Background suppression with machine learning in volcano muography

G. Galgóczi, G. Hamar, L. Oláh, D. Dezső

Wigner Research Centre for Physics & VMI

MODE workshop

26th July 2023

Princeton University

REGARD

INNOVATIVE GASEOUS DETECTORS

Eötvös Loránd University

National Research, Development and Innovation Office Hungary

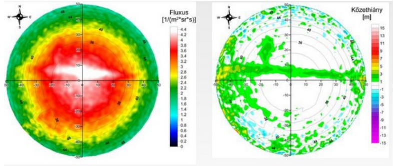
PROJECT FINANCED FROM THE NRDI FUND

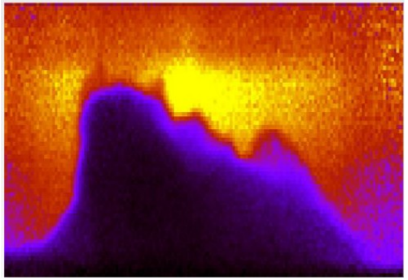
Outline of the talk

- Background for volcano muography
- Geant4 simulation of the Muography Observatory System
- With the G4 simulation:
  - Testing the “classic” χ^2 algorithm currently being used
  - Teaching a deep neural network to suppress background
- Can we use deep learning to enhance signal to noise ratio?
  - Especially important for volcano muography
- Applying the machine learning algorithm to MOS-08 measurements @ Sakurajima

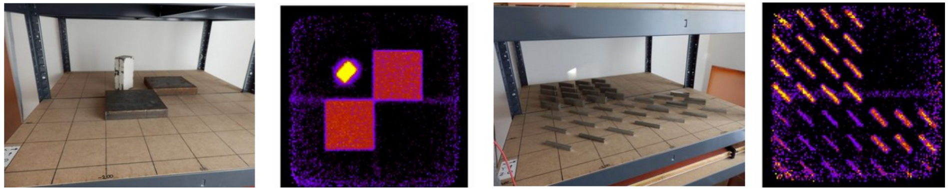
What can cosmic muons be used for?

- **Attenuation muography:**
  - Cosmic muon flux attenuated by material (density-length)
  - Directional measurement : muogram → density map of large objects
  - Geophyiscs, archeology, industrial, meteorology

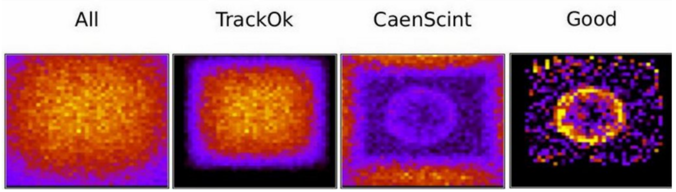


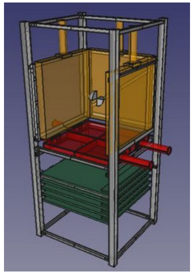


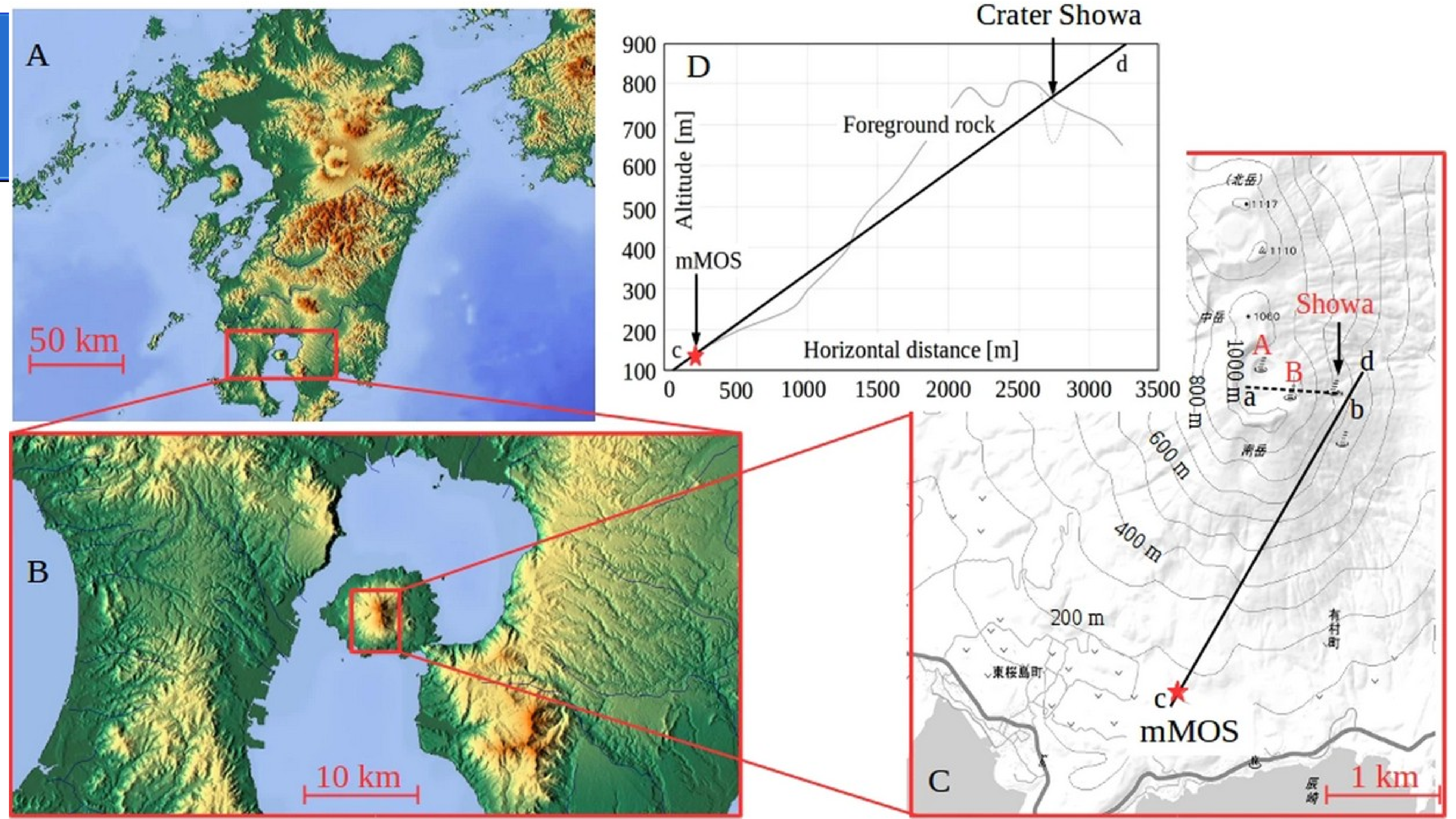
- **Muon scattering tomography**
  - Multiple scattering on high-Z material
  - Two tracklet matching :
    scatter map → high-Z materials
  - Disclose hidden objects, homeland security



- **Muon induced secondaries**
  - The type of secondaries that are created,
    absorbed and exit depends strongly on the material



