MUONS IN THE SNO+ EXPERIMENT

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- Water phase analysis
- Scintillator phase analysis
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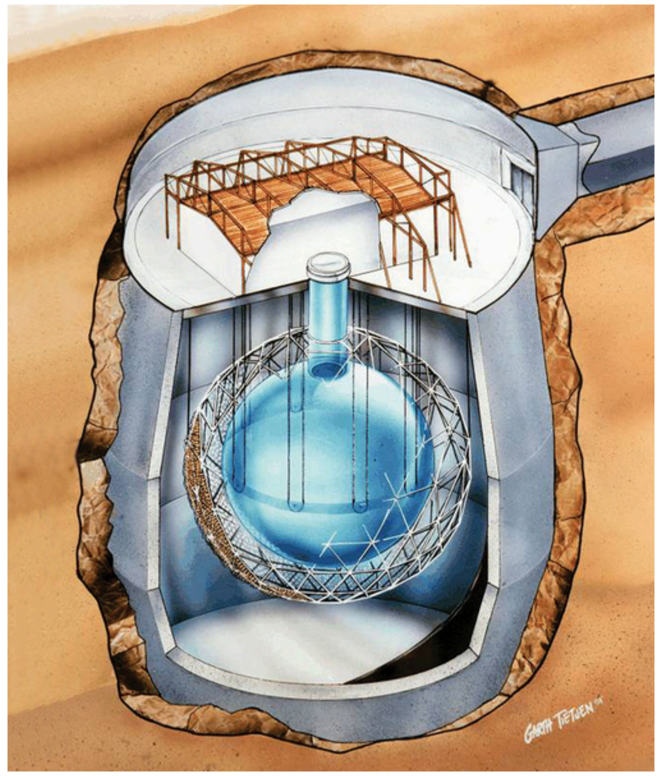
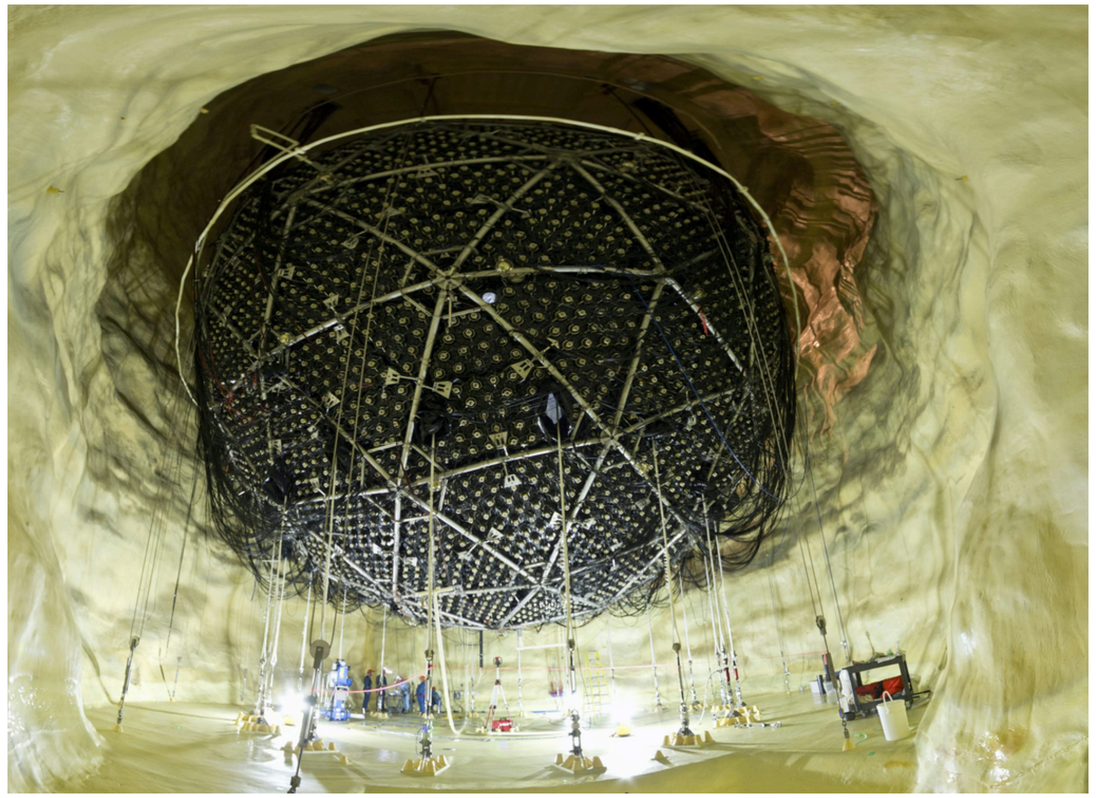
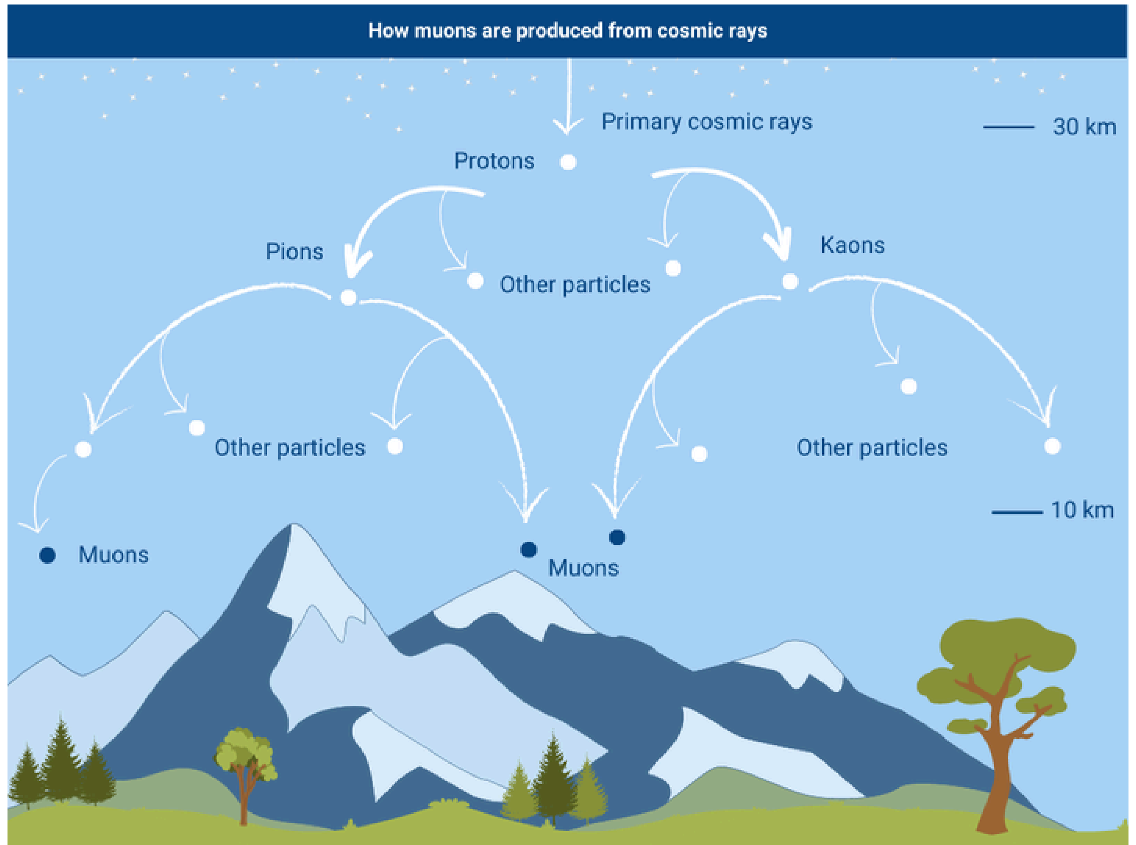
INTRODUCTION



