MUOGRAPHERS 2026

This international conference serves as a platform for presenting new discoveries and innovations, and for discussing future directions in muography.

BUDAPEST, 1-5 JUNE

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Muography detectors

Dezső Varga
HUN-REN Wigner Research Centre for Physics

Muographers 2026 – Muography School
1st June, 2026, Budapest

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA
MŰEGYETEM 1782
DRD1 Gaseous Detector Technologies
NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE HUNGARY
PROJECT FINANCED FROM THE NRDI FUND

Summary (anticipated)

- Introduction: instruments of an applied science
- Trackers in high energy physics experimentation
- What is fundamentally different from HEP
- Interaction of matter and particles: detection principles
- Background sources and mitigation
- Muon flux determination, detector characterisation, performance evaluation and monitoring

Detectors introduction

- Detectors originate from high energy physics instrumentation...
- .. but very different requirements! Most relevant conditions and parameters to consider in muography:

  -- Detector total area (flux precision)

  -- Efficiency (flux systematics)

  -- Angular resolution (imaging capability)

  -- Underground background and on-surface background

  -- Environmental conditions (temperature, humidity)

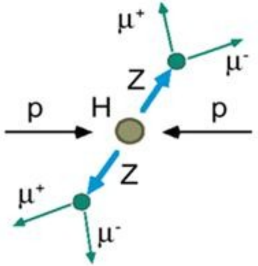
  -- Maintenance, cost and consumption (power, gas...)

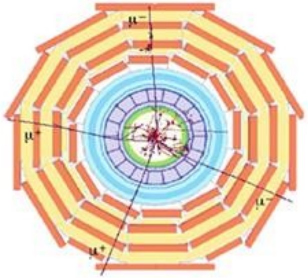
  -- Data acquisition, compression and transfer

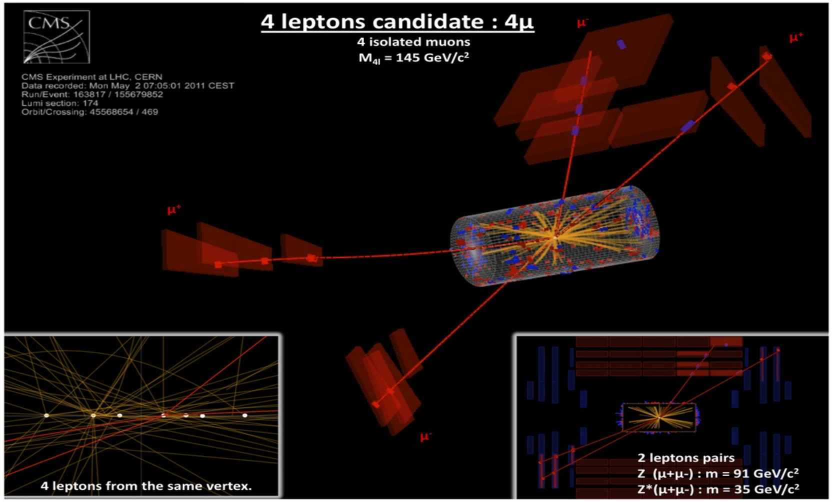
The “golden channel” of discovery:
Higgs → 4 muons

Nobel prize:
2012

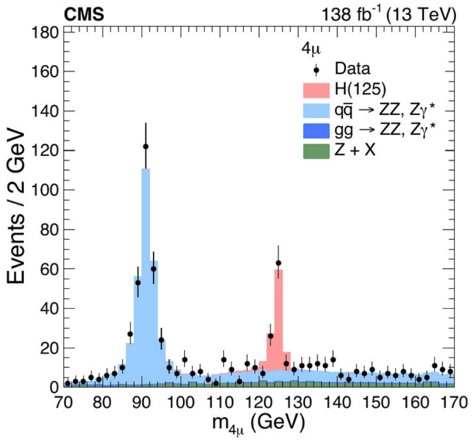
Muon signal particularly clean due to high penetrating power of muons



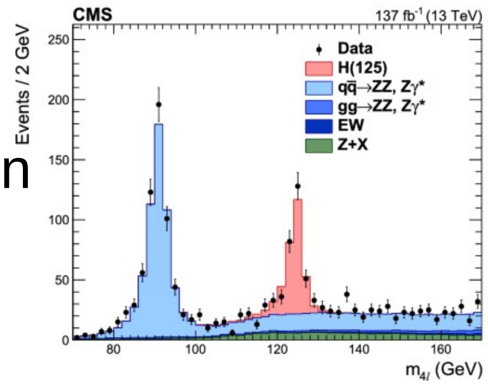




Muon only



Any lepton pairs
(e or mu)

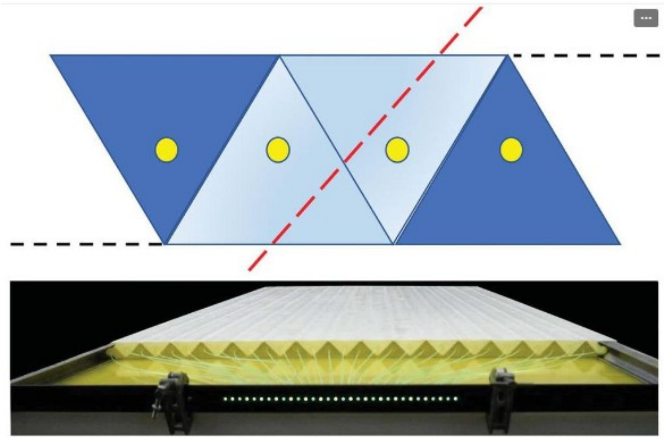


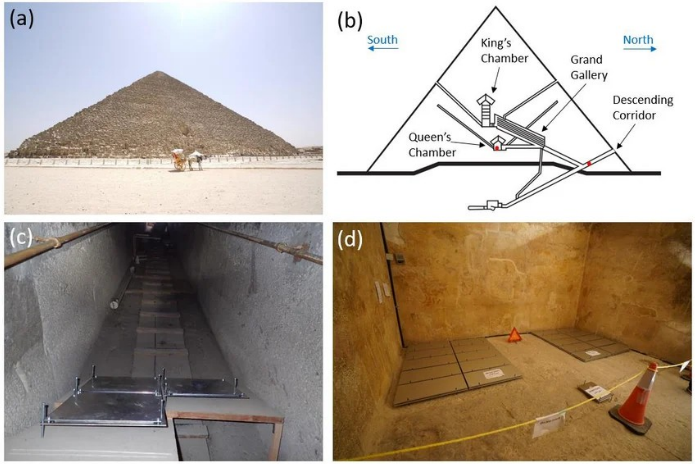
Cosmic muon detectors: “trackers” used in High Energy Physics