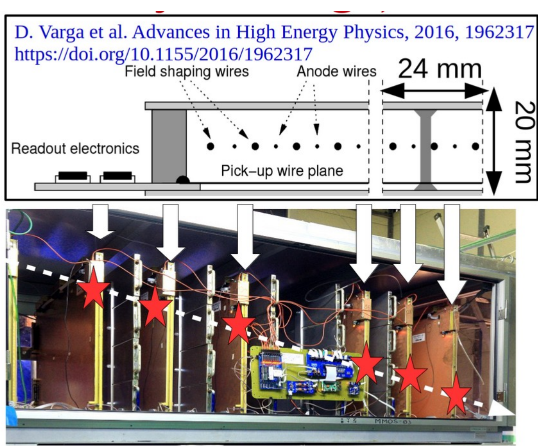


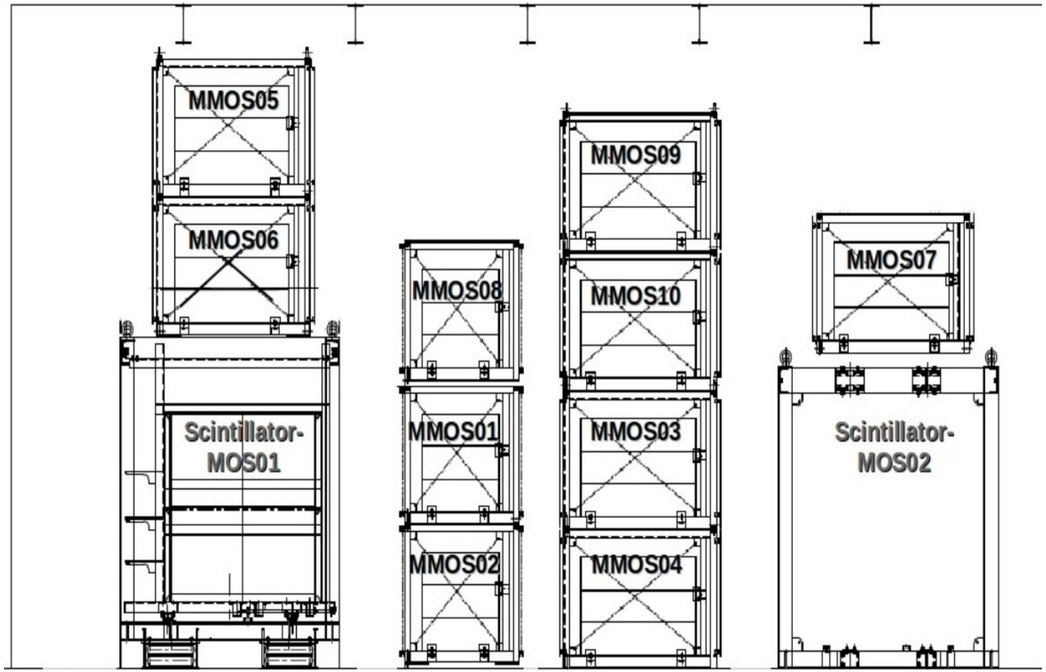

A
50 km
B
10 km
D
Crater Showa
900
800
700
600
500
400
300
200
100
Altitude [m]
Foreground rock
mMOS
c
d
Horizontal distance [m]
0
500
1000
1500
2000
2500
3000
3500
(北岳)
1117
1110
中岳
1060
Showa
A
B
1000 m
800 m
a
b
南岳
600 m
400 m
200 m
有村町
東桜島町
c
mMOS
C
1 km

Our detectors @ Sakurajima volcano

~ 10 m² sensitive area

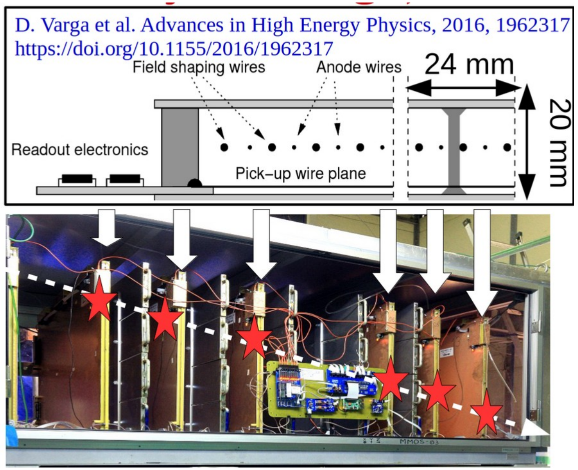
- Low signal (3 Hz) for a detector
- MWPC detectors
- Cost effective