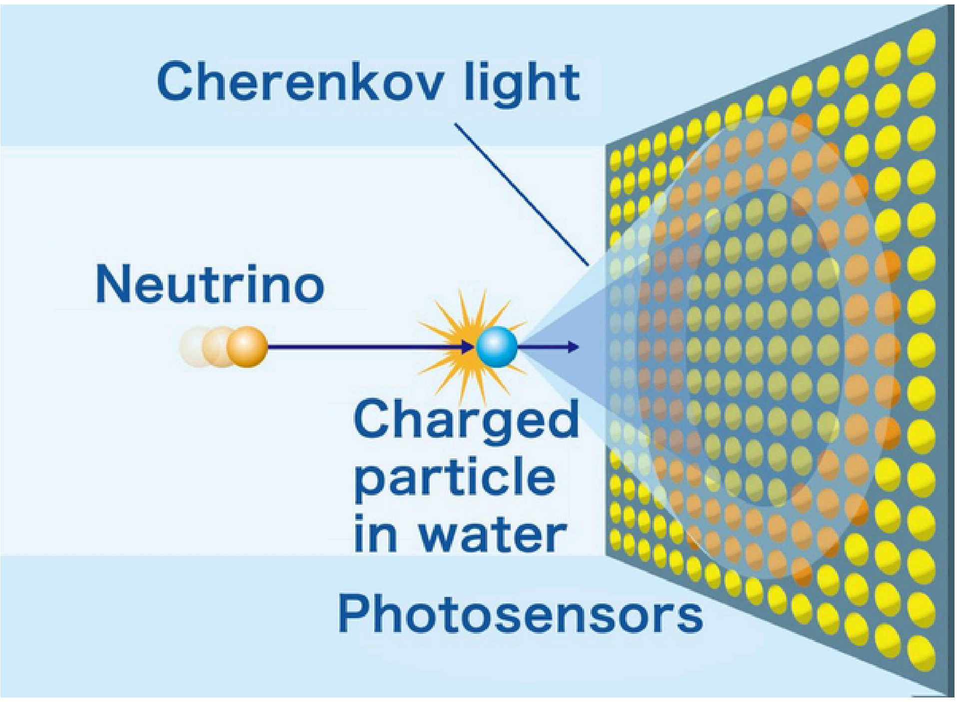


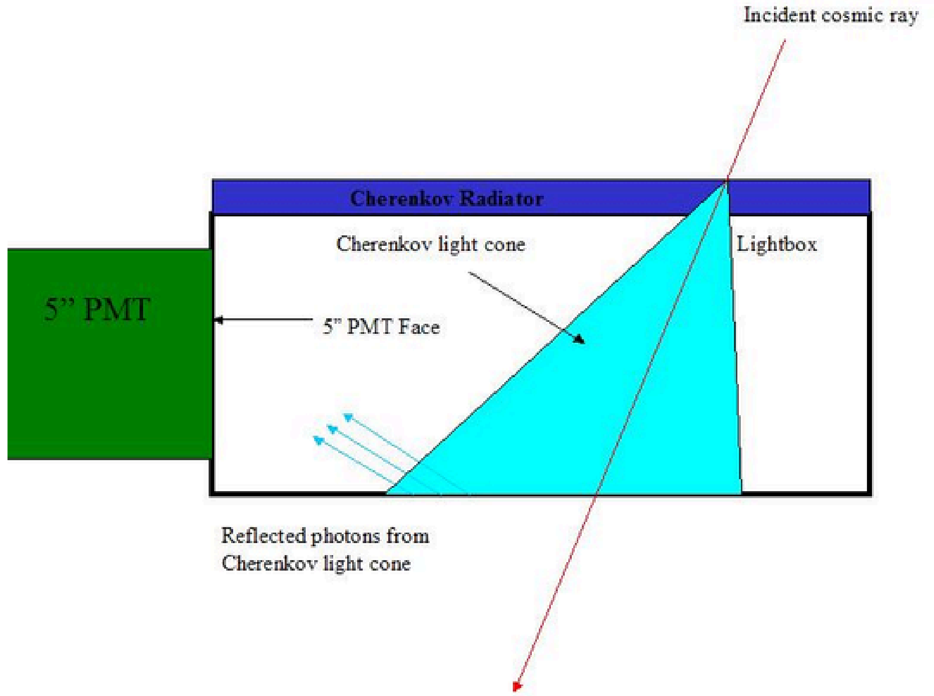
- SNO+ (Sudbury Neutrino Observatory) is an international particle detector situated at a depth of approximately 2 km (6000 m.w.e. - meters of water equivalent) inside the Creighton Mine in Sudbury, Canada.
- Cosmic-ray muons are secondary particles produced when primary cosmic rays interact with nuclei in the upper atmosphere, generating hadronic showers whose charged pions and kaons decay into muons and neutrinos.

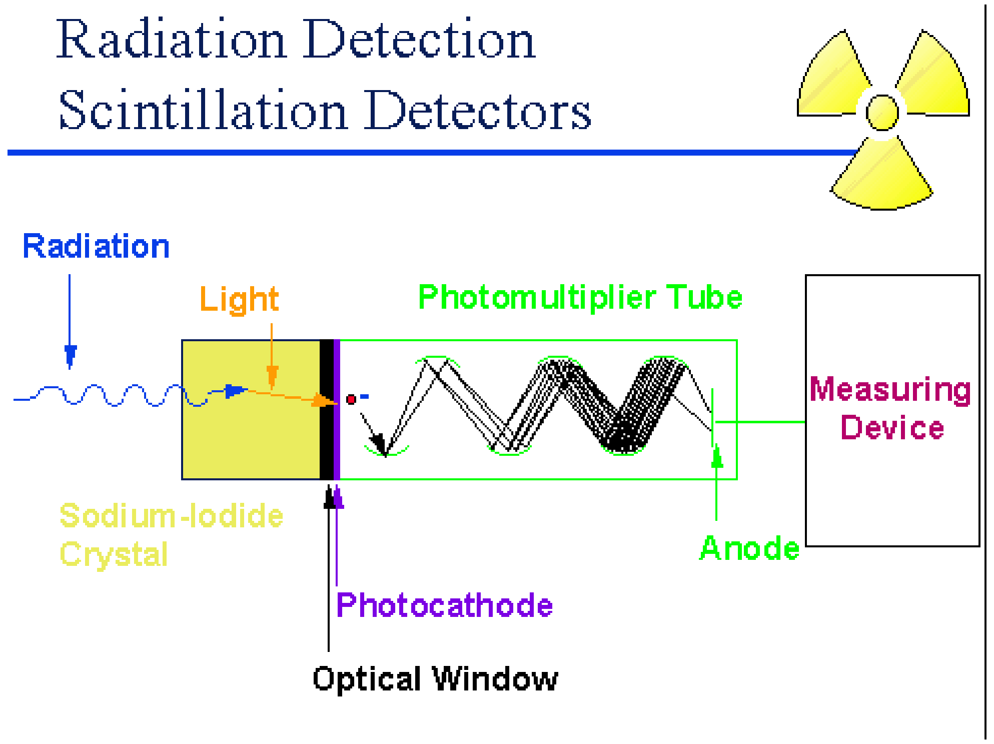


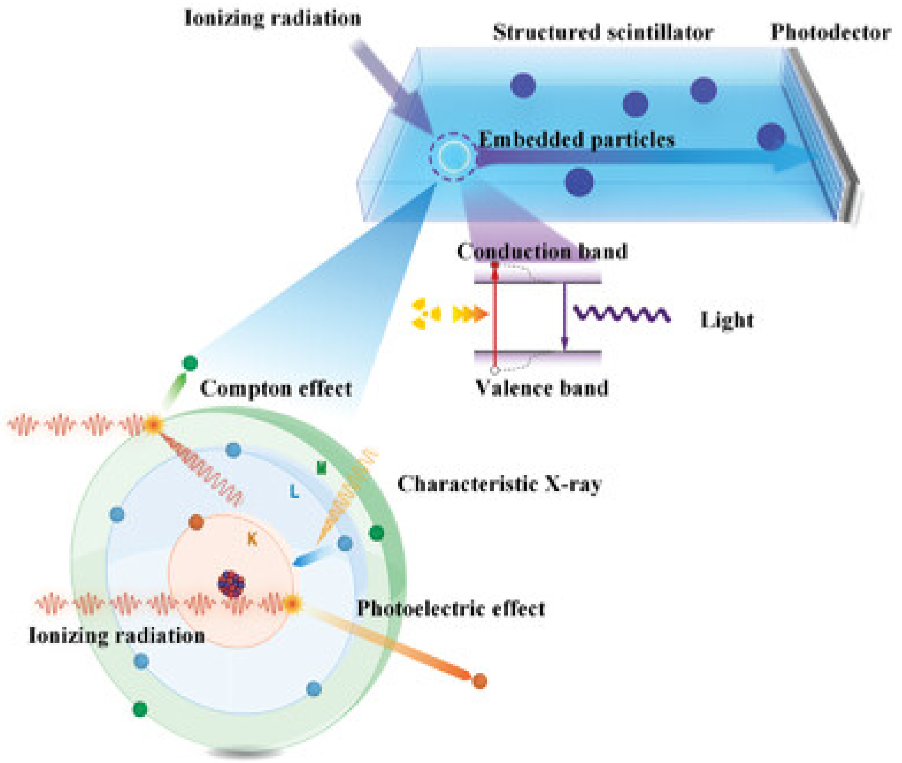
INTRODUCTION

- Cherenkov radiation is the characteristic blue light emitted when a charged particle, such as an electron, moves through a transparent medium (like water) faster than the speed of light in that medium.
- Scintillation radiation is produced when a charged particle deposits energy in a scintillating medium, exciting the larger, more complex molecules that compose it.









DATA DESCRIPTION

Important to mention that the scintillator medium still has Cherenkov radiation, and we are trying to differentiate it from scintillator radiation to help detect the directions of particles better

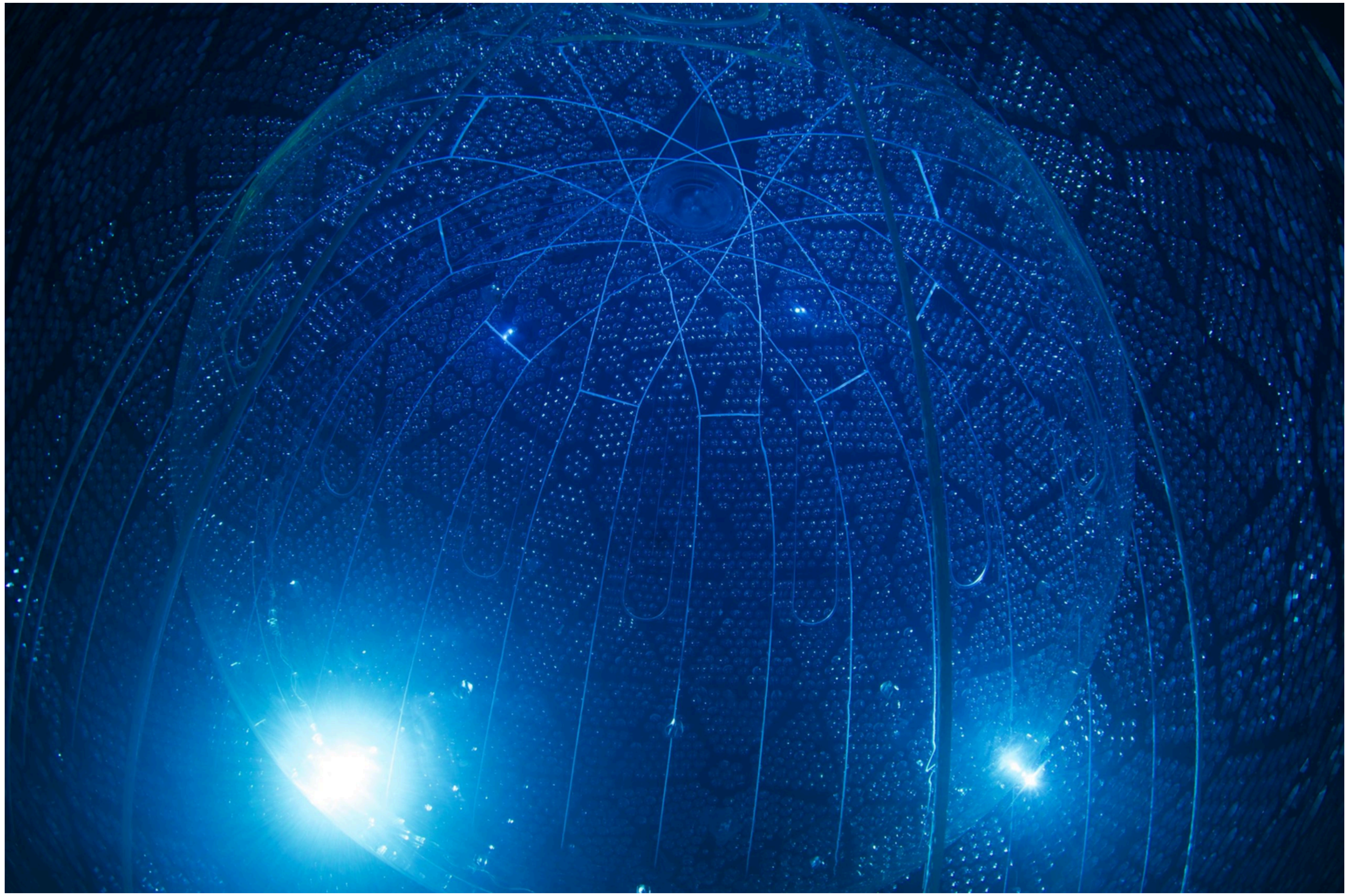
Water phase: 13690 muons over 321.38 days

from ultrapure water to a liquid scintillator between **October 2018** and **March 2021**

