Modelling Muon Flux in Huguenot Tunnel

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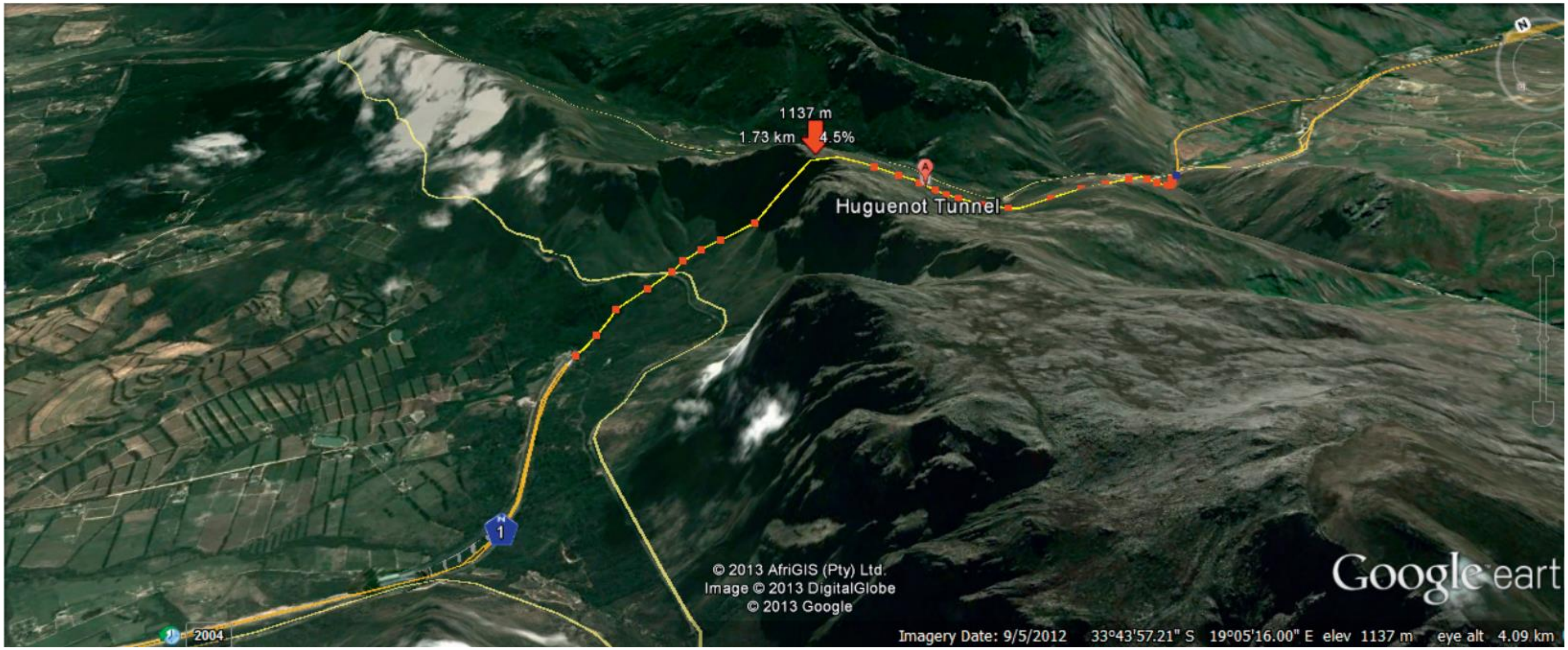

Inspiration

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PAUL (Paarl African Underground Lab)

- Interest in developing underground lab in South Africa.
- Cosmic radiation constantly bombard the earth.
- Cosmic rays creates secondary particles along with very penetrative muons and neutrinos.
- Low radiation background facilities need some sort of shield.
- What better shield than the earth itself.
- Underground is the perfect place where nature is used as your shield.

Aim of the game

PAUL (Paarl African Underground Lab)

- The aim of this project is to see what the muon flux in the Huguenot Tunnel looks like.
- See if PAUL would be a viable idea.
- Use Monte Carlo Code GEANT 4 to simulate scenario and get data from it.
- Compare to previous studies done and validate them. We will specifically try to validate de Villiers' study in 2022.

Muons

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What is it and where does it come from?

- Muon is a "fat electron" which weighs more than 207 times as much as an electron.
- Fundamental Lepton particle.
- Muons come from cosmic rays which constantly bombard the earth.
- Pion decay scheme
- Kaon decay scheme
- Very high energies looking at 100-1000GeV
- Muons have a heavier mass, so they emit less bremsstrahlung, resulting in them penetrating deeper

$$Pion: \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$
$$Kaon: K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$

Muons

What is it and where does it come from?

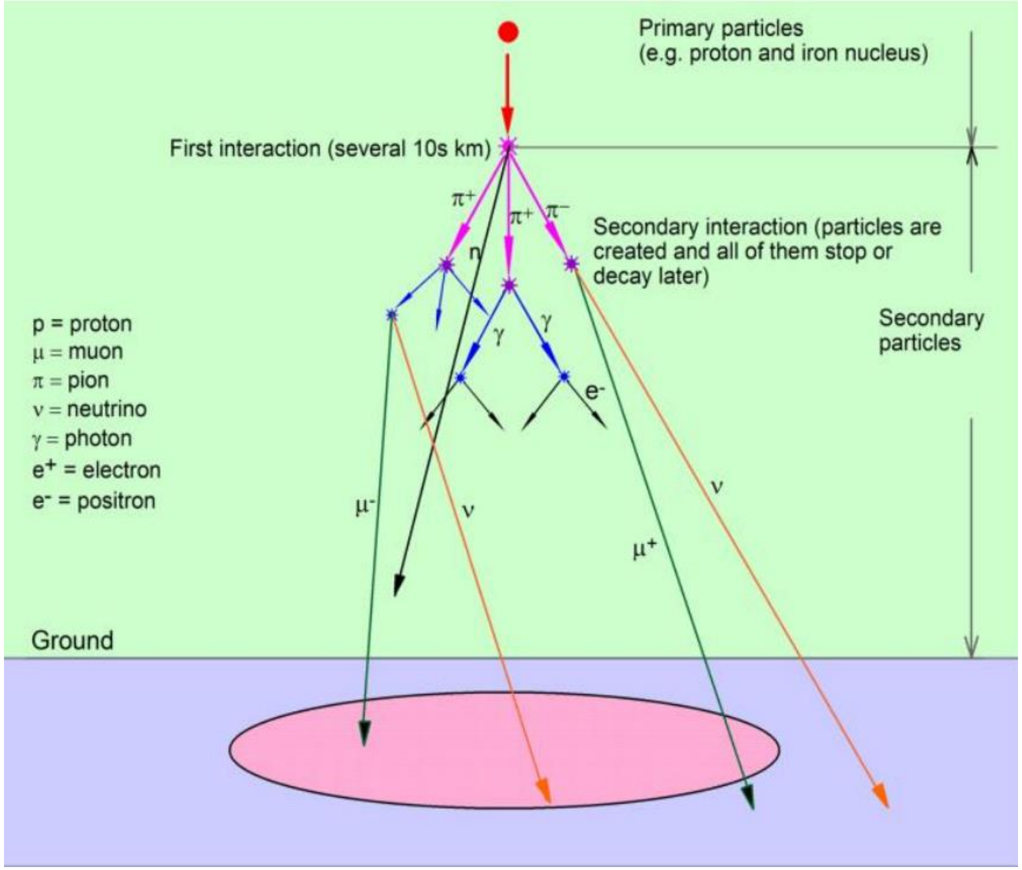

Image from [6]

Muon interactions

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How does muons interact with matter?

- Muon is a heavy charged particle.
- Charged particle interactions best described by stopping power.
- Stopping power is the amount of energy loss per distance traveled in material.
- Two categories electronic and nuclear stopping power.
- Electronic stopping power described by the Bethe Bloch Equation.

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

- Radiative effects are negligible at low energies but are more prominent at higher energies.

[7]

Muon interactions

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How does muons interact with matter?