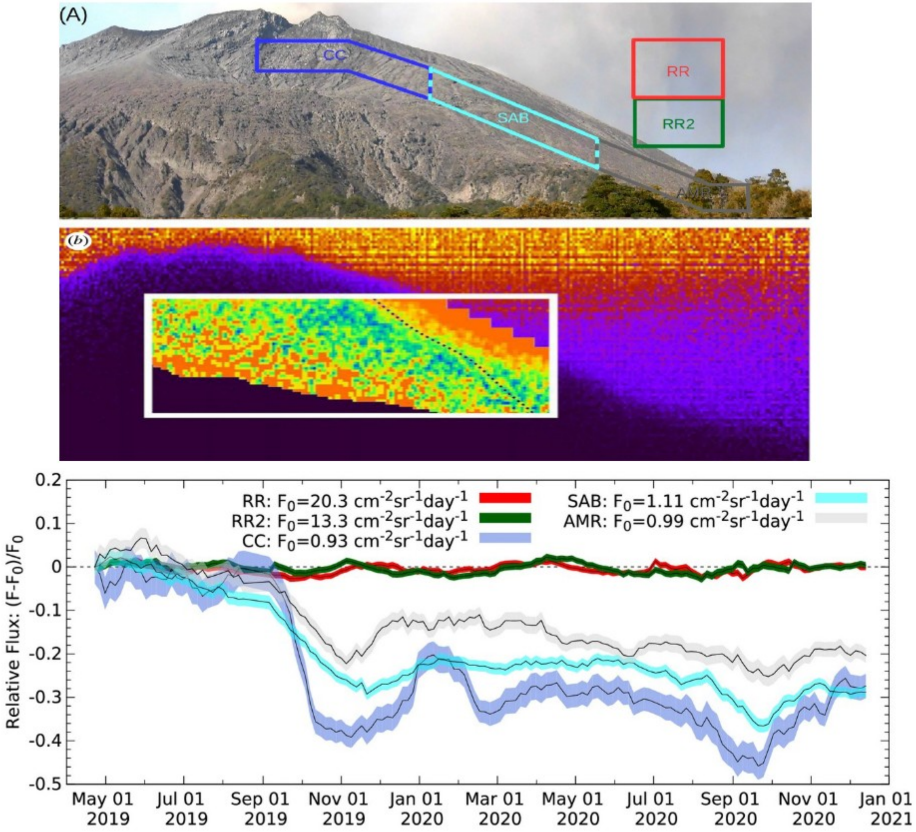




Our detectors @ Sakurajima volcano

- 4 years of data
- Challenge: no spectrometer
- ~10 m resolution @ volcano



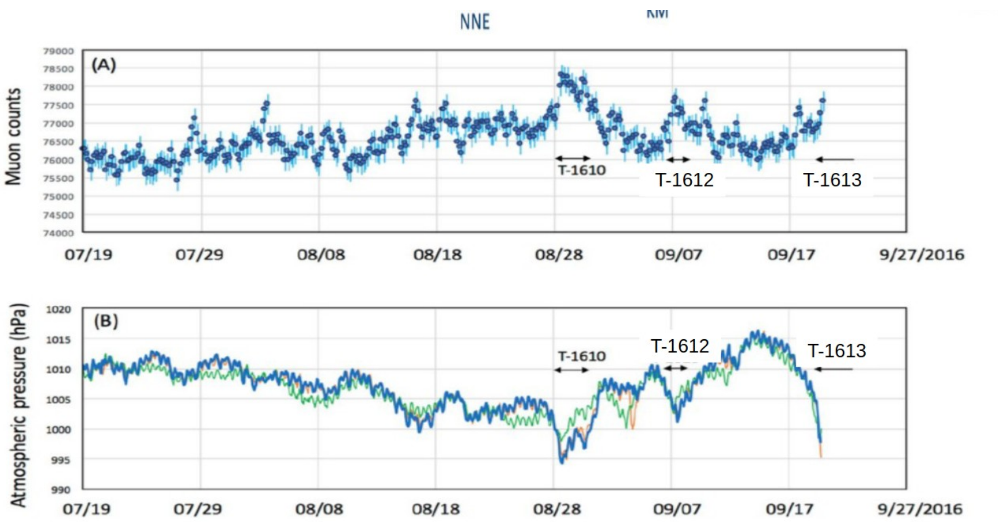


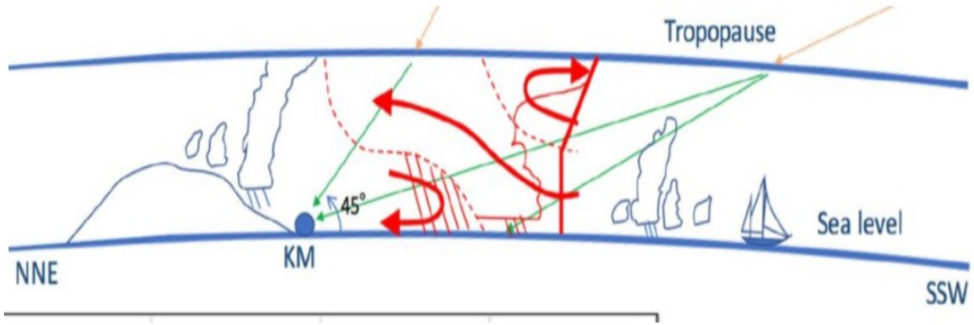
L. Oláh et al. Scientific Reports, 8, 3207, 2018,

https://doi.org/10.1038/s41598-018-21423-9

Muography of cyclones

- Increased pressure yields more μ decaying
- Low pressure → more μ
- 1 % pressure drop result in 2 % flux increase

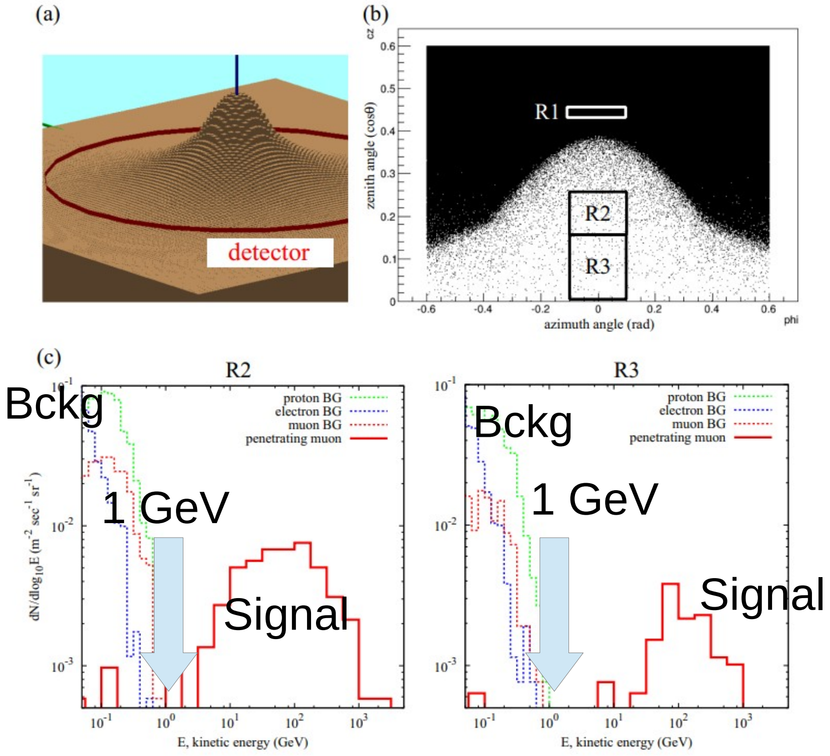




Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4

Backgrounds in volcano muography

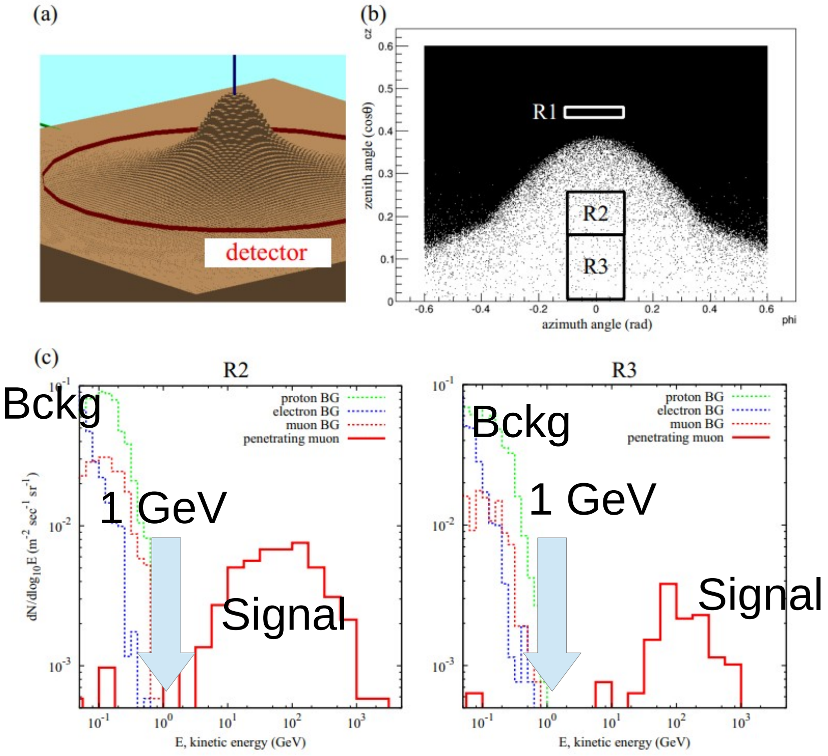
- Background depends on
  - Detector
  - Thickness of vulcano
  - Elevation angle
- R. Nishiyama et al. (2016) simulated a realistic background for a vulcano
- R2: 300-600 m rock
- R3: 600-900 m rock