Monte Carlo scintillator Simulation: 12000

Scintillator phase: 9961

WATER PHASE ANALYSIS



DETERMINING THE DEPENDENCY OF MUON INTENSITY ON ANGLE AND DEPTH

responsible for pions

$$I(h) = (I_1 e^{-h/\lambda_1} + I_2 e^{-h/\lambda_2}) sec\theta$$

responsible for kaons

$I_1 = (8.60 \pm 0.53) \times 10^6\ cm^{-2}\ s^{-1}$

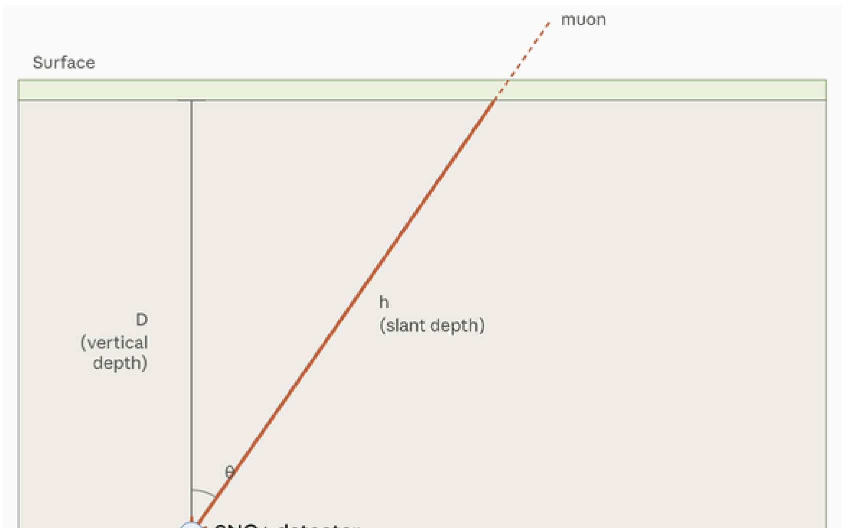
$I_2 = (0.44 \pm 0.06) \times 10^6\ cm^{-2}\ s^{-1}$,

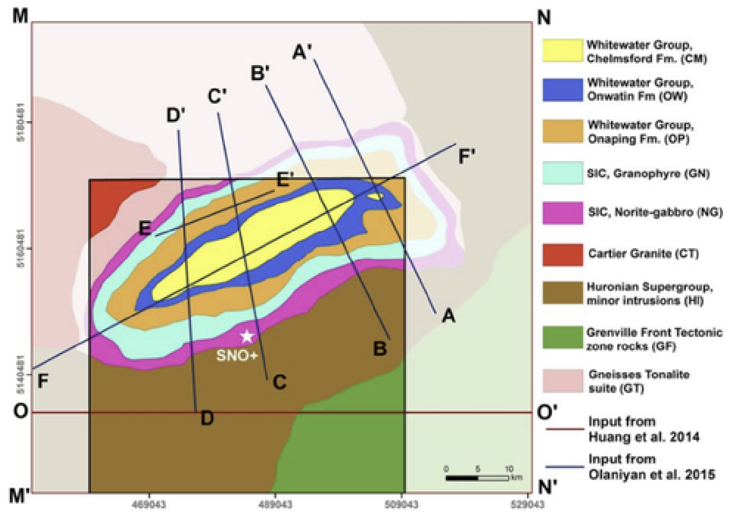
$\lambda_1 = 0.45 \pm 0.01$ km.w.e.

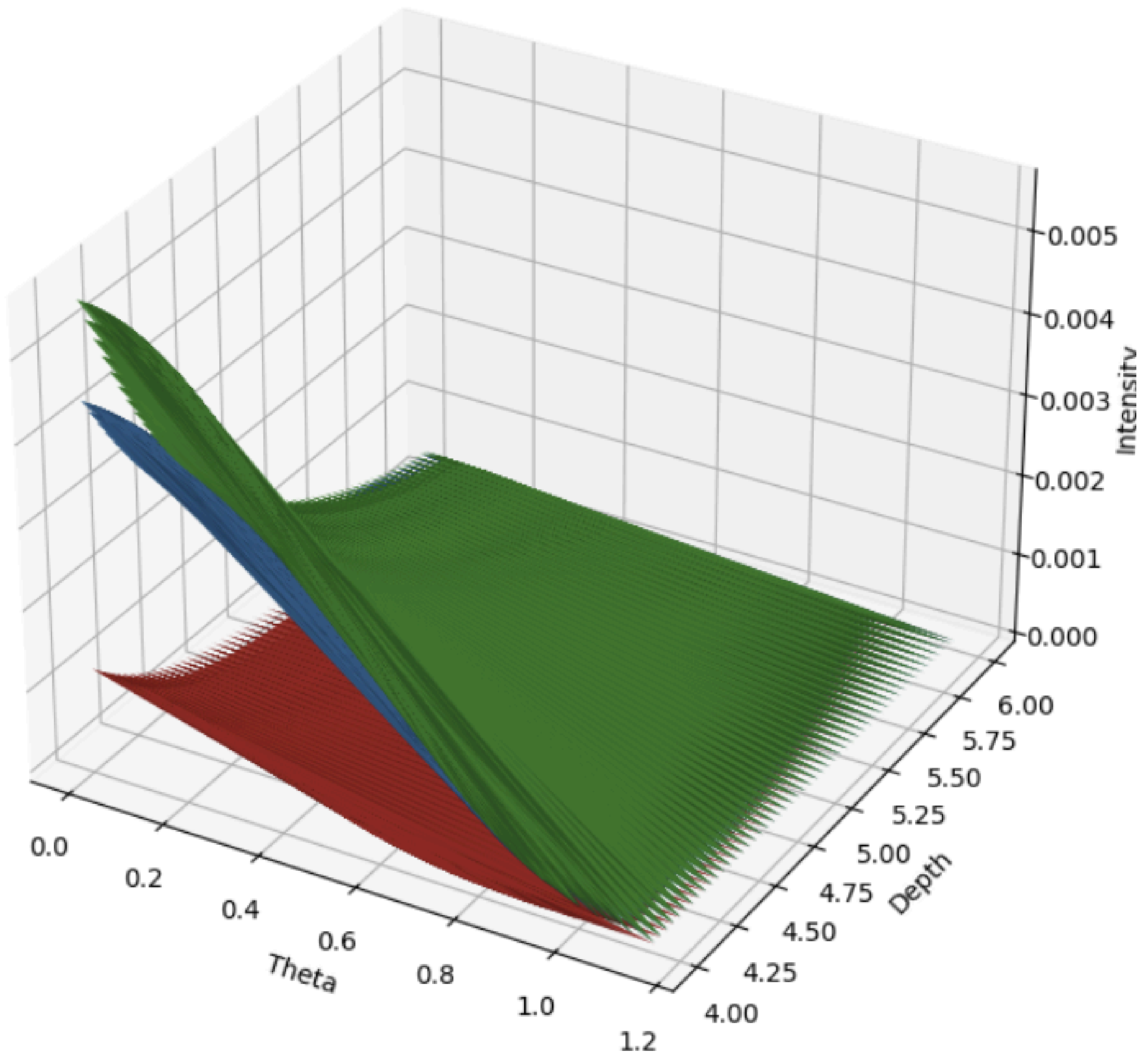
$\lambda_2 = 0.87 \pm 0.02$ km.w.e.

h is the slant depth — the amount of rock a cosmic muon passes through to reach the detector. Slant height varies with the subtraction of galleries and the pit (overburden).

Density of Norite-gabbro region rock: $2.83 \pm 0.10\ g/cm^3$







We can conclude that the second component almost does not contribute.

It is consistent with what we know about pions and kaons, as pions are much more abundant due to the fact that they require less energy to be created.

DETERMINING THE DEPENDENCY OF MUON INTENSITY ON ANGLE AND DEPTH

$$I(h) = (I_1 e^{-h/\lambda_1} + I_2 e^{-h/\lambda_2}) sec\theta$$

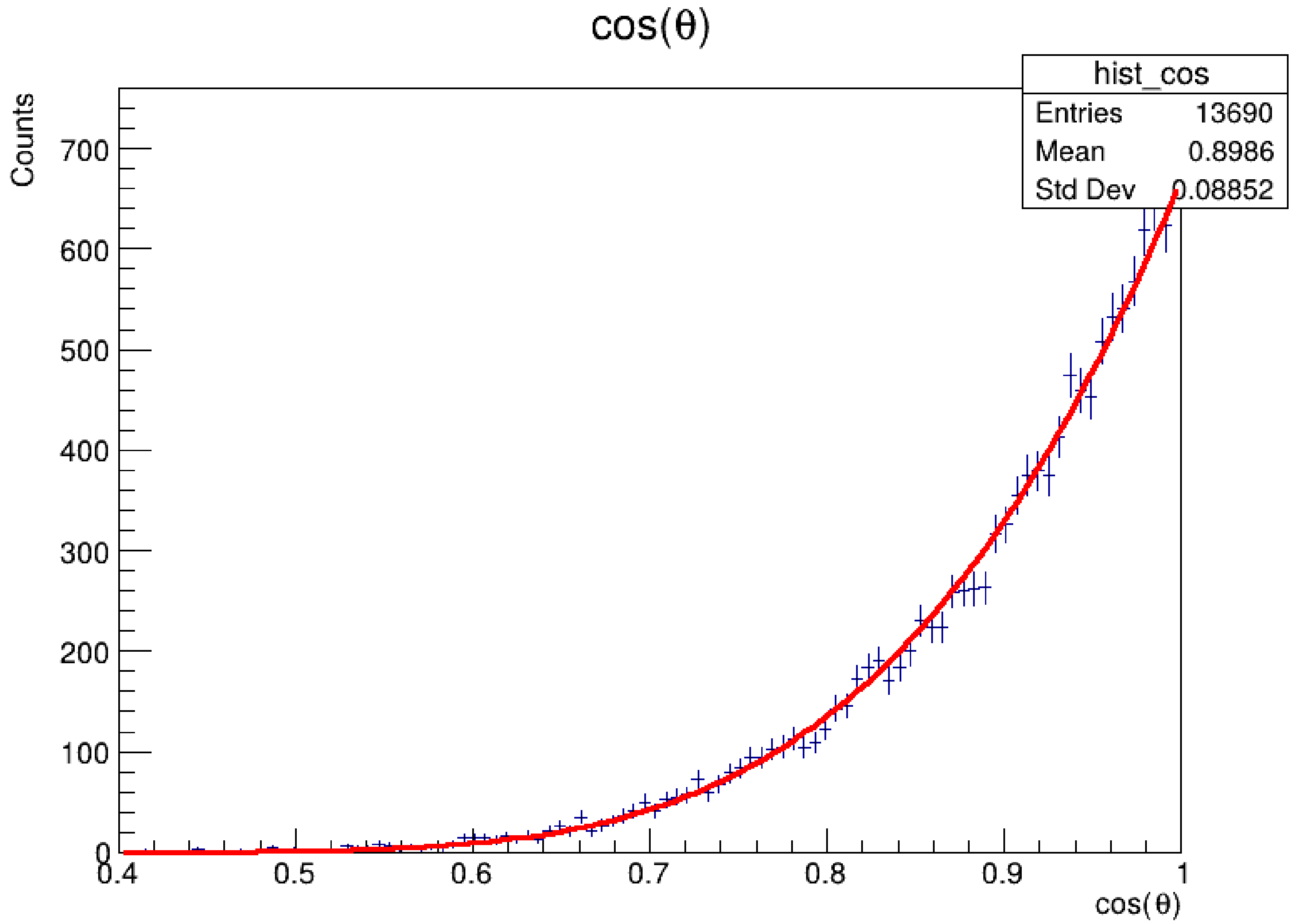
Slant depth: 6.27 ± 0.067 (stat) ± 0.046 (syst) k.w.e.

