Geant4 Simulations of the Apollonia Tumulus

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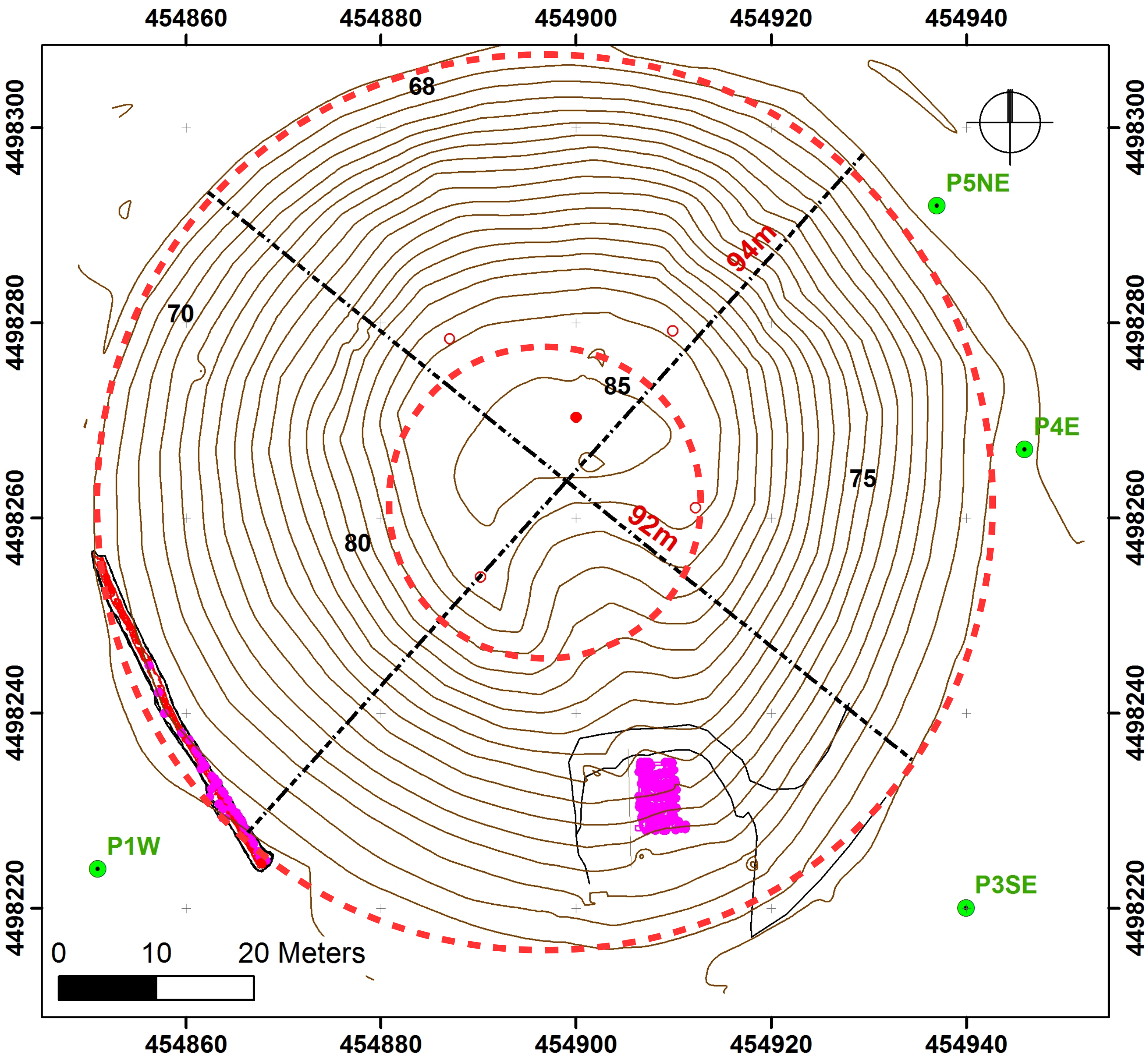
Geant 4 framework developed by LAPP

+ Some upgrades to optimize these studies (along the slides)

As for previous MUSIC simulations, two main inputs required

Geometry

Initial muon distribution (E, θ) at surface



Tumulus:

→ Standard Soil (ρ = 2.2 g/cm^3)

→ Truncated cone

Base diameter: 92 m

Top diameter: 32 m

Height: 17 m

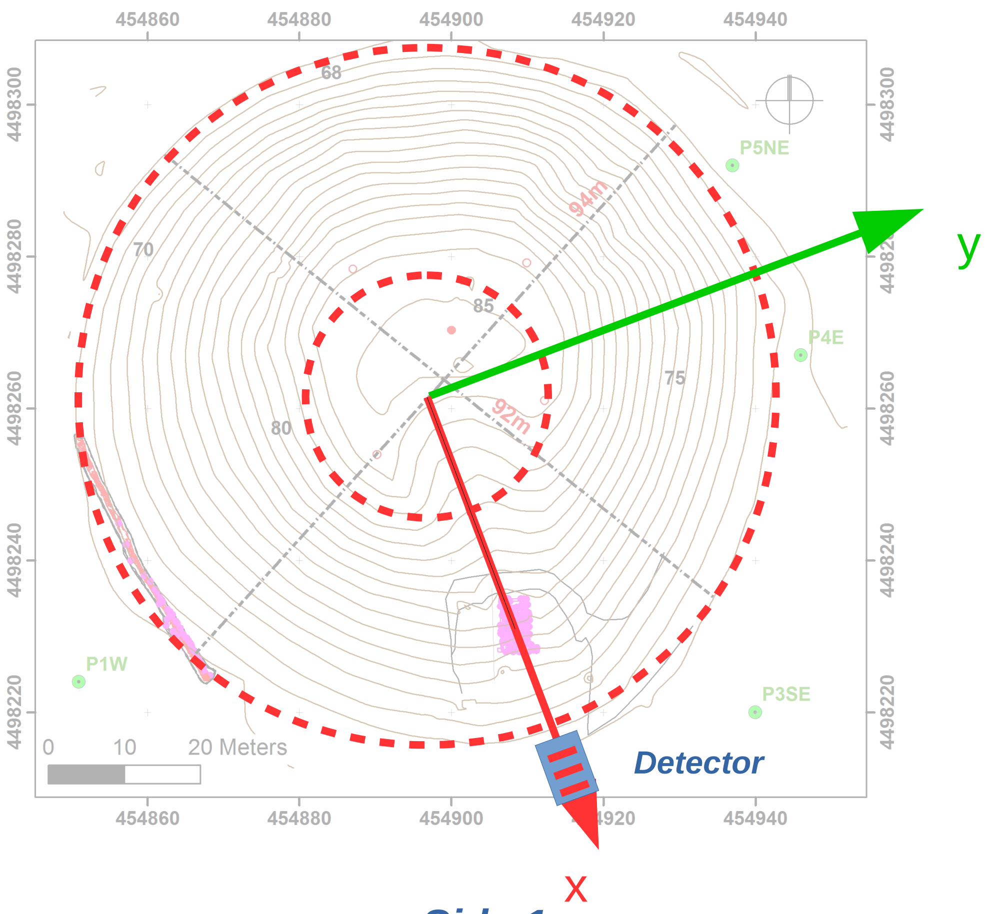
Hall (existing one):

→ $CaCO_3$ (ρ = 2.80 g/cm^3)
+ Air (ρ = 1.29 10^{-3} g/cm^3)

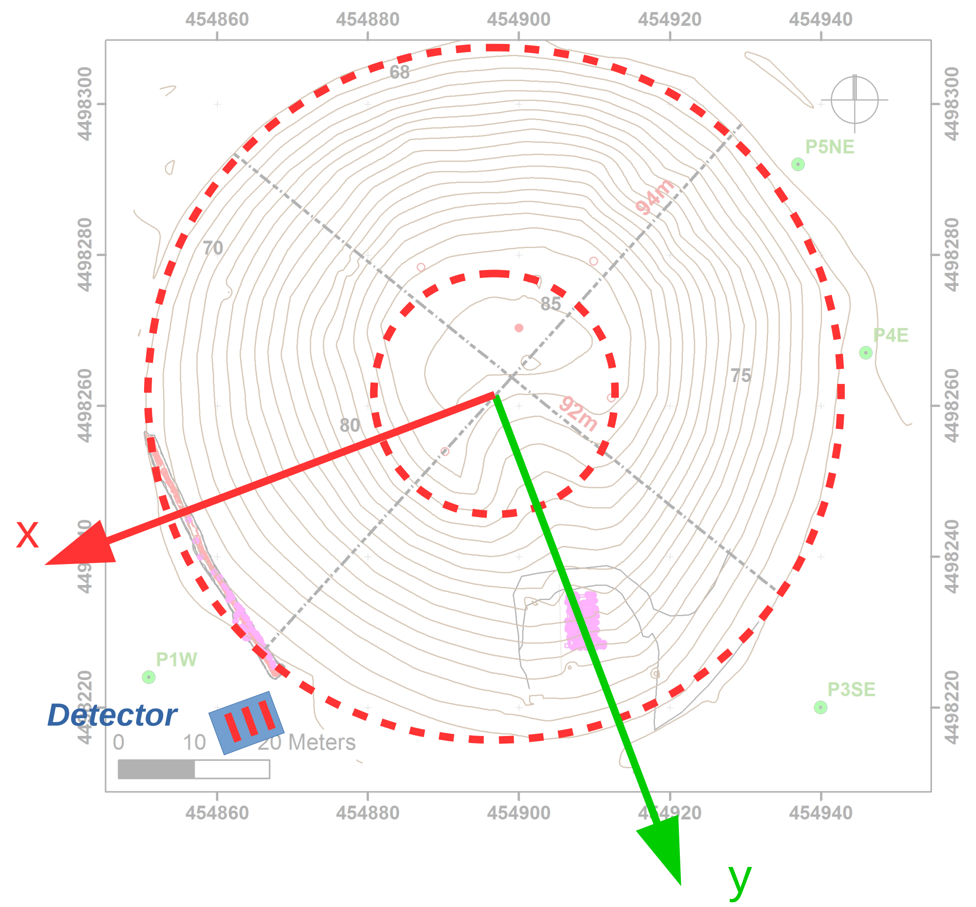
→ Box

l x w x h = 7.87 x 4.08 x 4.08 m

Marble Thickness = 1 m



Side 1



Side 2

- ✔ Highest elevation angle Detector – Hall → $\alpha = 13°$
  - → More muons crossing the hall

- ✔ Shortest muon path across the tumulus
  - → Lower energy muons reaching the detector
- ✖ Lower elevation angle → $\alpha \sim 6°$
  - → Less muon crossing the hall

- ***Four theoretical computations*** for the 2 detector position considered
- Muons traverse: **Tumulus soil only (Reference case)**

  Tumulus soil + "real tomb" (1 m thick marble walls)

  → **"Realistic" cases**

  Tumulus soil + solid marble tomb

  Tumulus soil + solid lead tomb
- Linear density $\lambda\ [g/cm^2] = d_{soil} \times 2.2\ g/cm^3 + d_{marble} \times 2.8\ g/cm^3 + d_{air} \times 1.29\ 10^{-3}\ g/cm^3 + d_{lead} \times 11.4\ g/cm^3$

  $d_{soil} + d_{marble} + d_{air} + d_{lead}$ *constant for all the considered cases*

λ[g/cm²]	***Side 1***	***Side 2***
Soil only [Ref.]	***13684***	***10014***
Marble "real" tomb	***12513 (-8.6 %)***	***9677 (-3.4 %)***
Marble solid tomb	14156 (+3.5 %)	10259 (+2.4 %)
Lead solid tomb	20924 (+52.9 %)	13768 (+37.5 %)

Lower linear density when muons cross the tomb

Excess of muons expected??

Not trivial since the density is not homogeneous

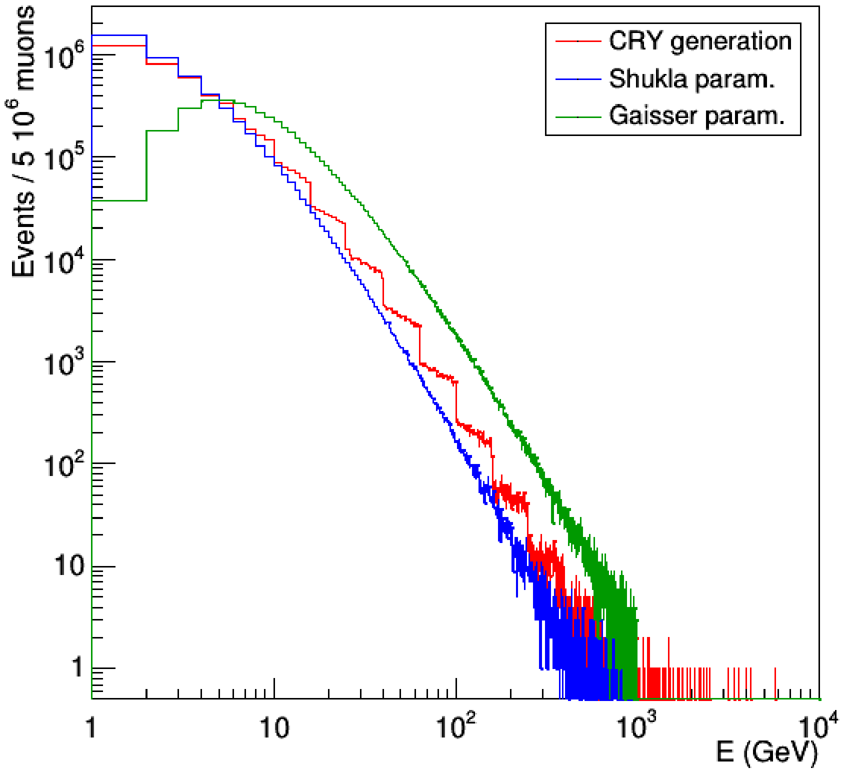
Can give us an idea of the influence of the marble thickness?

- ***Three muon models*** *considered*
  - ***Extended Gaisser*** *parametrization*
    - ✔ *Based on the standard Gaisser formula*
    - ✔ *Validated by Double Chooz studies down to 20 GeV*
    - *Originally, parametrization not valid for low energy → Valid with the modifications?*
  - ***CRY*** *generation*
    - ✖ *Muons generated from data tables coming from full MCNPX 2.5.0 simulations of muons*
    - ✖ *Not analytical formula, "discretization" effects*
    - ✔ *Compared/Validated with Ratsin measurements in the 4 – 3000 GeV range*
  - ***Shukla*** *parametrization*
    - ✔ *Analytical formula with parameters obtained from best-fit with data*
    - ✔ *Valid for all zenith angle range*
    - ✔ *Analytical function fits with data in the 1 – 1000 GeV energy range*

Selected ***E_{thr} = 1 GeV***

→ Lower Energy for which one of the models has been compared with data (Shukla)

→ Assuming standard soil (ρ = 2.2 g/cm^3), 1 GeV muon mean free path is ~2.4 m
(it can induces some inaccuracies in the tumulus borders)



	Mean Energy (GeV)	*RMS (GeV)*
CRY	7.73	17.24
Shukla	5.69	10.81
Gaisser	18.87	31.84

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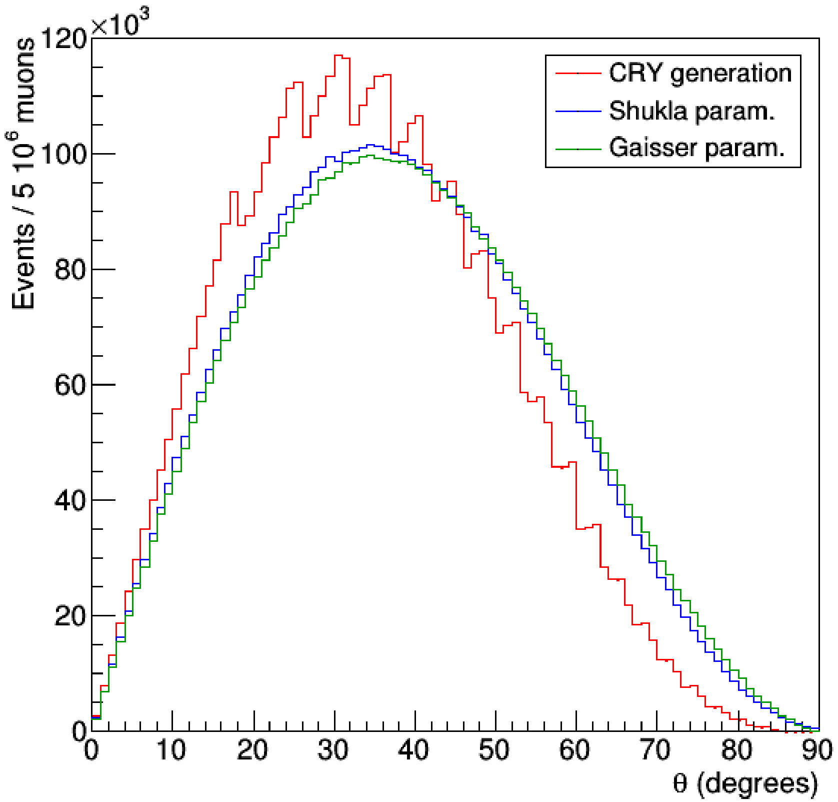

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	Mean Zenith	***RMS***
CRY	34.48	16.12
Shukla	38.00	17.67
Gaisser	38.68	17.92

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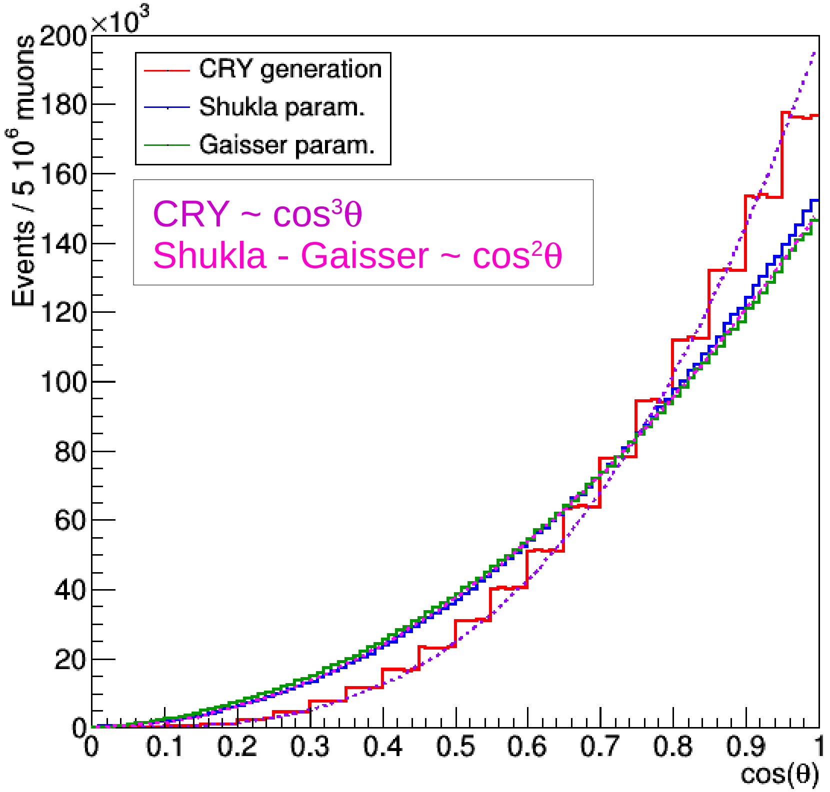

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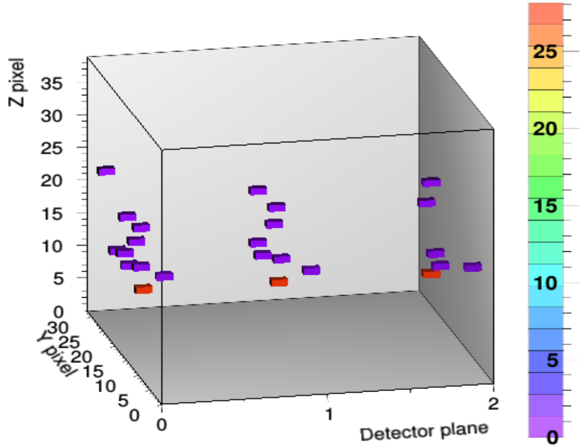
Some studies reveal that low energy muons (< 1 GeV) seem to be distributed following cos^{3}θ more than cos^{2}θ
(S. Cecchini and S. M.Spurio: Atmospheric muons: experimental aspects. Geosci. Instrum. Method. Data Syst., 1, 185–196, 2012)

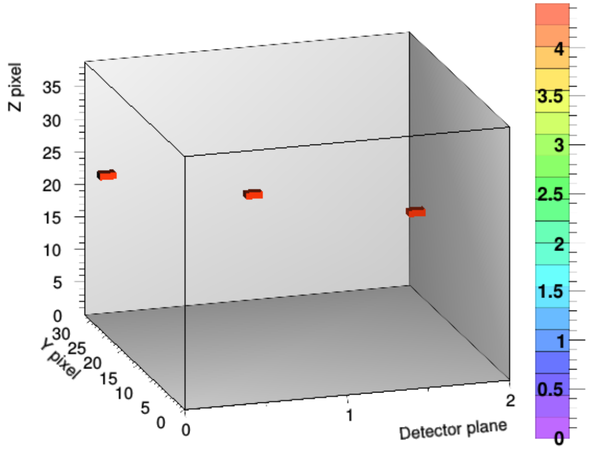
→ CRY can be useful to preliminary study the cos^{3}θ distribution

For the 2 scenarios (***Side 1 and Side 2***) and the 3 muon models at surface (***CRY, Gaisser, Shukla***) considered:

- Detector features
  - 3 planes (1 x 1 m^2) separated 50 cm
  - Detector pointing in both cases to tomb centre → Best detection efficiency
    - However the results are given in the absolute coordinates i.e. ***α = 0 is the horizontal***
- Primary generation (new implementation)
  - Muons, following the E,θ distribution given by the model
  - Emitted from a horizontal plane above the tumulus pointing to any point of the detector → NO POINT DETECTOR APPROACH

Event (muons) selection and reconstruction (C++/ROOT routine, out of G4 simulation)





This event display considers the detector pixelization (32x32 pixels by plane) but for the moment the direction reconstruction does not take into account this pixelization (implementation of the muon telescope model in G4 to be done)