R. Nishiyama et al. (2016)

Backgrounds in volcano muography

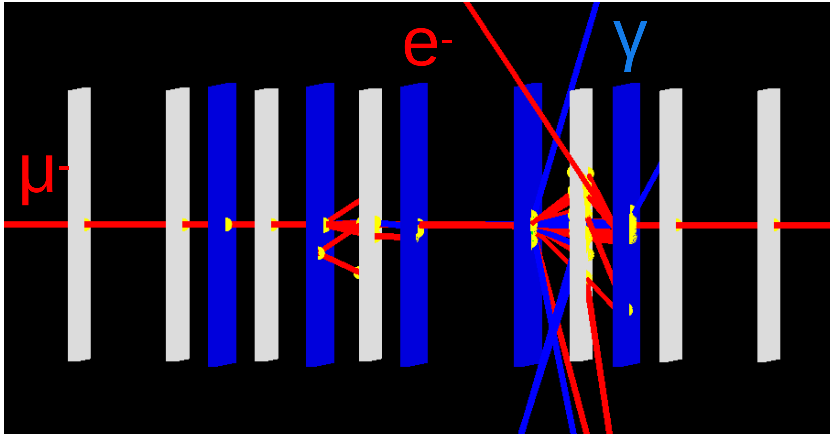
- Background: protons, electrons and muons (hadronic origin)
- IF we could use a cut at ~1 GeV there would be almost no background!
- In our detetors due to absorbers very suppressed total background:
  - ~~Electrons~~
  - Protons
  - Scattered muons



R. Nishiyama et al. (2016)

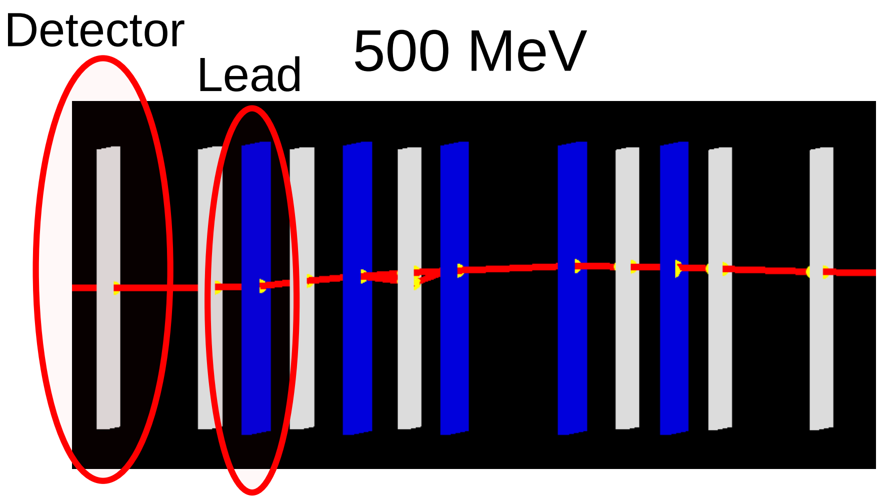
Geant4 simulation of the MOS-08

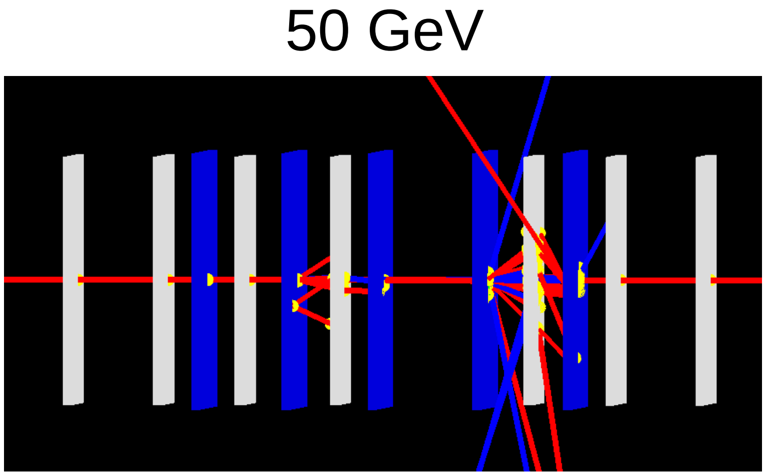
- Dedicated simulation developed
- Gas volume voxelized
- Output of simulation is in same format as the measurement pipeline
  - Important for testing the tracking algorithm
- Output analyzed with same tracking algorithm (N-1 point χ^2)



- Some “detector” effects are very hard to simulate → take the distribution from measurements

Muon energy dependent features

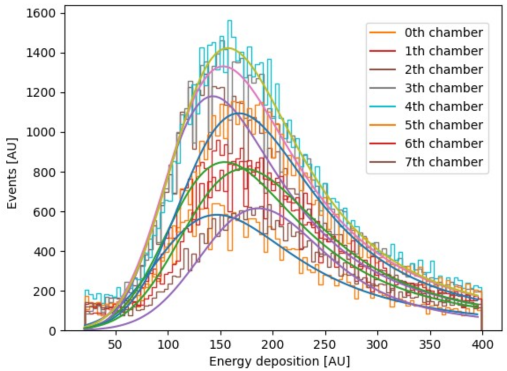


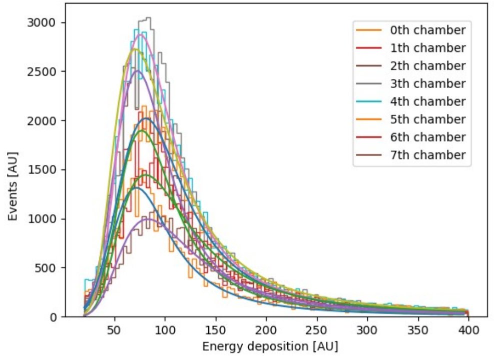


- Scattering   (used by χ^2 algorithm)
- Secondary creation:
  - Energy deposition (NOT used by χ^2 algorithm)
  - Lots of clusters (NOT used by χ^2 algorithm as input)

Detector effects

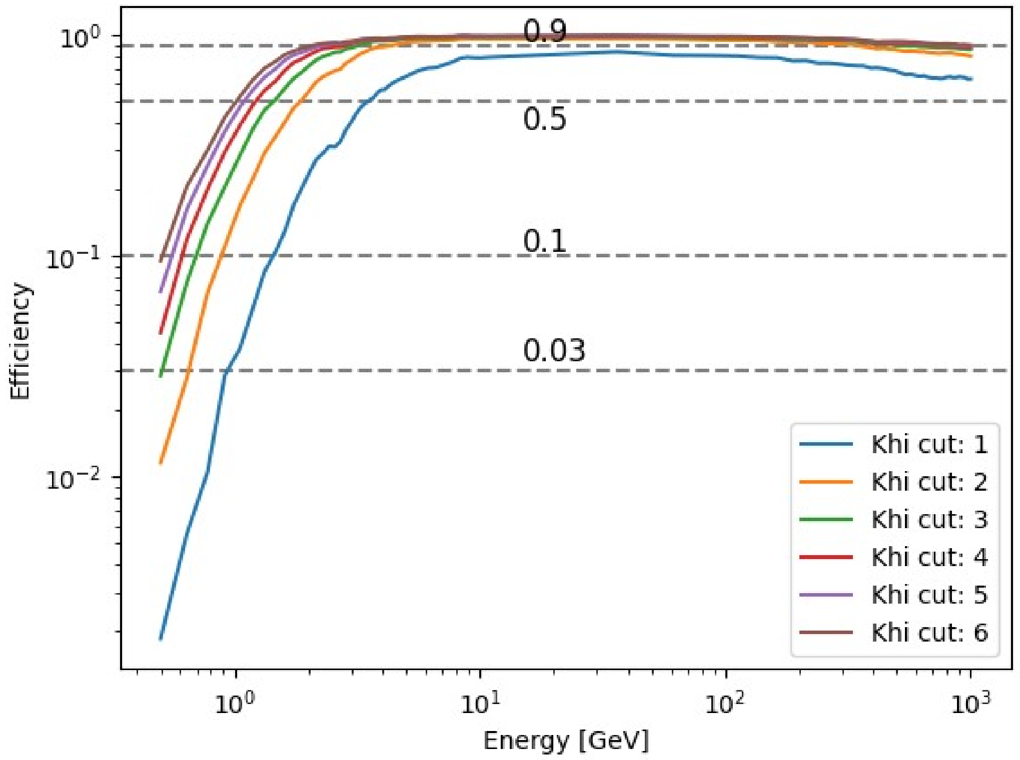
- Need to include these in the simulation to reproduce measurements
- Cluster size
- Gain changes:
  - Changing weather
  - Non homogenous gain (due to wires)
- Important for Machine Learning!