→resulting density 3.14 ± 0.04 g/cm^3

10% higher than expected

Cosine (θ), with A (normalisation constant) and X(slant depth) as fitting parameters →

Parameter changed	X	A
$I_1 = 8.07$	6.2758 ± 0.0659	2.0199×10^6
$I_1 = 9.13$	6.2699 ± 0.0662	2.0014×10^6
$I_2 = 0.36$	6.2619 ± 0.0667	2.4159×10^6
$I_2 = 0.50$	6.2787 ± 0.0658	1.7855×10^6
$\lambda_1 = 0.44$	6.2854 ± 0.0655	2.0511×10^6
$\lambda_1 = 0.46$	6.2564 ± 0.0668	1.9584×10^6
$\lambda_2 = 0.85$	6.1115 ± 0.0653	1.9551×10^6
$\lambda_2 = 0.89$	6.4299 ± 0.0669	2.0512×10^6

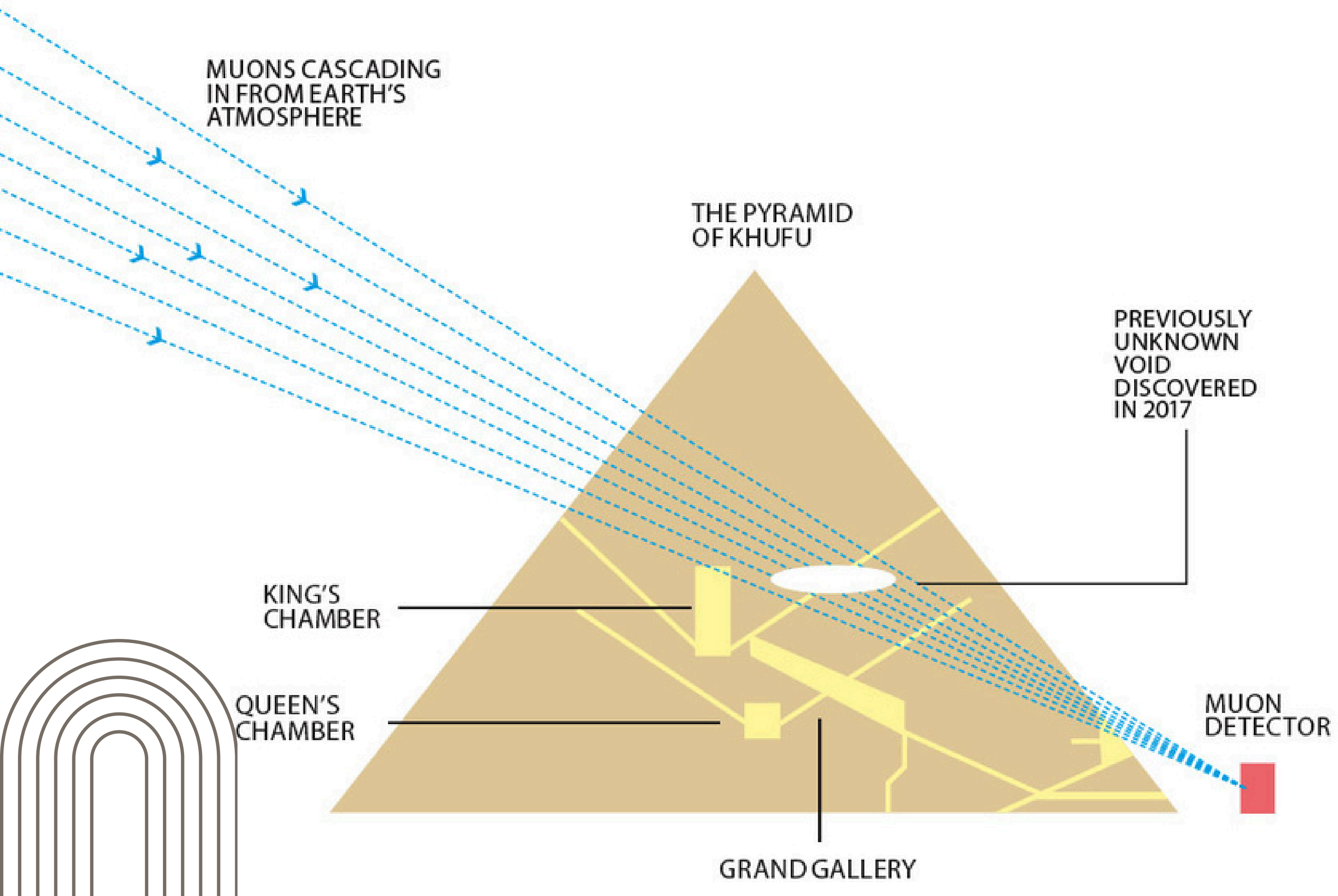


Optimal number of bins: 100

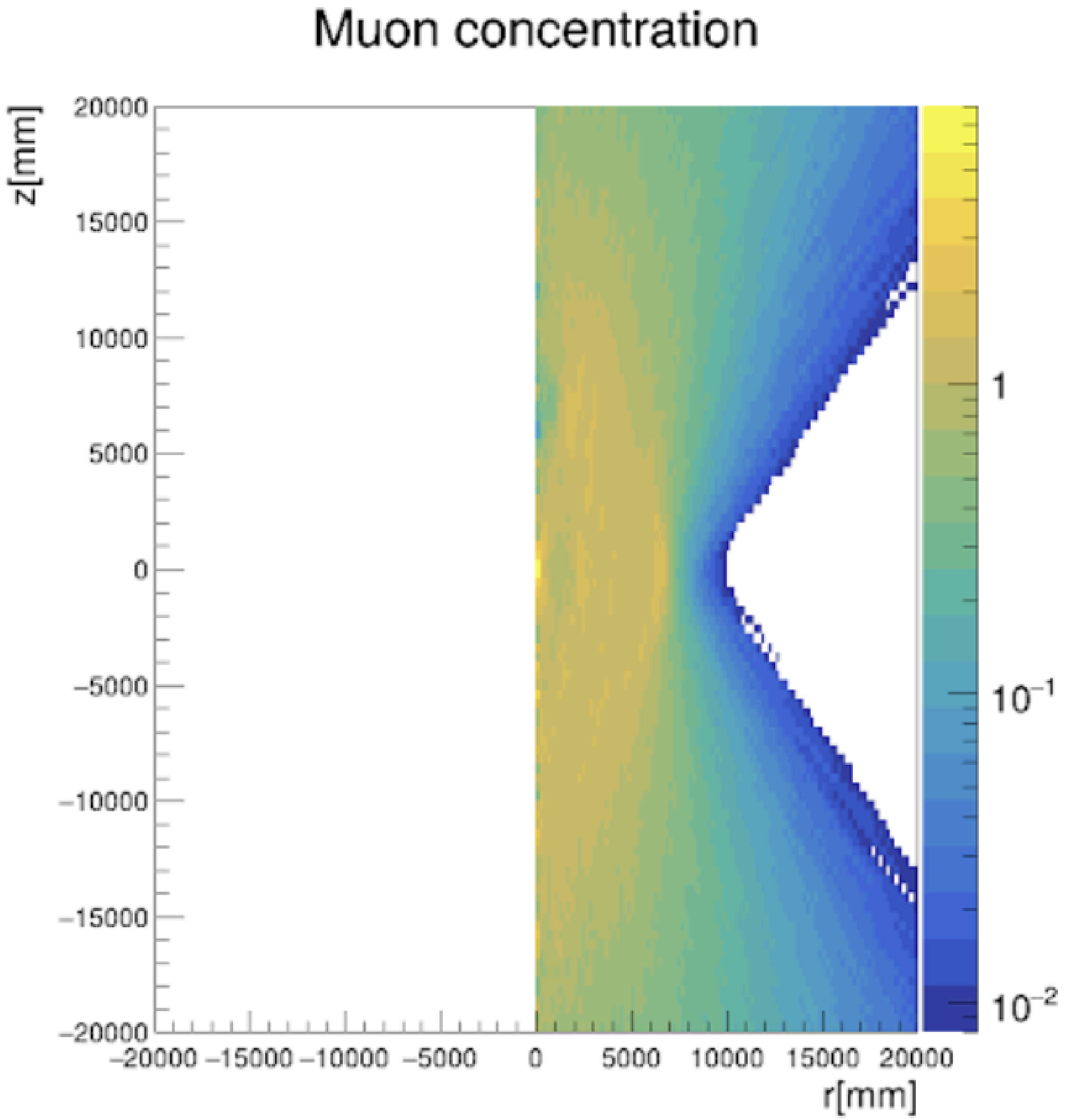
χ^2/ndf : 0.94

MUOGRAPHY OF THE CREIGHTON MINE GALLERIES AND DETERMINING THE DENSITY OF THE SURROUNDING ROCK

Muography is an image technique that allows the obtaining of two- and three-dimensional images of massive structures using muons in cosmic rays.