- Scintillators: robust, reliable, high efficiency, moderate resolution

- Gaseous: more complex, high resolution, cost efficient

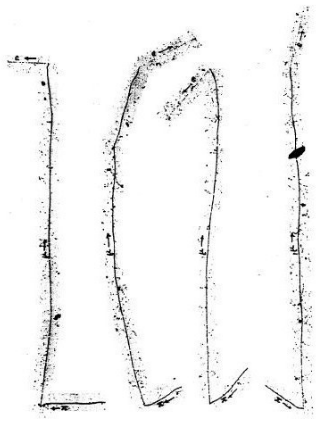
- Emulsions: easy deployment, high resolution, only time integrated

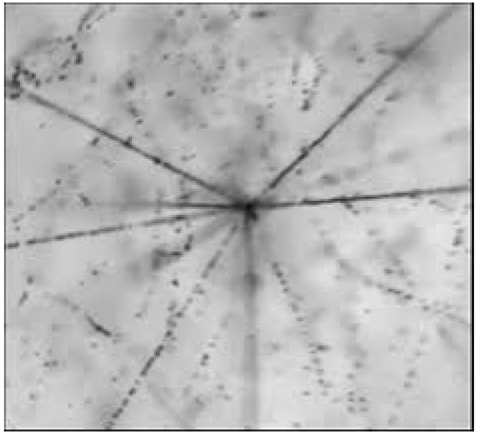


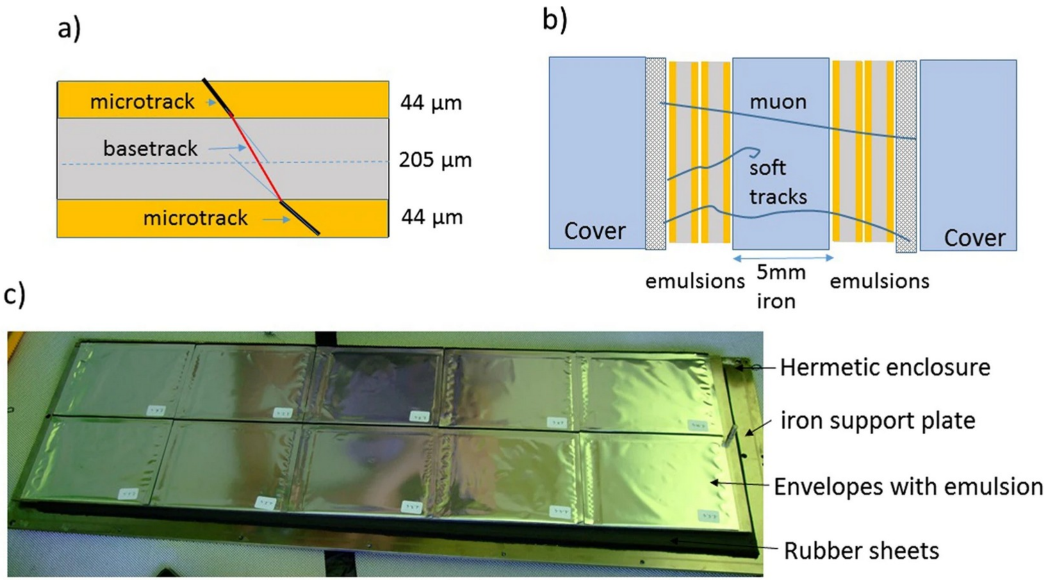


Nuclear emulsions

- Similar to the photon-sensitive material used for a century. Experiences a new renaissance (improved materials, image data processing) particularly in neutrino physics
- Can reach precision of a few 100nm!

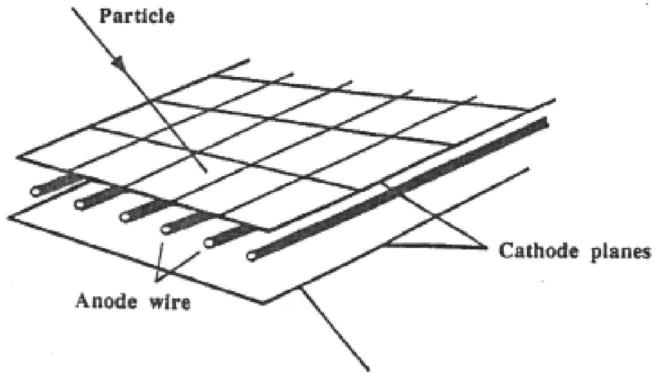


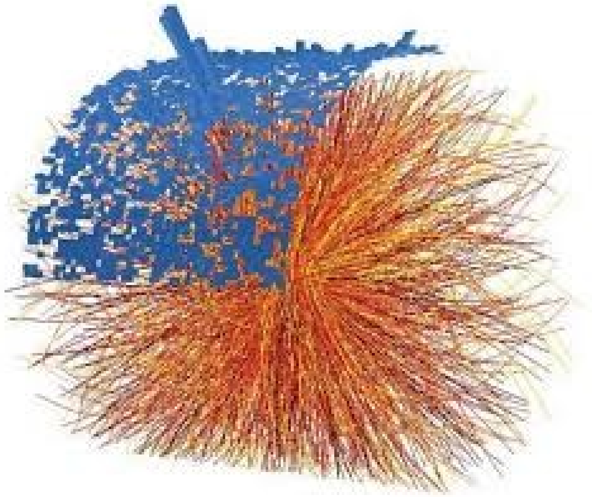




Gaseous tracking detectors

- Tools developed during the “electronic revolution” of particle physics (Nobel prize Charpak 1992)
- Can be constructed in various forms and for various precision requirements and sizes





DRD1
Gaseous Detector Technologies

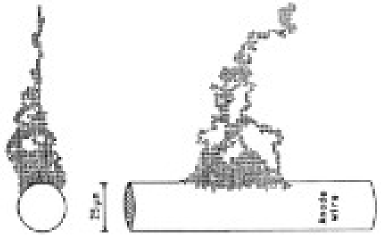
CERN-initiated Collaboration for the development of gaseous detectors in HEP and beyond