All the energy deposits in the 3 detector planes are considered

Selection of those energy deposits bigger than E_{thr}

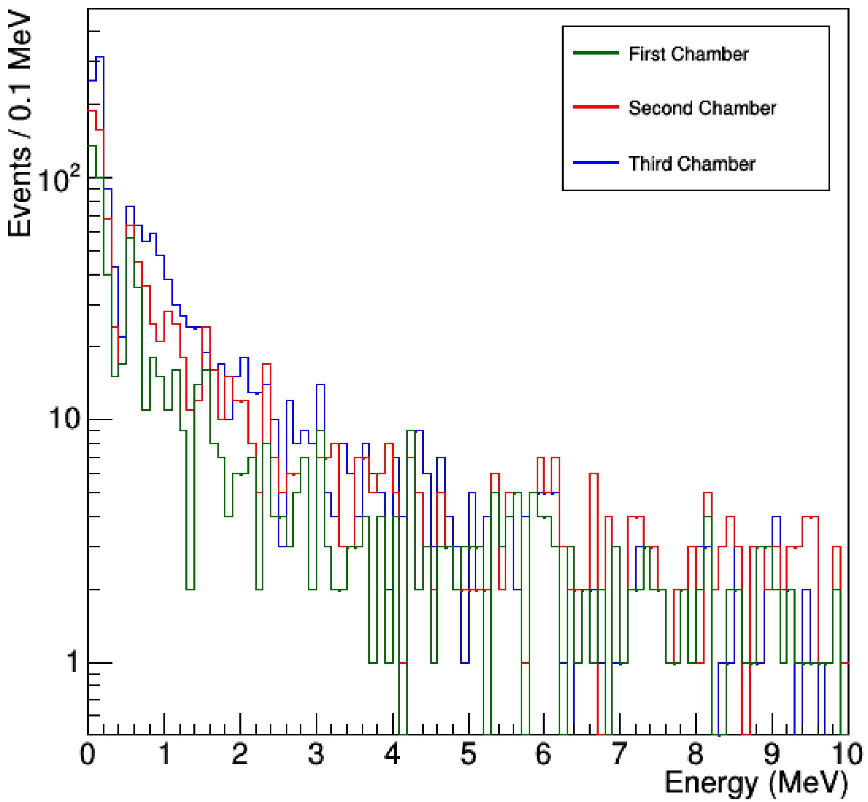
Muons selected → Those having 1 energy deposit ($E > E_{thr}$) in the 3 planes

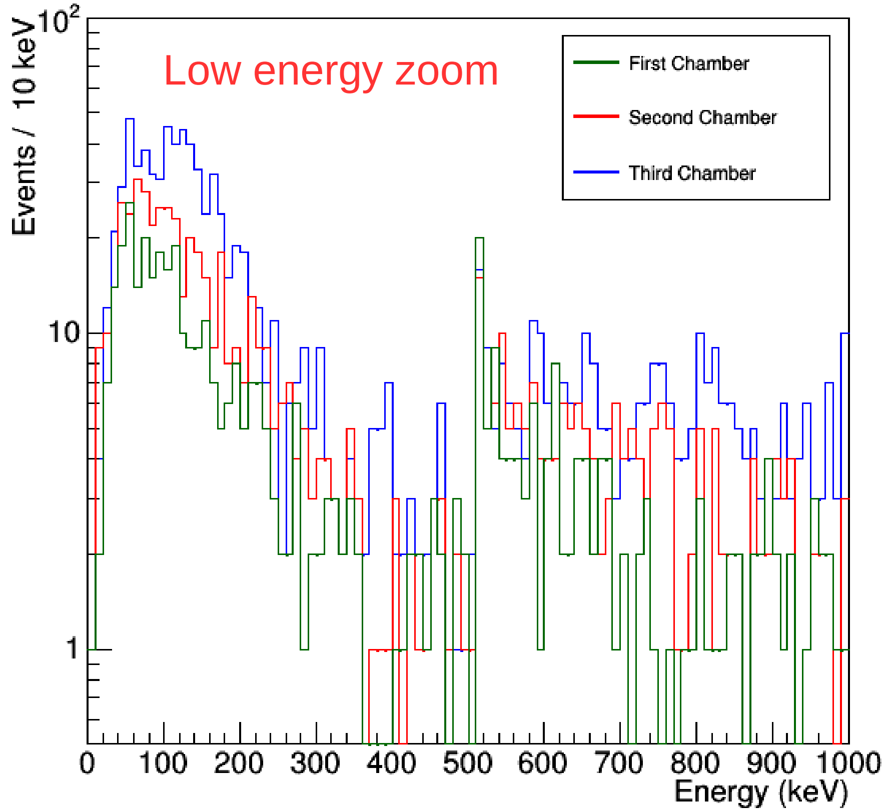
Reconstruction:

Linear fit of the position of the energy deposits selected (real position, ***pixelization not considered***)

Considering muons crossing by the centre of the tumulus (i.e. 62 m of soil traversed)

→ An energy spectrum per detector plane can be obtained from all the energy deposits



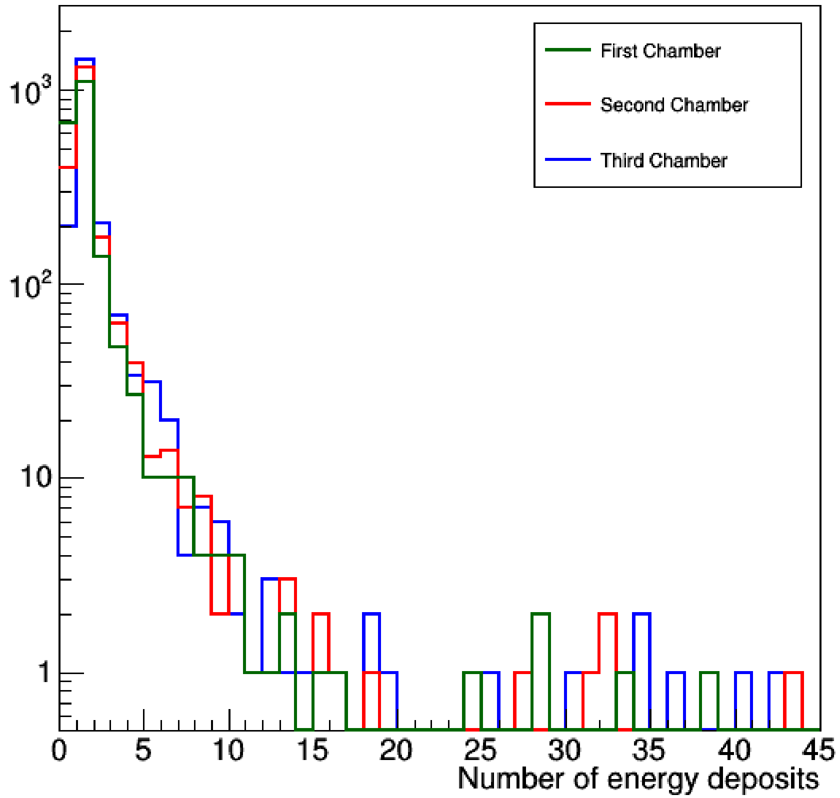


Possible threshold effect at 500 keV

Considering muons crossing by the centre of the tumulus (i.e. 62 m of soil traversed)

→ An energy spectrum per detector plane can be obtained from all the energy deposits

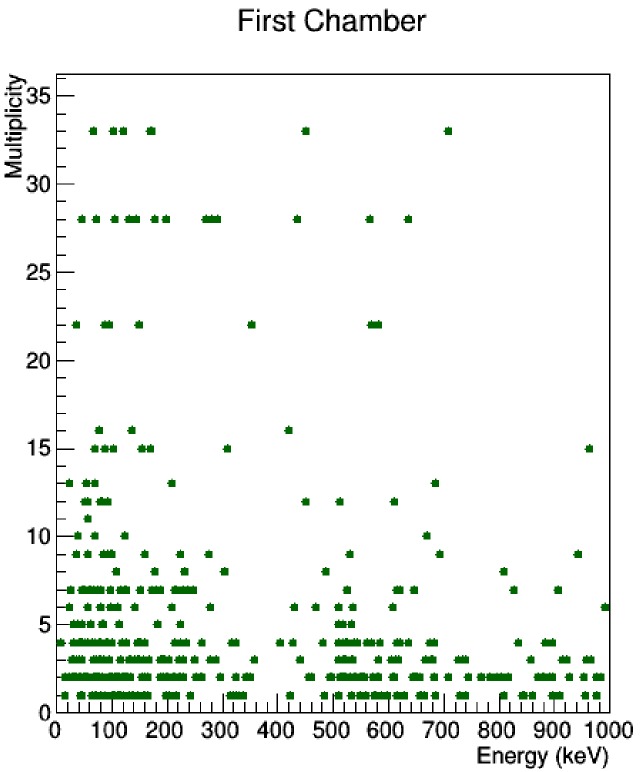
→ The distribution of number of energy deposits per event (mulitplicity) can be also obtained

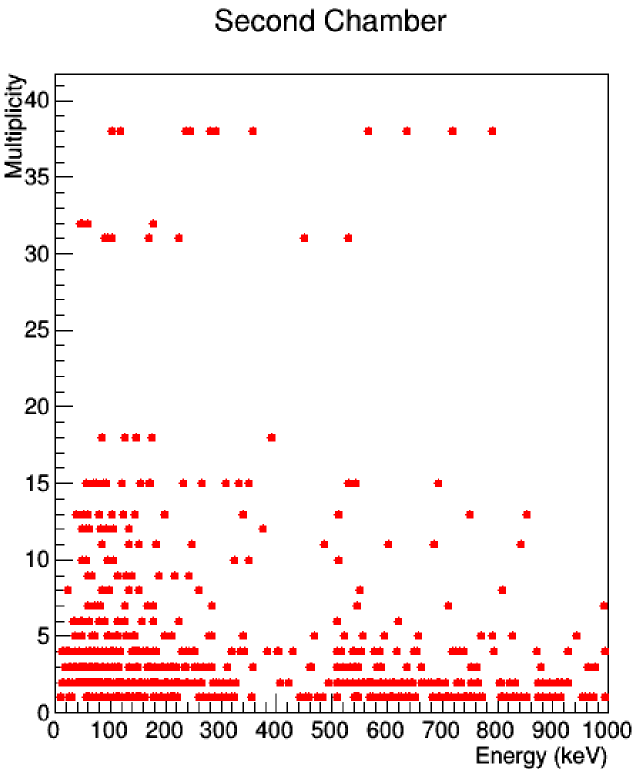


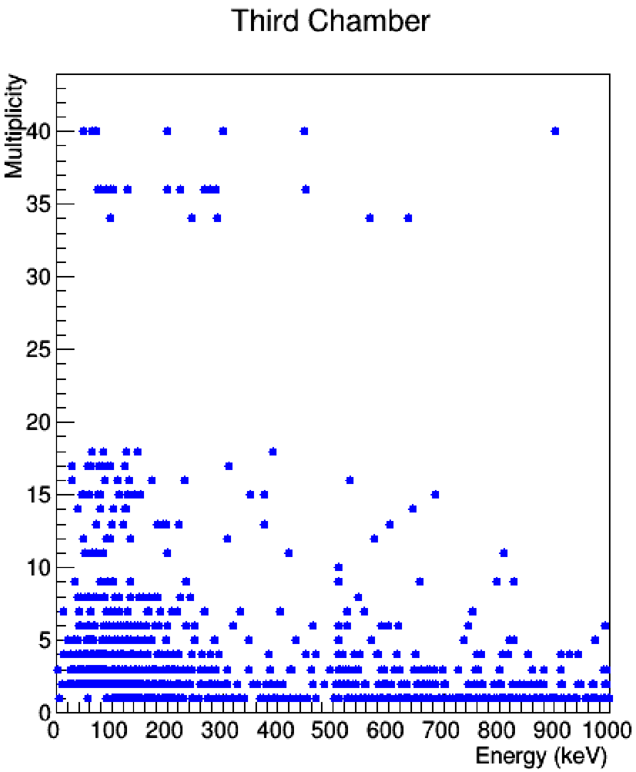
Combining the multiplicity and energy distributions the, $\boldsymbol{E_{thr}}$ for the muon selection can be optimized

Considering muons crossing by the centre of the tumulus (i.e. 62 m of soil traversed)

→ Energy vs Multiplicity distributions for each of the detector planes



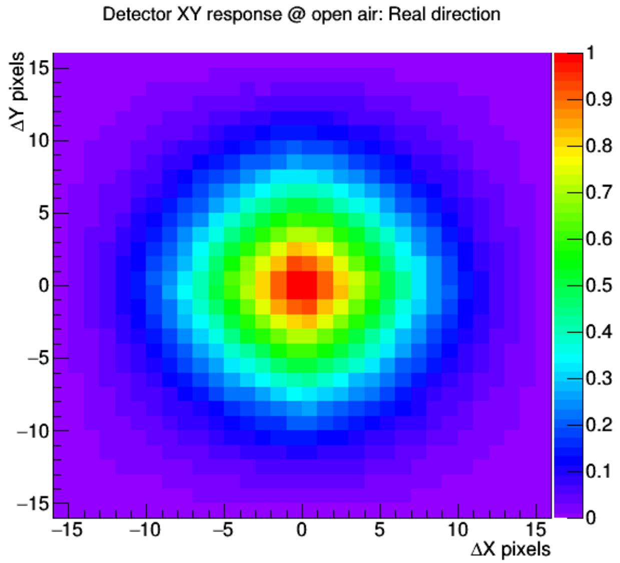


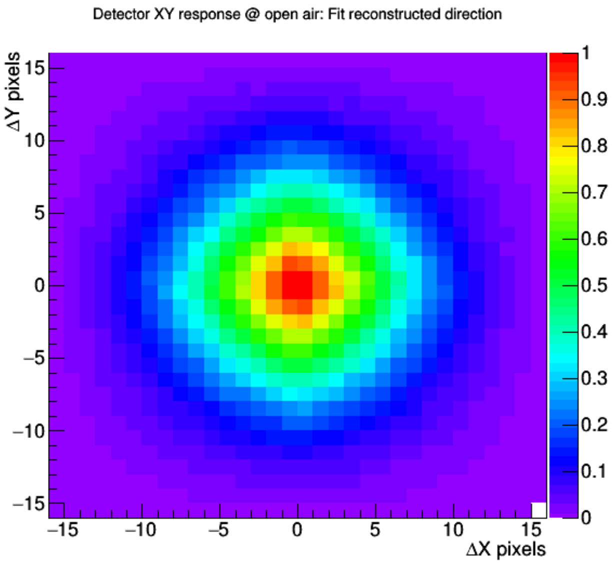


***E_{thr} = 500 keV** seems to be a good value to "clean" muon signals*

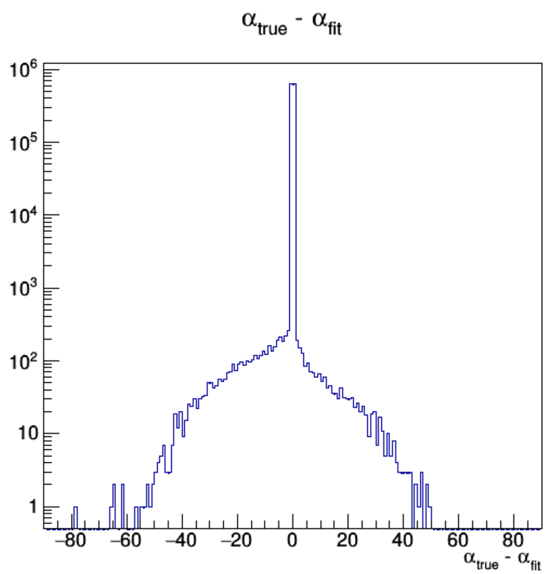
Open air measurement with the detector in vertical position

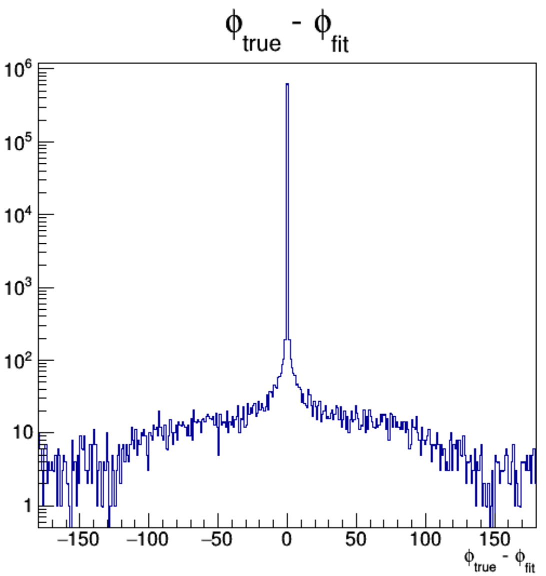
α and ϕ angles comparison between the ***real direction*** @ detector and the reconstructed one by ***fit***





Typical acceptance measurements





For the ***99.5%*** of the reconstructed muons the angular difference (both α and ϕ) is ***less than 1°***

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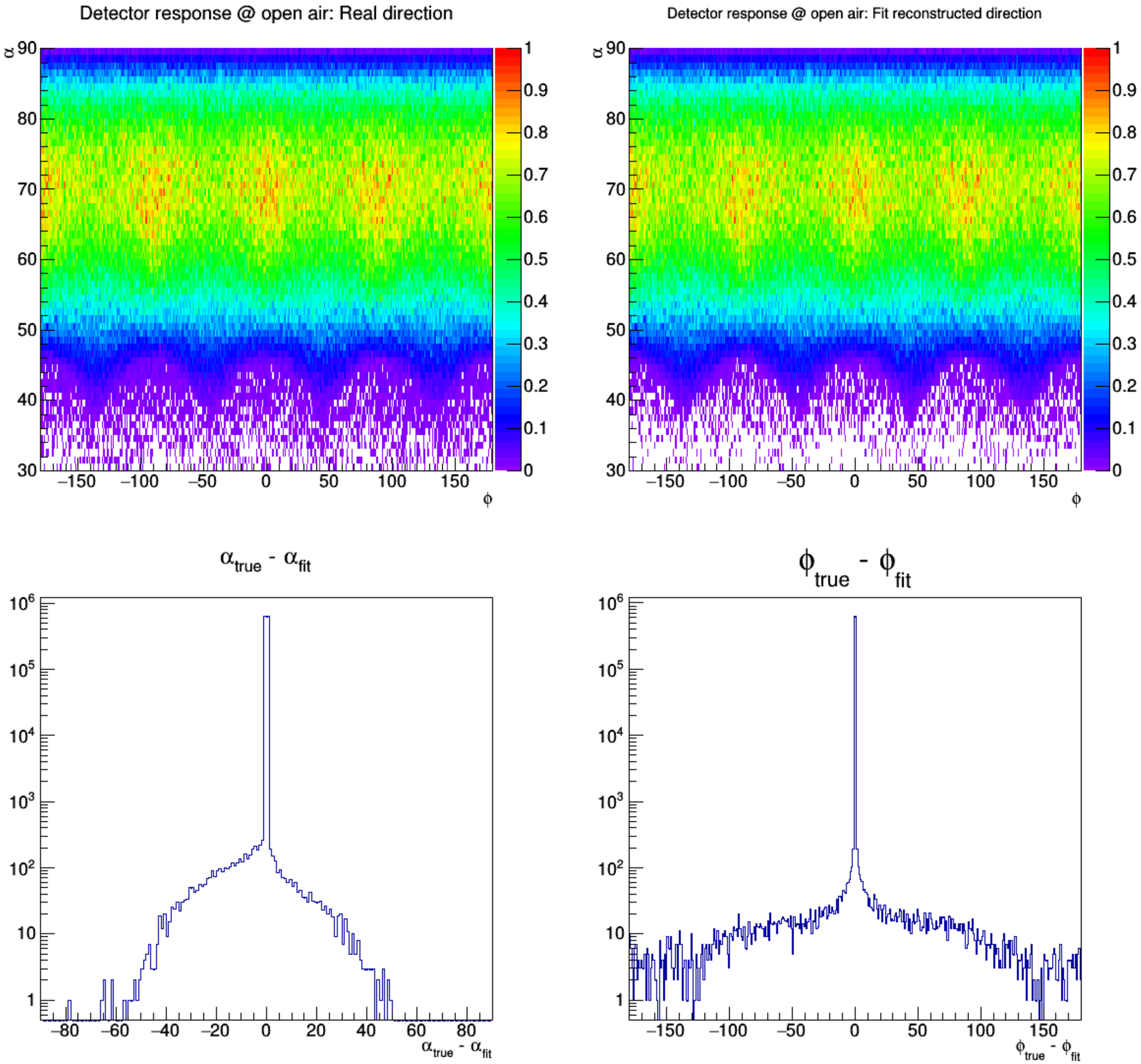
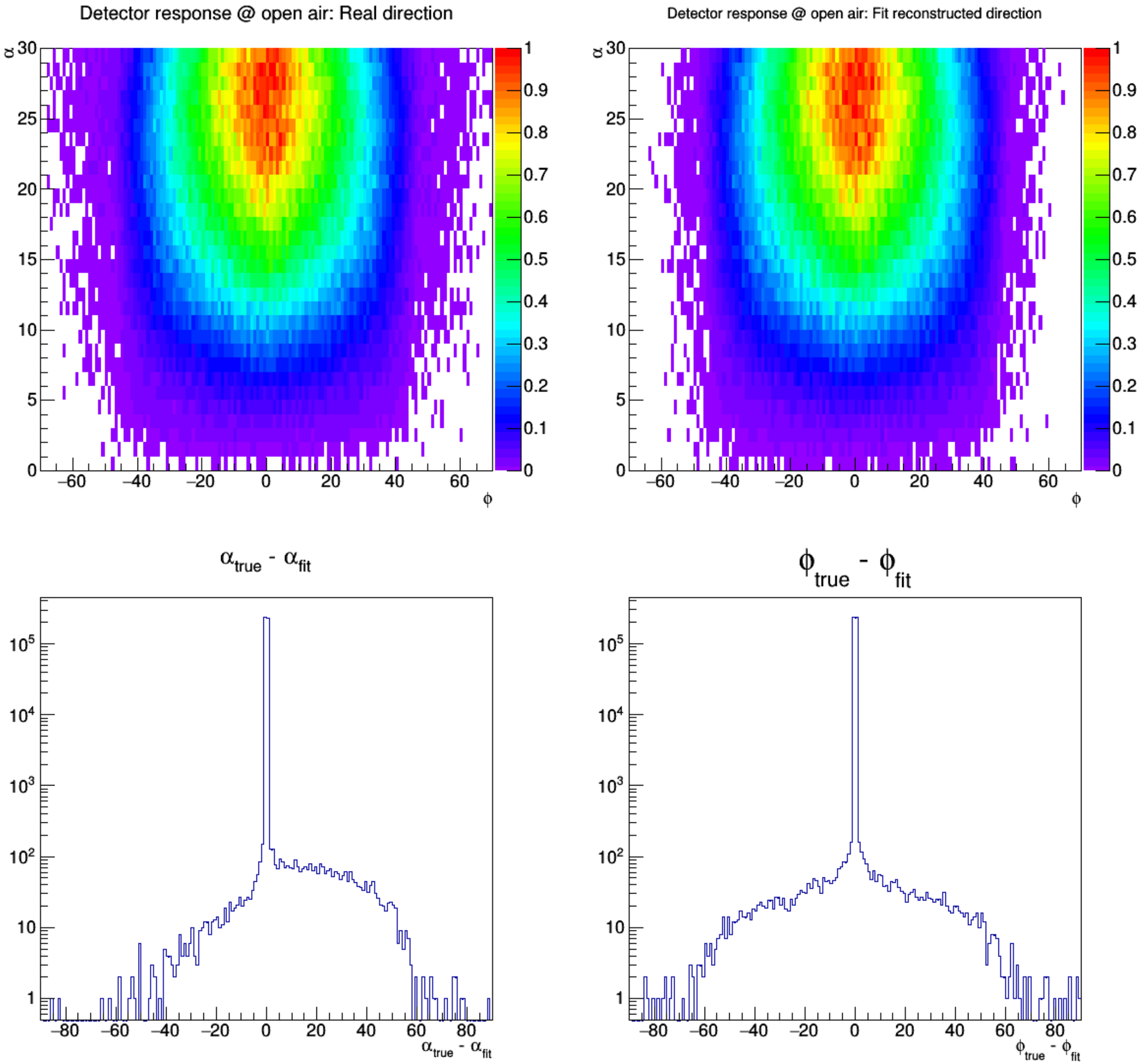


For the ***99.5%*** of the reconstructed muons the angular difference (both α and ϕ) is ***less than 1°***

Open air measurement for the *Side 1* case

α and ϕ angles comparison between the ***real direction*** @ detector and the reconstructed one by ***fit***



For the ***99.2%*** of the reconstructed muons the angular difference (both α and ϕ) is ***less than 1°***

For the Side 2 configuration the percentage is 99.0 %

→ Effect on the diffused distribution associated to the detector orientation

SIMULATION RESULTS

Shukla parametrization results are presented here

→ It seems that it is the best parametrization for [1 – 10^6] GeV energy range

Corresponding plots for the other parametrizations are included in the ***Backup***

- All the simulations have considered ***6 months*** of measurement and 1 month of “open air” measurement

→ How many simulated muons does it means?