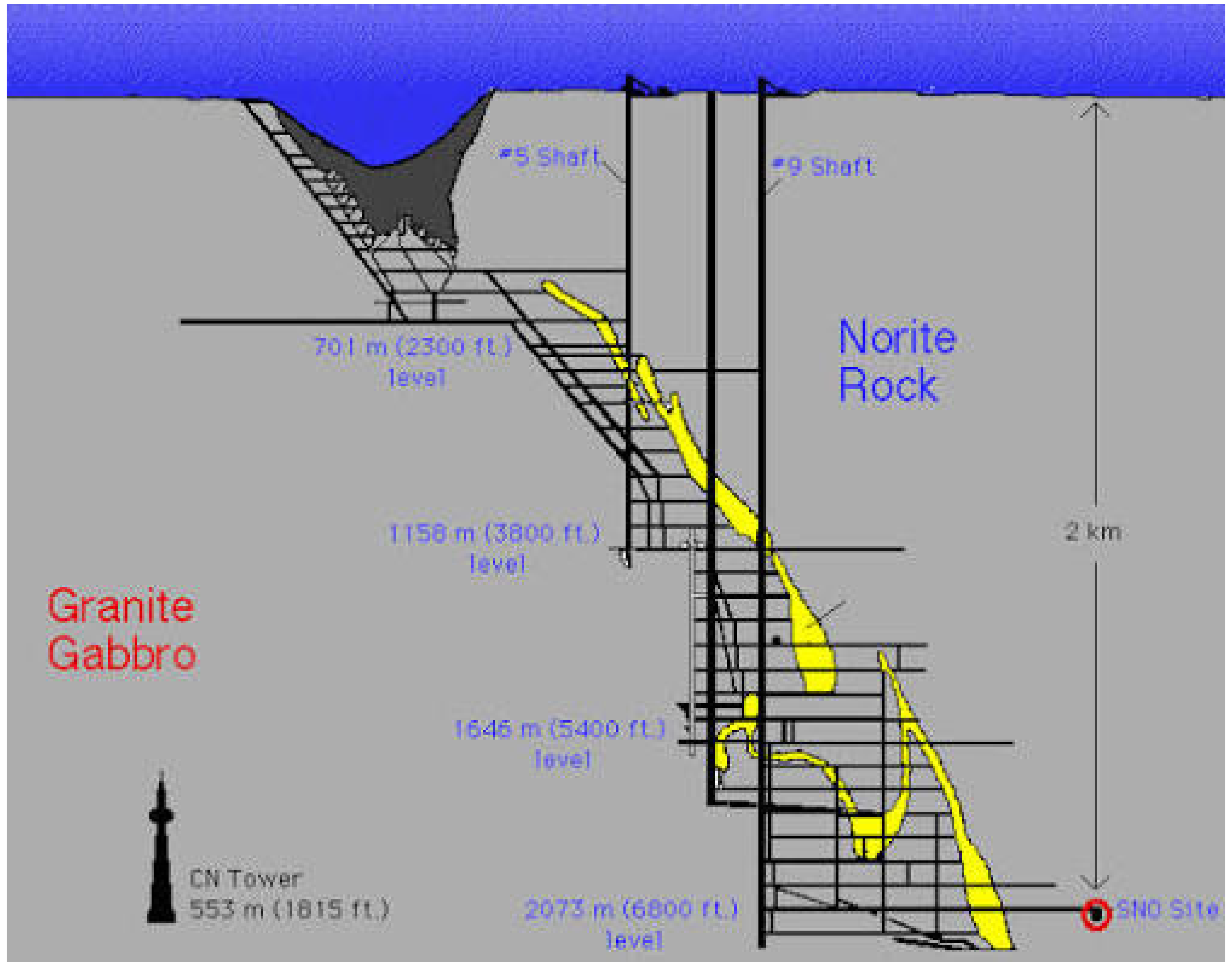


The analysis revealed the spherical walls of the detector and a void at the top.
This void proved to be a lack of PMTs, which caused less sensitivity in that region.

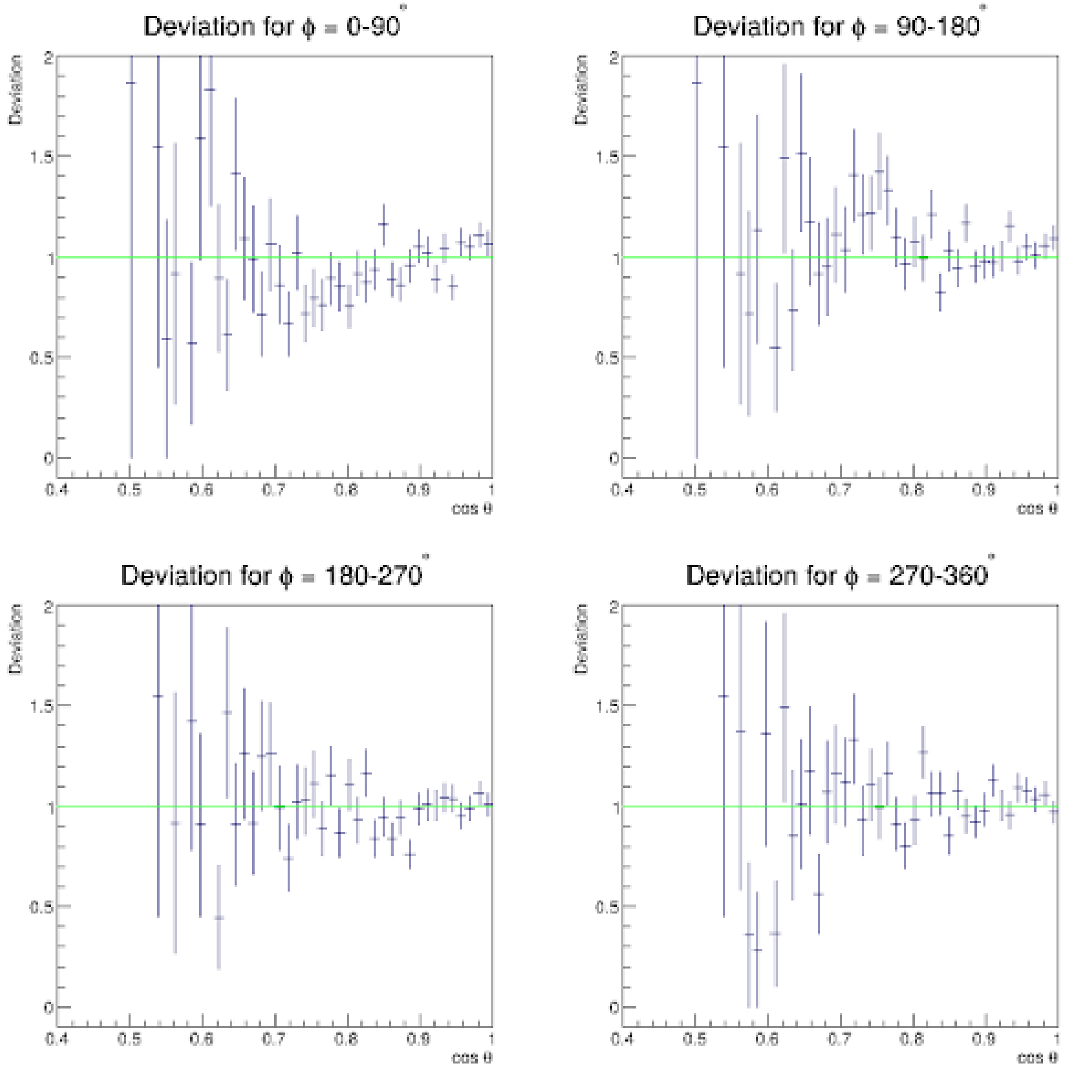


MUOGRAPHY OF THE CREIGHTON MINE GALLERIES AND DETERMINING THE DENSITY OF THE SURROUNDING ROCK

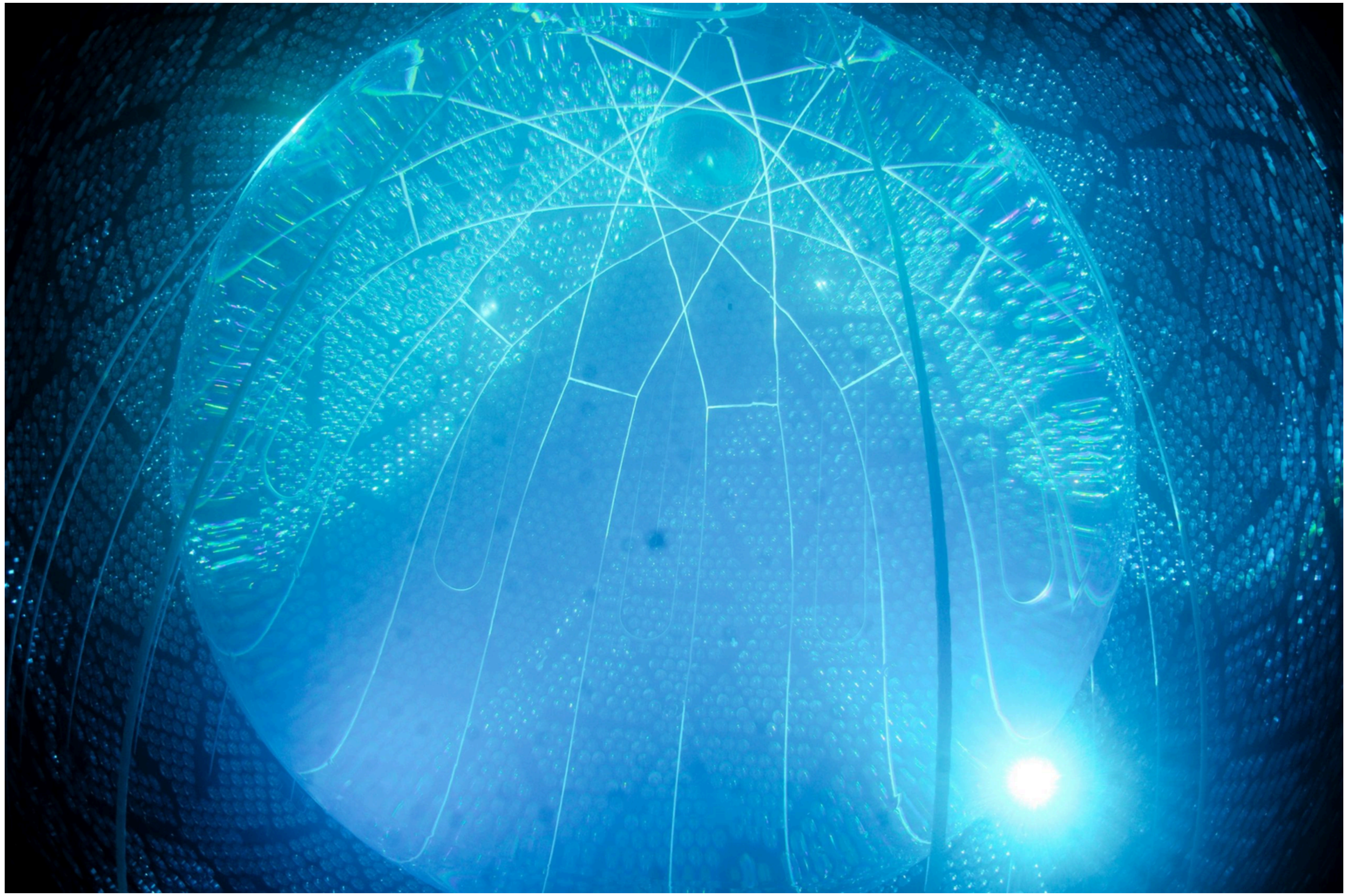
Unfortunately, imaging the Creighton Mine galleries proved impossibl, with the current dataset, as the required angle was ~85º, yet the data is cutoff at 60º.