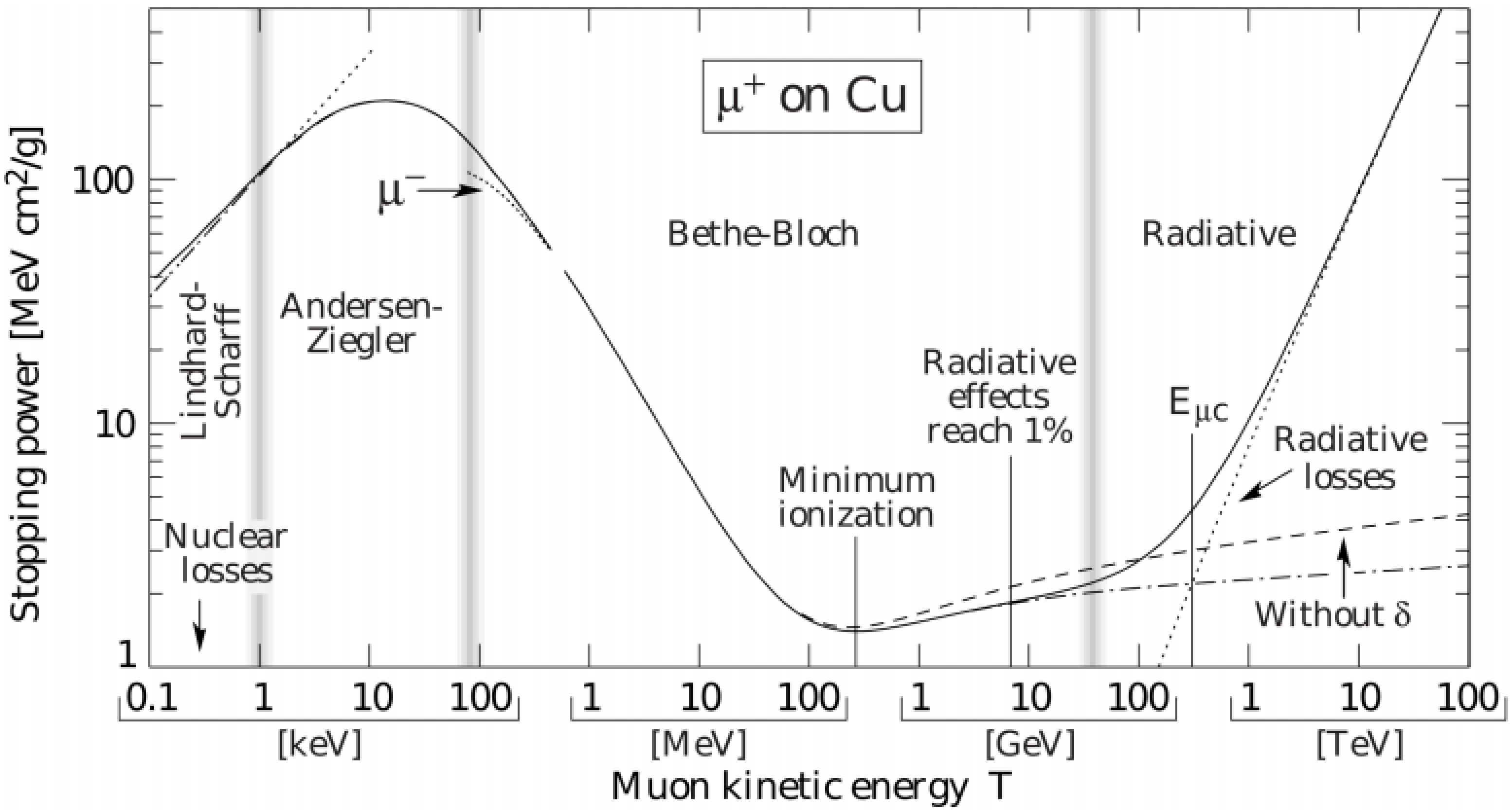

Image from [8]

Radiative effects

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How we implement radiative effects.

- Our muons are high energy, so we need to implement radiative effects somehow.
- Radiative effects like pair production, bremsstrahlung and photonuclear interactions.
- We will add an extra term:

$$-\frac{dE}{dx} = a(E) + b(E)E$$

- Where:

$$b \equiv b_{brems} + b_{pair} + b_{nucl}$$

[8]

Compounds/Mixtures

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How stopping power works for mixtures

- Mountainous overburden definitely not one single element but a bunch.
- Use Bragg's Rule to account for the mixture.
- Average stopping power over each element weighted by the fraction of electrons belonging to that specific element.

$$\frac{1}{\rho}\frac{dE}{dx} = \frac{w_1}{\rho_1}\left(\frac{dE}{dx}\right)_1 + \frac{w_2}{\rho_2}\left(\frac{dE}{dx}\right)_2 + \cdots,$$

- Where:

$$w_i = \frac{a_i A_i}{A_m} \qquad A_m = \sum a_i A_i$$

[7]

Muon depth/intensity relation

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Vertical muon flux

- Model we will use to get differential energy flux as described in [9].

$$j(E_\mu,\theta) = \frac{dN_\mu}{dE_\mu} \approx \frac{0.14E_\mu^{-2.7}}{GeV.sr.s.cm^2} \times \left(\frac{1}{1+1.1E_\mu cos\theta/115GeV} + \frac{1}{1+1.1E_\mu cos\theta/850GeV}\right)$$

- Relationship between differential energy flux and vertical muon flux from [13].

$$I_v(X) = N_\mu\left(> E_0^{min}(X)\right) = \int_{E_0^{min}(X)}^{\infty} j(E,0)dE$$

[9]+[13]

Muon Depth/Intensity relation

Vertical Muon Flux Underground

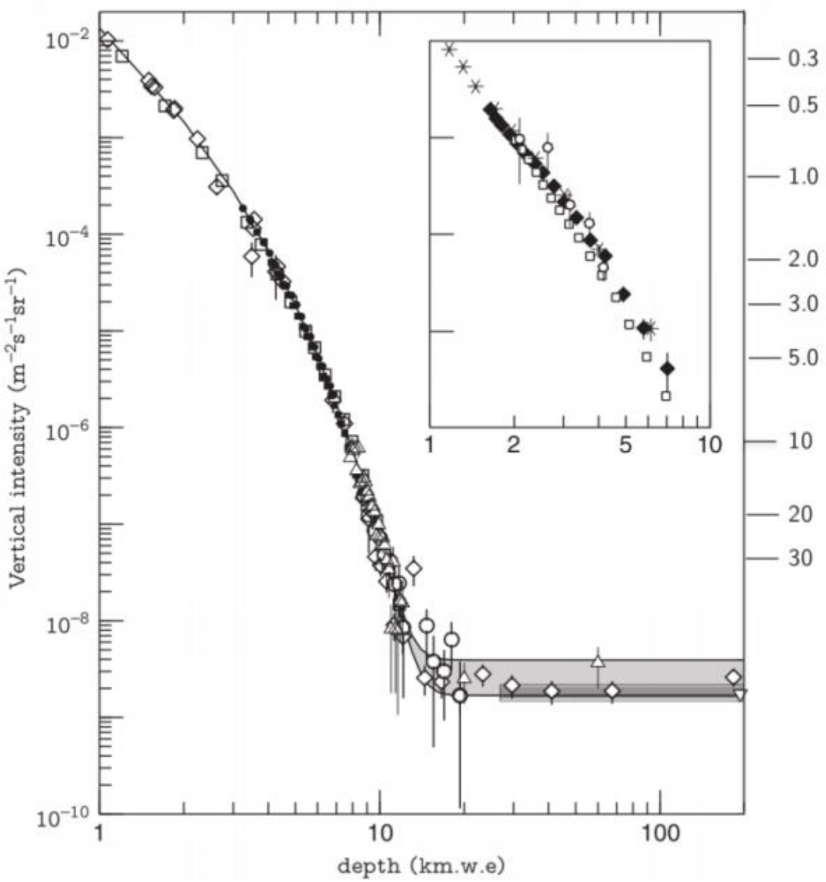

Image from [13]

Muon Angular dependance

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Atmospheric muons

- It is assumed that the angular dependance of atmospheric muons is the following as stated by [9]

$$I_v(X) \propto (cos\theta)^2$$

- Would mean that vertical muon flux is greater than as at any angle.

[9]

Muon Angular dependance

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Atmospheric muons angular dependance

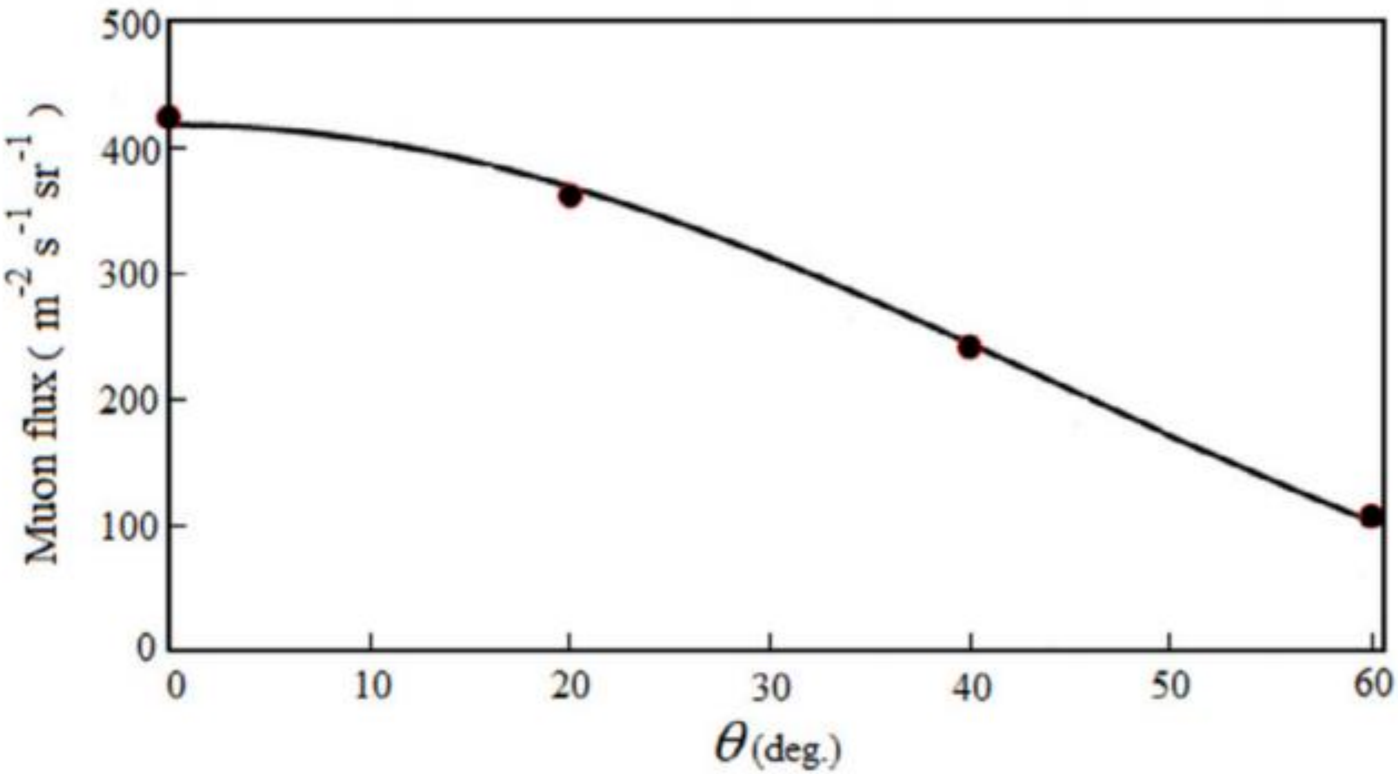

Image from [14]

Muon Angular dependance

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Angular dependance of the muon flux underground for SNO detector.