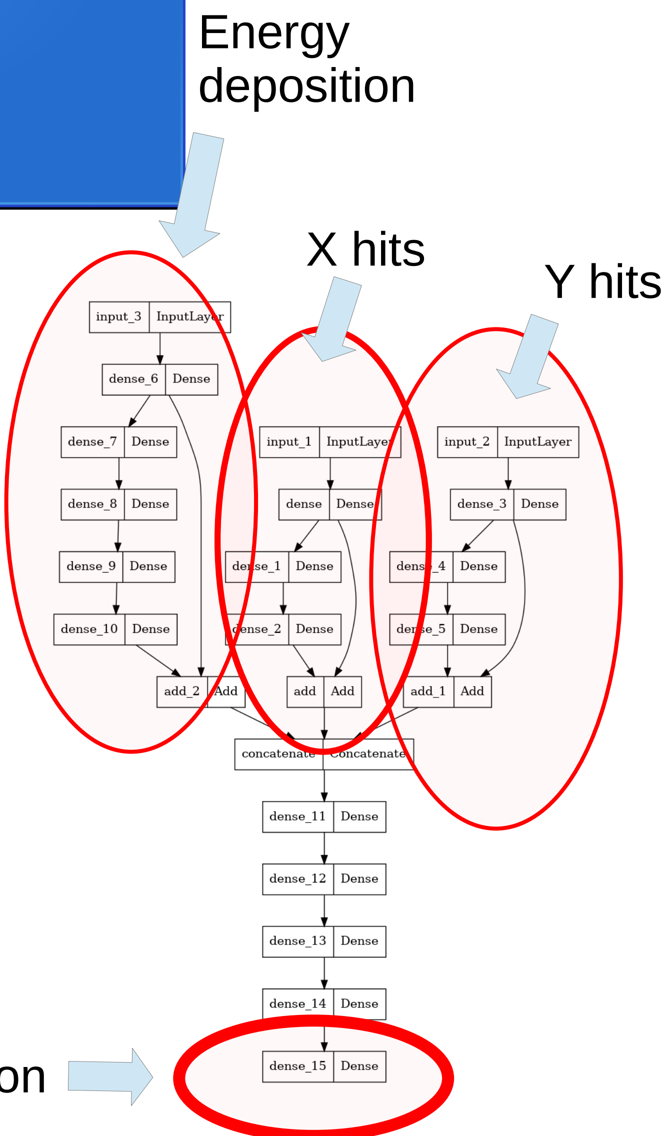
Testing the tracking algorithm

- Simulation data
- Different χ^2 cuts shown
- χ^2<4 cut is used in this talk
- Suppresses 0.5 GeV muons with 95% chance
- ~98% efficiency @ 5 GeV
- ~90% efficiency @ 1 TeV



Neural network

- Used together with χ^2 algorithm → Direction
- Binary classification:
  - Was the muon above a certain energy (5 GeV used in this presentation)
- Residual layers for robustness
- Decouple the information sources
- Output: score (1 double) ~ probability of belonging to one class (it's mapping)
- Three subnetworks:
  - X direction (8 x 64 wires, 0 or 1 – hit or not)
  - Y direction (8 x 64 wires, 0 or 1 – hit or not)
  - Energy deposition (8 double)



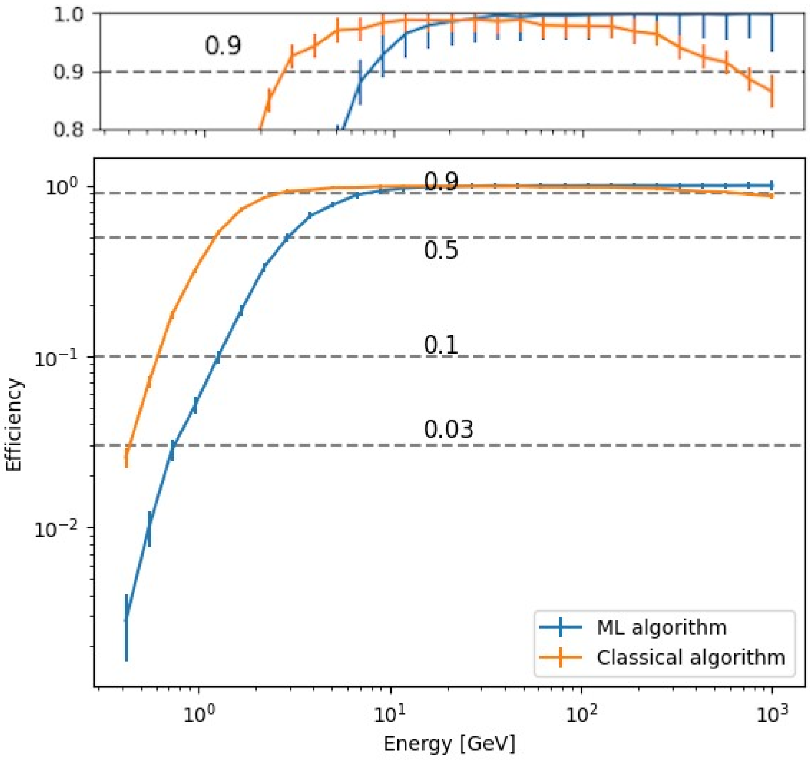
Final decision

Teaching the ML

- ~ 1 day on a single GPU
- 20 million muons
- 12 GB of events data
- Accuracy: 0.900
- Most used metric for classification AUC = 0.952

Results of the ML

- Cut at score 0.4
- Cut can be tuned on demand
- Suppresses 1 GeV protons
  - 6x more then $\chi^2<4$ algorithm
- ~99.5% efficiency @ 1 TeV

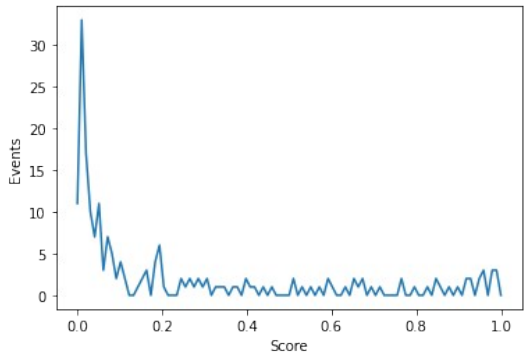


What does the ML predict to measurements?