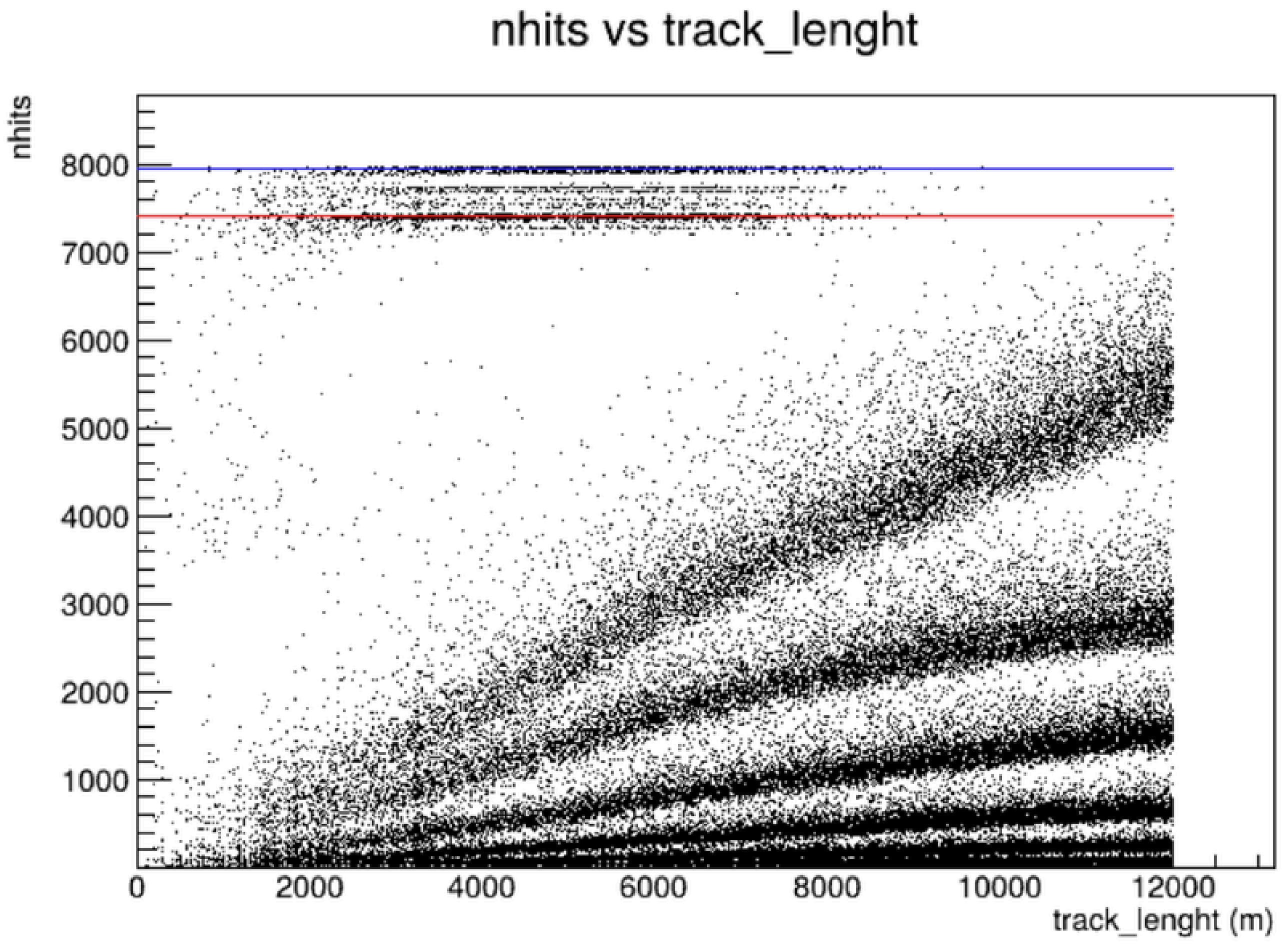
The next step was to look at the muon flux to determine the rock density. Any deviations 2 sigma from the line would indicate anomalies. The analysis proved that the rock density is uniform.



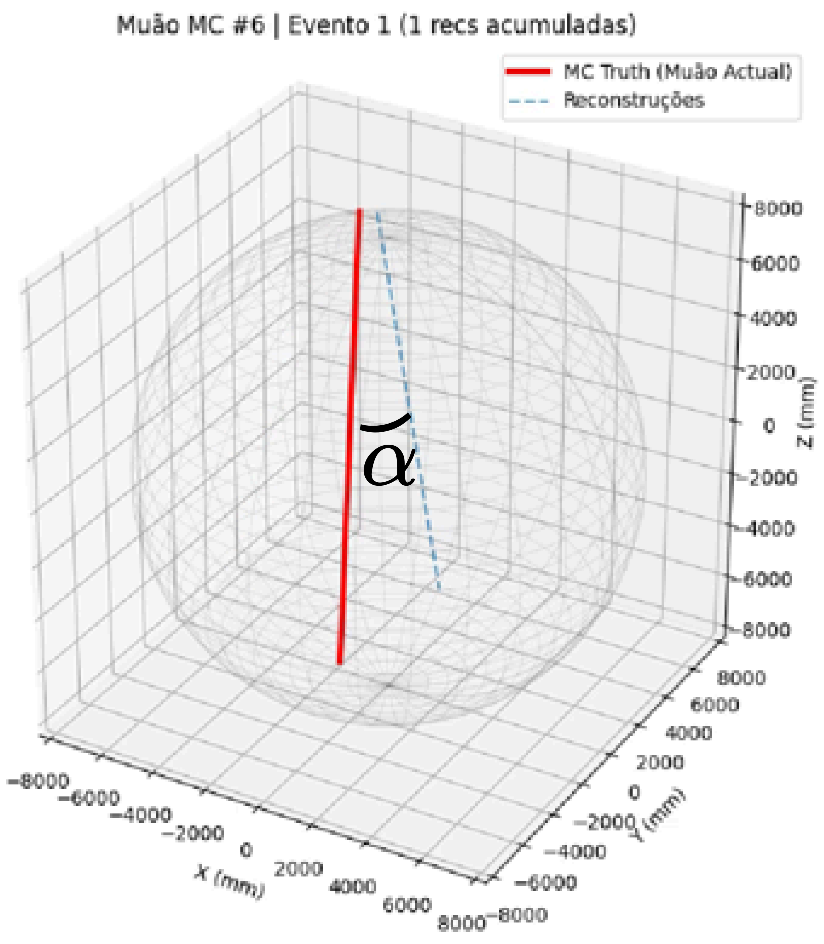
SCINTILLATOR PHASE ANALYSIS



SIMULATION



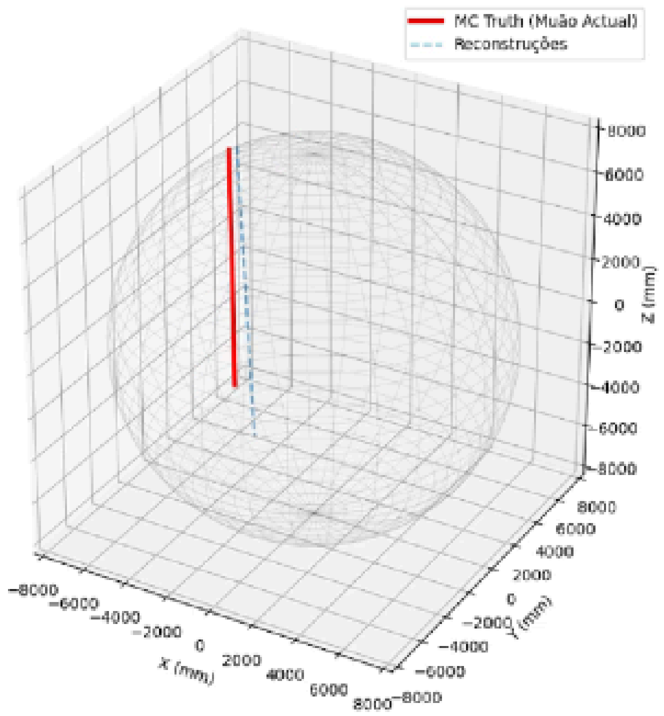
- Event index >0 means that the same muon gives origin to more than one event that we call "echos" → the most information is at event 0→ cut at event index =0