- Side 1: E > 1 GeV

  $60° < \theta < 90°$

  $-70° < \phi < 70°$

- Side 2: E > 1 GeV

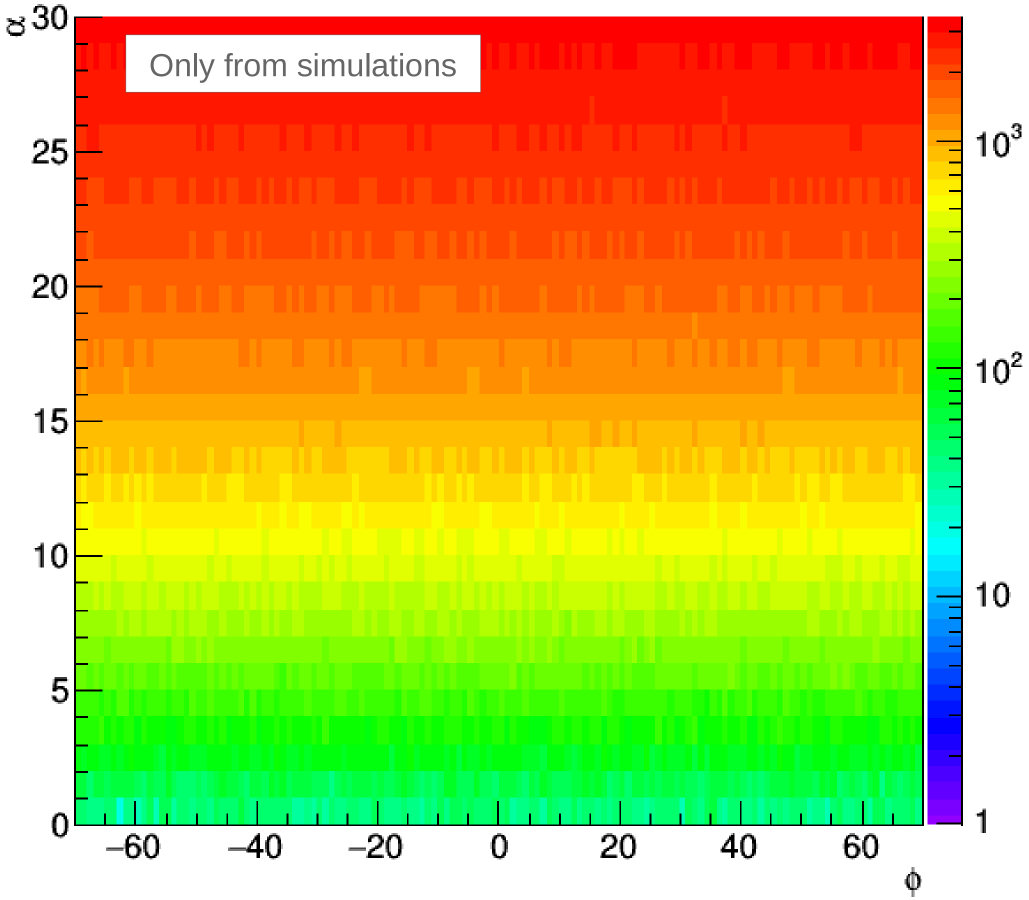
  $60° < \theta < 90°$

  $-42° < \phi < 18°$

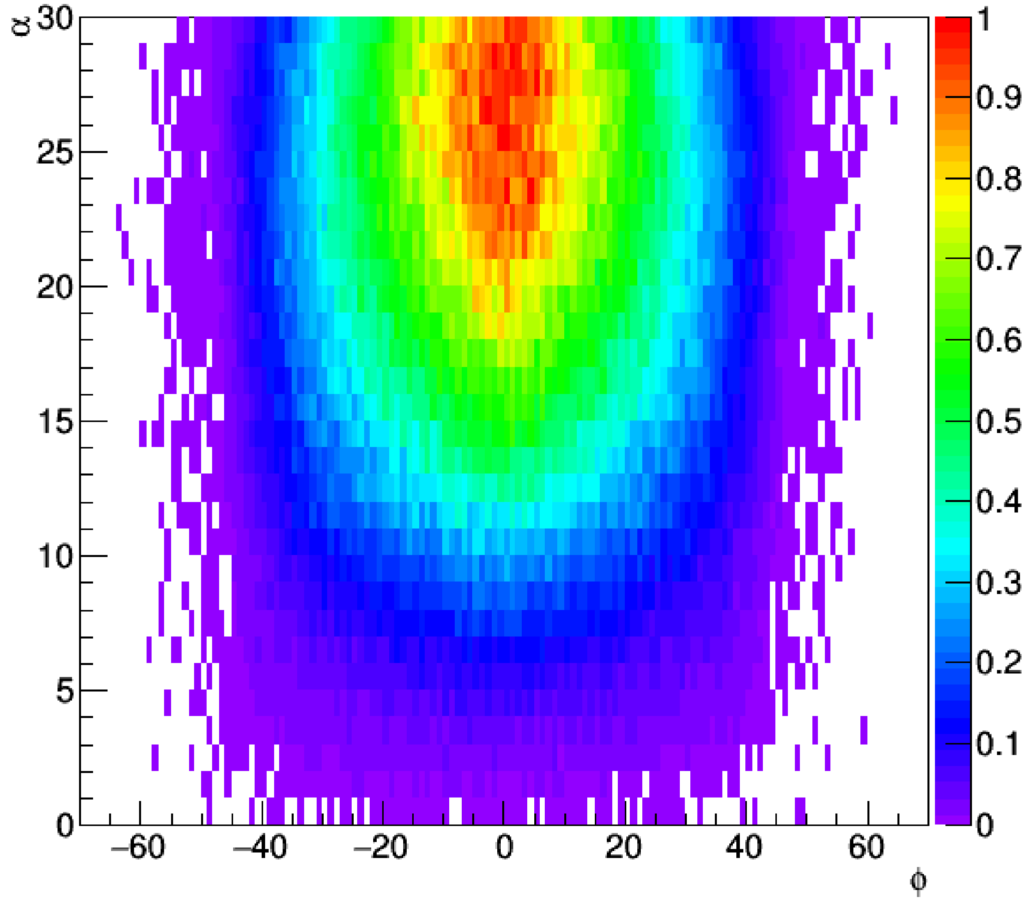
Simulated events corresponding to 1 month measurement

	Gaisser	CRY	Shukla
Side 1	$6.7\ 10^{6}$	$6.9\ 10^{6}$	$13.3\ 10^{6}$
Side 2	$2.9\ 10^{6}$	$3.0\ 10^{6}$	$5.7\ 10^{6}$

Initial angular distribution



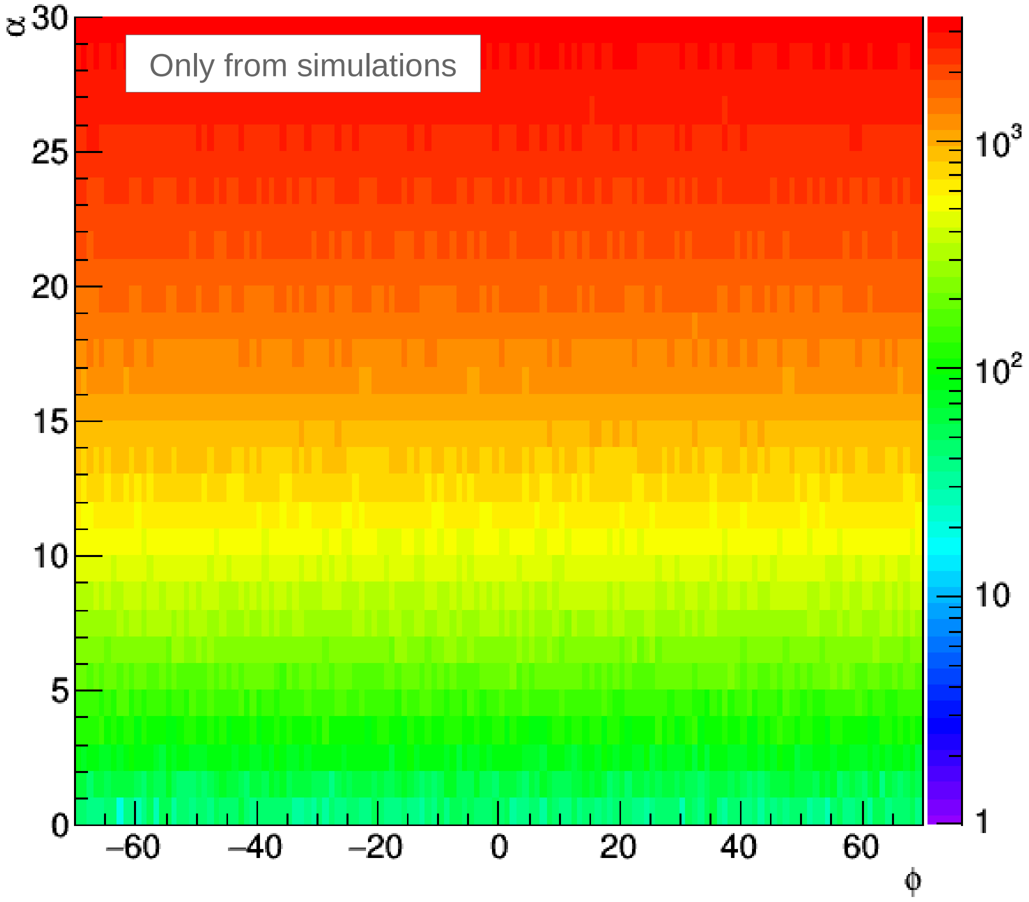
Detector response @ open air



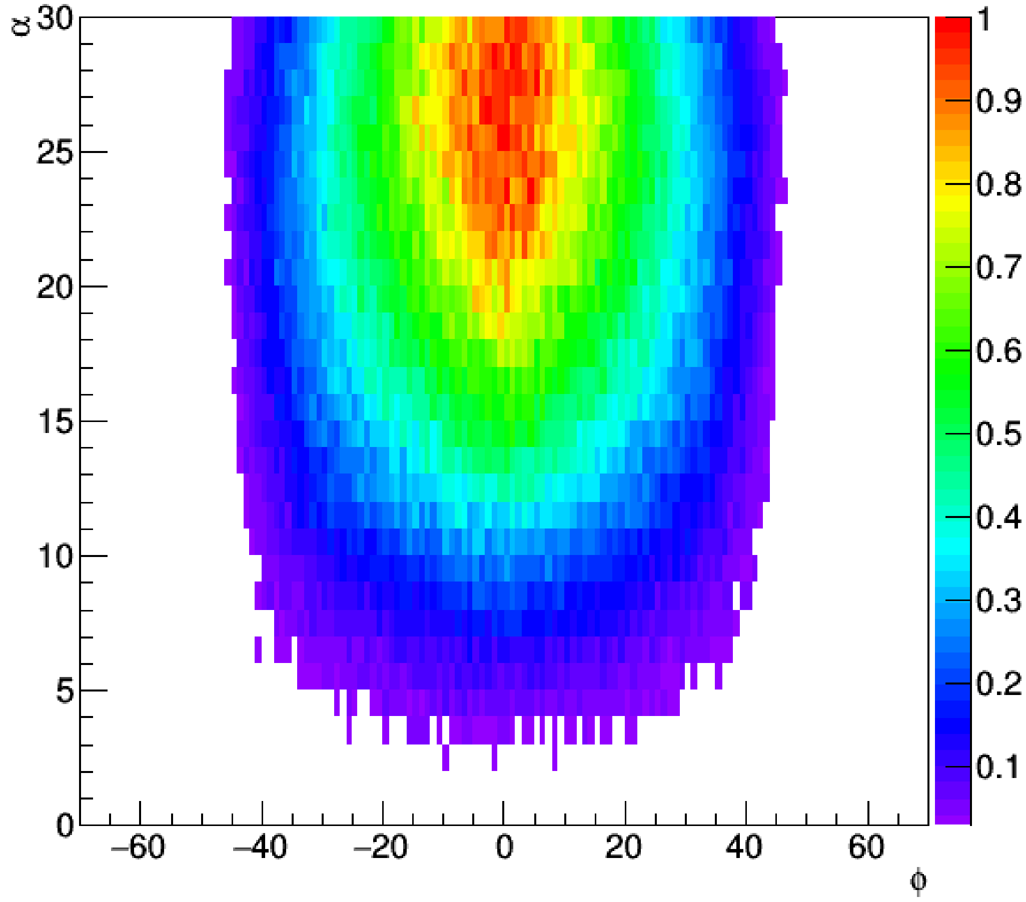
Relative efficiency map (ε)

Those directions with less than ***3%*** of relative efficiency would not be considered in further analyses.

Initial angular distribution



Detector response @ open air



Relative efficiency map (ε)

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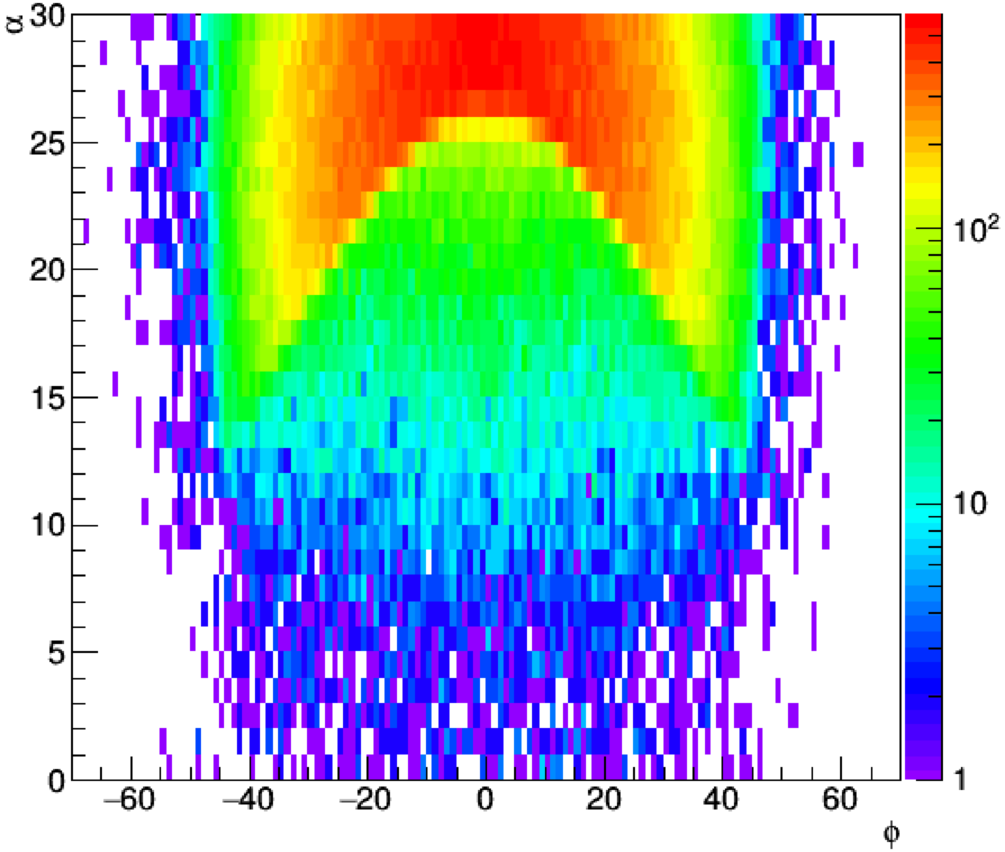
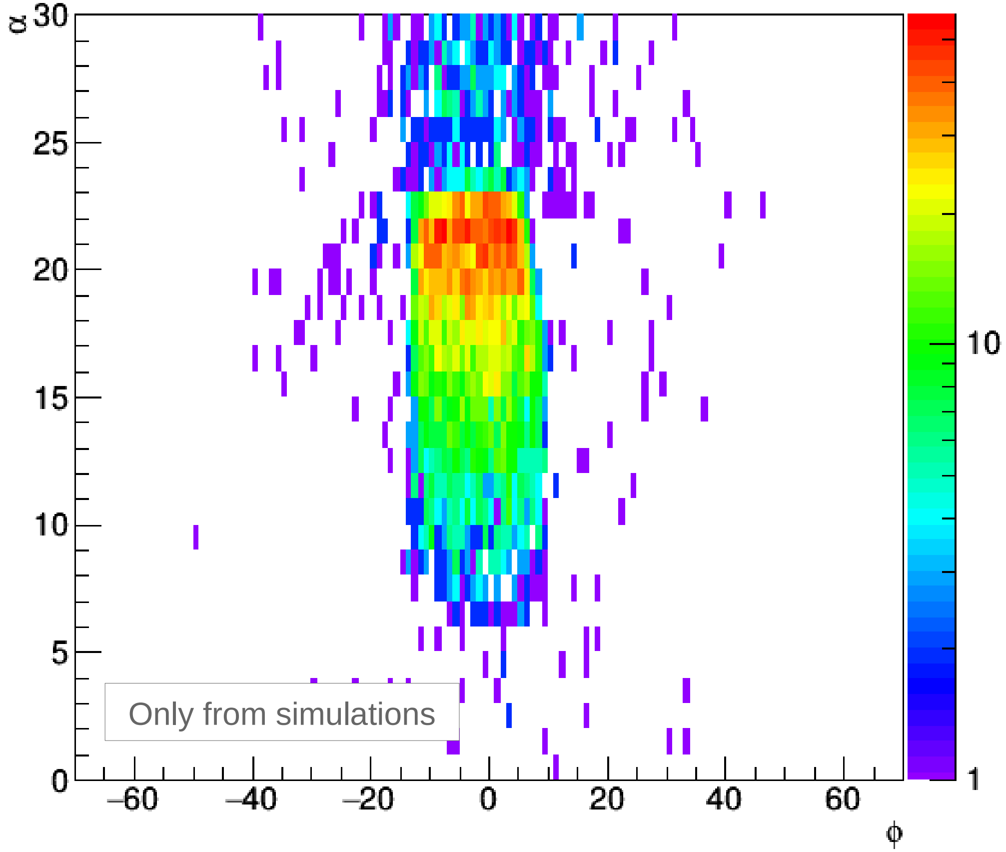
Angular distribution at detector **N**



Angular distribution of Tomb events

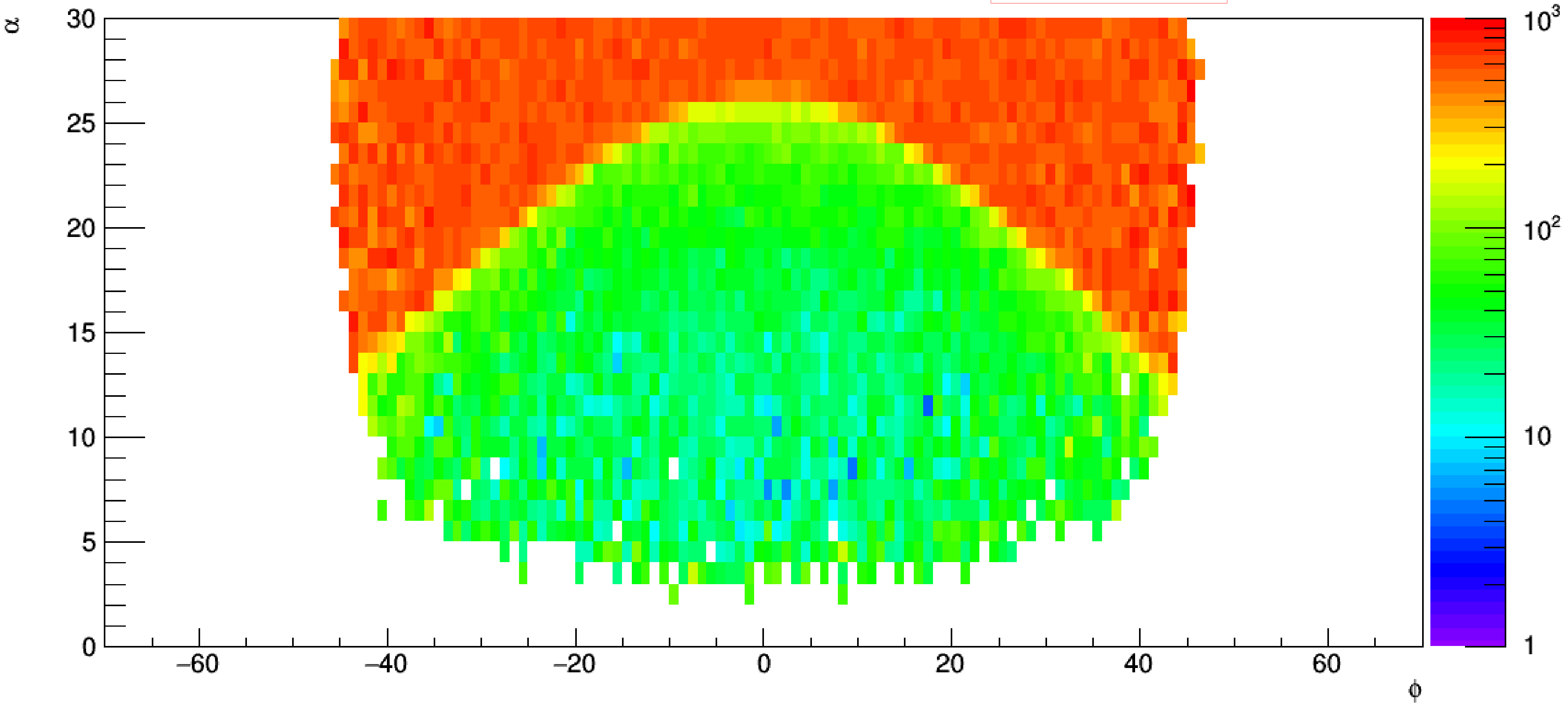


Raw measurement (only track reconstruction)