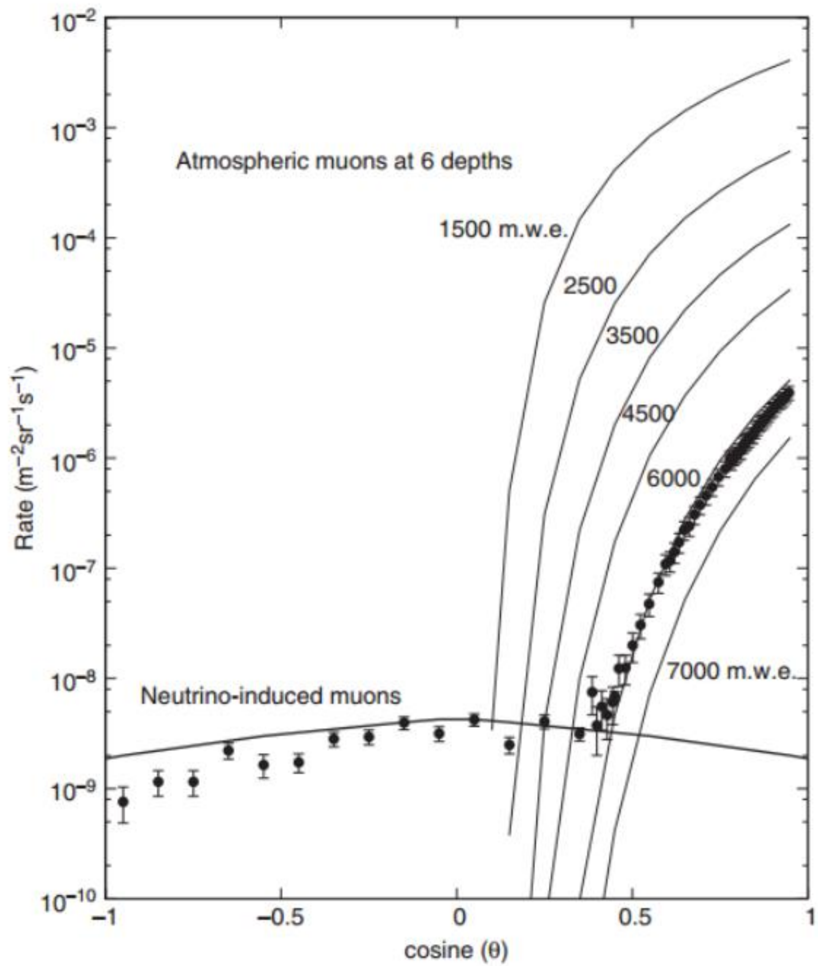
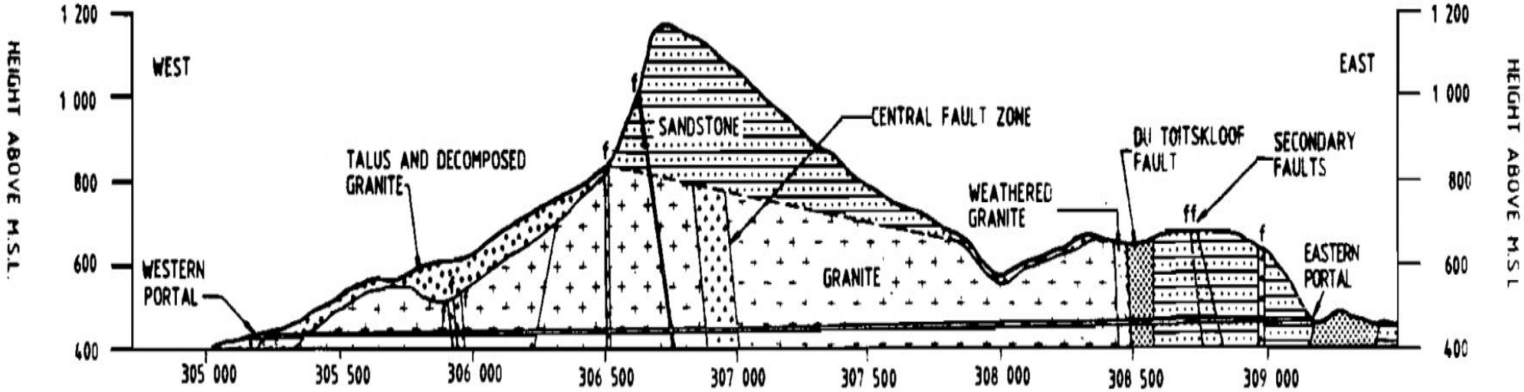


Image from [13]

The Star of the show

The Huguenot Tunnel.

- Du Toitskloof mountain range, separates Paarl from Worcester.



Sample	O (*w*%)	Na (*w*%)	Mg(*w*%)	Al (*w*%)	Si (*w*%)	P (*w*%)	K (*w*%)	Ca (*w*%)	Ti (*w*%)	Mn(*w*%)	Fe (*w*%)
Feldspathic basalt	0.44352	0.02923	0.02404	0.06711	0.23944	0.00172	0.00769	0.07866	0.01408	0.00132	0.09321
Compact basalt	0.44537	0.03282	0.02058	0.06329	0.24496	0.00238	0.00833	0.06438	0.01699	0.0013	0.0996
Volcanic rock	0.43426	0.03885	0.02455	0.06147	0.22211	0.00372	0.01166	0.08656	0.02173	0.00207	0.09302
Pink granite	0.48764	0.03831	1.9E−05	0.05495	0.35835	0.00025	0.04102	0.00497	0.00103	0.00024	0.01322
Sandstone	0.52667	0.00011	2.1E−05	0.02813	0.43703	0.00017	4.3E−05	0.00218	0.0007	6.4E−05	0.00488
Dolerite	0.43996	0.02976	0.02287	0.06466	0.22981	0.00152	0.00259	0.07076	0.02251	0.00167	0.1139

Image from [15]+[21]

Conversions

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Standard rock and meter water equivalent

- m.w.e. enables us to measure the attenuation one meter of water has on cosmic rays
- Intensities are generally converted to intensities under standard rock.
- Standard rock:
  - $Z = 11$
  - $A = 22$
  - $\frac{Z}{A} = 0.5$
  - $\rho = 2.650\ g.cm^{-3}$
- Conversion factor to easily convert between different rock depths [6]. Depth in arbitrary rock multiplied with factor

$$F(X, Z, A) = \frac{X_{SR}}{Z_{Z,A}} = \frac{X(E, 11{,}22)}{X(E, Z, A)}$$

[9]

Monte Carlo Code

- Monte Carlo codes uses a computer-based analytical method in which uncertain variables are represented by ranges of possible values.
- Developed at CERN in C++
- Mandatory User Classes
  - **Main**: Controls the simulation
  - **Construction** : Setup of anything physical in experiment
  - **PrimaryGeneratorAction**: Generates the primaries
  - **Detector**: This class deals with the data once detector detects a particle
  - **RunAction**: Creates and writes in output files
  - **ActionInitialization**: Hands over actions to Geant4 manager for execution
- Physics list **FTFP_BERT** (Default for GEANT4)
- Production cuts
- Tracking secondaries
- Root for data handling

[18]+[19]

Quality assurance

Test our code

- Put our code to the test in small scale scenario. Muons traversing 3m block of iron. Following graph done in MARS14.