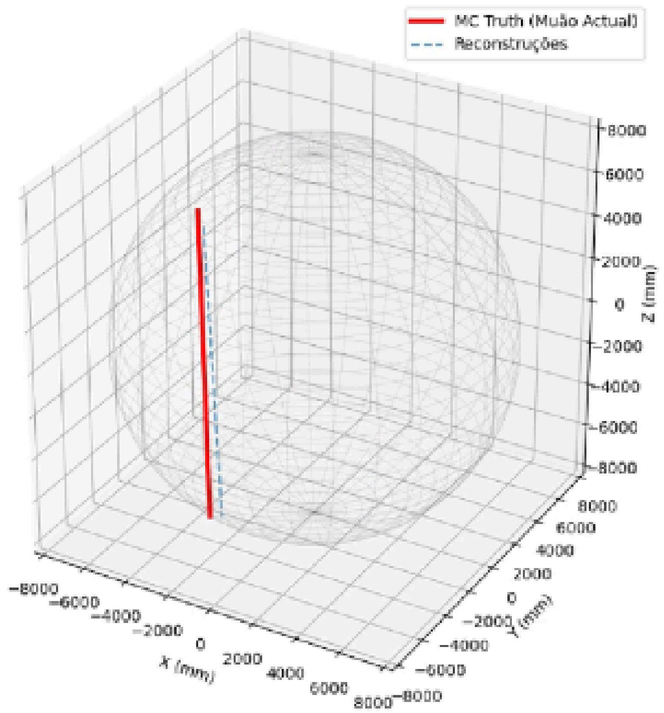


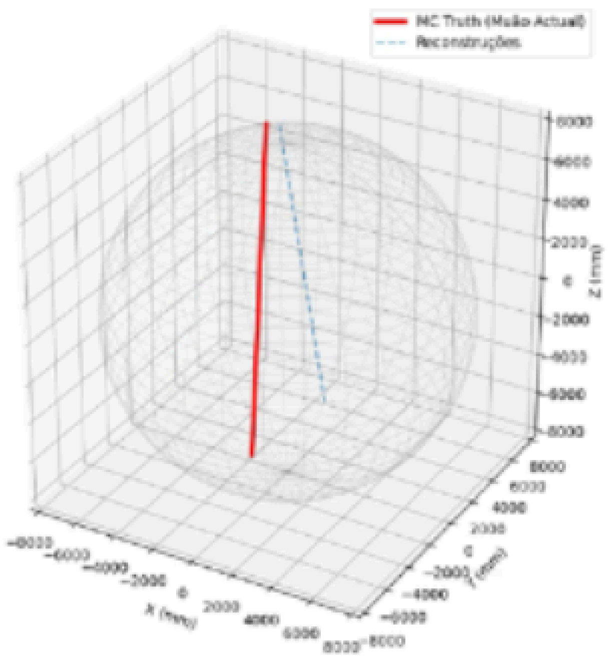
α – angle between simulated trajectory an reconstructed

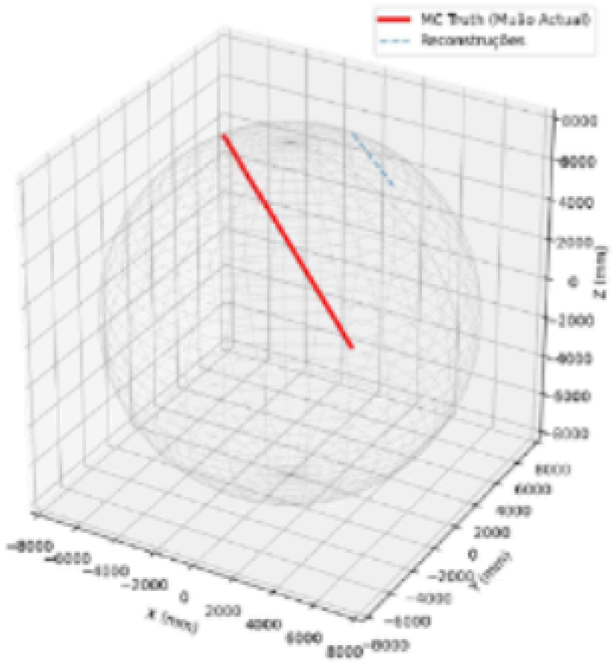
COMPARISON BETWEEN SIMULATED AND RECONSTRUCTED TRAJECTORIES

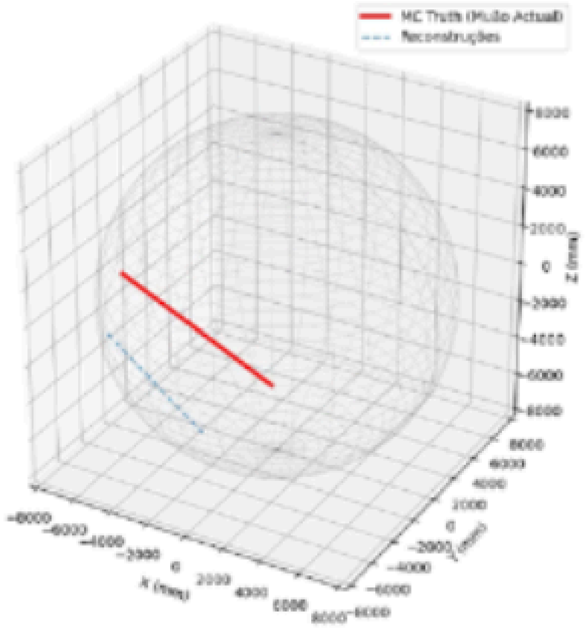
To evaluate the accuracy and performance of the re-construction algorithm on Monte Carlo (MC) simulated events, a 3D visual and quantitative analysis was performed, comparing the true trajectory of the simulated muon with its corresponding reconstructed track inside the active volume of the SNO+ detector.











We have been chosen as rep-representative examples of trajectories, for which incomplete or asymmetric hit patterns across the photo-multiplier tube (PMT) array

QUALITY CUTS

Stage	N	Sel. Eff.
Total	9961	100.0%
Event Index	9961	100.0%
pos and dir valid	8225	82.6%
Cleaned ratio > 0.8	7974	80.1%
correctedNhits > 5000	4182	42.0%
Track reconstructed > 5 m	4104	41.2%
dirFOM > 0	4104	41.2%

Quality cuts on real scintillator data

α

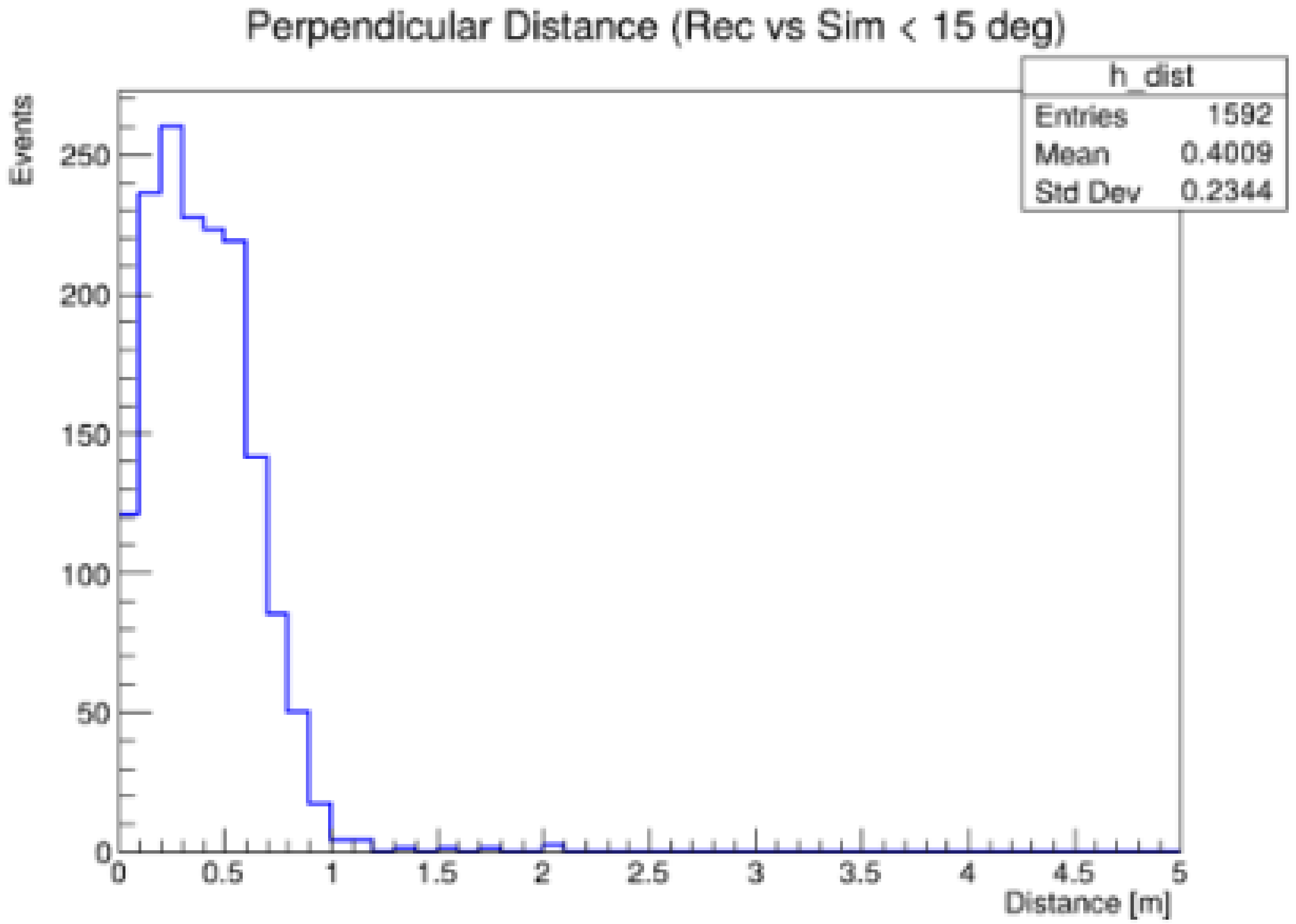
Stage	N	< 10°	< 15°	< 20°	< 30°
Total	83968	9.2	15.8	20.7	31.2
Event Index	12325	47.0	73.6	81.4	88.2
pos and dir < 99999	12220	47.4	74.2	82.1	88.9
dirFOM > 0	12220	47.4	74.2	82.1	88.9
Cleaned ratio > 0.8	12220	47.4	74.2	82.1	88.9
correctedNhits > 5000	12082	47.9	75.0	82.9	89.6
Track reconstructed > 5 m	10002	57.3	87.5	93.8	97.0

Quality cuts on mc scintillator data

$$Efficiency = \frac{\text{number of muons that passed the angle tolerance}}{\text{total number of muons that passed the cut}} \times 100$$