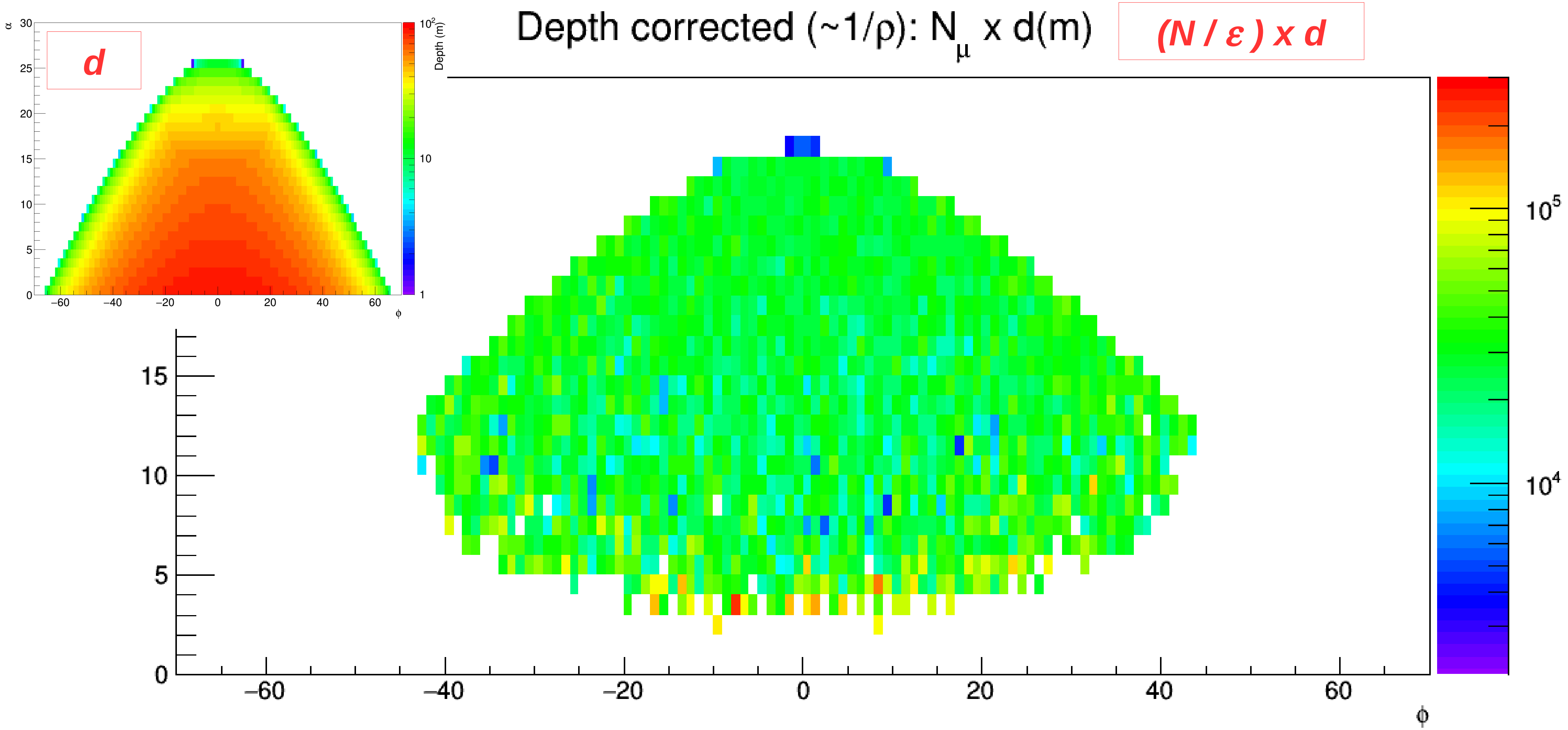
→ Normalize by the acceptance measurement

→ Normalize by tumulus traversed distance (***result ~ ρ***)

Normalized tomography $N_{\mu} = N / \varepsilon$



Reminder: only directions with more than 3% of relative efficiency are considered



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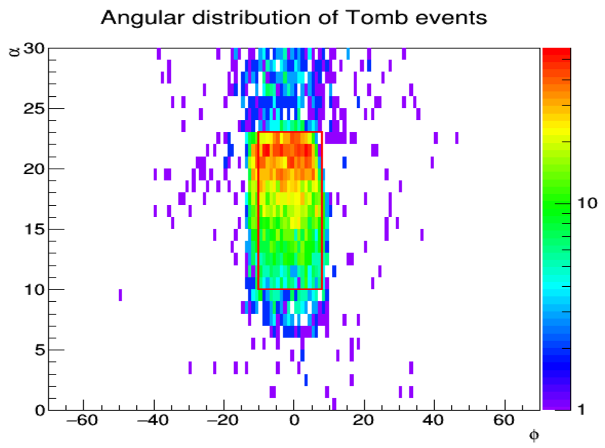
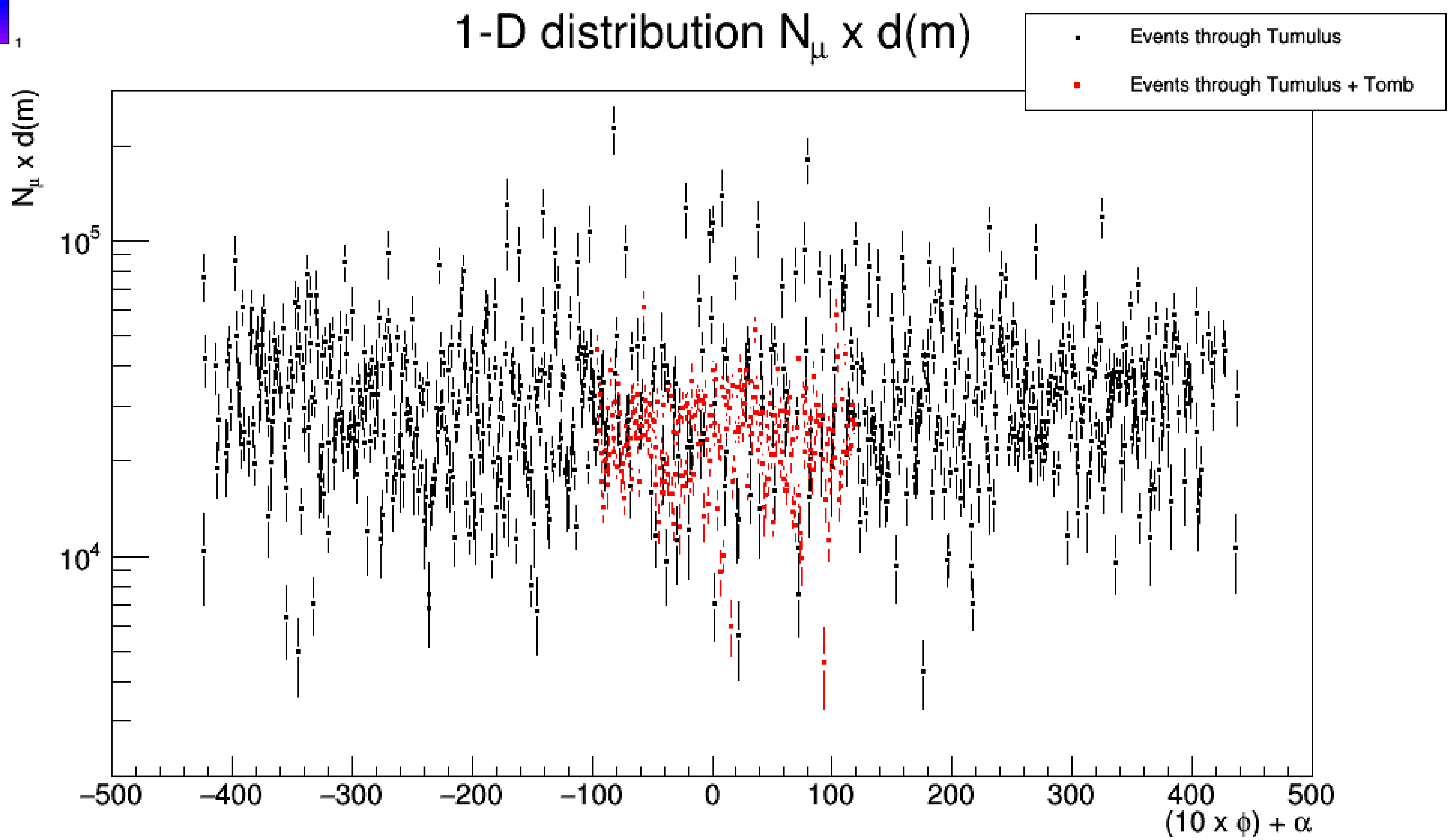


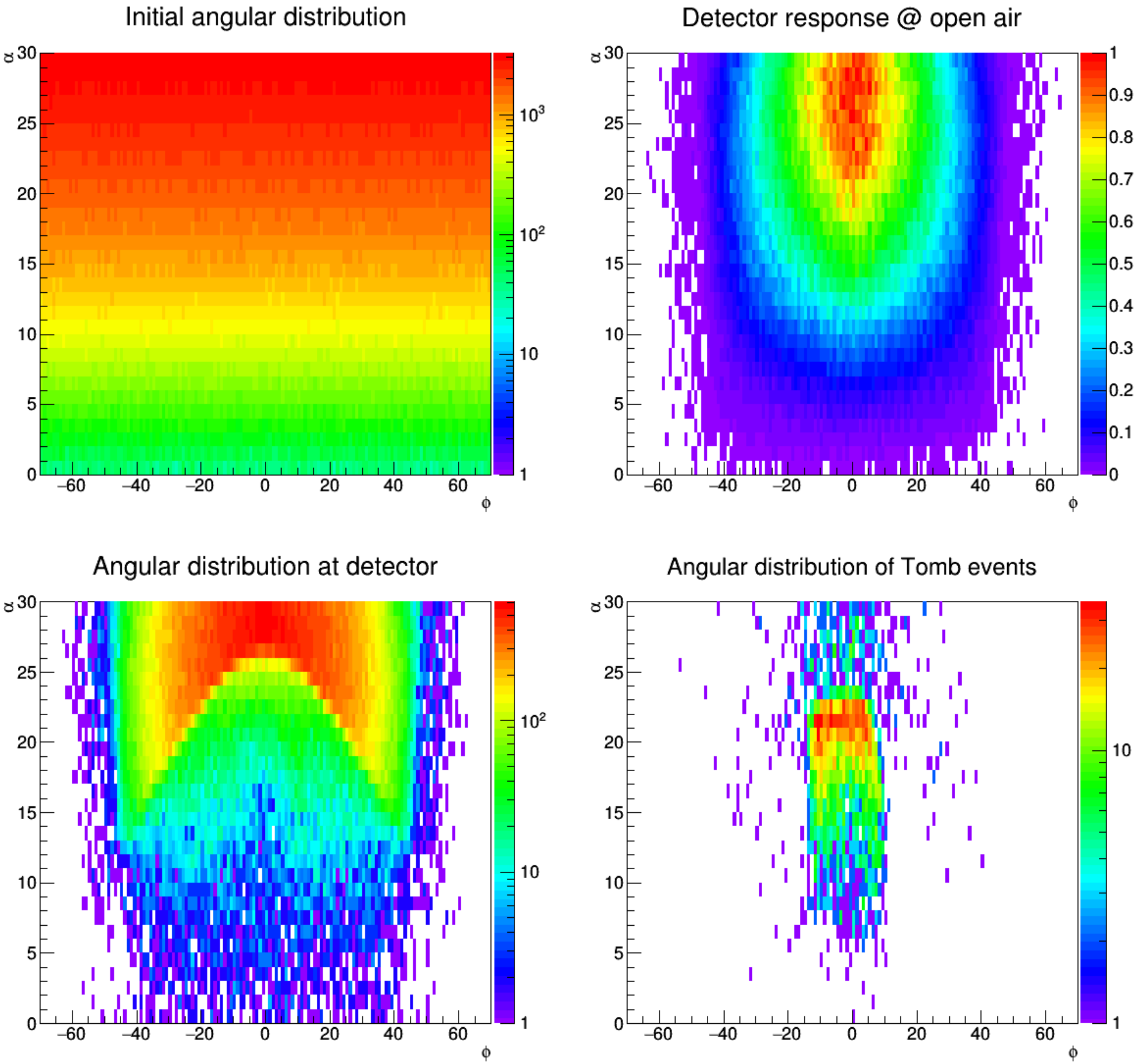
$$\sigma_{N_\mu \times d} = (N_\mu \times d)\sqrt{\left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_d}{d}\right)^2 + \left(\frac{\sigma_\varepsilon}{\varepsilon}\right)^2}$$

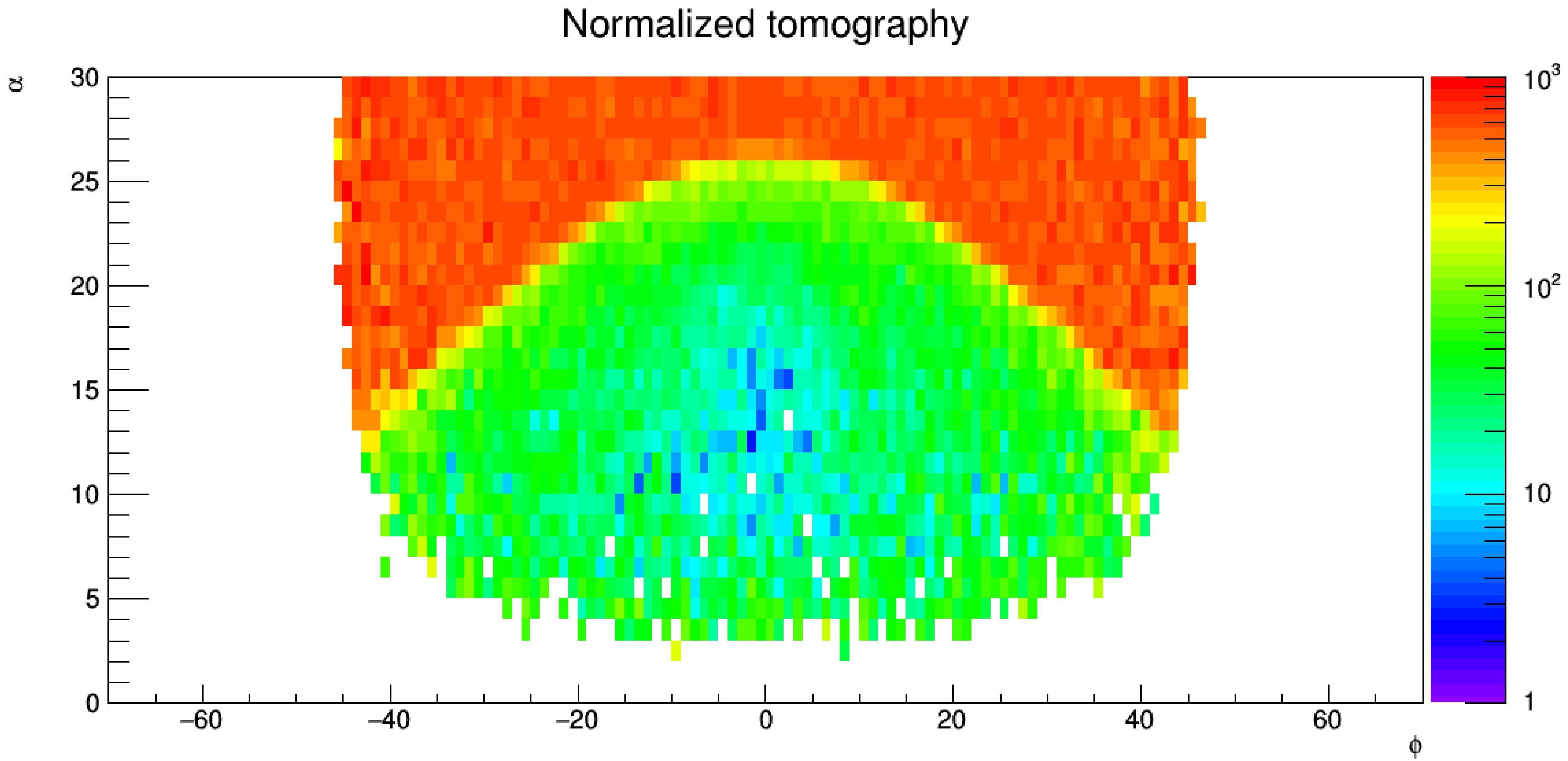
No tomb evidence statistically significant



Considering a Lead Tomb

It has no realistic interest but can give us an idea about how an internal structure looks like


Initial angular distribution
Detector response @ open air
Angular distribution at detector
Angular distribution of Tomb events
α
ϕ



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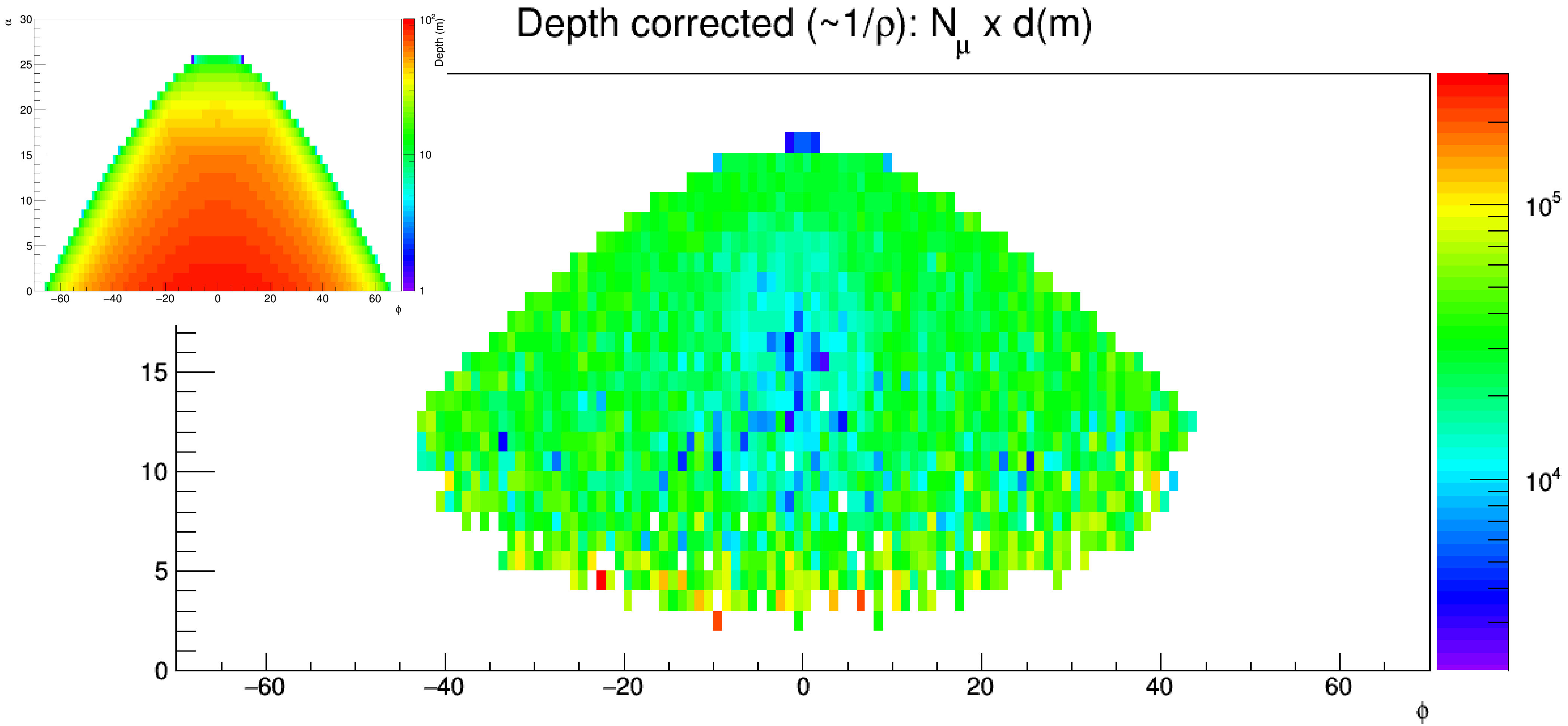

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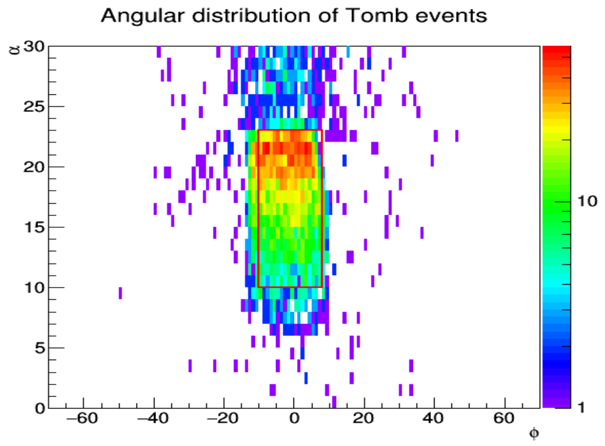
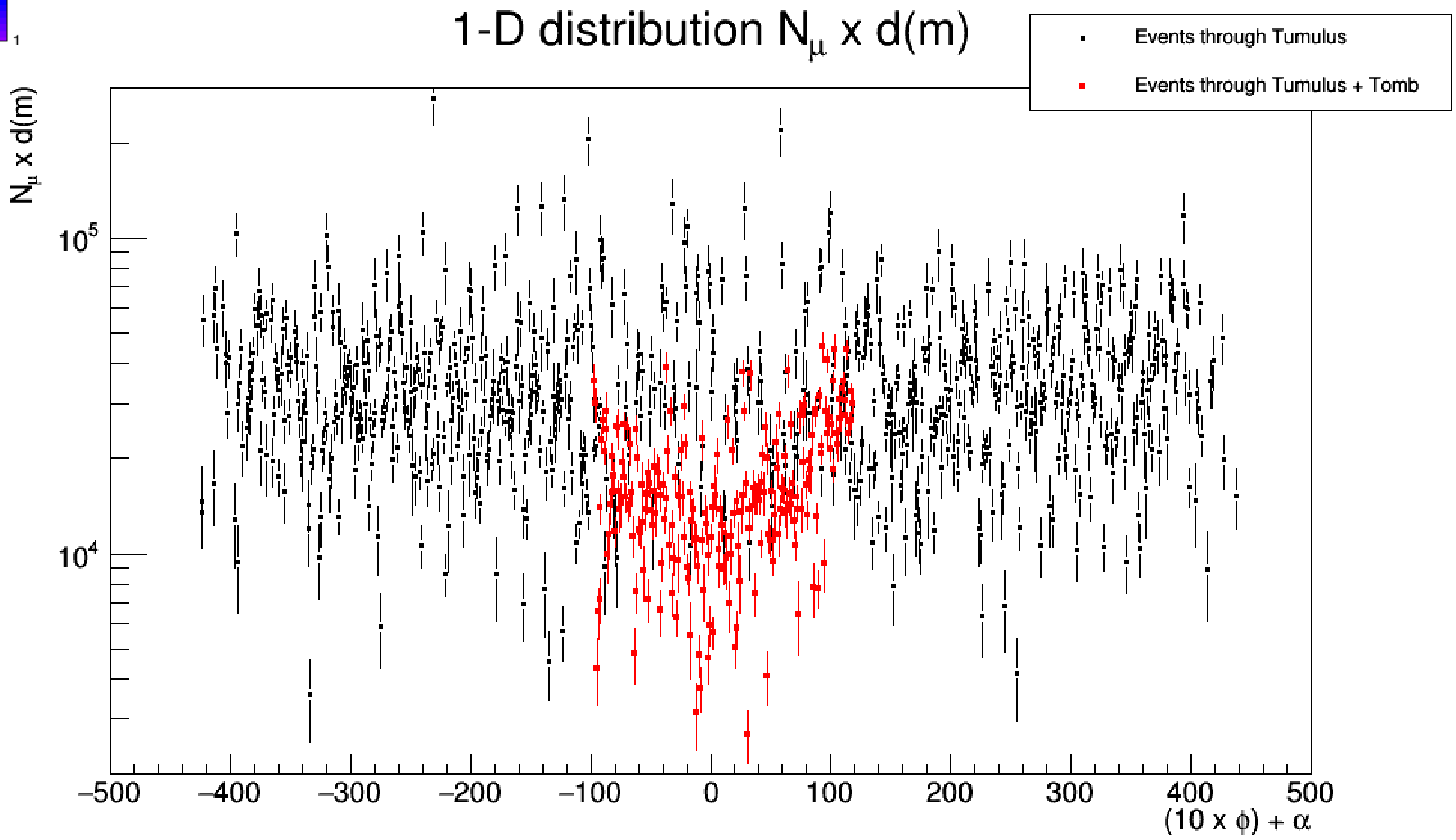
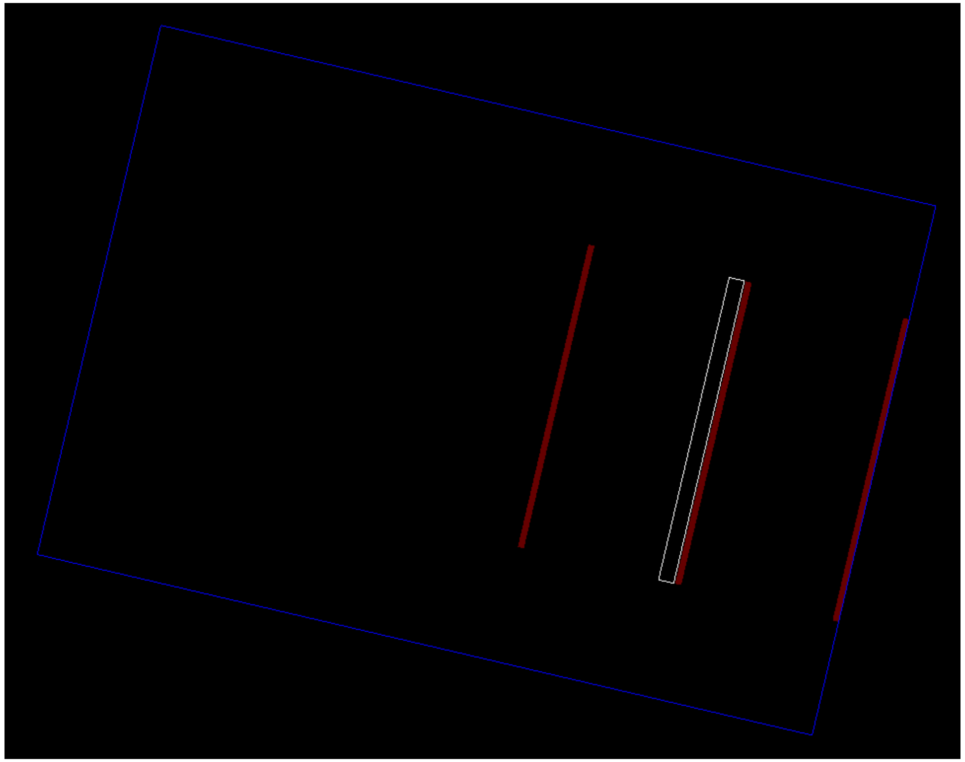