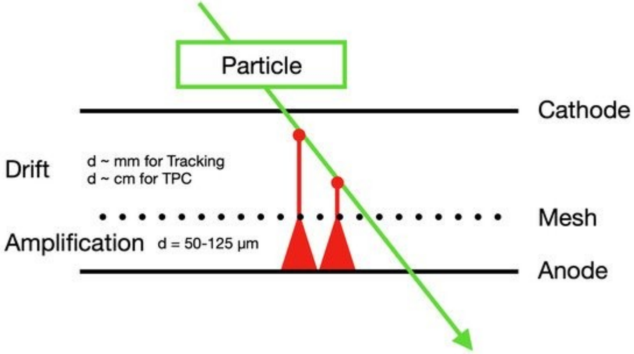
Gaseous detectors principles

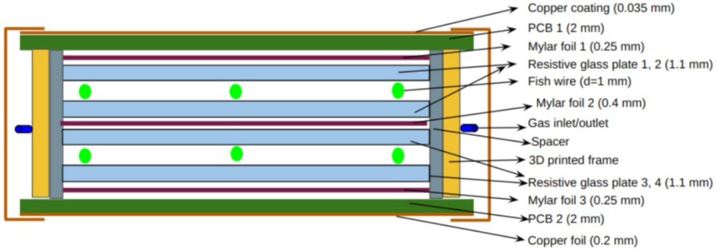
(1) Guiding electron drift (usually between parallel cathode plains)

(2) Avalanche formation

- MWPC: thin anode (positive) wire
- MicroMesh: parallel mesh
- RPC: “spark”-like avalance between precisely parallel plates

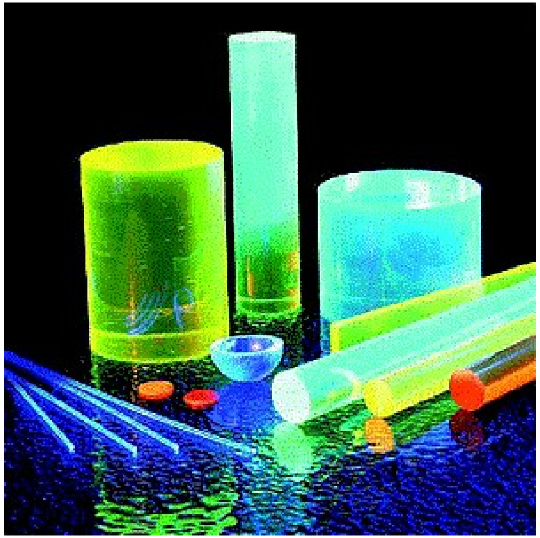






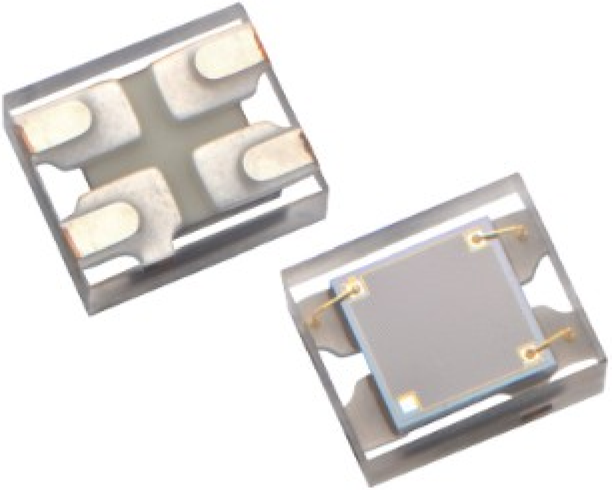
Scintillator detectors

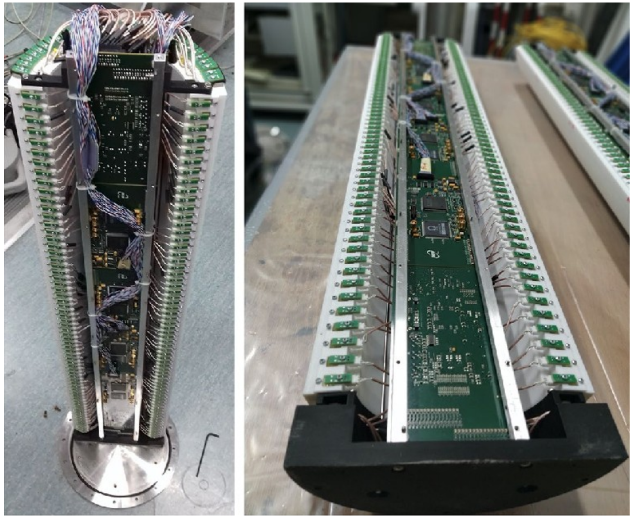
- Light (from ionization) created in a few cm thick transparent plastic layer
- Usually very reliable, technologies well understood



Scintillator readout: PM vs. SiPM

- Silicon Photomultipliers (SiPM-s) apparently quickly replace classical vacuum-based PM-s
- Small area poses challenges – improved light collection, or wavelength-shifting fibres are needed
- Temperature dependence can also be a challenge, due to increased noise



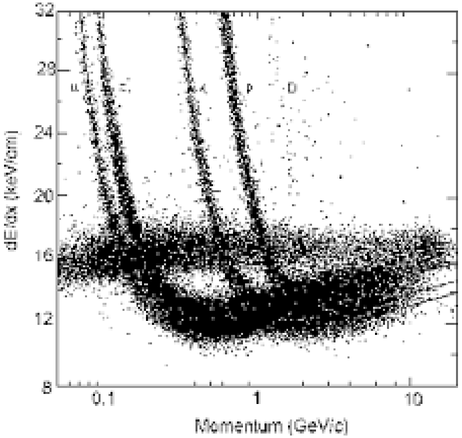


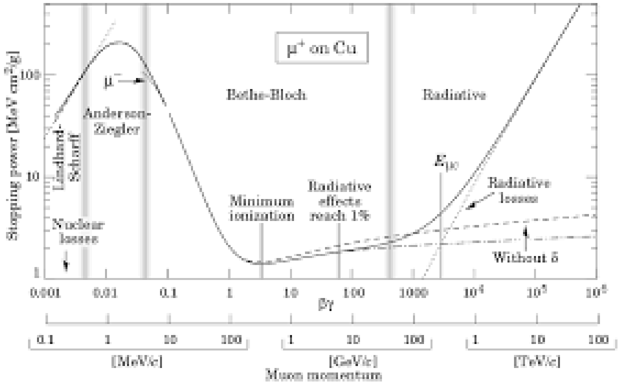
Interaction of muons (particles) with matter