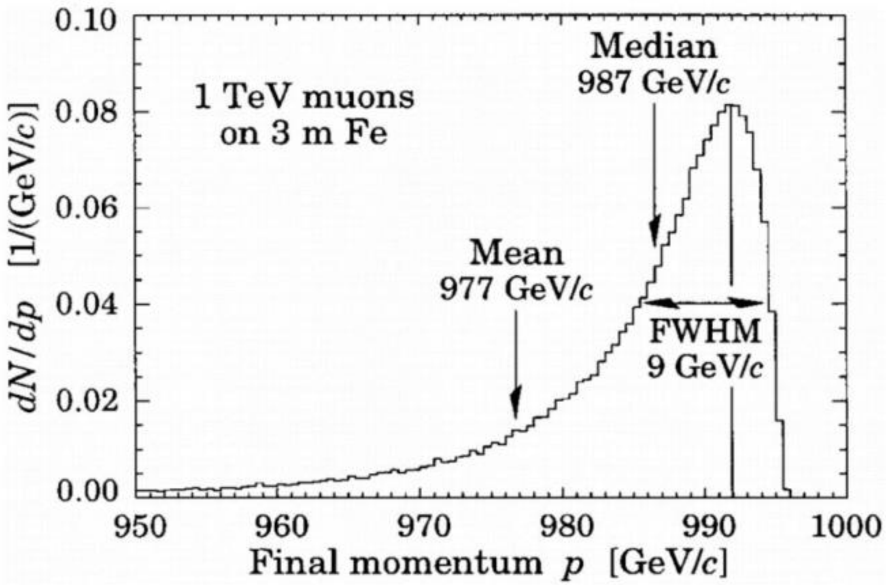
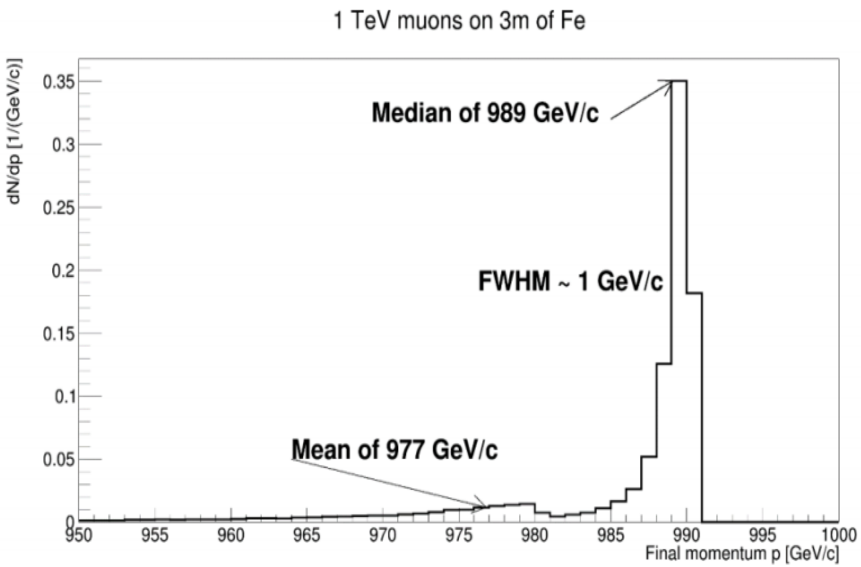


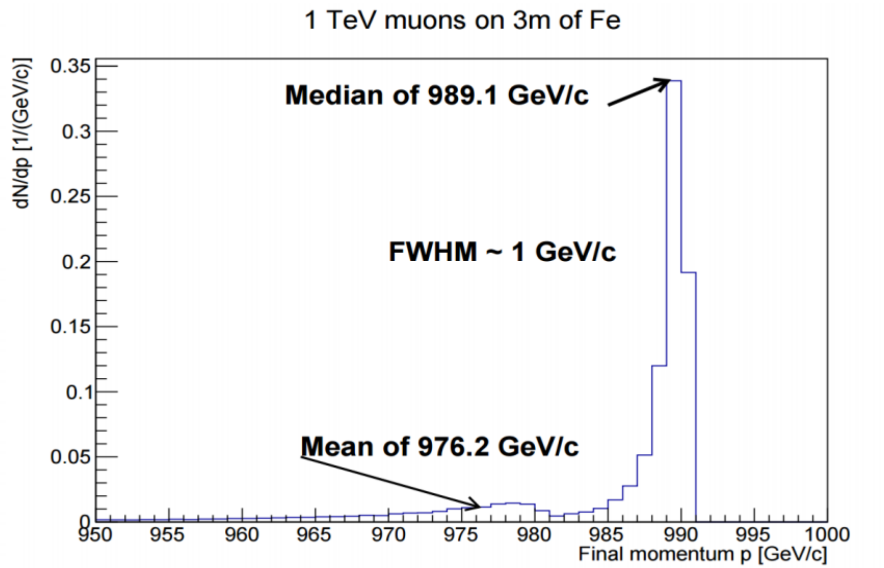
Image from [15]

Quality Assurance

QA results for 2022 (de Villiers) and 2023



- 2022 de Villiers



- 2023

Image from [20]

Our Experiment

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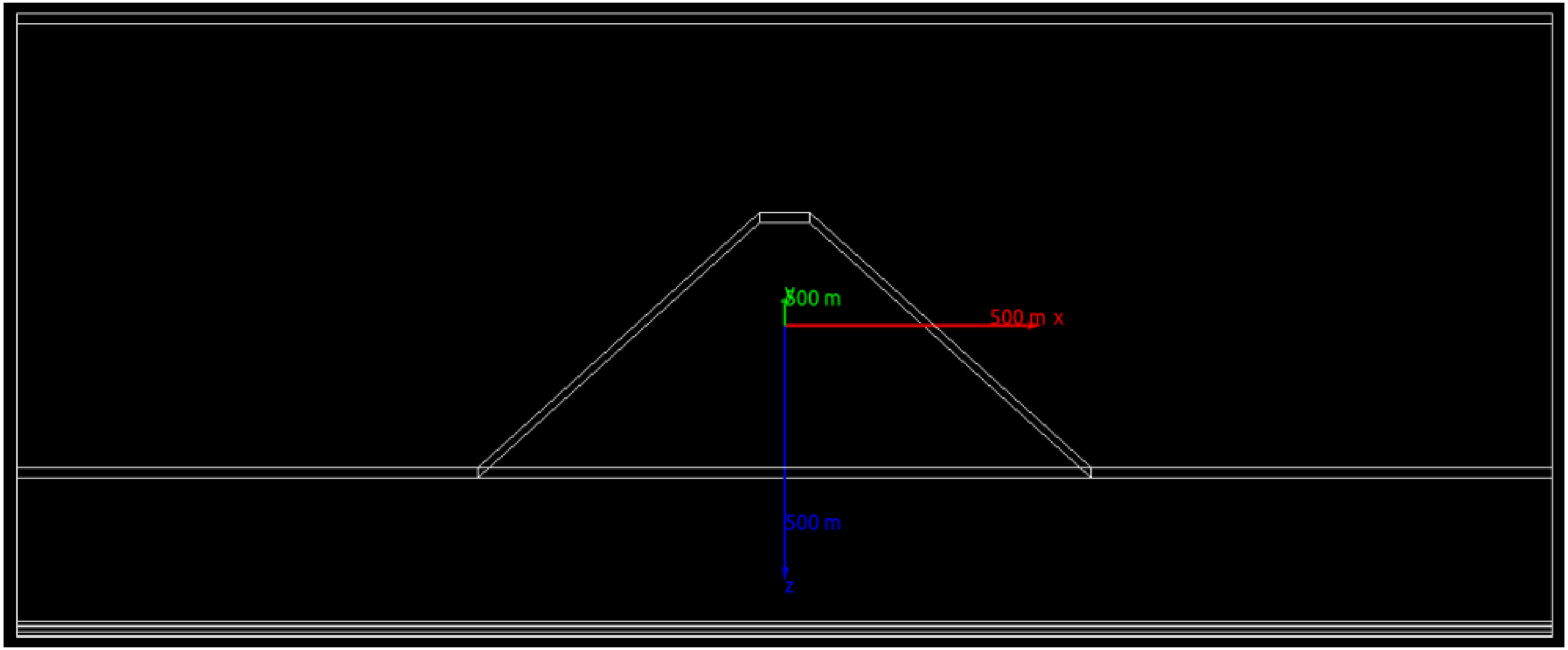
Side profile of our modeled mountain