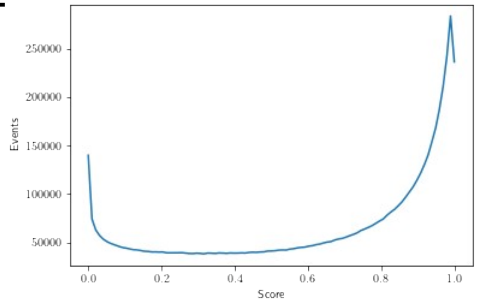
- Measurements taken

  @Sakurajima
- Score distribution

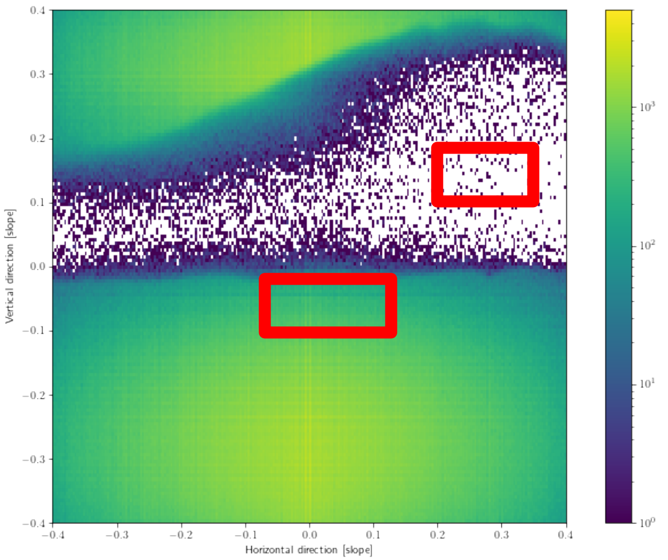
  for different regions
- Middle of the mountain
  - 7 km of rock → Only low E
- Open sky ~ horizont
  - High E



Middle of mountain



Open sky → High energy

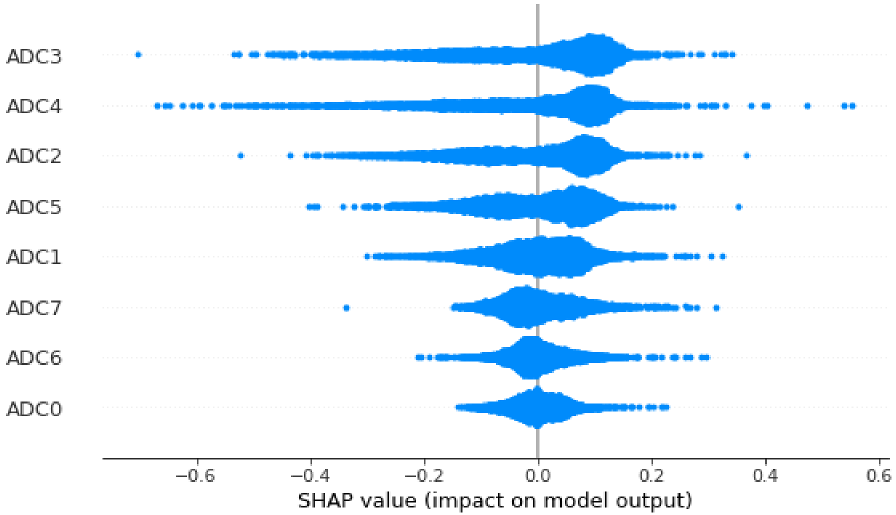


3.5 years of data analysed with χ^2
MOS-08@Sakurajima

Interpretibility – SHAP values

- Tool to understand most ML algorithms
- From game theory
- Lloyd Shapley, Nobel prize
- Remove a subset of inputs

  calculate the output of the model
- Additive values
- Energy deposition after lead absorbers are used mostly



$$\Phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N|-|S|-1)!}{|N|!}(v(S \cup \{i\}) - v(S))$$

Conclusion

- Designed a detailed Geant4 simulation of MOS system
  - Included detector effects (changing gain, cluster size)
  - Tested the classical tracking algorithm
- Designed a dedicated Deep Neural Network to classify low vs. high E muons
  - Taught the network with simulation data
- The neural network:
  - Suppresses low energy muons better than χ^2
  - Identifies high energy muons with complicated clusters better than χ^2
- Applied the ML to measurements taken at Sakurajima:
  - The preliminary results agree with the expected tendencies

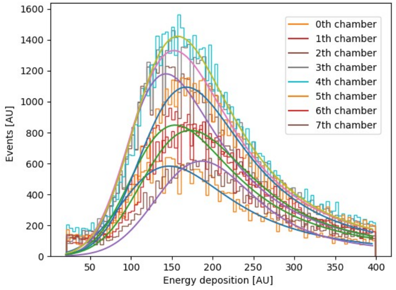
Outlook

- Try additionals models:
  - GNN (working @ IceCube)
  - Vision transformers
- Optimize the geometry!
- Test the machine learning with measurements:
  - Dedicated measurements to collect muons with known energy bands
- Could the lessons learned from ML be used in classical tracking?
  - E.g. Use cut on number of wires fired besides using χ^2
- Perform anomaly detection on Sakurajima data to look for vulcanological events in the last 4 years


That's all Folks!
SUPERB wallpapers

Simulations, detector effects

- Need to include these in the simulation to reproduce measurements
- Important for Machine Learning!
- Read out electronics:
  - 2 or 3 wires / pads connected for cheaper readout
- Gain changes:
  - Changing weather
  - Non homogenous gain (due to wires)



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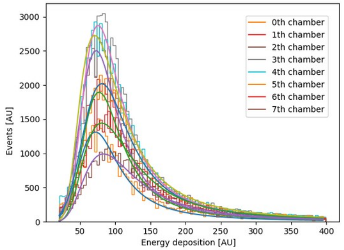
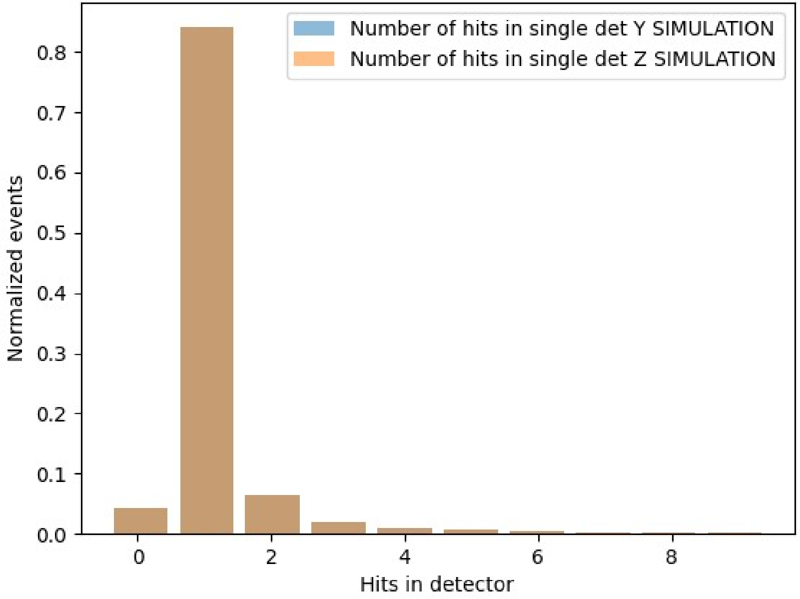