- Muon detection most relevant method: ionization
- Ionization basics, MIP, typical forms
- Stopping power -- energy cutoff (GeV range)
- Electrons and EM showers, effects in detectors
- Scattering of muons

Interaction with matter: **Ionization**

- **Includes all kinds of atomic energy transfers, interaction with electron shells**: electron release, excitations (relevant for noble gases, for example), charge rearrangement, hole/electron pairs in semiconductors
- **Ionization is a small, nearly constant energy loss** (few MeV/cm in solids): this is why muons can travel far
- **Minimum Ionizing Particle, MIP**: at sufficient sensitivity ALL charged particles can be detected. This is a key design feature of detectors. **Cosmic muons are nearly always appear as MIP**.
- Depends approximately only on **DENSITY.** In “average” rock, around 0.5 GeV/m





Forms of ionization

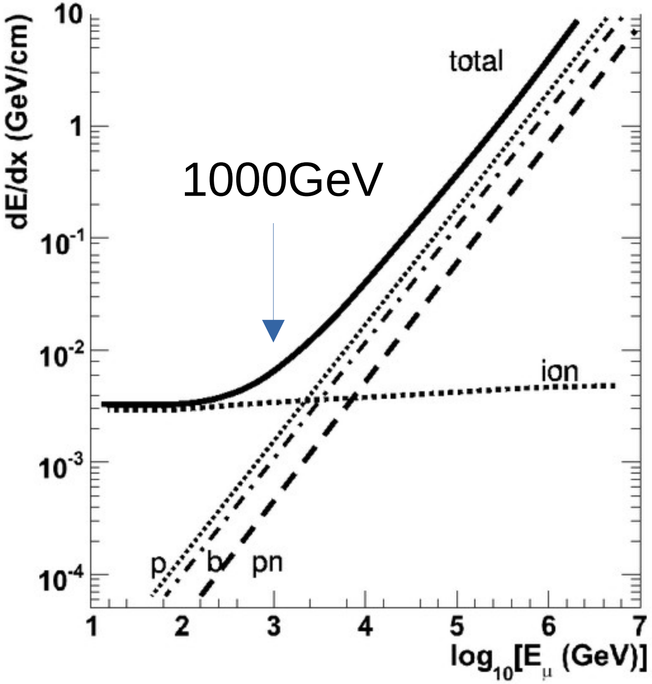
- True **ionization** process (creating ions or electrons): in solids around 10 electrons / micron, in gases 100 e/cm
- **Scintillation**: light creation due to atomic de-excitation. Requires special additions to the transparent material. Order of 1000 visible photon / MeV, and usually pretty fast (ns)
- **Semiconductors** electron / hole pair (few 10 pairs / micrometer)
- Energy deposit and nucleation **in nuclear emulsions**

Stopping power: total enegy loss

- At lower energies (below 1000GeV, 500m rock length) ionization is dominant. This is constant energy loss, depends **only on density**
- Higher energies radiation becomes dominant (Brehmstrahlung, see later: proportional to energy)

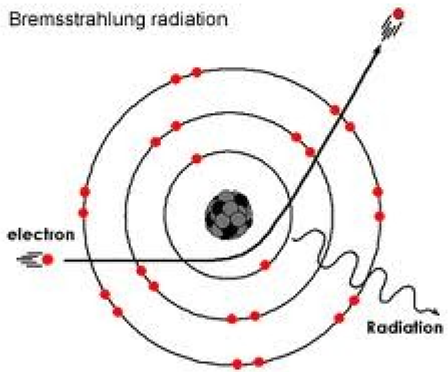
$$dE/dx = A + B*E$$

(x is path length)


1000GeV

Parameter **A:** “Average” rock **approx. 0.5 GeV/meter**

Brehmstrahlung (“breaking radiation”)

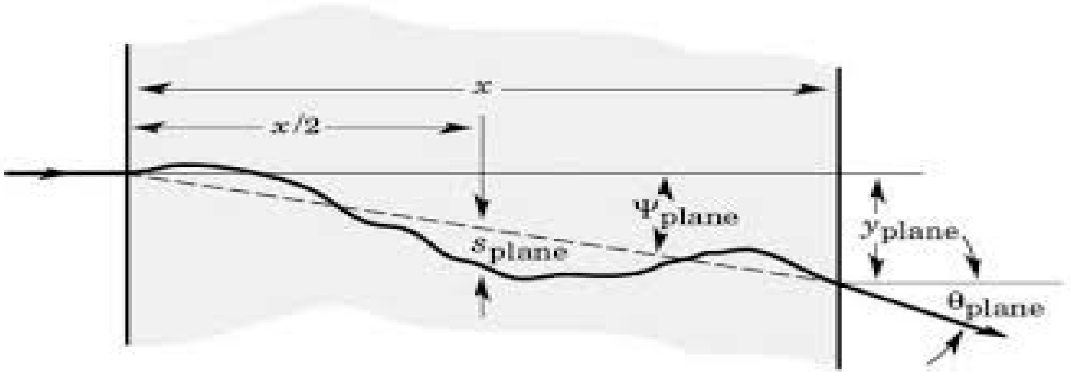


- Still the German term is used generally
- Mainly important for **electrons. Relevant for high energy muons (above 500m rock length)**
- Critical energy: where the ionization and the BS is approximately the same, e.g. 50MeV for electrons, 400GeV for muons
- Radiation length is strongly material dependent! Goes with $1/Z^2$
- x_0 examples: Lead 6mm, “average rock” 10cm, polyethylene 50cm, air 300m

Multiple scattering, MS

- **Slight directional change by Brehmstrahlung and ionization. Nearly Gaussian for fixed energy**
- Proportional to 1/E (reduces with energy) and square root of path length
- Mean scattering angle (in radians) approx. (14MeV)/E*sqrt(X/X0)
- X0 is the radiation length (material dependent)

X0 for lead: 6mm, “average” rock 10cm, iron 4cm, polyethylene 45cm, air 300m



Muography background sources and mitigation (soft EM, low energy muons)

- Underground background from low-E (few MeV) electrons from natural radioactivity