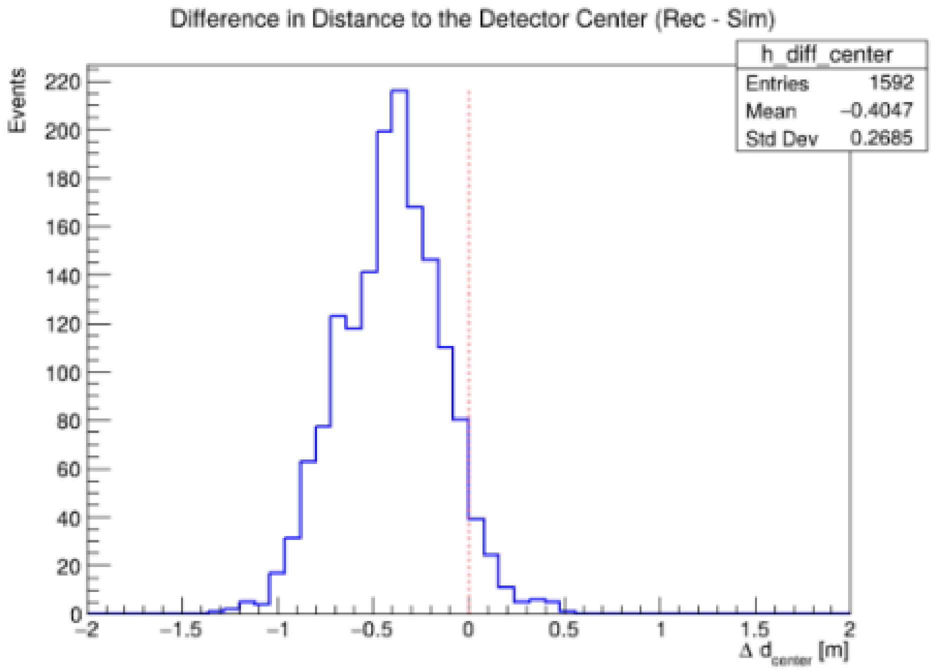
PERPENDICULAR DISTANCE ANALYSIS

To assess the spatial reconstruction accuracy alongside the angular resolution, the impact parameter, defined as the minimum perpendicular distance between the reconstructed track and the simulated true trajectory, was evaluated.

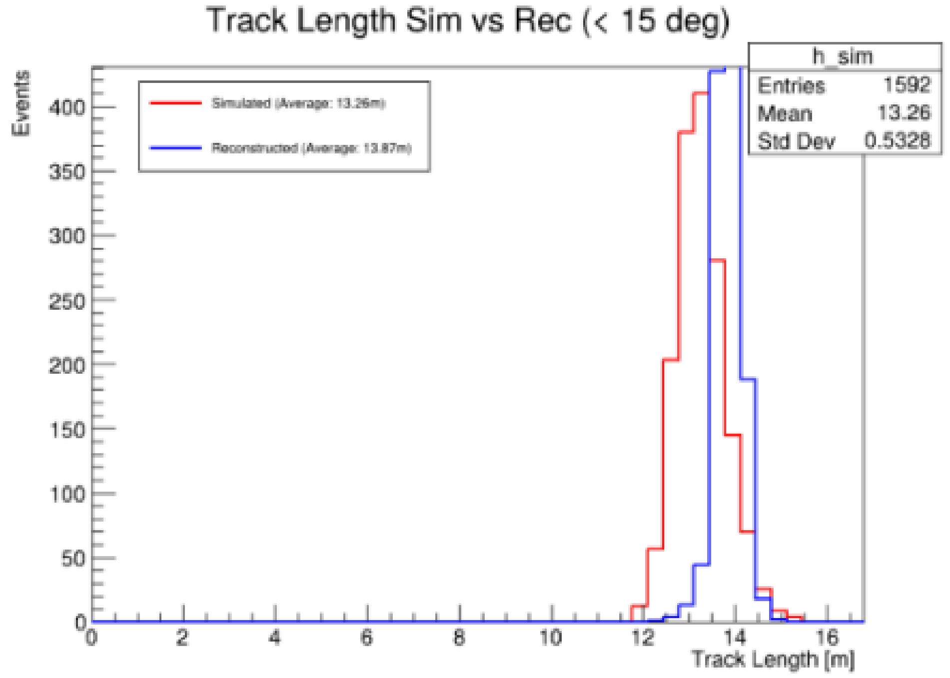


RADIAL POSITION AND TRACK LENGTH BIASES

To evaluate radial bias in the spatial reconstruction, the difference between the reconstructed distance to the detector centre and the true simulated distance (Δdcentro = dRec − dSim) was analysed.



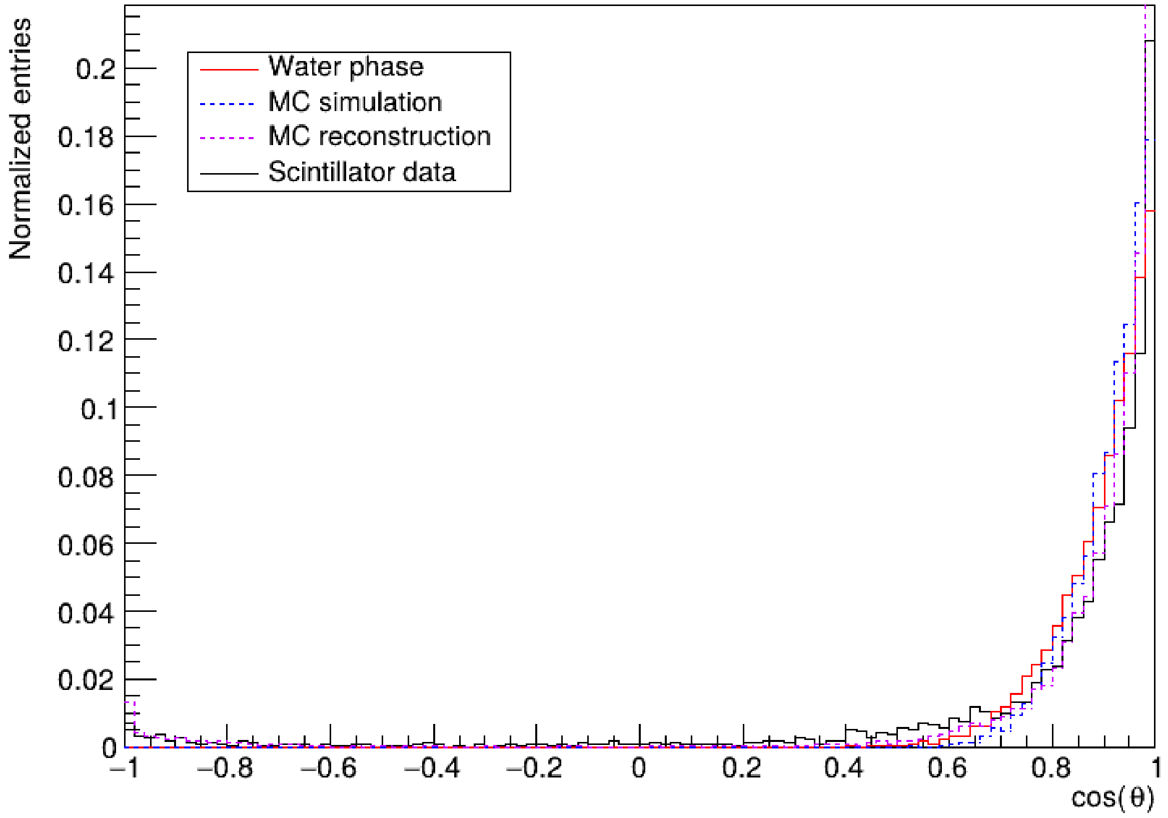
To evaluate the algorithm’s capability in estimating path lengths within the detector, the reconstructed track length (LRec) was directly compared against the simulated true length (LSim) for events satisfying the angular cut (Δθ < 15◦).



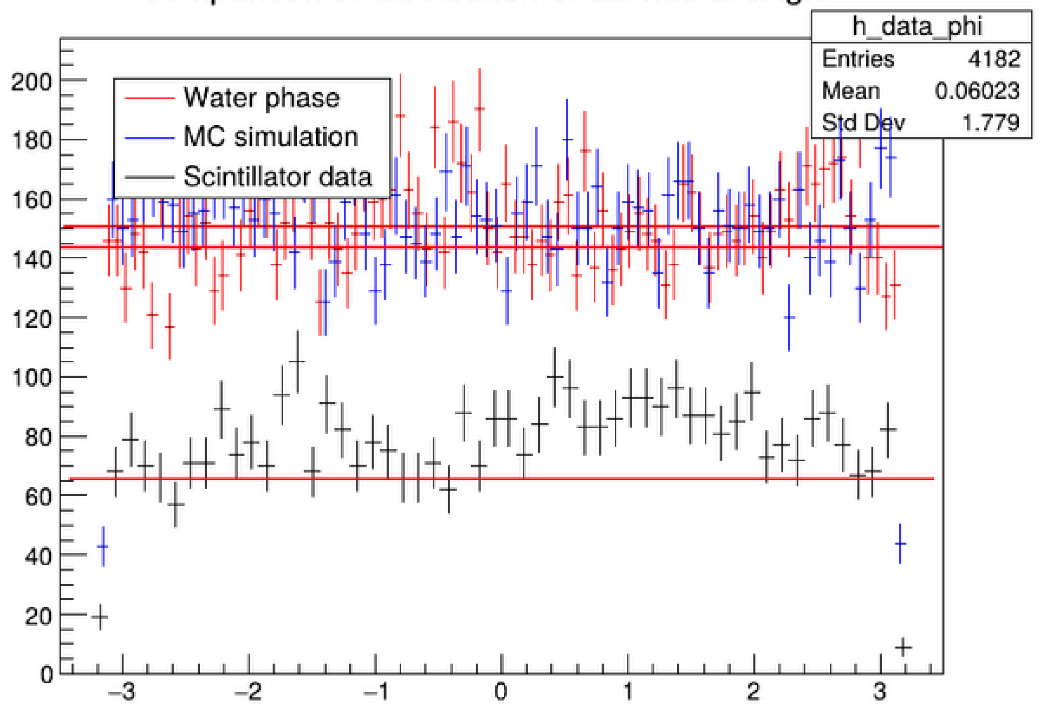
CONCLUSION

- Muon intensity vs. depth matches two-exponential secθ model (best fit: $\chi^2/ndf = 0.94$)
- Slant depth: 6.27 ± 0.067 (stat) ± 0.046 (sys.) k.w.e.
- Muography of Creighton Mine not feasible with current analysis and data sets ($\theta < 66°$ vs. required ~85°, cosine of 0.087)
- Preliminary evidence of a locally denser rock medium — warrants further quantitative study
- Quality cuts greatly improve reconstruction accuracy (31% → 97%) at a sample-size cost.
- Radial (−0.40 m) and track-length (+0.61 m) biases indicate a correctable systematic error, not random noise.
- SNO+ data is suitable for cosmic-muon studies with proper cuts; mine imaging requires a different approach

cos(θ) distribution comparison



comparison of distribution of azimuthal angle



The two datasets are consistent between themselves and with model

THANK YOU

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