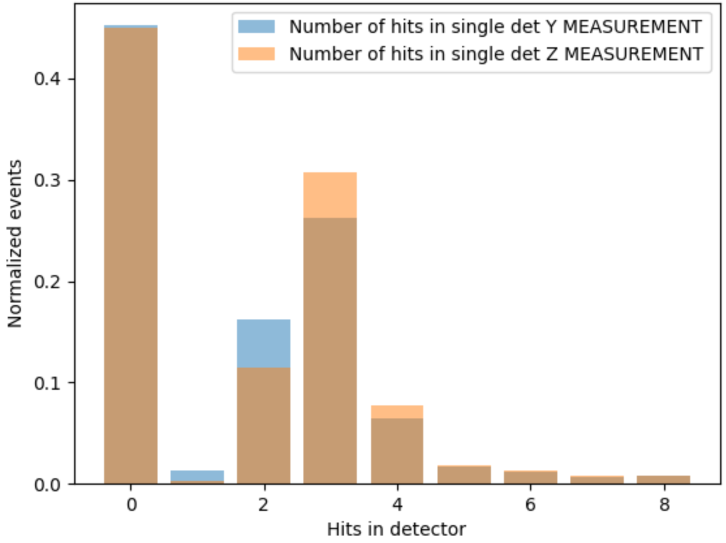
16/11/2019

Number of fired wires per layer

Simulation before including detector effects

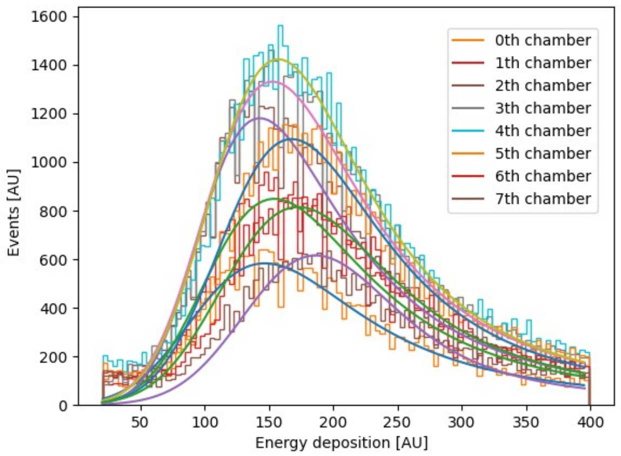


Measurements



Changing gain

- Fitted Landau distribution to the energy deposition for every ~ 2 hour
- Scaled measurements to simulation for ML



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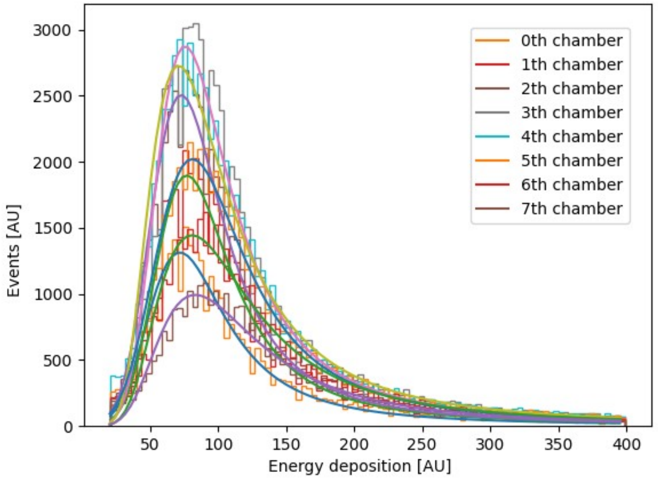

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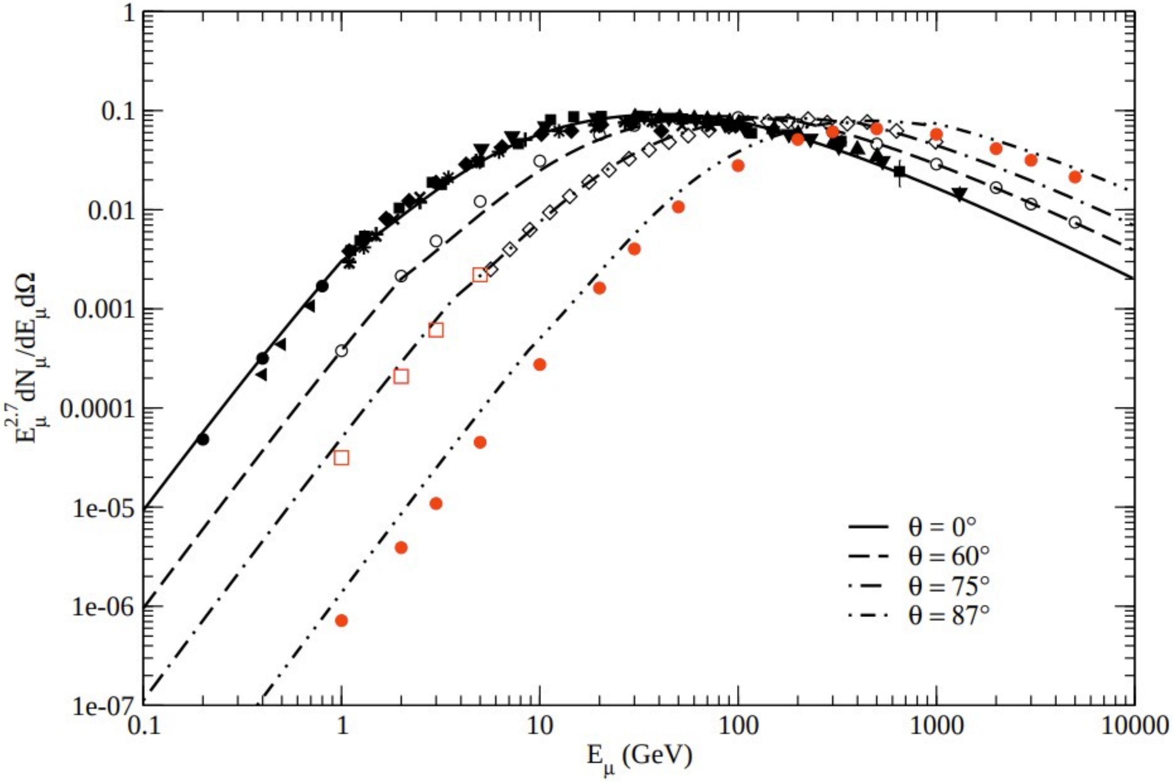
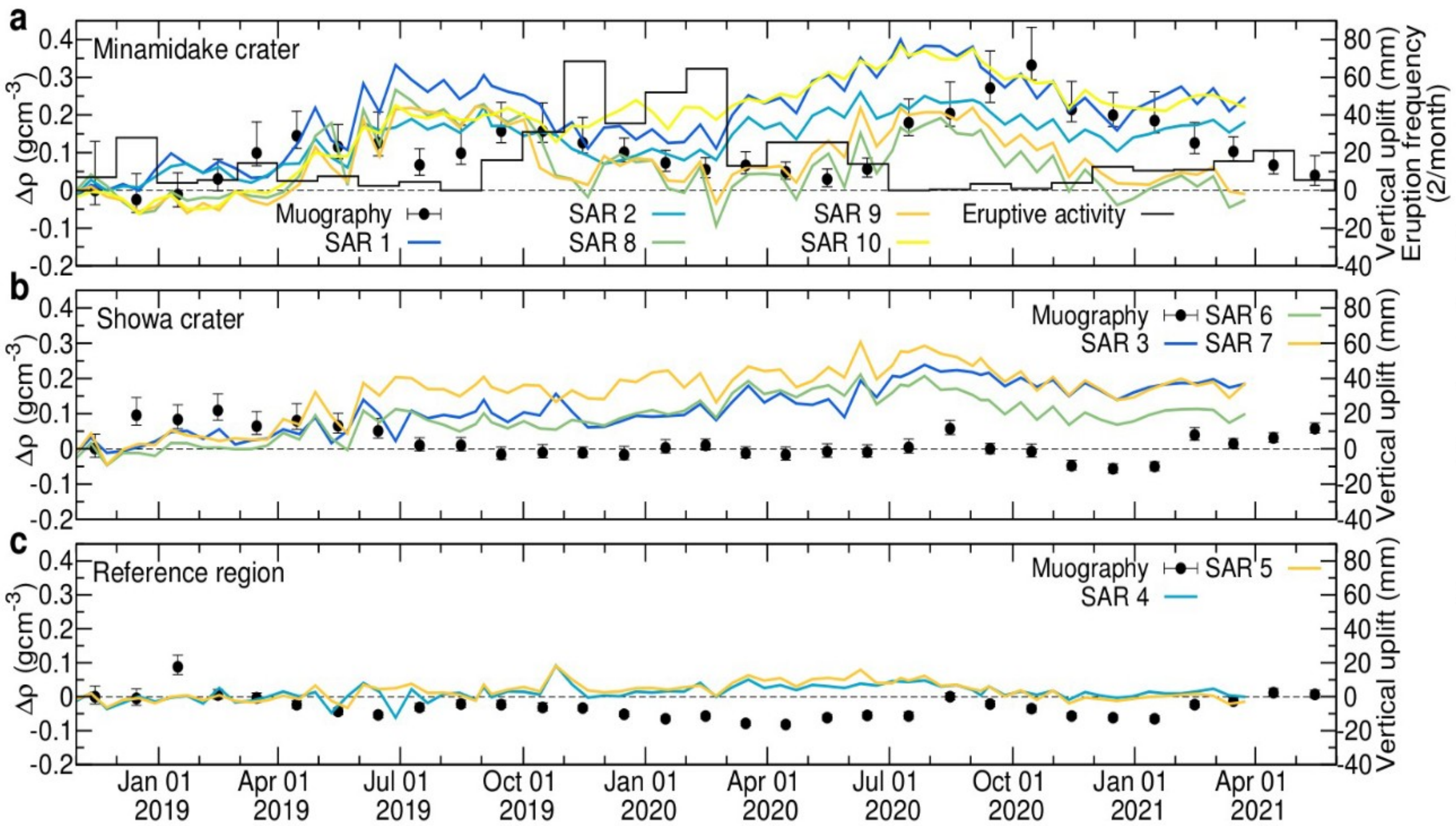
Modified Gaisser dist.