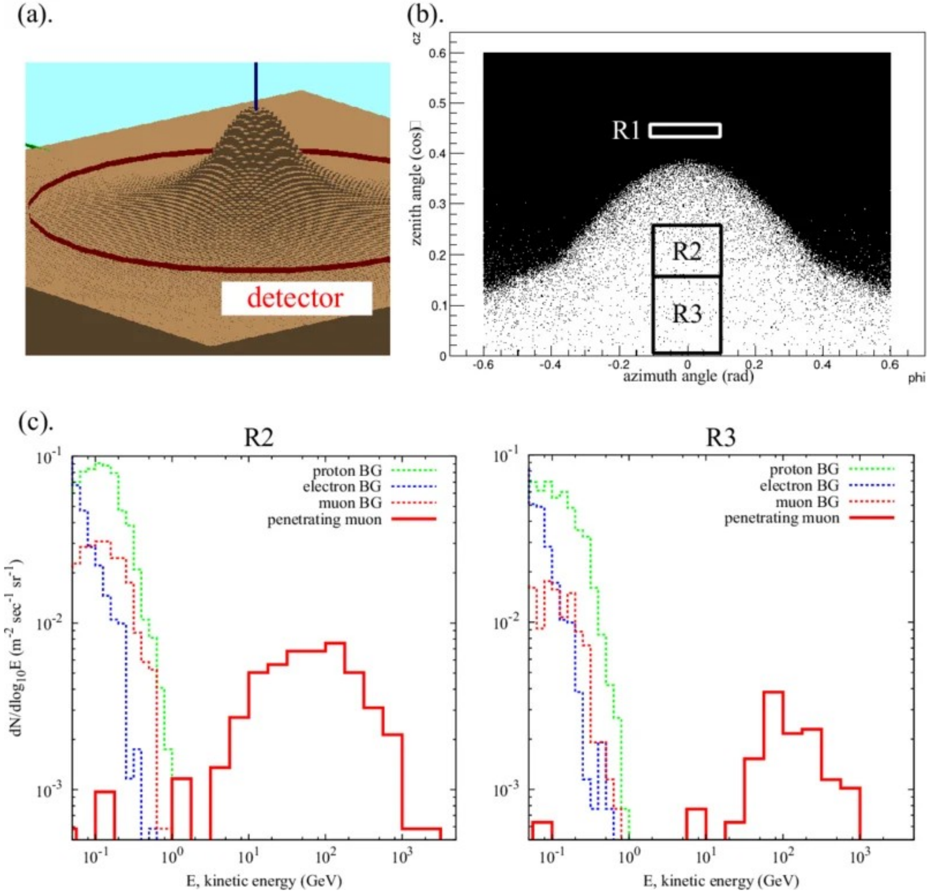
  ==>> high energy cutoff (10MeV), multi-layer

- On-surface background from low-E (up to GeV) muons from shower hadronic interactions

  ==>> high energy cutoff (1 GeV) with thick absorber, scattering material)

Surface-based background: ”low” energy muons

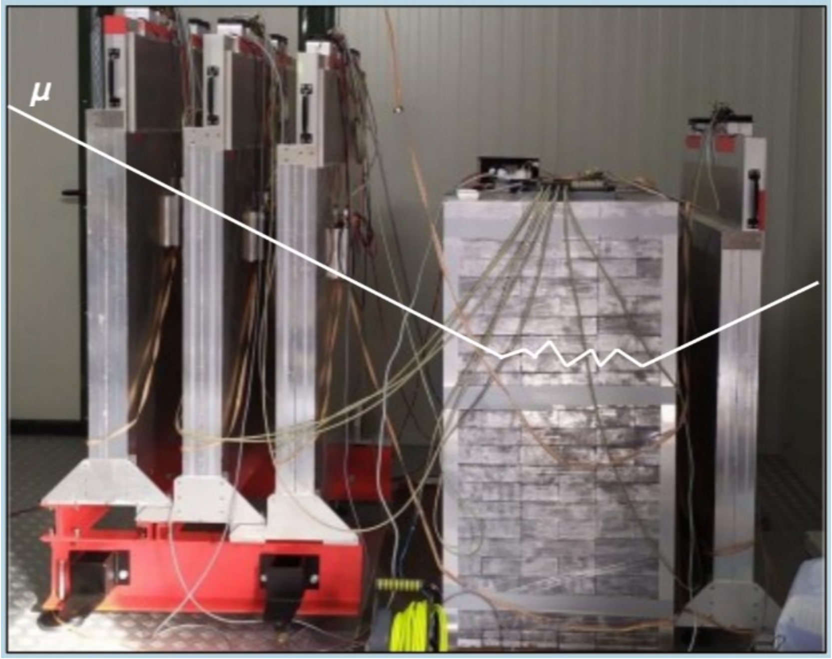
- Background (muons which do not cross the mountain) reach up to 1GeV energy!
- Need to have a high energy cutoff at GeV++



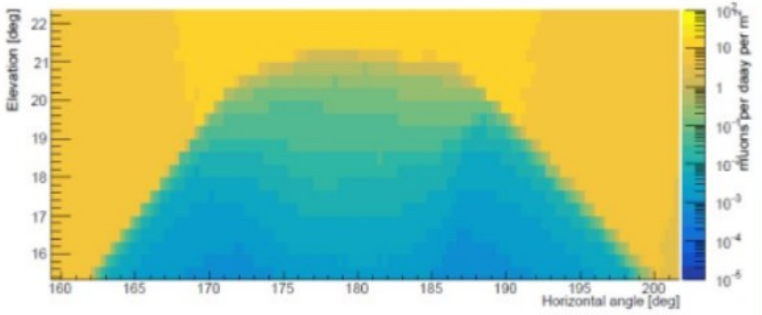
Nishiyama DOI:10.1093/gji/ggw191

Background suppression for surface-based detectors

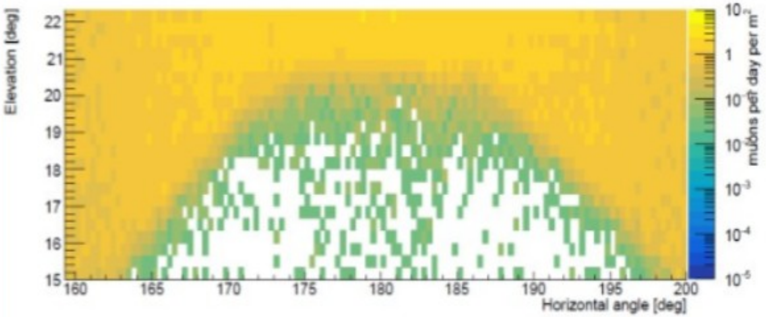
- Sufficiently thick absorber / scatterer (MURAVES example at Vesuvius)
- Veto detector behind absorber