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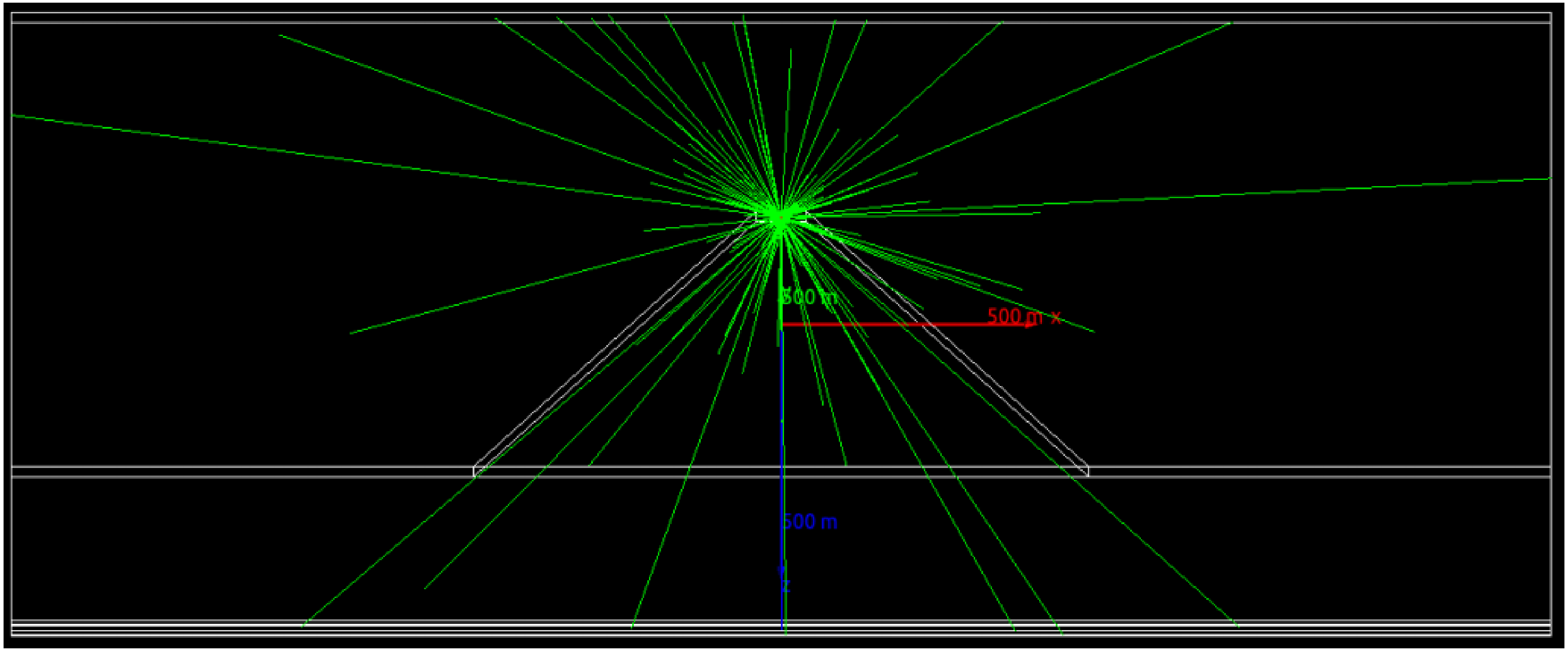
Singular event started directly above peak



Our Experiment

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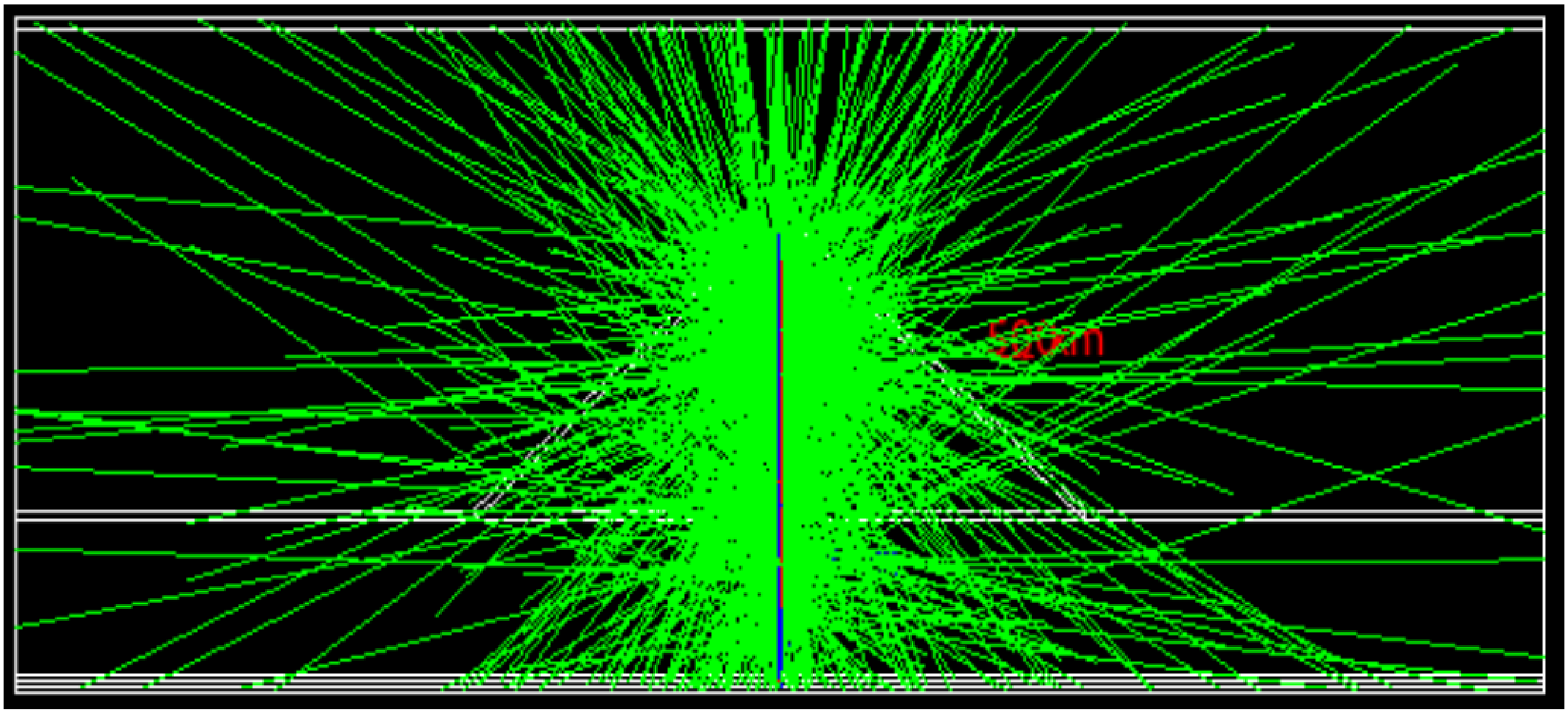
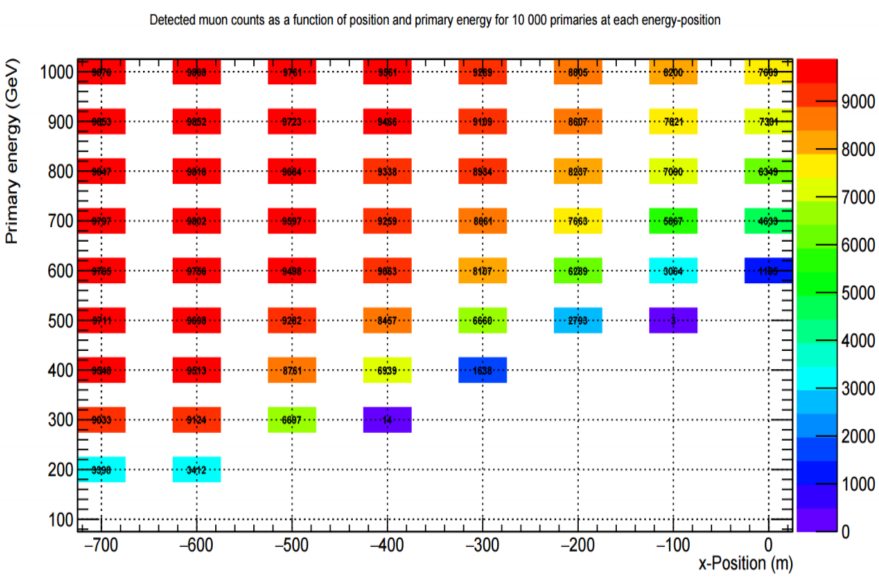
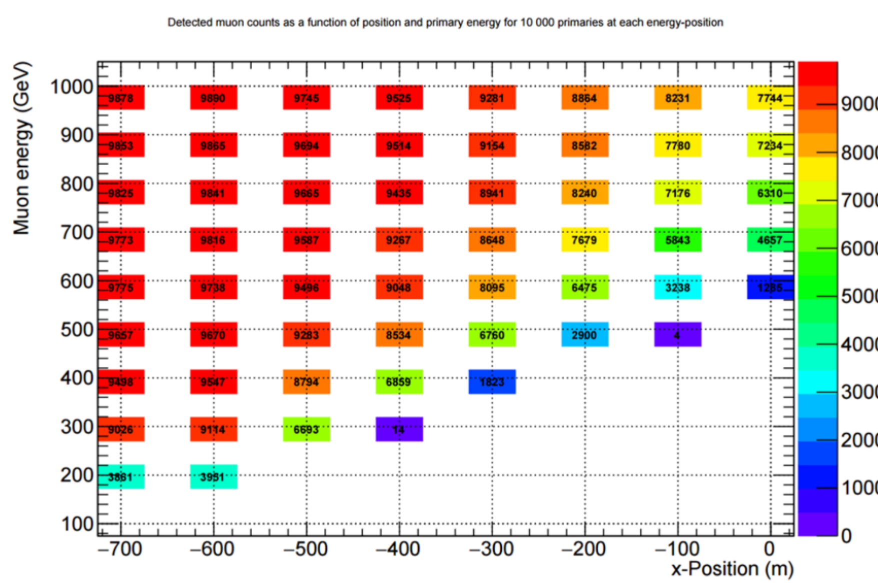
100 Events started directly above peak



Results

Detected muons at each energy-position





- 2022 de Villiers
- 2023

Image from [20]