Angular distribution of Tomb events
α
φ
-60
-40
-20
0
20
40
60
0
5
10
15
20
25
30
1
10

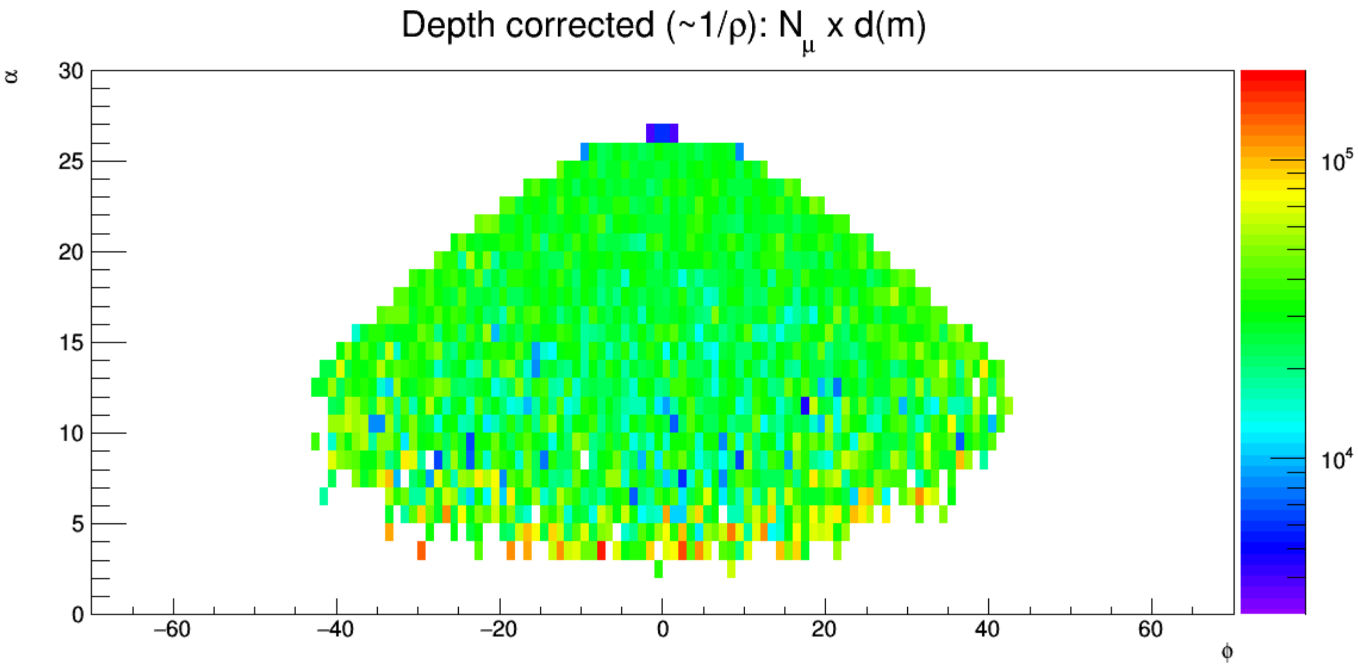

1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
10^4
-500
-400
-300
-200
-100
0
100
200
300
400
500
(10 x φ) + α

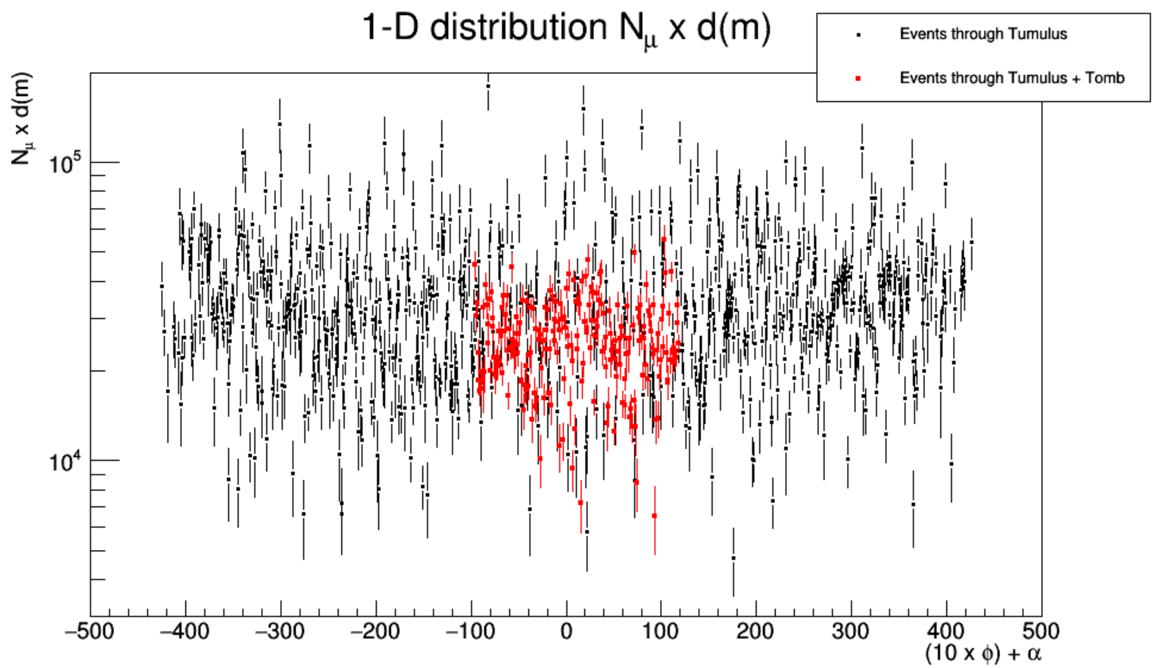
Adding a Lead layer in the detector



5 cm thick layer of lead in front of the middle plane

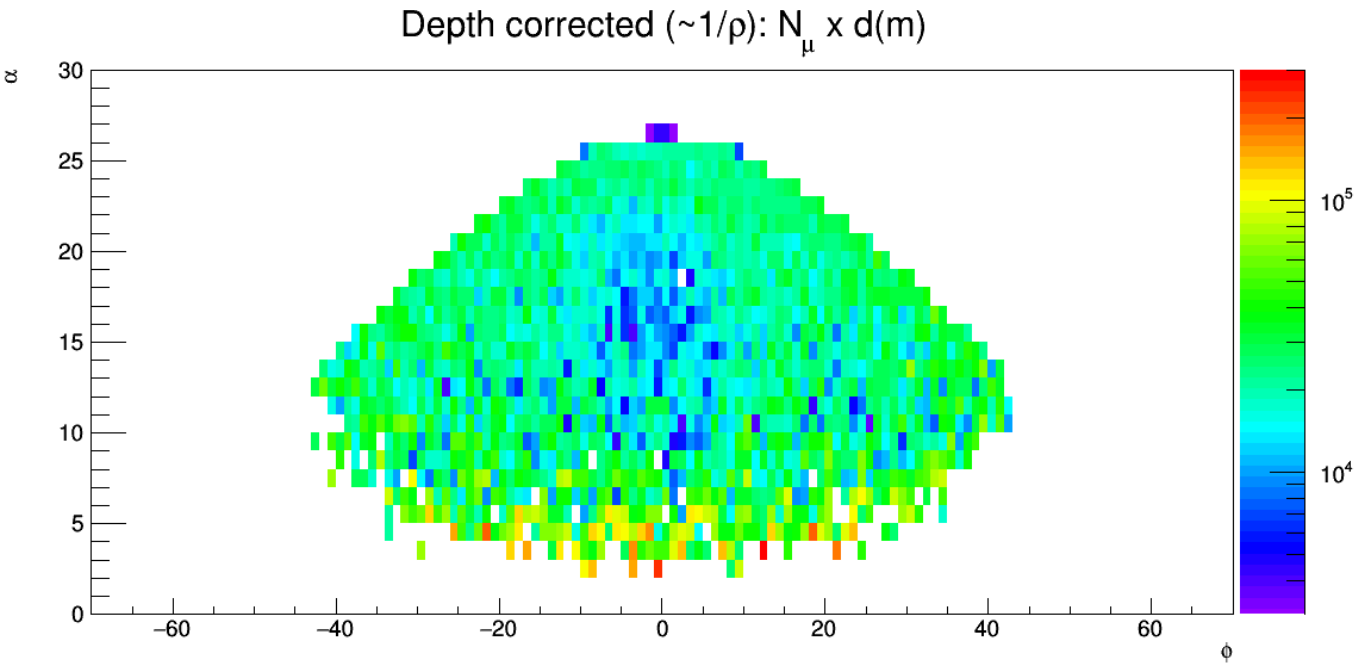
Full simulation of Shukla – Side 1 case (Real and Lead tomb and open air)

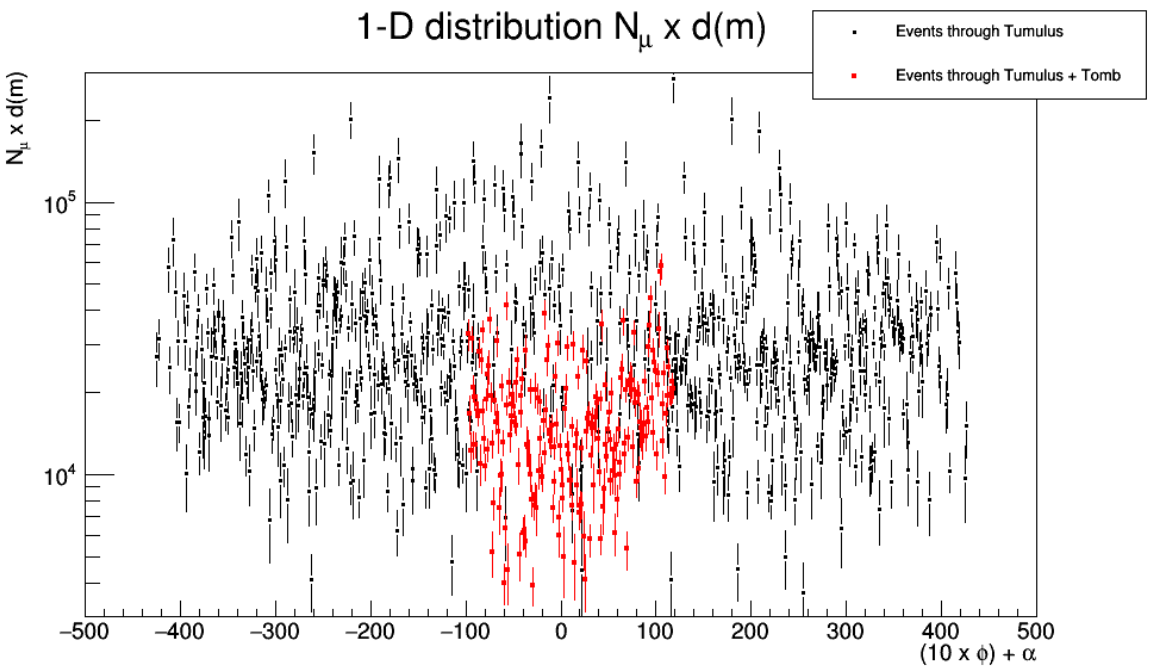




No significant difference with the no lead case

As expected? Only muons were simulated





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As expected? Only muons were simulated

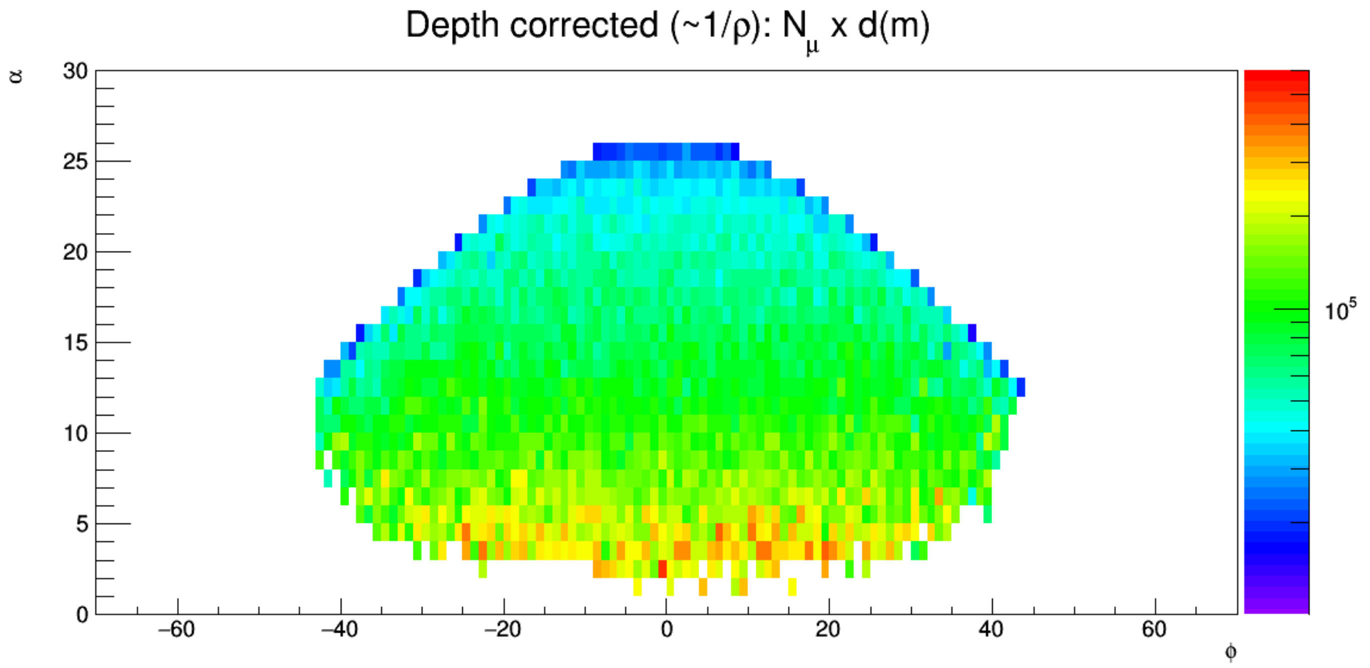
Summary & Prospects

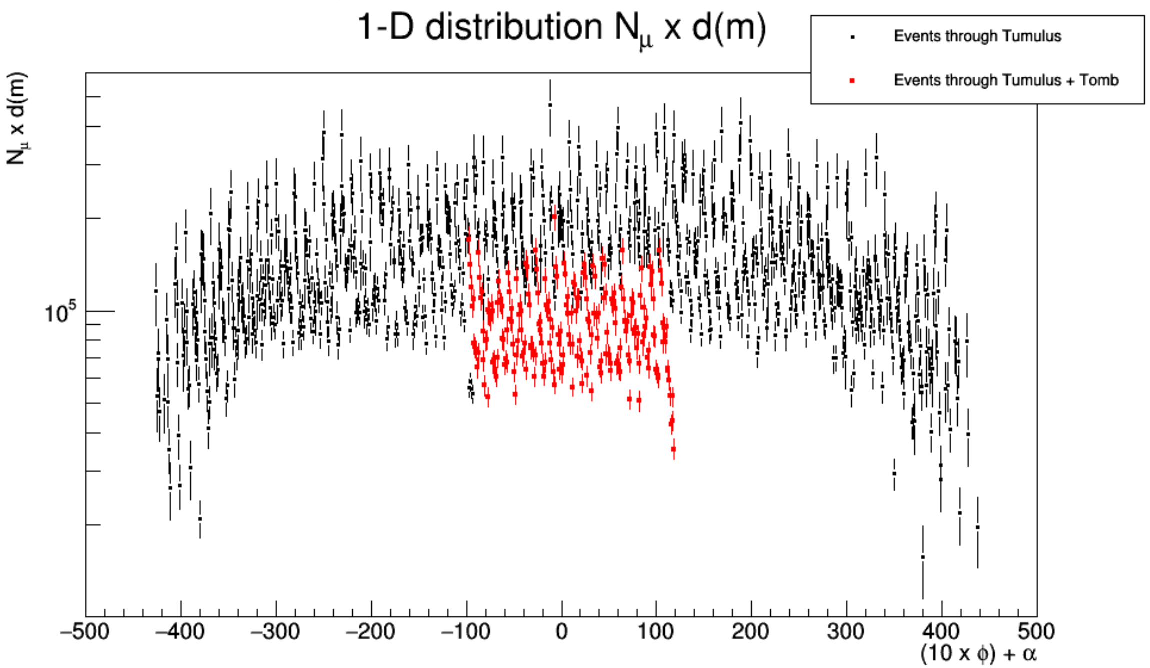
- The Geant 4 simulation framework developed by LAPP has been tuned to perform Apollonia tumulus simulations
  - Good approximation of the geometry
  - Capable to test different muon models
- Data from simulations can be analysed in a similar way to the muon telescope experimental data
  - Fit of the tracks
  - Energy threshold of the fired pixels
- 2 cases have been considered for a 6 months measurement + 1 month “calibration”
  - Only in Side 1 positions seems possible to identify the existing Hall
  - Results highly dependent of the muon model

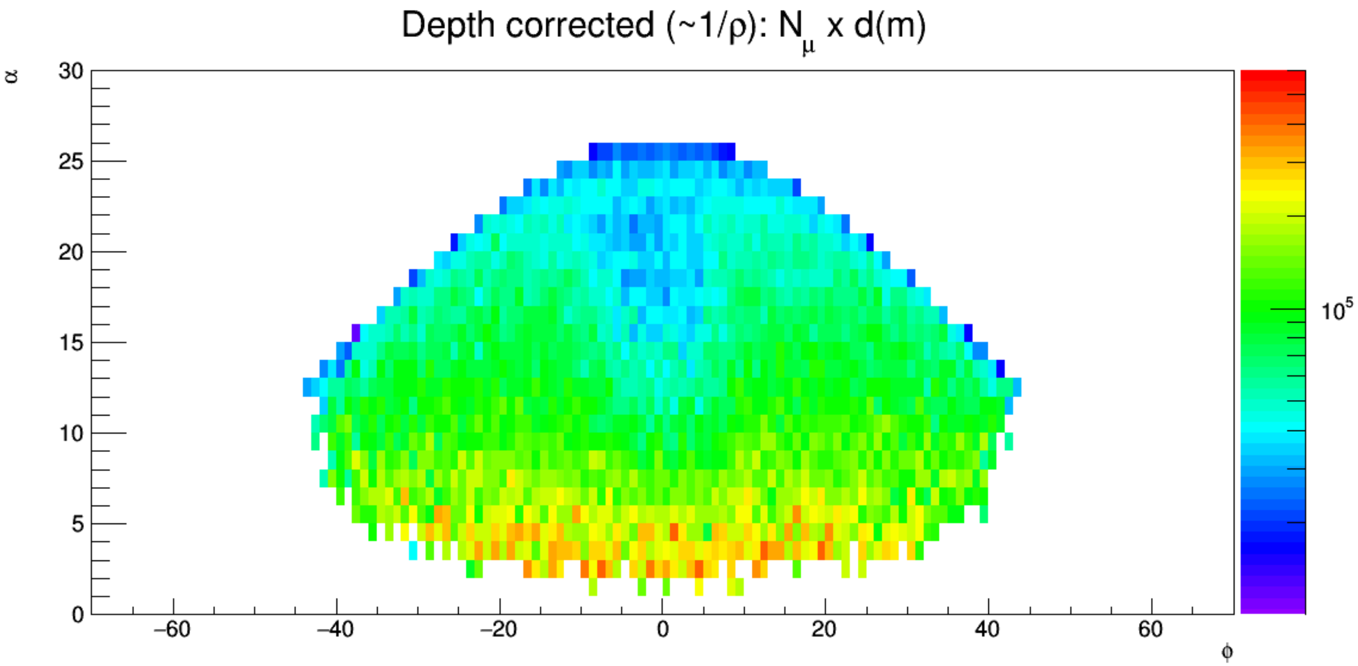
- In order to make more precise de simulations:
  - Implementation of a more accurate model of the muon telescope in the simulations (provided by K. Jourde)
    - Be capable to mimic the experimental data analysis in the simulations
  - Update the geometry of the explored hall (marble thickness, entrance door...)
  - Keep studying the muon models, specially at low energy range
  - Study of background events?