Expected muon flux (PUMAS, taking the lead wall energy threshold into account)

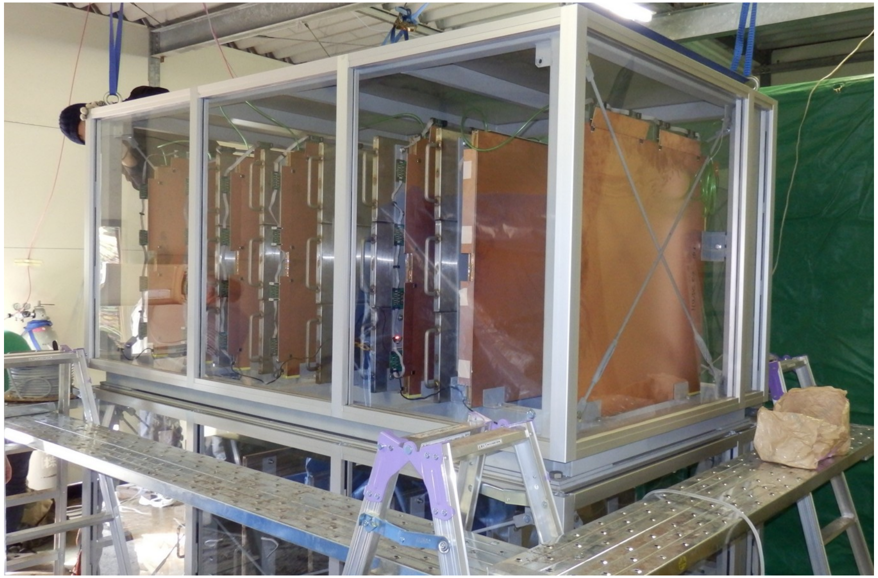


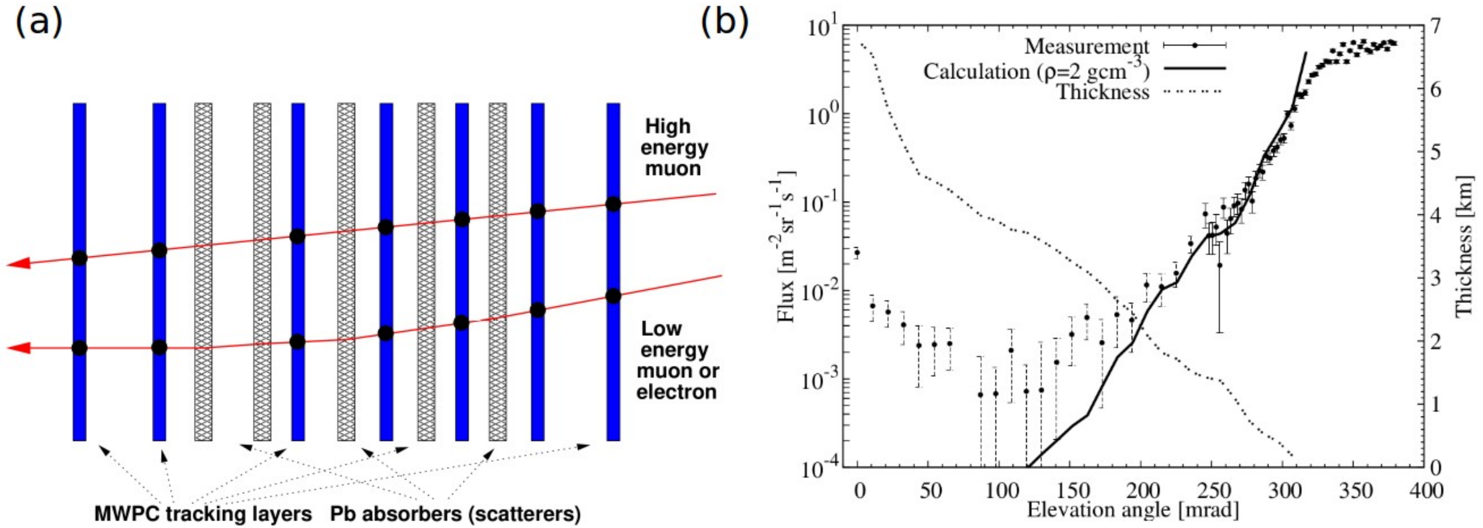
Measured flux obtained from one of the datasets



Background suppression for surface-based detectors

- Scattering material (Pb) layers (Sakurajima Muography Observatory) with good resolution multi-layer detector



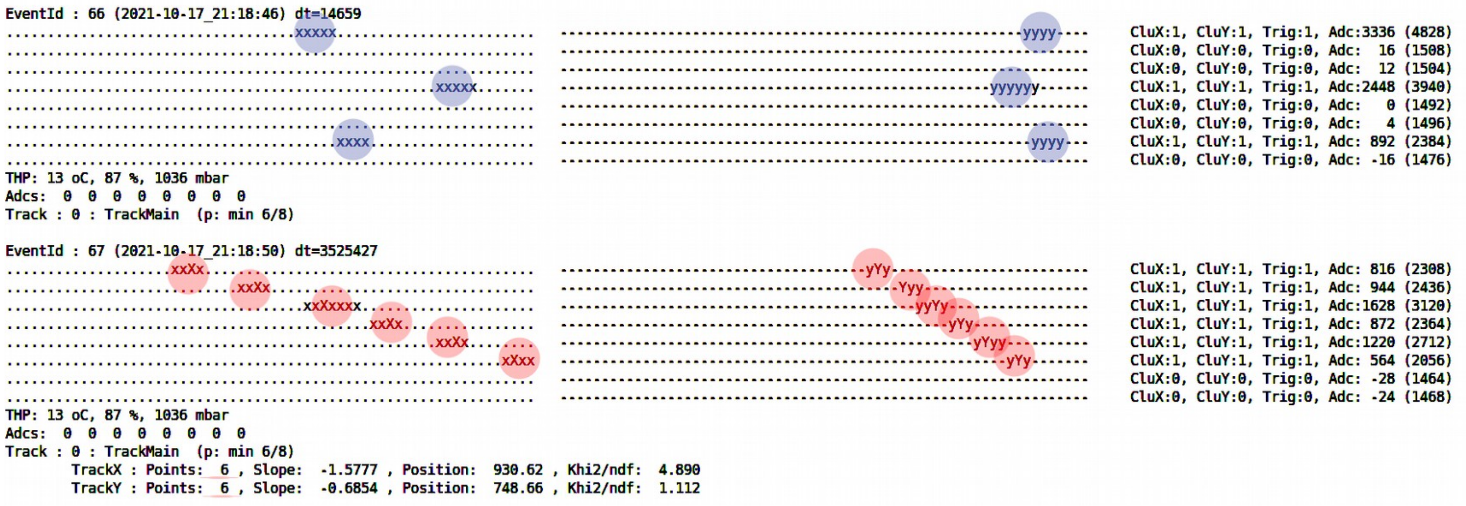


Background suppression underground

- Low energy gamma / electron signals
- Usually non-correlated low multiplicity hits
  (up to 4 hits!)