Results

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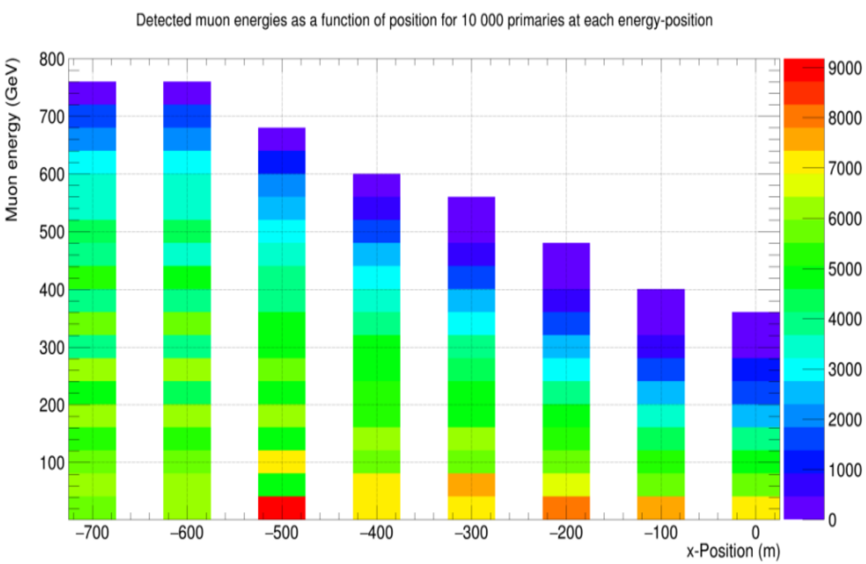
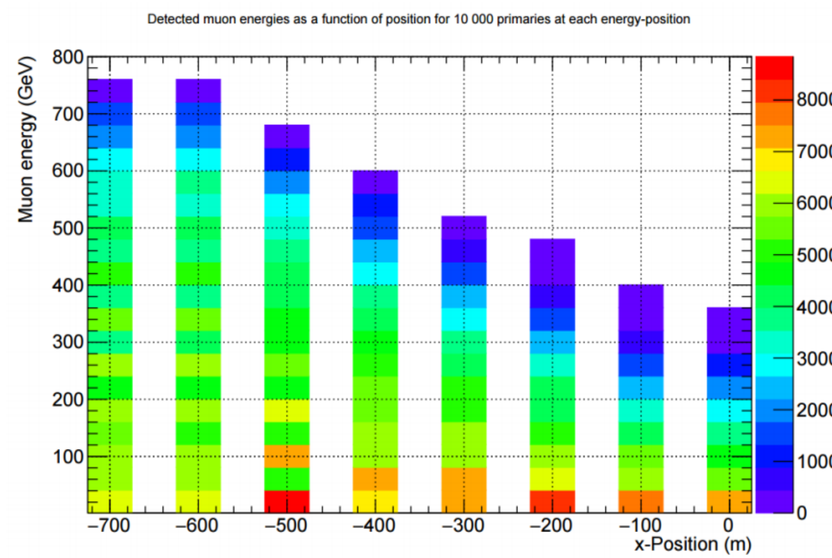
Detected muon energies for each energy-position



- 2022 de Villiers



- 2023

Image from [20]

Calculations

Our main results

X-value (m)	E_0^{min}(X) (GeV)	Vertical Muon Flux ($10^{-3} m^{-2} s^{-1}$)	m.w.e (m)
0 (Thick overburden)	721	5.33	1905
0 (de Villiers Thick overburden)	721	5.33	1905
-100	668	6.38	1791
-200	559	9.62	1557
-300	464	14.7	1353
-400	372	24.1	1144
-500	275	46.71	887
-600	220	75.41	732
-700 (Thin overburden)	222	73.98	738
-700 (de Villiers Thin overburden)	228	69.6	756
Soudan (MINOS)	730	3.64	2100

[20]

Calculations results

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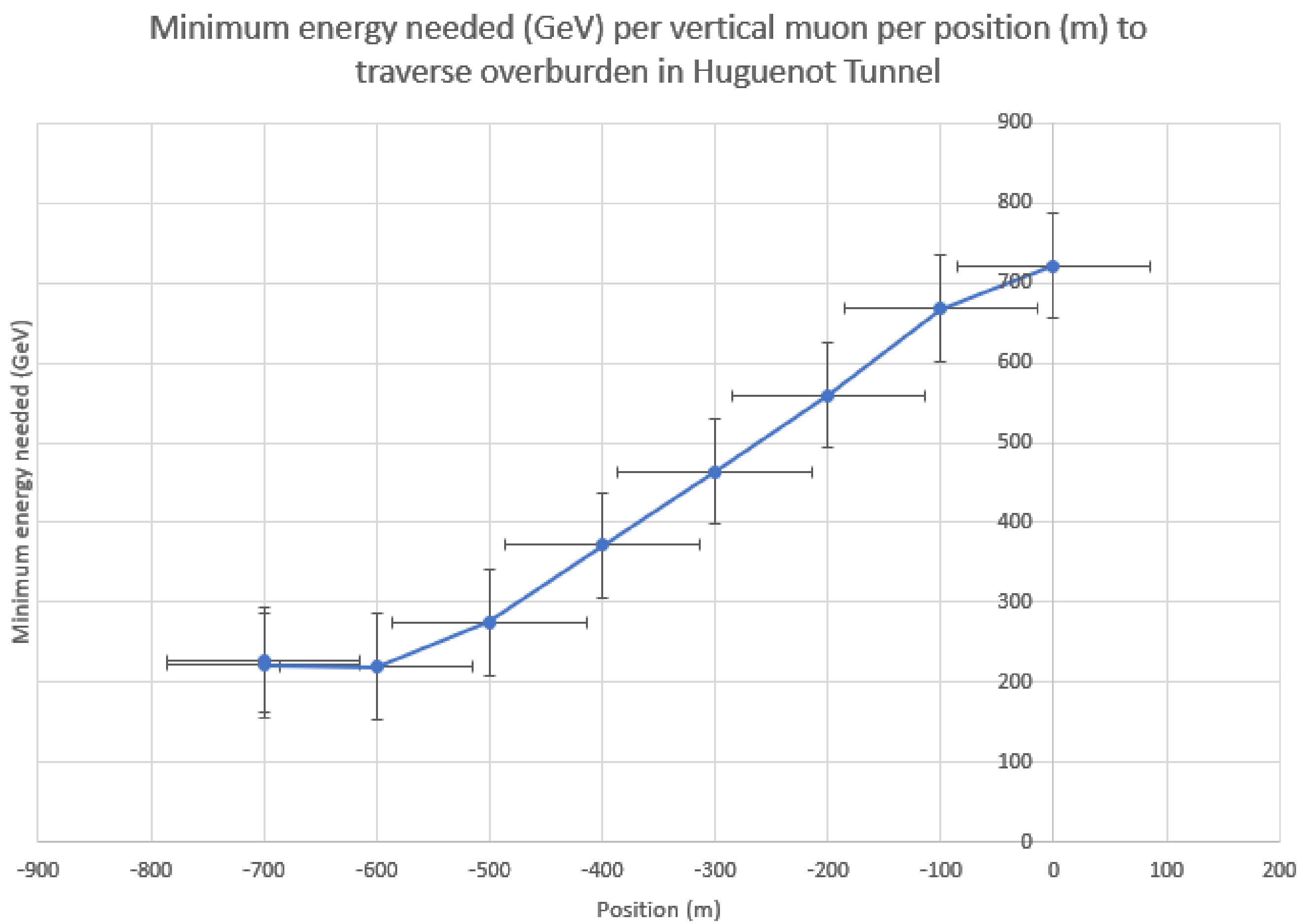
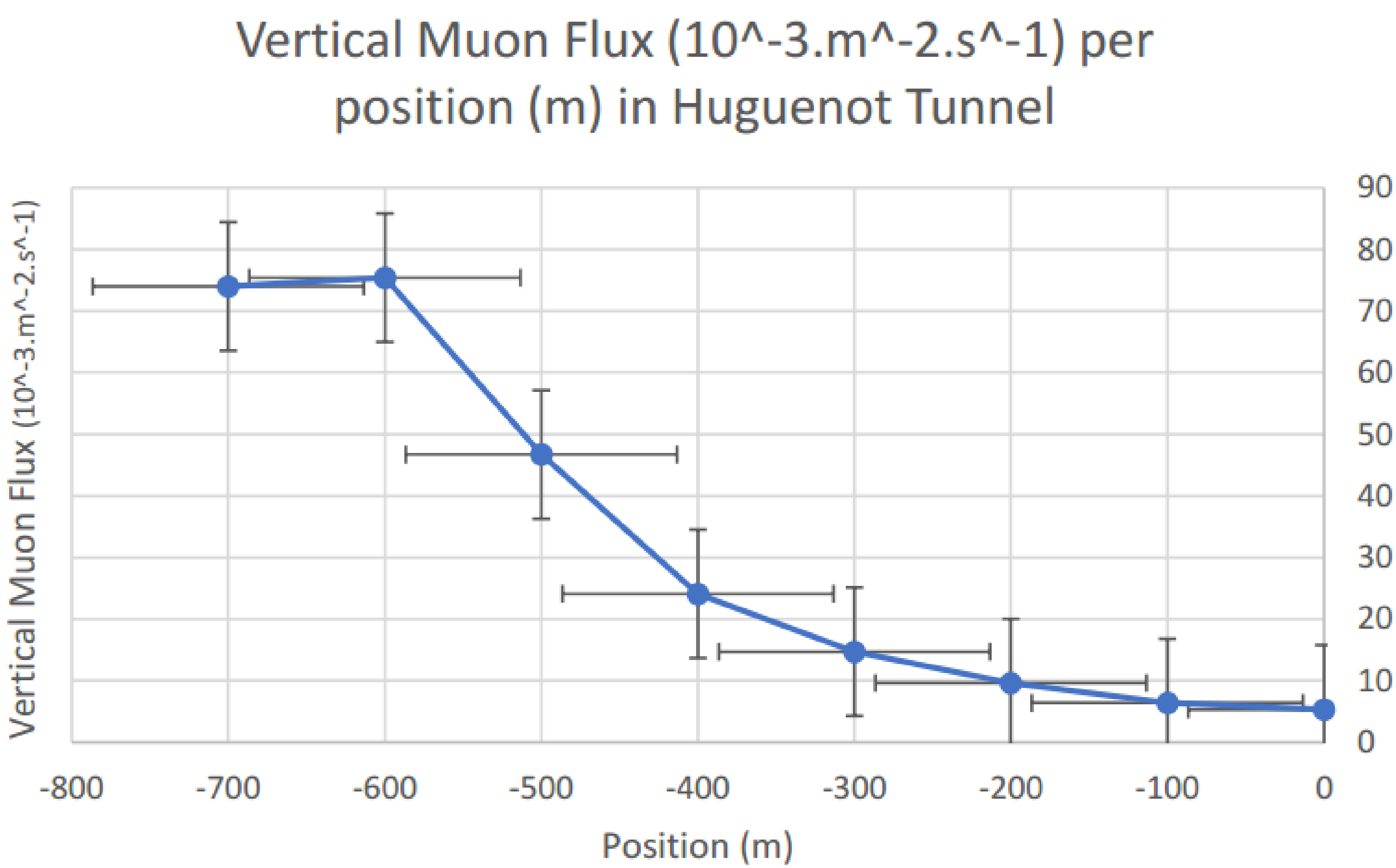
Minimum energy required per muon per position