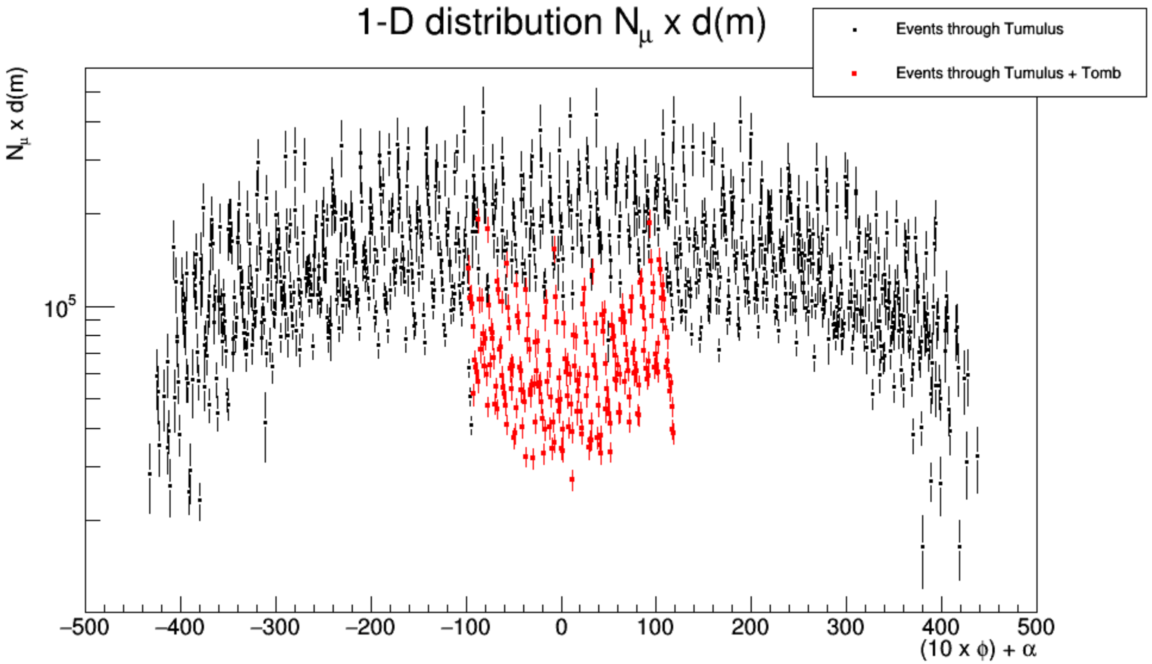
Back up

Results for other muon models and Side 2 scenario


Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−60
−40
−20
0
20
40
60
ϕ
10^5

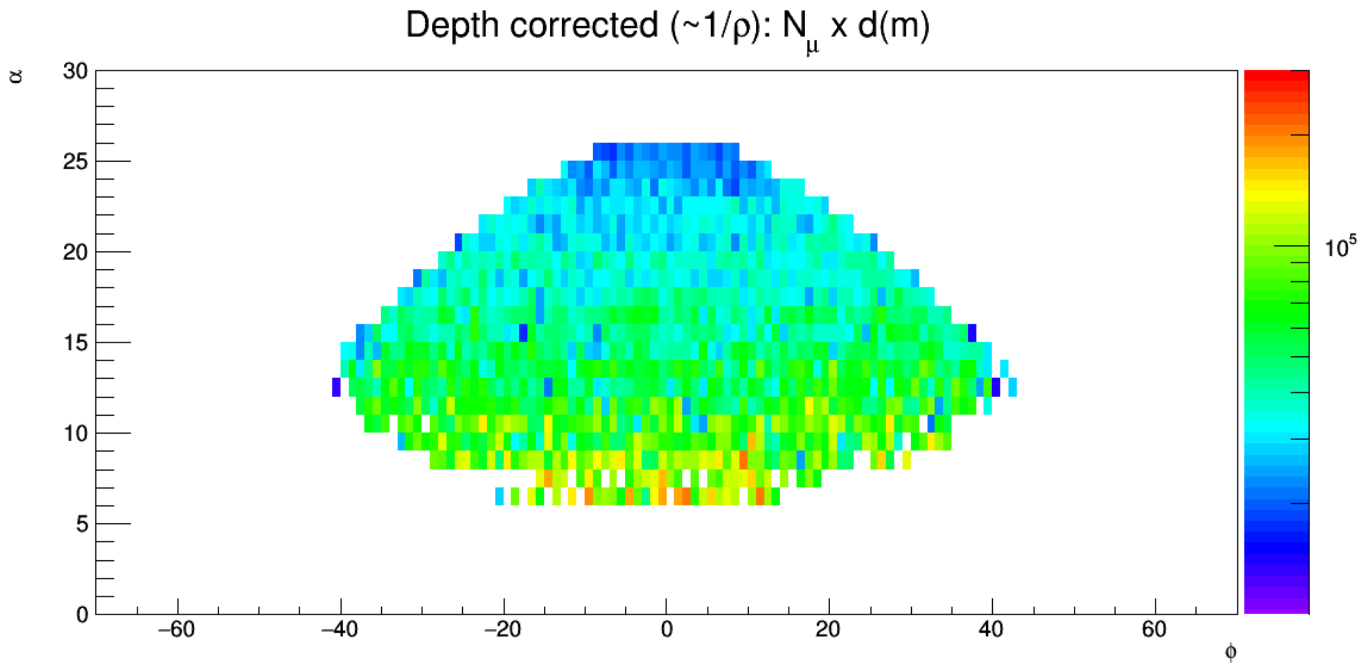

1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
−500
−400
−300
−200
−100
0
100
200
300
400
500
(10 x ϕ) + α

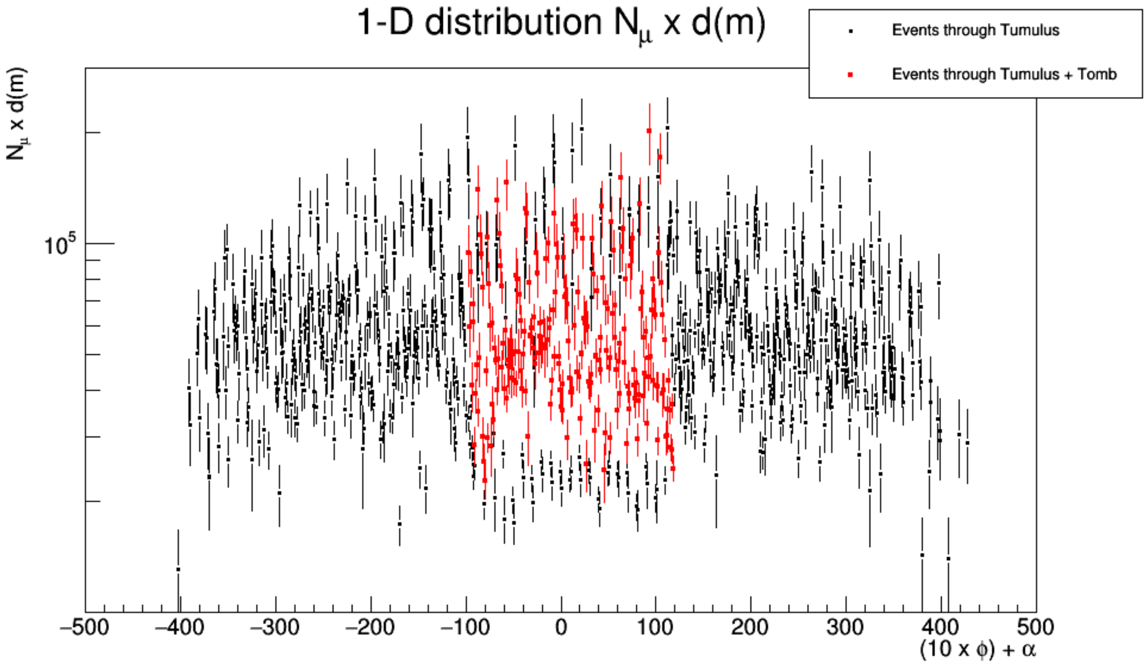

Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−60
−40
−20
0
20
40
60
ϕ
10^5

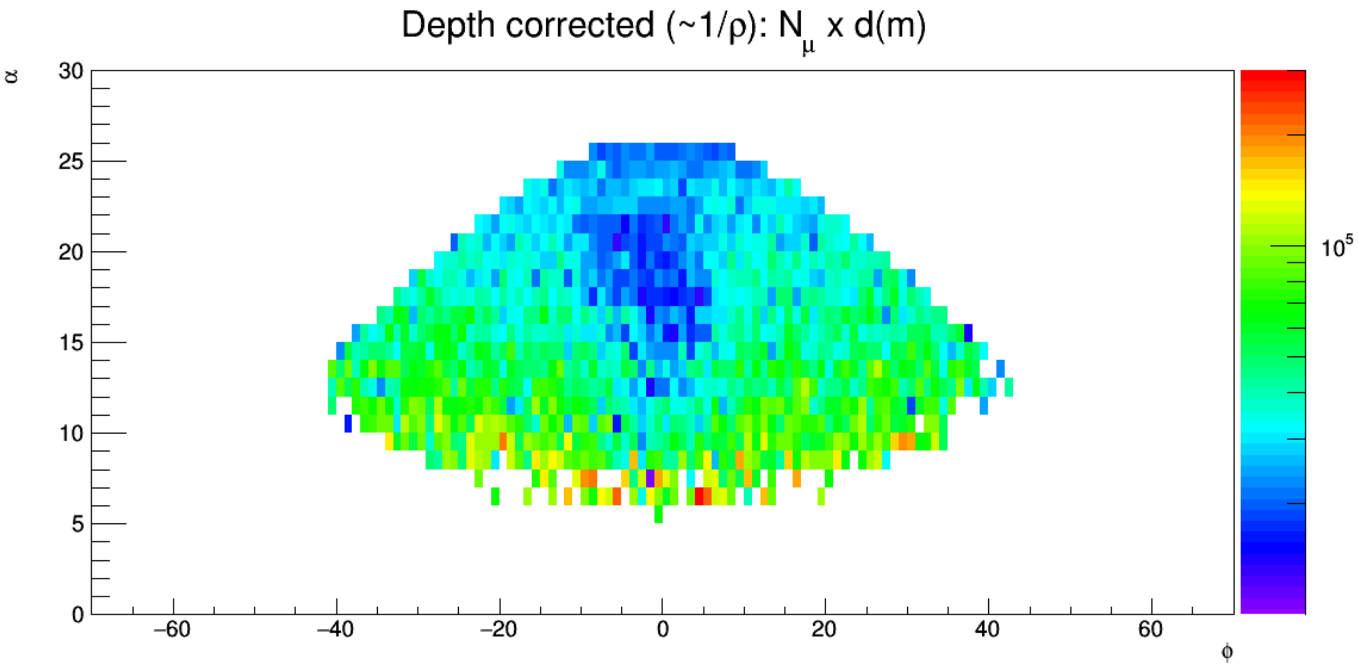

1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
−500
−400
−300
−200
−100
0
100
200
300
400
500
(10 x ϕ) + α

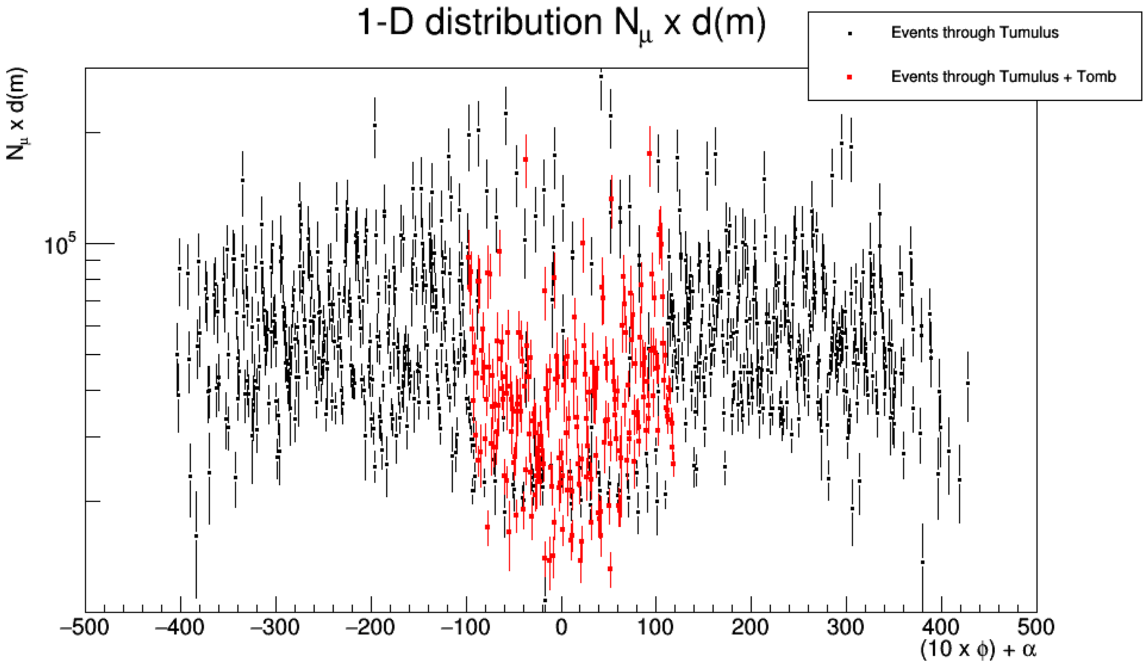
CRY - Side 1 geometry

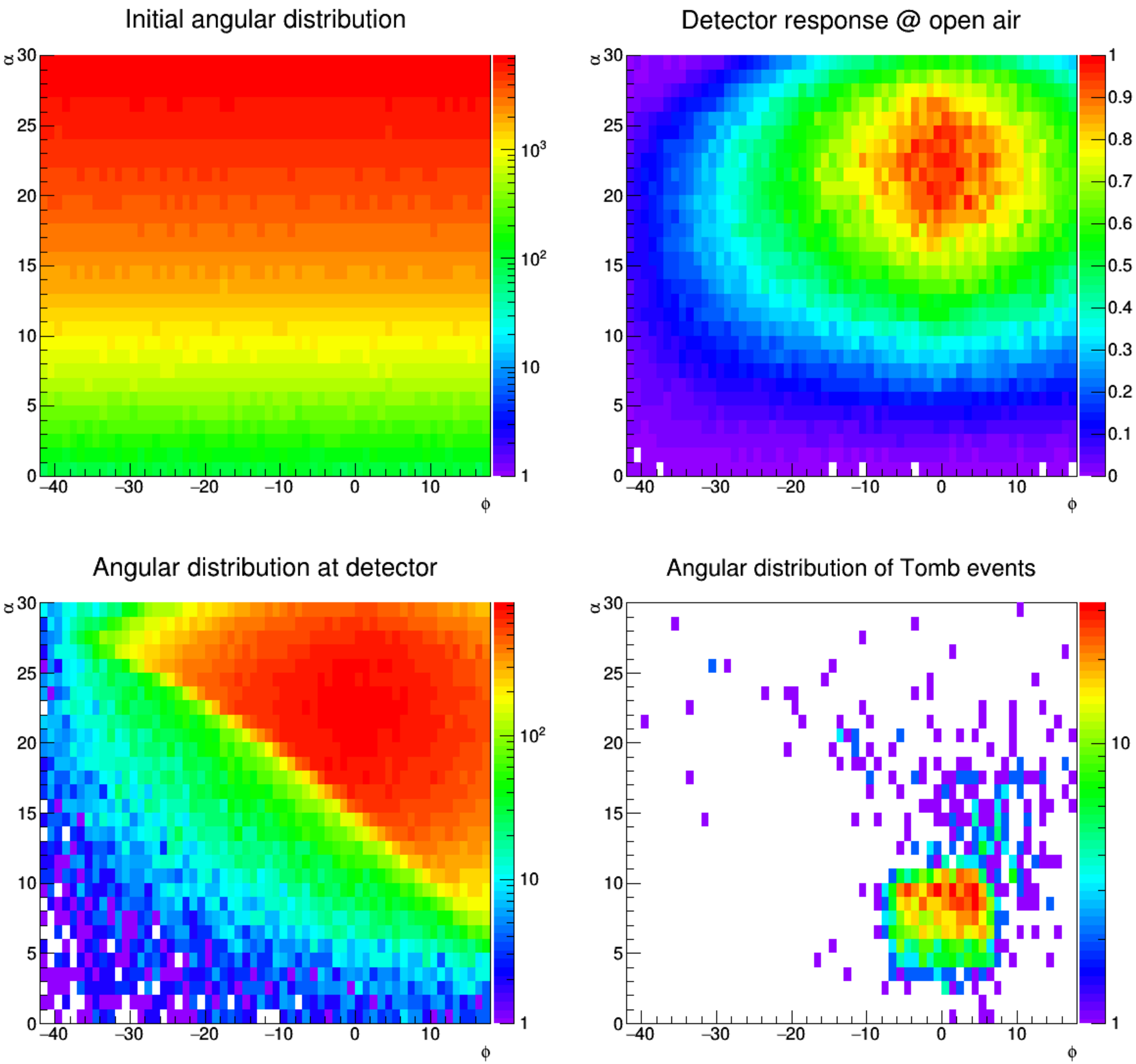
"Real" Tomb

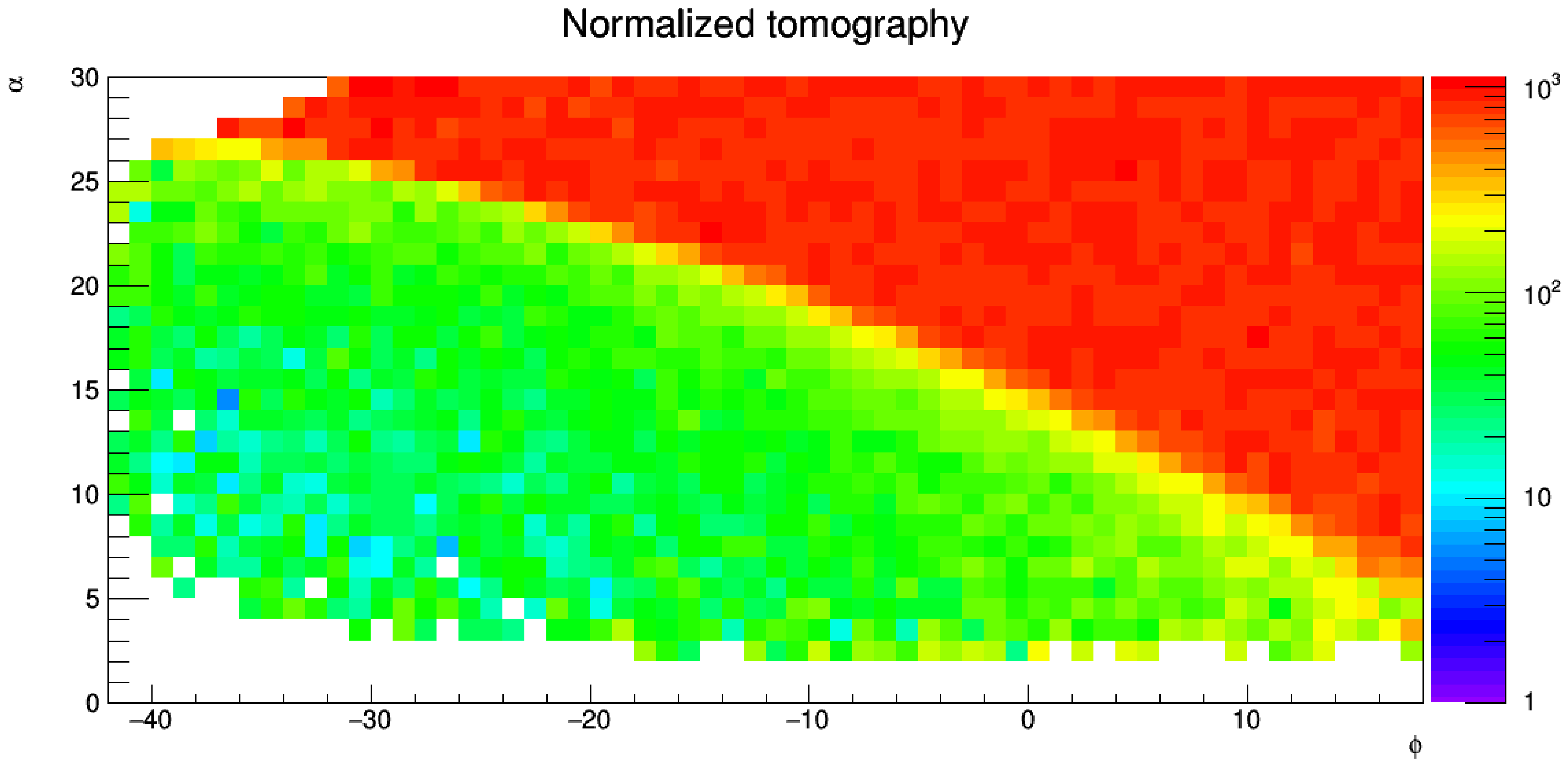




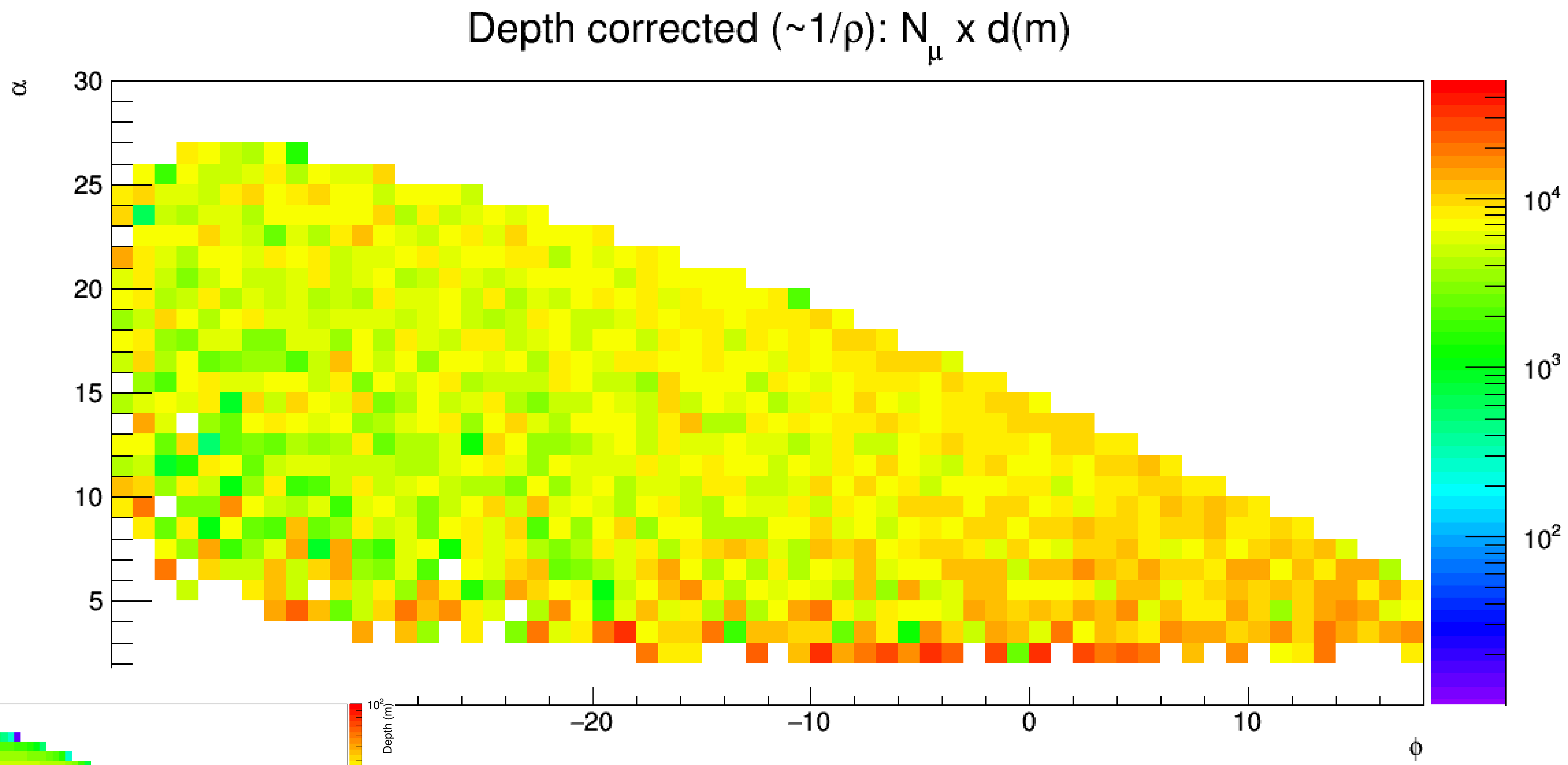

Depth correcte (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−60
−40
−20
0
20
40
60
ϕ
10^5