Background event

Muon track (signal)



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........................................xxxx....................   ---------------------------------------------------------yyyy---     CluX:1, CluY:1, Trig:1, Adc: 892 (2384)
................................................................   ----------------------------------------------------------------     CluX:0, CluY:0, Trig:0, Adc: -16 (1476)
THP: 13 oC, 87 %, 1036 mbar
Adcs:  0  0  0  0  0  0  0  0
Track : 0 : TrackMain  (p: min 6/8)

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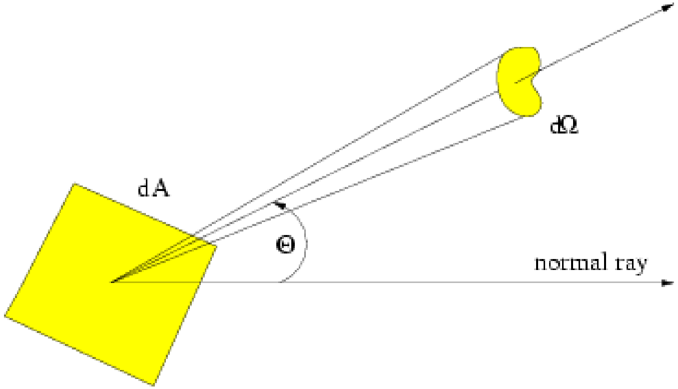
................................................................   ----------------------------------------------------------------     CluX:0, CluY:0, Trig:0, Adc: -24 (1468)
THP: 13 oC, 87 %, 1036 mbar
Adcs:  0  0  0  0  0  0  0  0
Track : 0 : TrackMain  (p: min 6/8)
        TrackX : Points:  6 , Slope:  -1.5777 , Position:  930.62 , Khi2/ndf:  4.890
        TrackY : Points:  6 , Slope:  -0.6854 , Position:  748.66 , Khi2/ndf:  1.112
```

Muon flux: detector indpendent

- Integrated flux definition:
- Integrated flux from measured quantities:
- N_{track} during *t* measurement time within dΩ solid angle, above E_{cut} energy
- dS_n is the effective area (normal to the direction)

$$f=\int_{E_{cut}}^{\infty} J(E)\,de=\int_{p_{cut}}^{\infty} J(p)\,dp$$

$$f=\frac{N_{track}}{t\,d\Omega\,dS_n}$$



Determination of effective area (acceptance)

- Usually the most complicated calculation

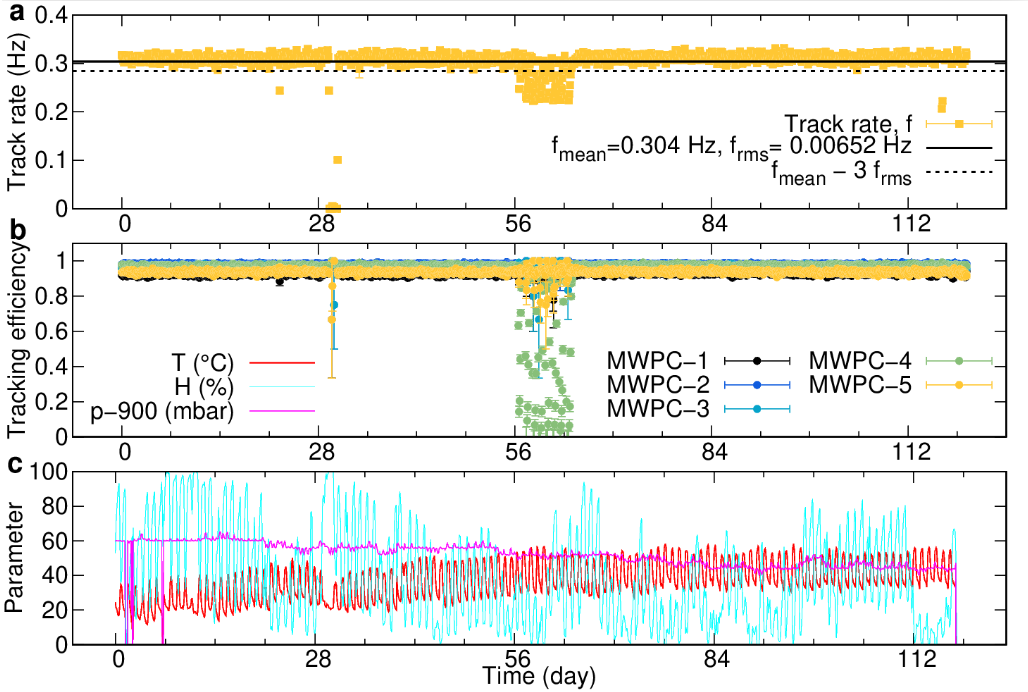
$$dS_n = \cos(\theta) \int_{(S\,det.\,area)} \epsilon(S)\, dS$$

- Integrating over the full detector area the track detection efficiency ($\mathcal{E}$) which depends on position within detector, angle, number of layers crossed…