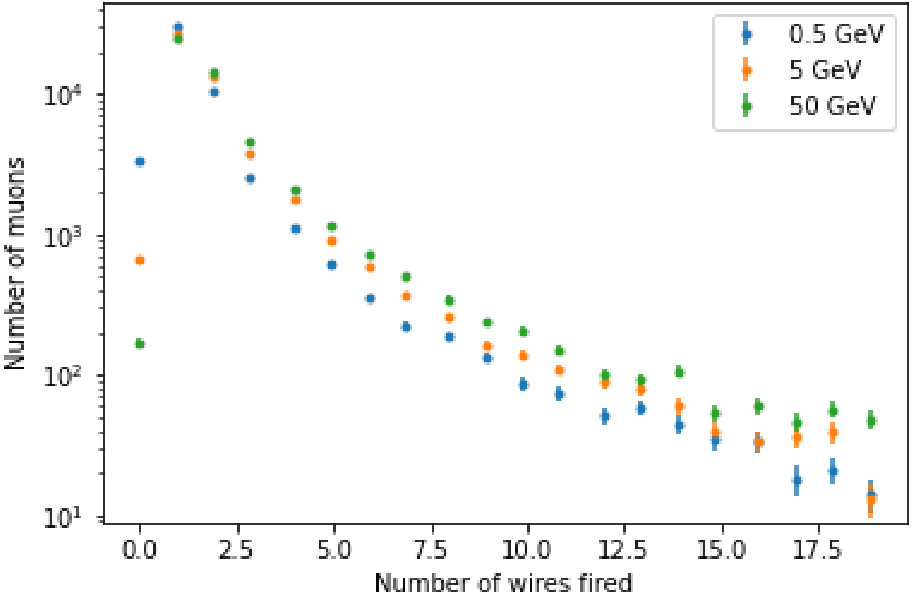
- Muon flux for diff. E




a
Minamidake crater
Δρ (gcm-3)
Vertical uplift (mm)
Eruption frequency (2/month)
Muography
SAR 1
SAR 2
SAR 8
SAR 9
SAR 10
Eruptive activity
b
Showa crater
Muography
SAR 3
SAR 6
SAR 7
c
Reference region
Muography
SAR 4
SAR 5
Jan 01 2019
Apr 01 2019
Jul 01 2019
Oct 01 2019
Jan 01 2020
Apr 01 2020
Jul 01 2020
Oct 01 2020
Jan 01 2021
Apr 01 2021

Muon energy dependent features

- A dedicated simulation to understand effect of muon E on secondary detection
  - One 2 cm lead and 1 detector
- Secondary creation:
  - Number of fired wires
- For high E many clusters
  - “Bad” for χ^2 algorithm (lot of clusters)
  - “Good” for ML

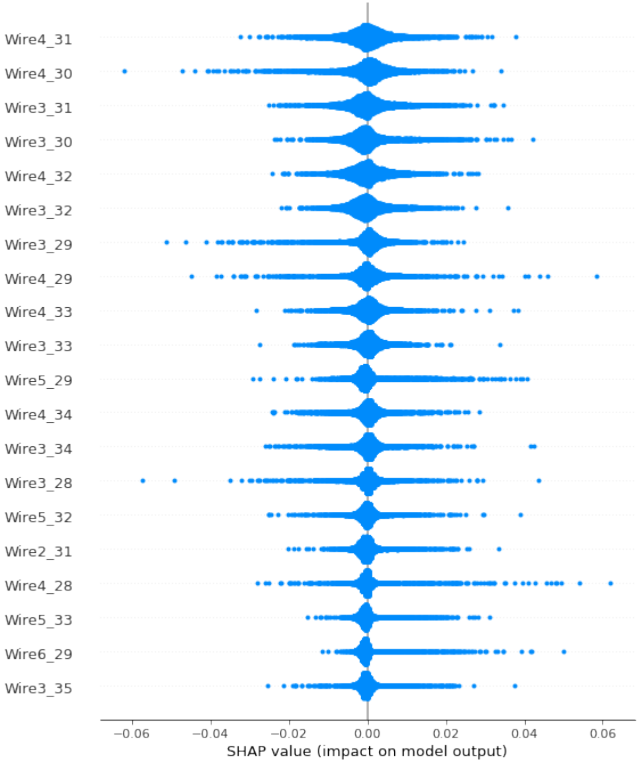


Highlights

- The ML presented is used for volcano muography
  - Special use case: signal is very low for ~200 m rock thickness
- Pros:
  - Lots of data: ~ 4 years measurements 10 m^2 at Sakurajima volcano alone
- Cons:
  - No Measurements with KNOWN primary muon energy not taken
- Personal experience:
  - detector effects are very important

SHAP values for wires

Y wires



Y wires