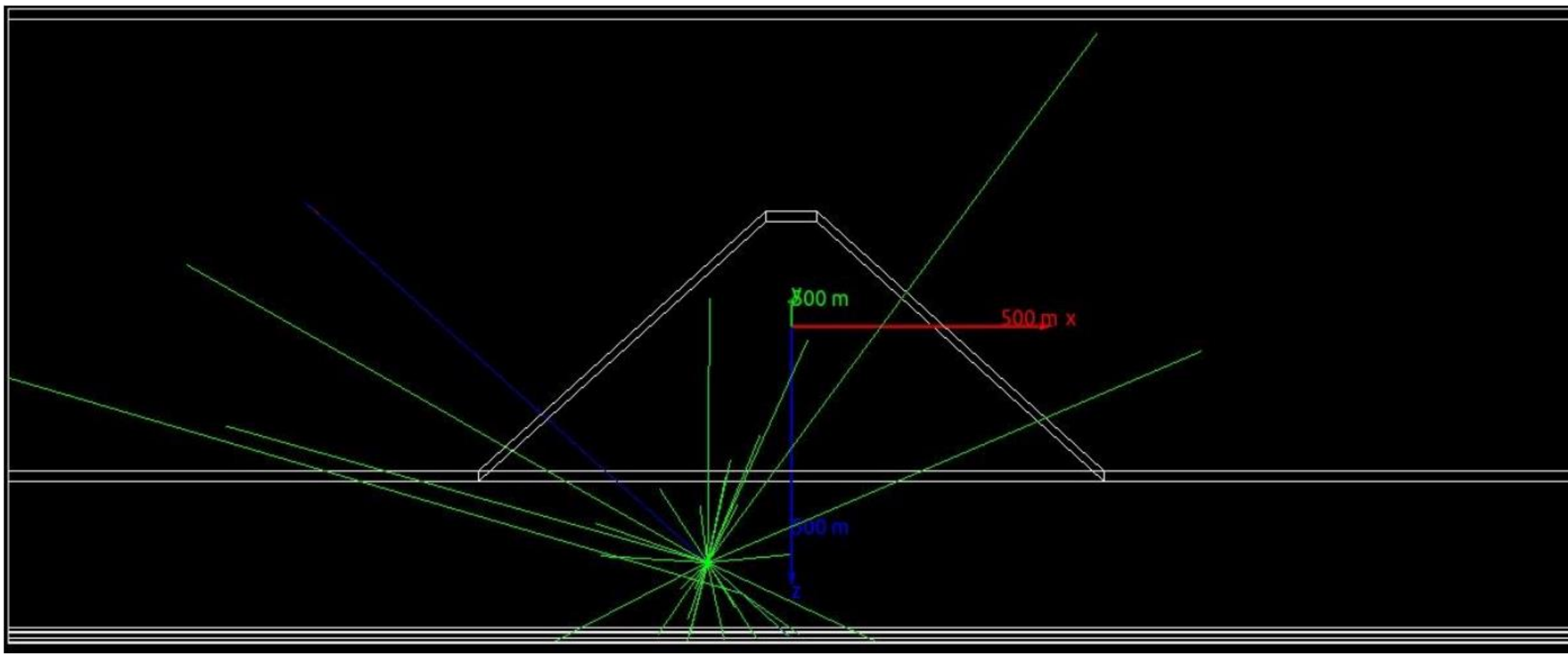
Calculations results

Expected vertical muon flux in tunnel



Angular dependance

Our experiment



Angular dependance results

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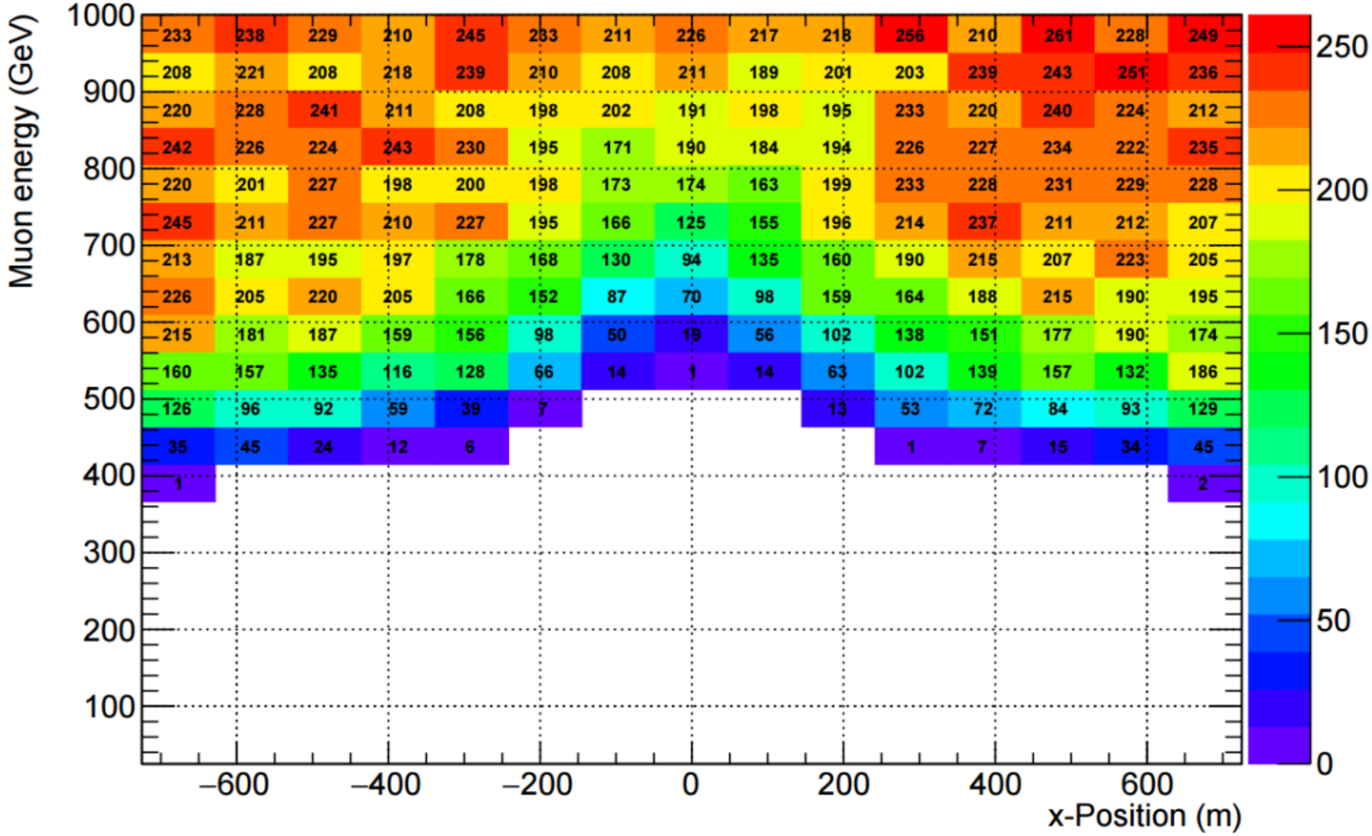
Detected muon energies at random starting positions directed towards x=0m for 100000 events



