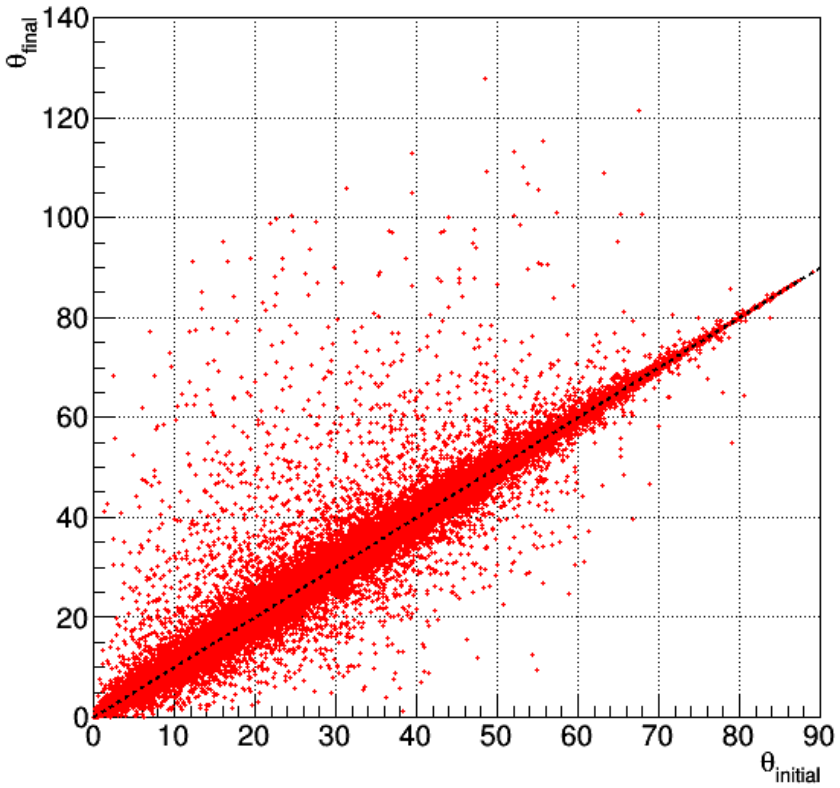

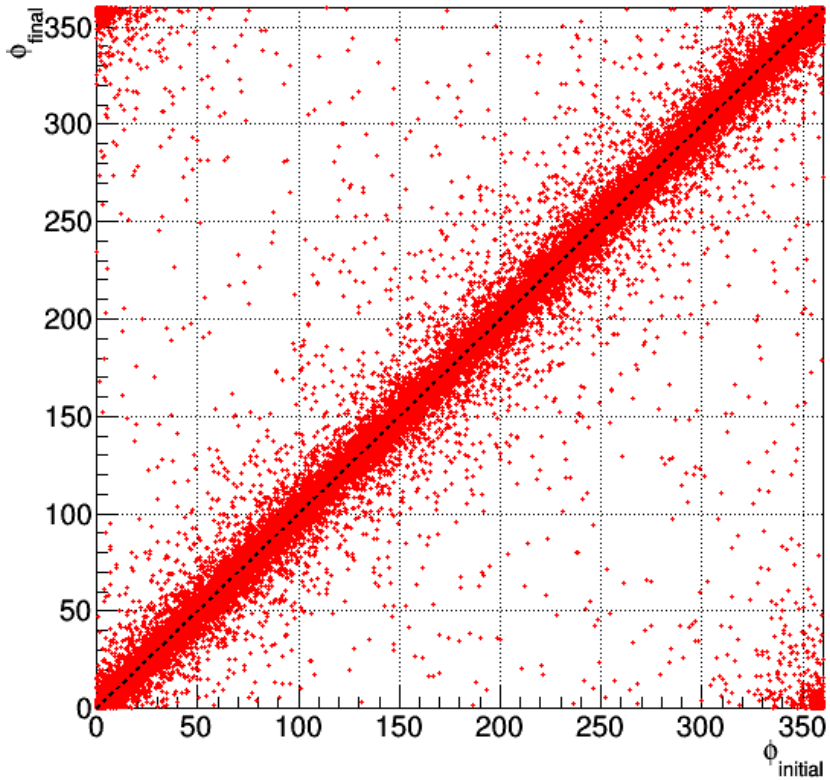

- The effect of deflected muons leading to bad direction reconstruction is important for muons of E_μ < 1 GeV
  - Based on CRY muon spectrum, E_μ < 1 GeV represents ~18% of total flux
- With MUSIC is difficult to evaluate the impact on the tomography measurements → ***Re-visit with G4 framework?***