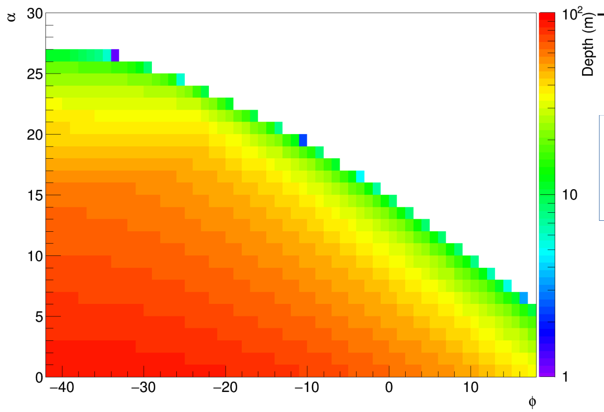

1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
−500
−400
−300
−200
−100
0
100
200
300
400
500
(10 x ϕ) + α


Initial angular distribution
α
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
ϕ
10^3
10^2
10
1
Detector response @ open air
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Angular distribution at detector
Angular distribution of Tomb events

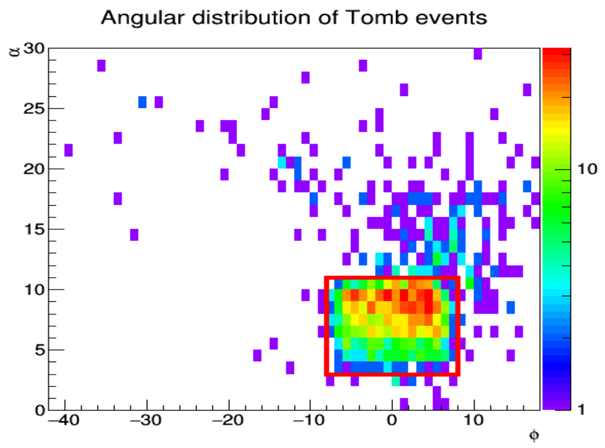


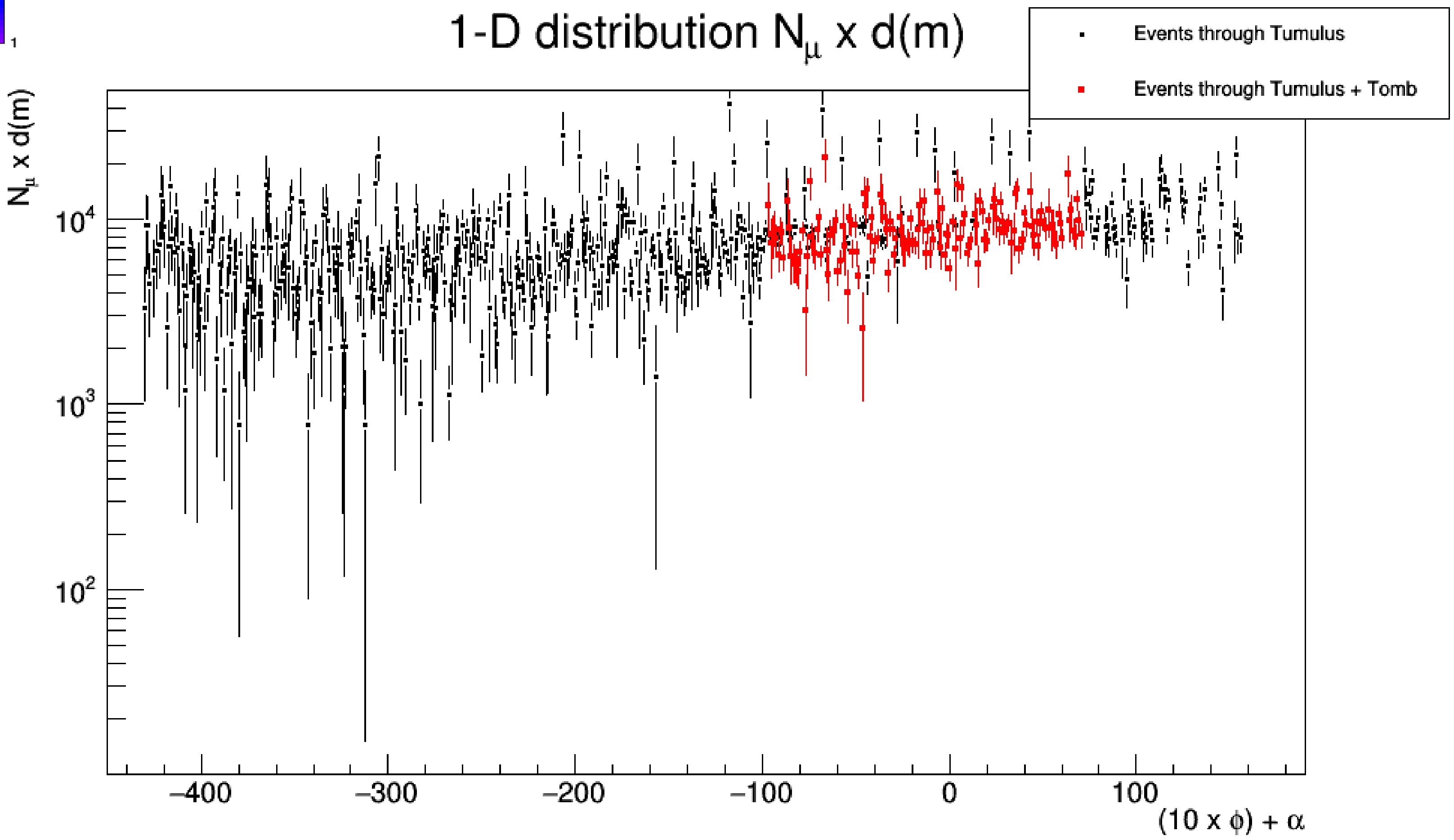
Reminder: only directions with more than 3% of relative efficiency are considered

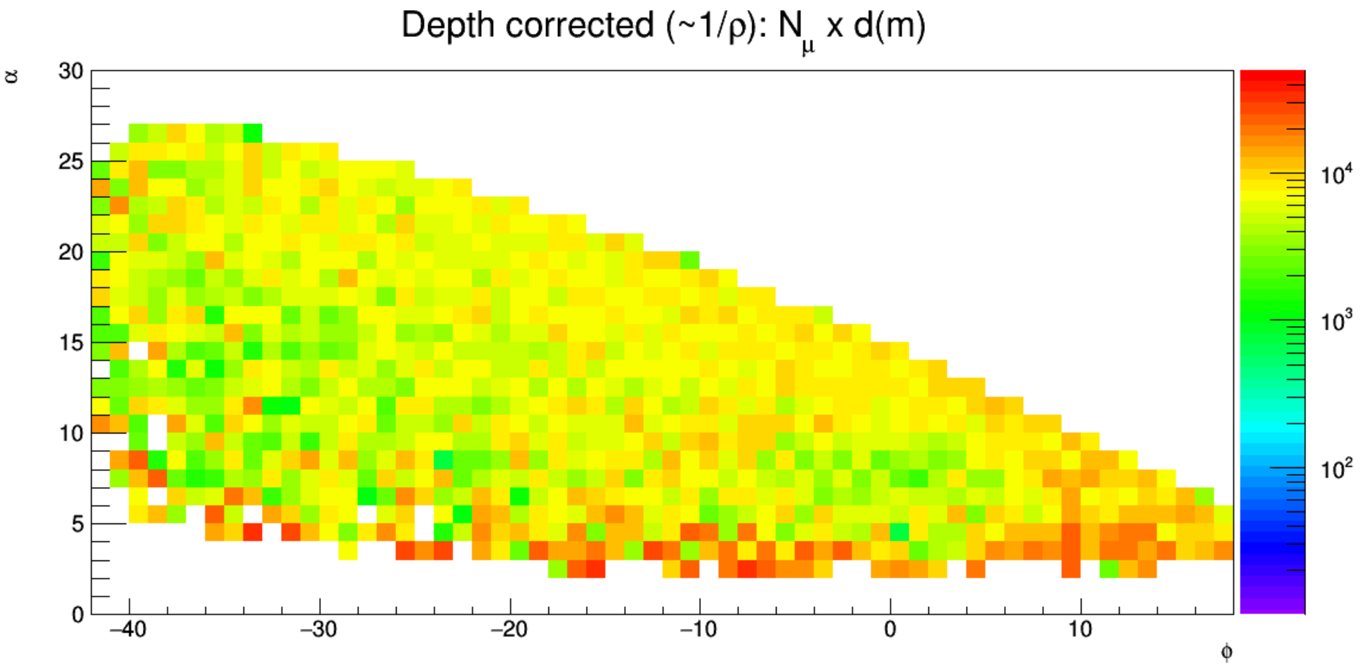


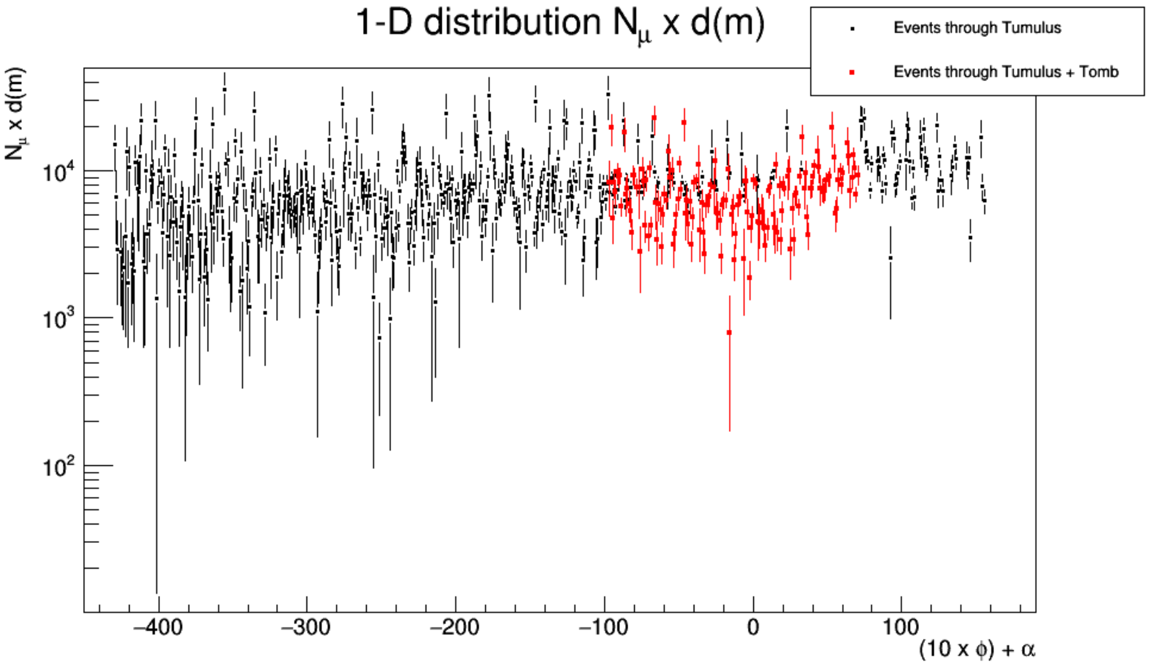


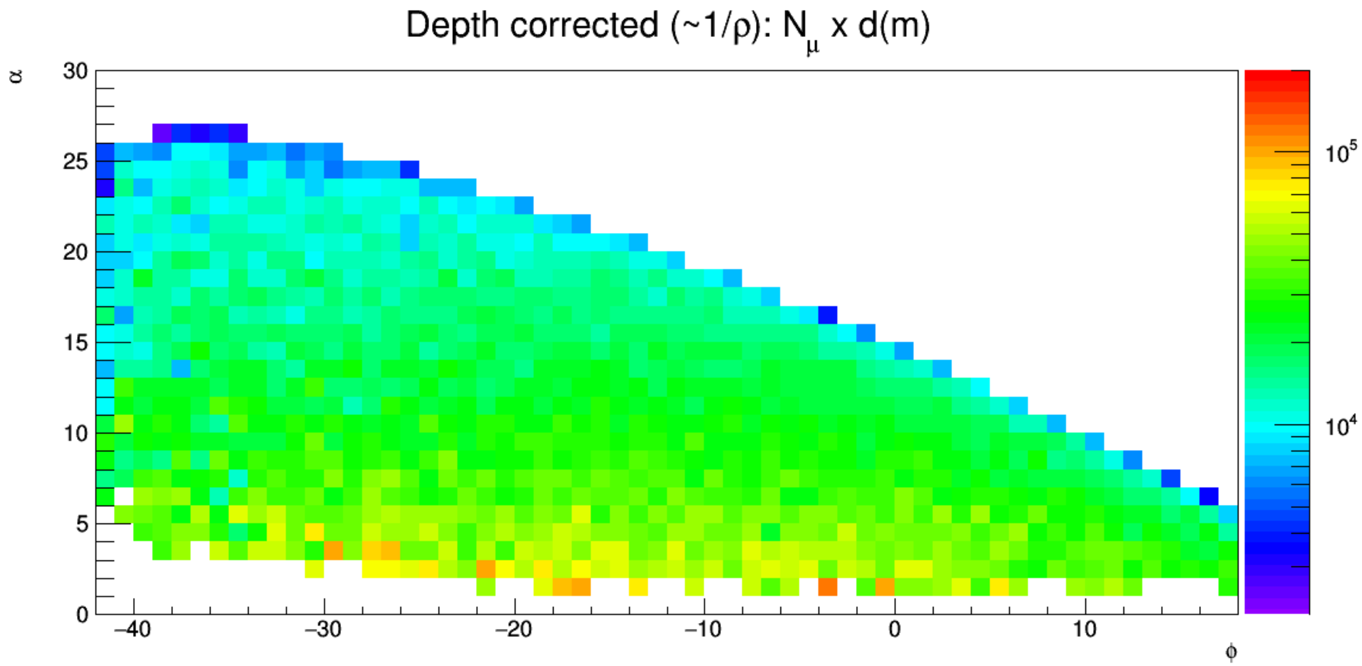
Reminder: only directions with more than 3% of relative efficiency are considered

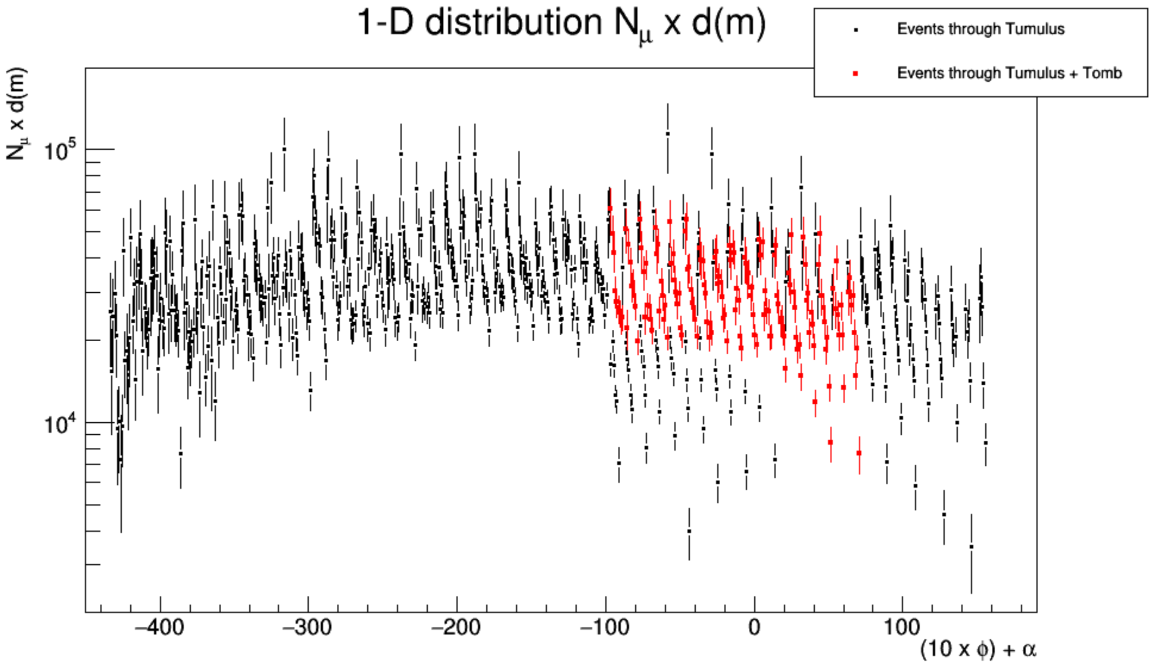

Angular distribution of Tomb events
α
φ


1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
(10 x φ) + α


Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
ϕ
10^4
10^3
10^2


1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^4
10^3
10^2
−400
−300
−200
−100
0
100
(10 x ϕ) + α


Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
ϕ
10^5
10^4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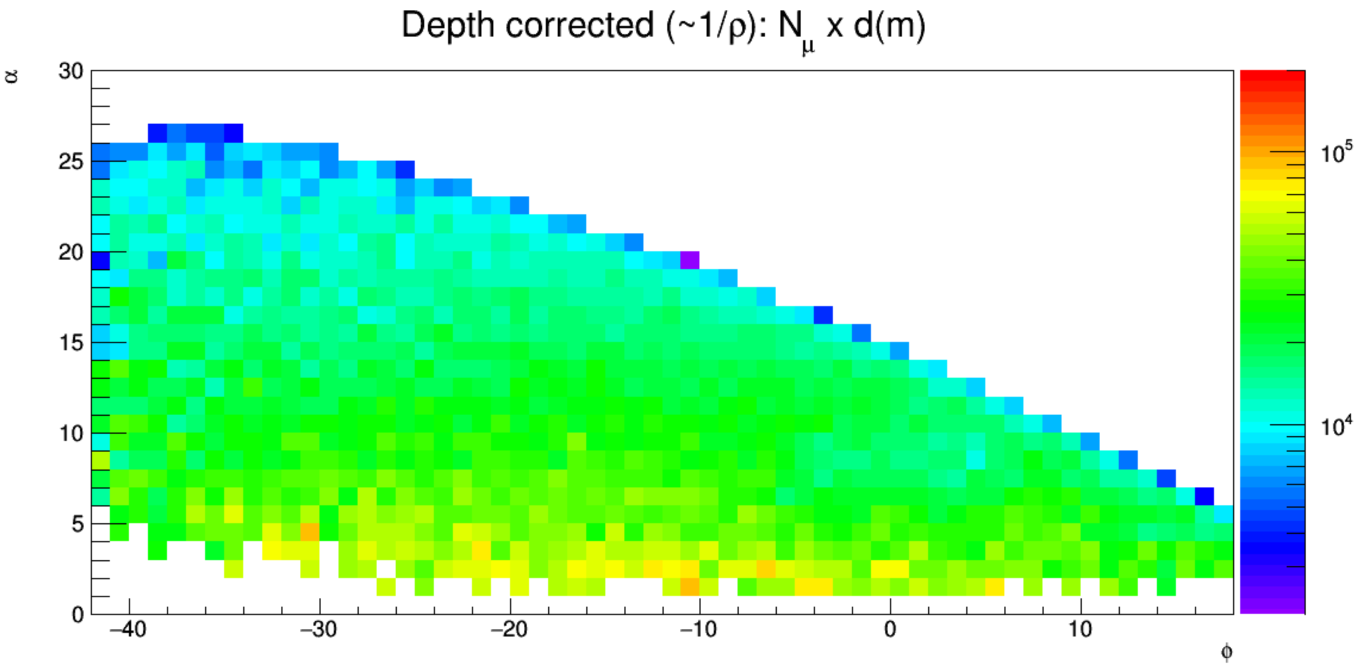
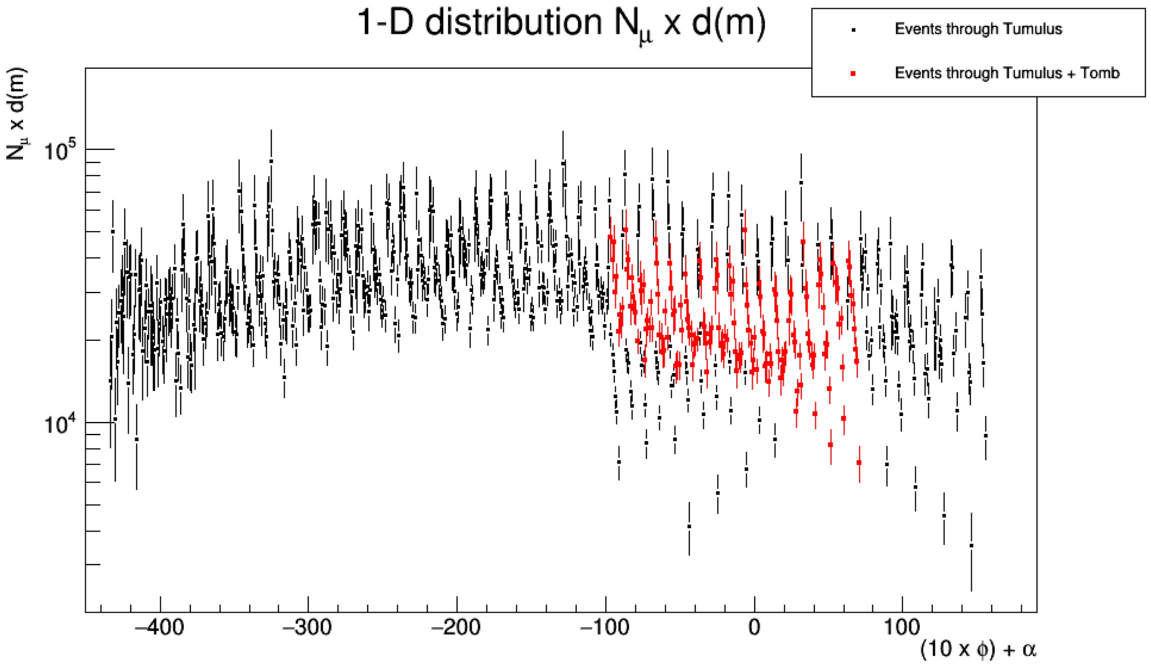
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
10^4
−400
−300
−200
−100
0
100
(10 x ϕ) + α


Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
ϕ
10^5
10^4


1-D distribution N_μ x d(m)
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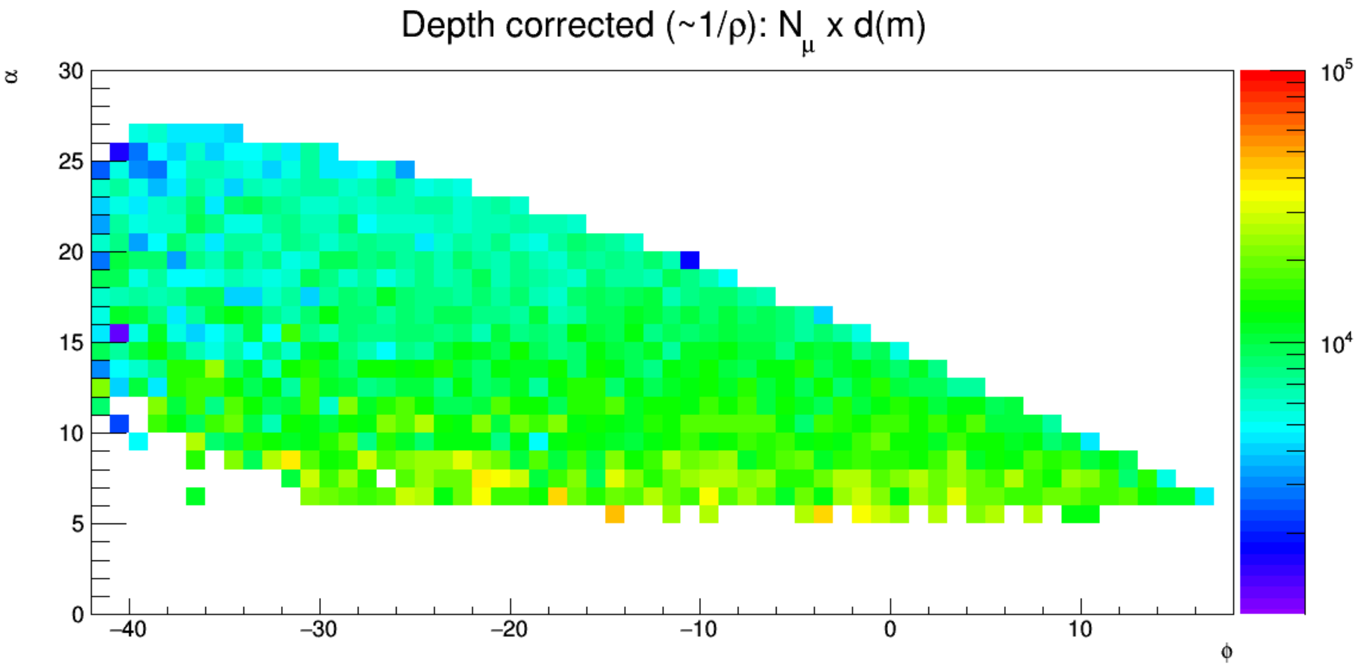
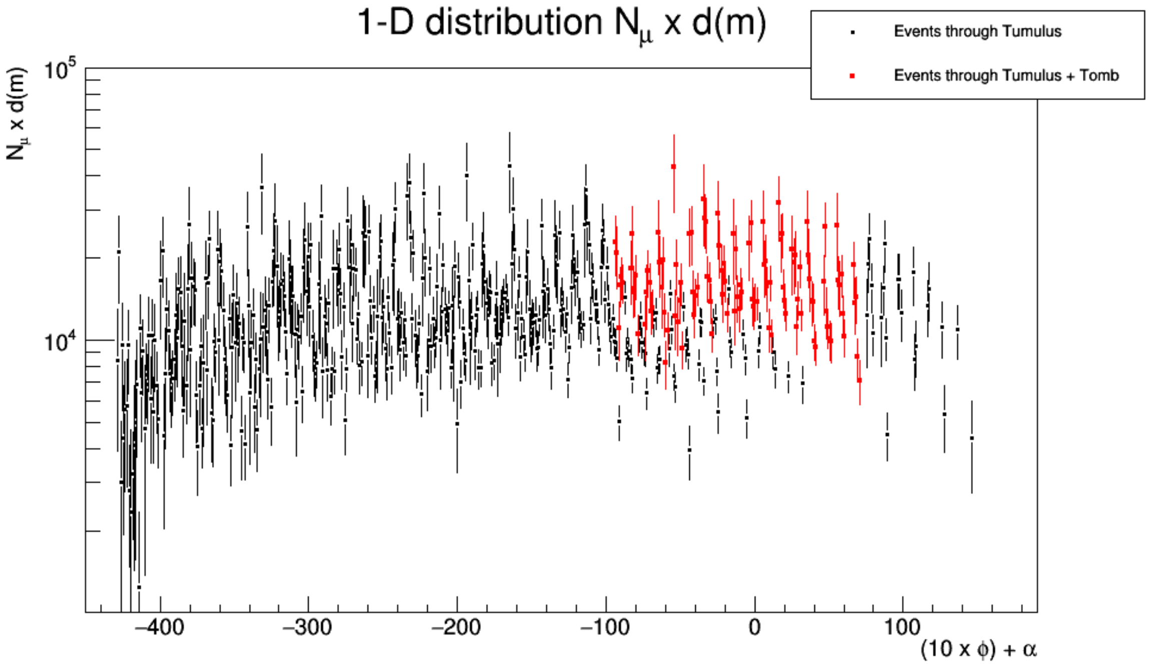
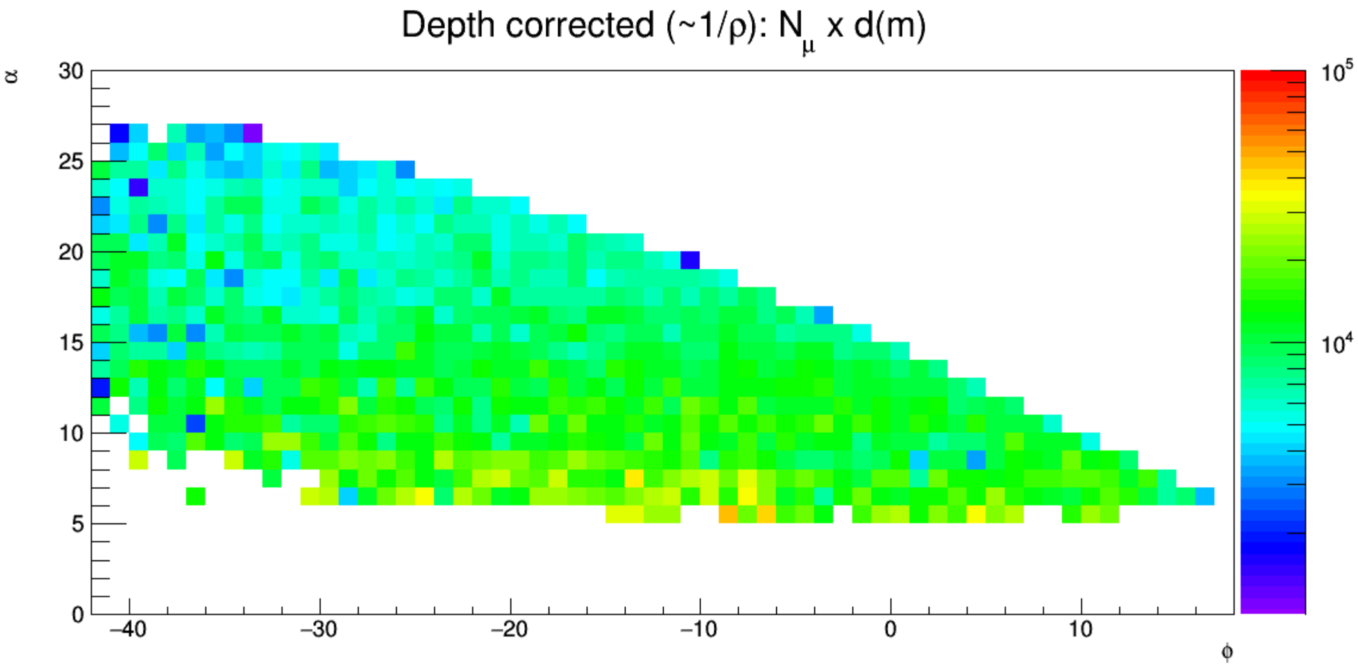
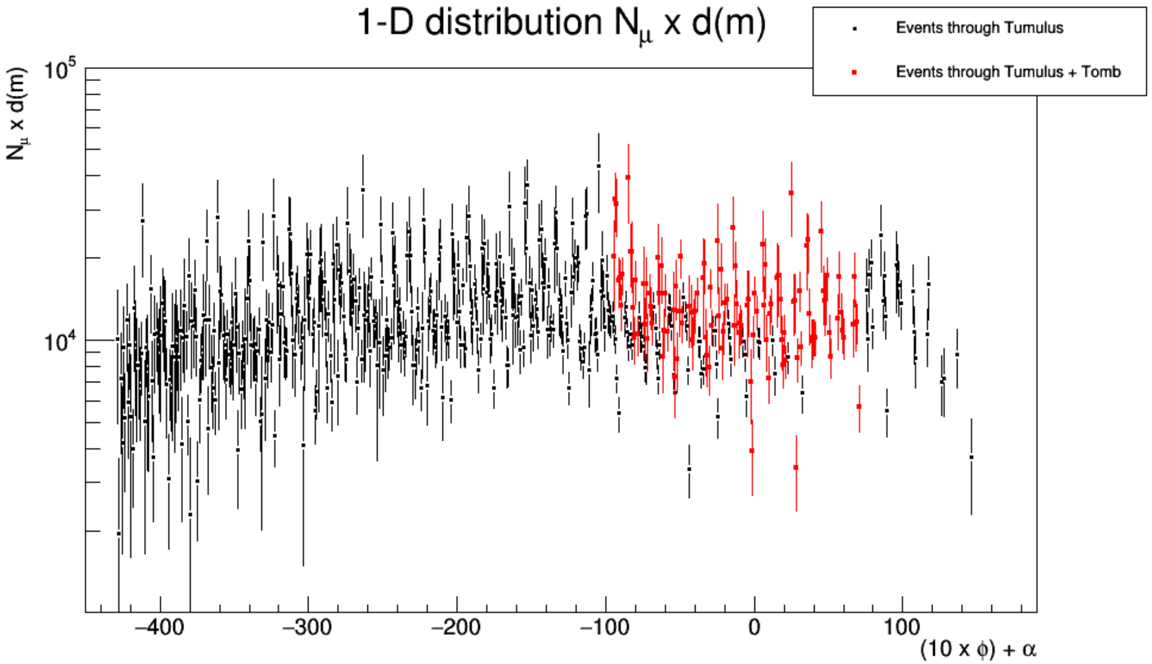
10^5
10^4
−400
−300
−200
−100
0
100
(10 x ϕ) + α


Depth corrected (~1/ρ): N_μ x d(m)
α
ϕ
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
10^5
10^4


1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
(10 x ϕ) + α
10^5
10^4
−400
−300
−200
−100
0
100


Depth corrected (~1/ρ): N_μ x d(m)
α
30
25
20
15
10
5
0
−40
−30
−20
−10
0
10
ϕ
10^5
10^4


1-D distribution N_μ x d(m)
Events through Tumulus
Events through Tumulus + Tomb
N_μ x d(m)
10^5
10^4
−400
−300
−200
−100
0
100
(10 x ϕ) + α

Geant4 Simulations of the Apollonia Tumulus

Muon Diffusion studies

Héctor Gomez

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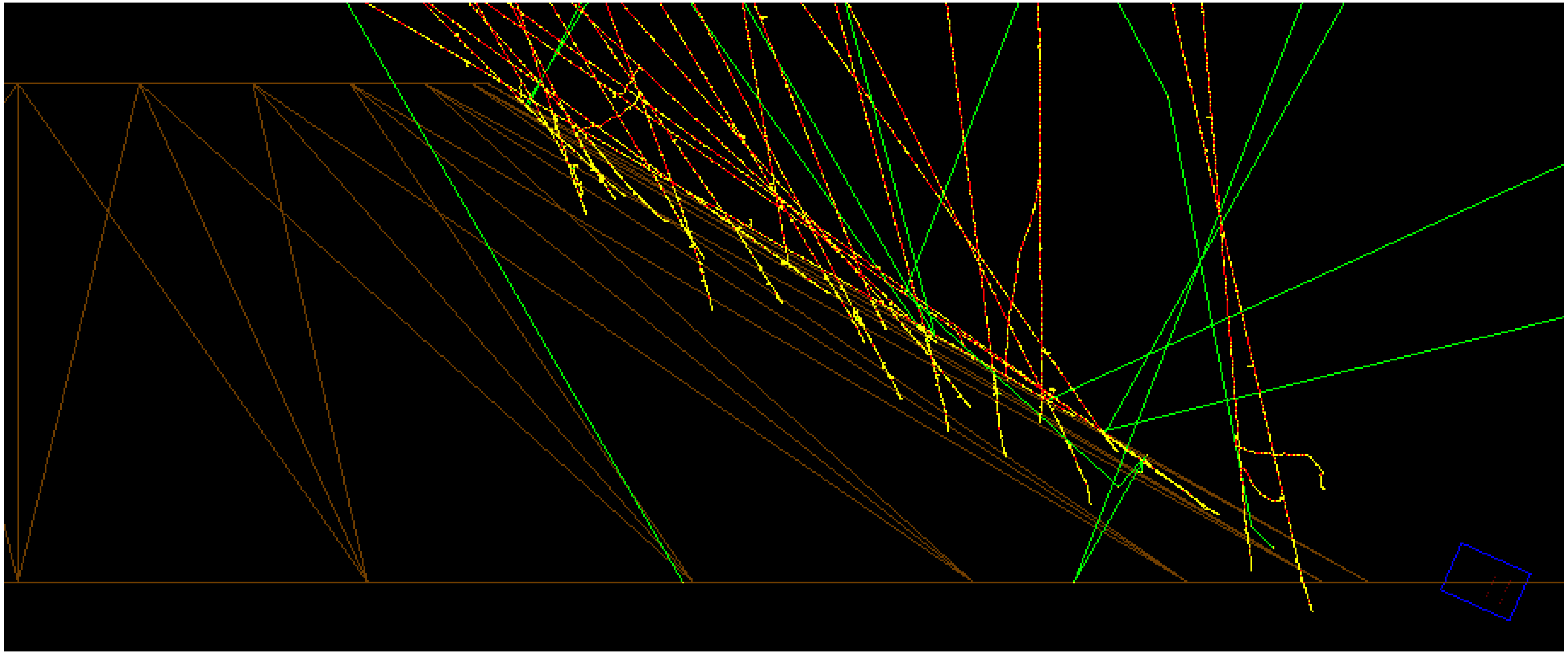
Simulated case



Generated muons:

Energy from 1 MeV to 10 GeV

Zenith angle from 0° to 60° (which corresponds to the tumulus slope)

Azimuth angle 0°

Muons throw to any point of the tumulus slope

Detector:

Same geometry that for the other studies

3 1m^2 planes, 50 gap ...

Pointing to ½ of the tumulus height

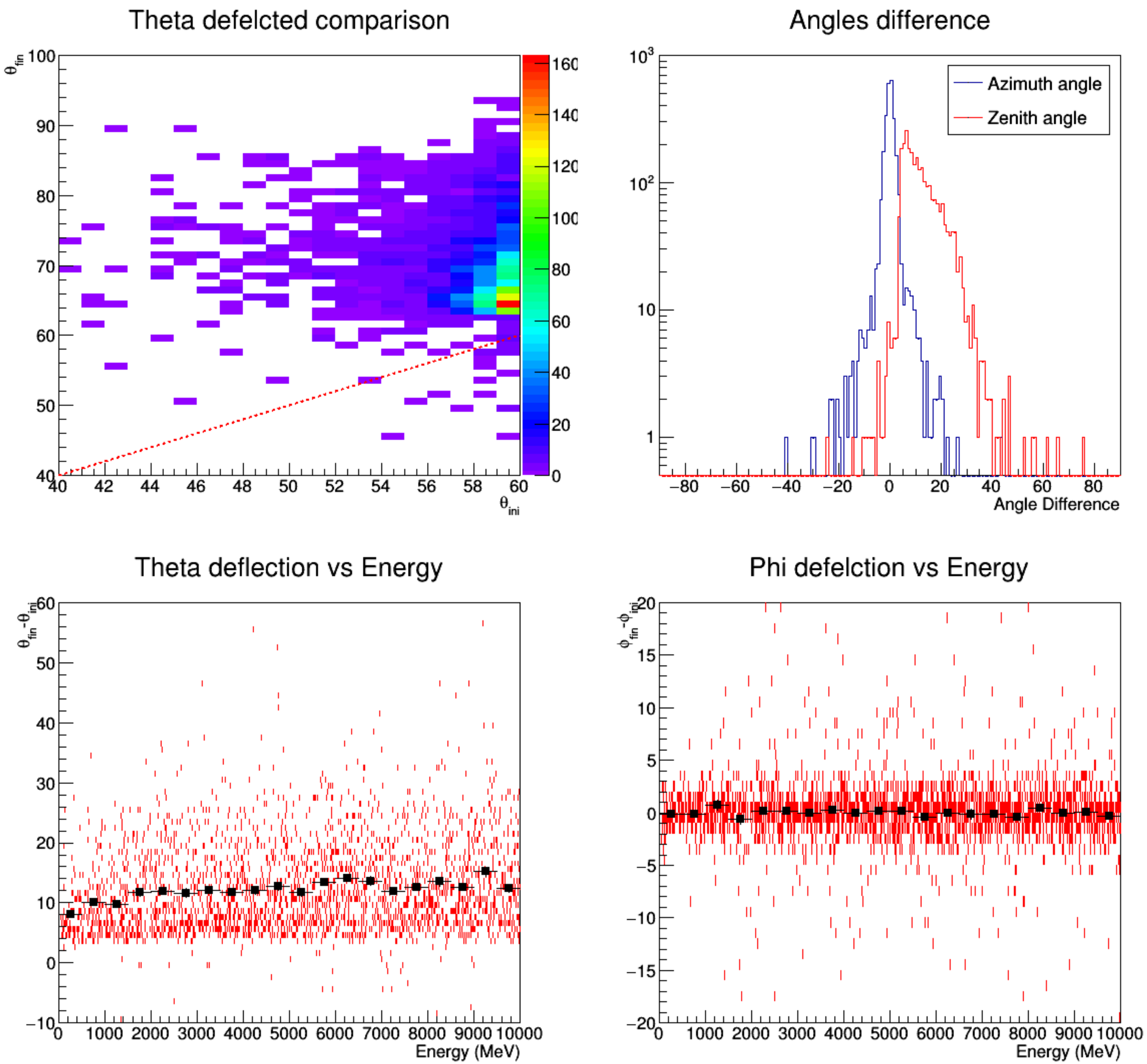
If there is no diffusion, None of the simulated muons should reach the detector

Results

- Muon selection is the same that for the sensitivity studies
- Parameters studied:
  - Initial and final zenith angles: θ_{ini} and θ_{fin}
  - Initial and final azimuth angles ϕ_{ini} (always 0 by definition) and ϕ_{fin}
  - Diffusion angle α, defined for the initial direction ***u*** and the final direction ***v*** as:

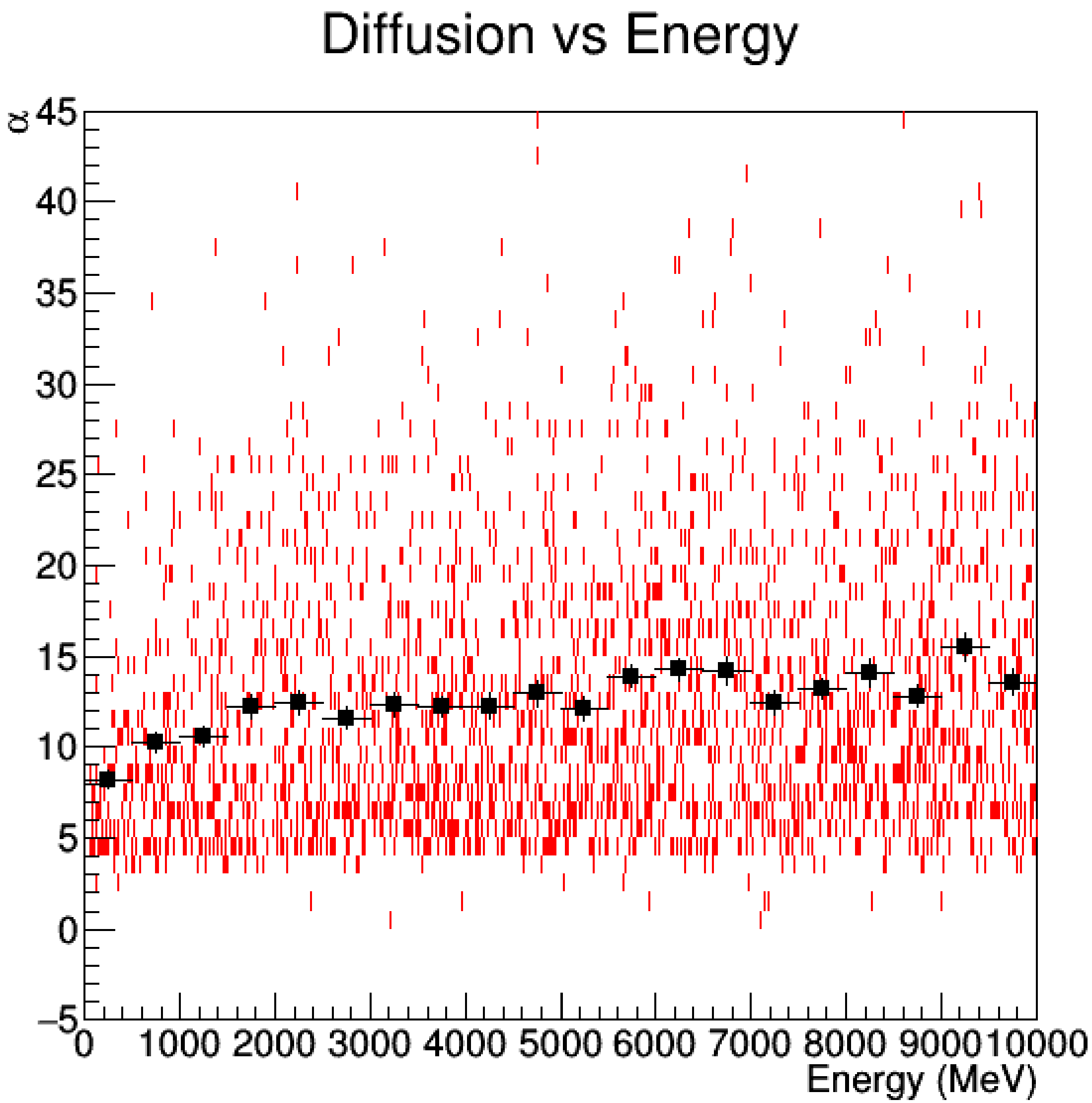
$$\cos(\alpha) = \frac{\vec{u}\,\vec{v}}{|\vec{u}||\vec{v}|}$$

Results (1/2)



- ***0.05 %*** of the simulated muons detected (passing muon selection cuts) because of diffusion
  - Negligible impact?
  - Need to normalize this simulation to the overall simulation
- Zenith angle (θ)
  - Only more horizontal muons diffuse
  - Enter more “parallel” to the tumulus surface
  - Slight dependence with muon energy
- Azimuth angle (ϕ)
  - Symmetric diffusion
  - Between [-5° - 5°] range
  - No energy dependent

Results (2/2)



- ***0.05 %*** of the simulated muons detected (passing muon selection cuts) because of diffusion
    - Negligible impact?
    - Need to normalize this simulation to the overall simulation
- Diffusion angle (α)
    - Equivalent conclusions that for the zenith angle
    - As expected since α is a combination of θ and ϕ