- (Complications include edge effects, broken channels, sensor borders, estimation of efficiency ...)

Considerations on environmental conditions

Environmental conditions in Oman

- Daily temperature cycling (up to 20 deg) and summer maximum above 50 deg
- Humidity above 90%RH during night



Possible issues related to specific technologies

- Scintillators: temperature dependence of SiPM-s
- Gaseous: gain variation, leakage currents, gas expansion
- Emulsions: high temperature image dimming

Usually, individual technologies find individual solutions, which are not quite transferable among technologies...

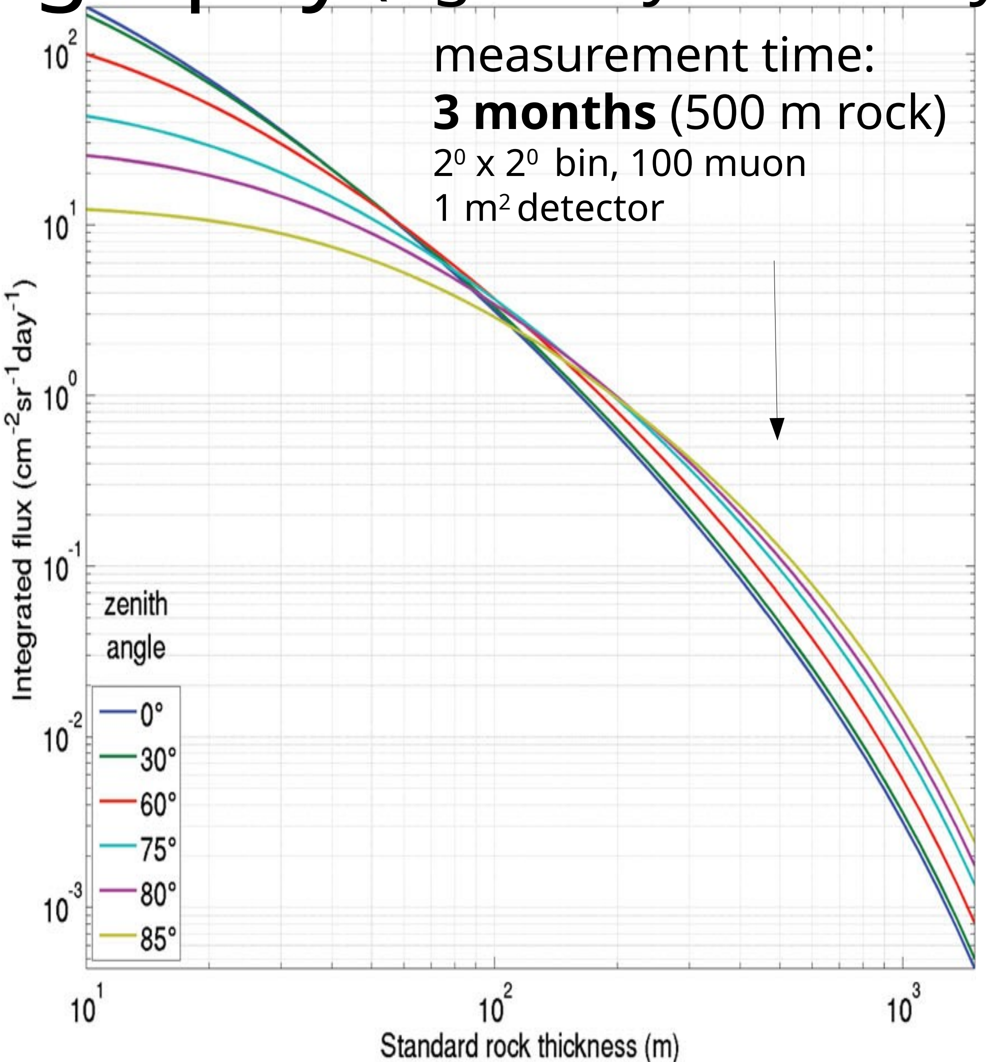
Conclusions

- Muography detectors originate from High Energy Physics instrumentations, and rely on an extensive literature and experience
- … but drifted away quite bit, due to very different challenges (ultra-low rate relative to HEP, moderate position resolution; need for very robust and environmentally stable solutions, cost- and power efficient low maintenance systems)
- There are amazing developments, and improved communication within the Muographers community helped a lot of successful campaings
- There is room for improvement: the application-oriented nature of the research field (commercialization) does not favour know-how transfer

Backup

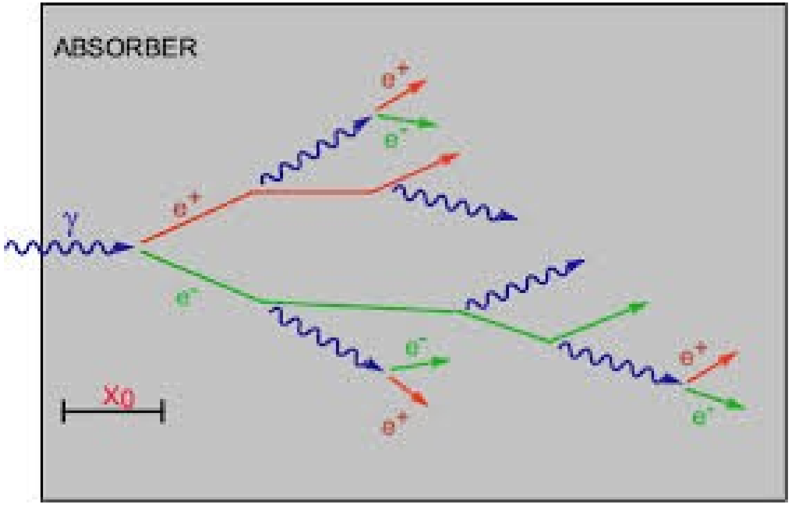
Quantitative muography (figure by Gabor Nyitrai)

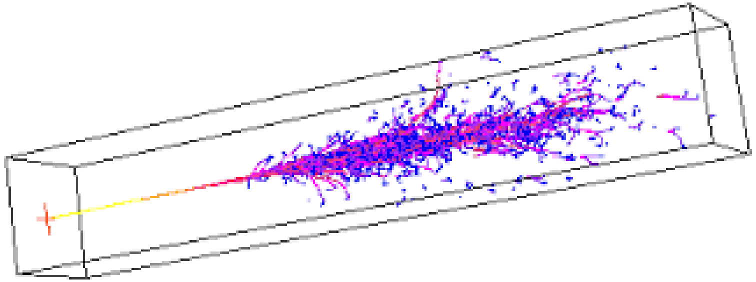
- Exposition time with sufficient area detector
- Surface map (DEM)
- Flux calculations
- Conversion from flux to density-length



measurement time:
3 months (500 m rock)
2^0 x 2^0 bin, 100 muon
1 m^2 detector

High energy photon interaction: Electromagnetic shower





- Electron/positron/photon shower: contains many particles, continues until most particles are at electron critical energy
- Relatively easy to suppress in a muon detector