Calculations

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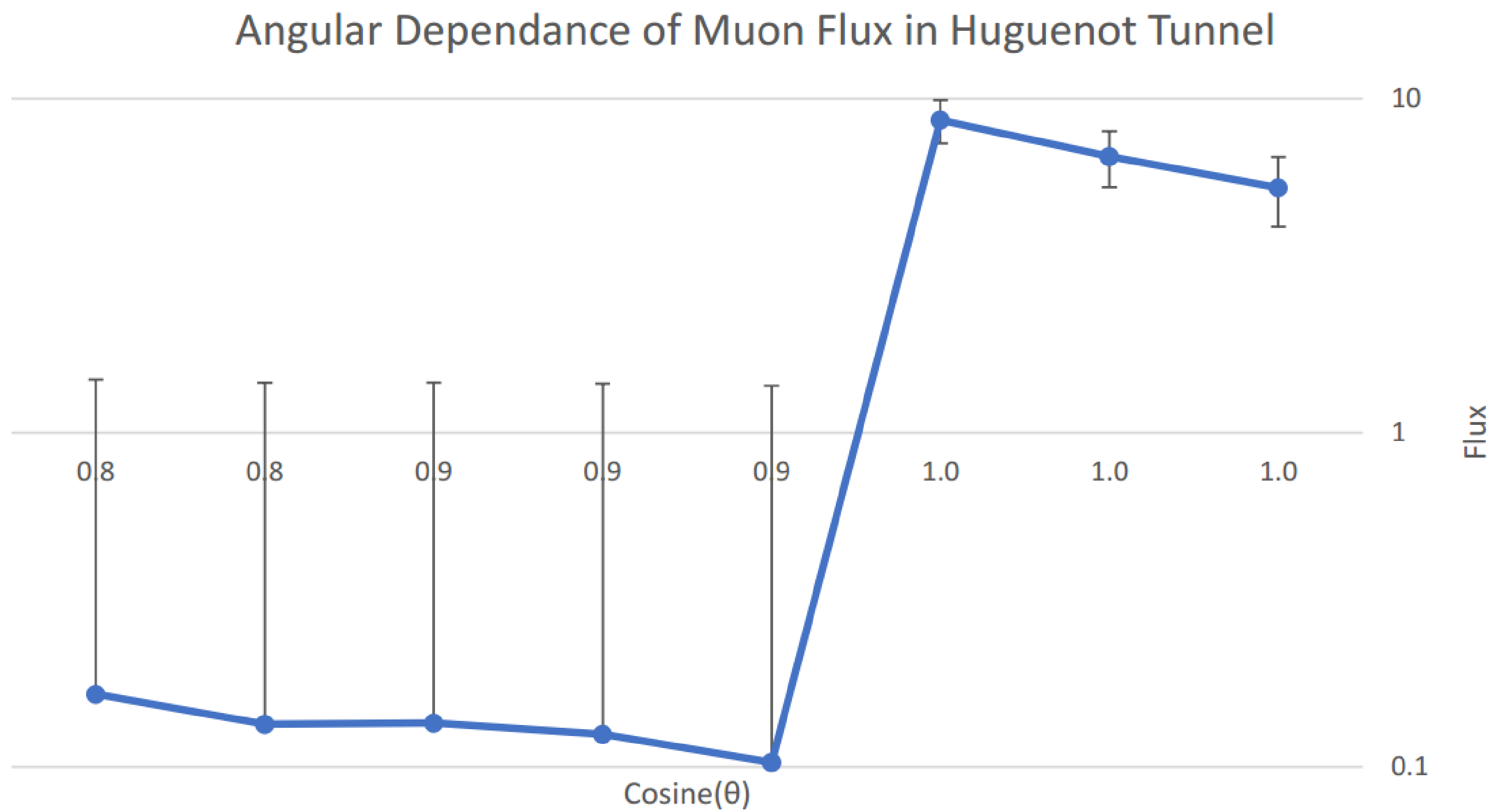
Our main angular dependance results

Starting X-value (m)	E_0^{min}(X,θ) (GeV)	Angle (radians)	Angle (degrees)	Angular Muon Flux $(10^{-3}m^{-2}s^{-1})$
0 (Vertical)	717	0	0	5.41
100	655	0.121	7.0	6.71
200	591	0.239	13.7	8.62
300	550	0.351	20.1	0.10
400	511	0.454	26.0	0.13
500	500	0.548	31.4	0.14
600	509	0.632	36.2	0.13
700	469	0.707	40.5	0.17

Calculations results

Angular dependance of the muon flux underground for Huguenot Tunnel under the peak



Conclusion

General conclusions

- GEANT4 simulation was essential in this study and yielded meaningful results.
- Our results were in agreement with de Villiers' study, validating what he has determined.
- 1905 m.w.e for thick and decreases to 738 m.w.e at thin overburden.
- Vertical muon flux of 5.33 $(10^{-3}m^{-2}s^{-1})$ and maximum angular flux at an angle of $\approx 14^{0}$ of 8.62 $(10^{-3}m^{-2}s^{-1})$ under the peak.
- PAUL viable and valuable asset.

Looking to the future

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What will be in store for PAUL?

- Low level background radiation experiments.
- Dark matter experiments.
- Neutrino studies and experiments.
- Antineutrino studies from Koeberg.
- Radiation Biological studies.
- Earth's mantle tomography (Earth project).
- Muon tomography (Muography)
  - Starting this year!
  - The first extension to this study is to have the real measurement of the muon background in the tunnel done in collaboration with Jacques Marteau and his team.

PAUL

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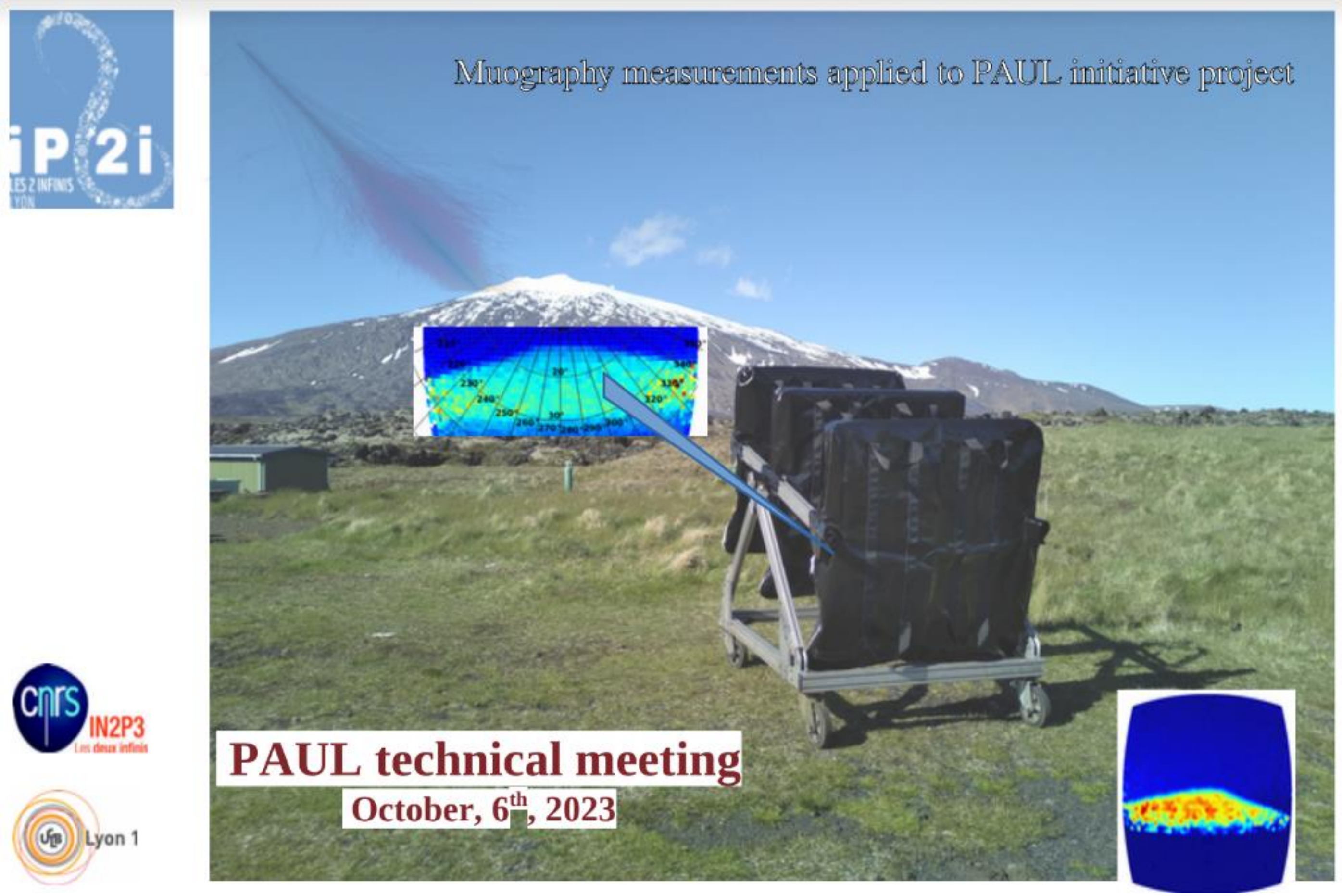
What will be in store for the lab?



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