Muography School

Brief Introduction to Tracking and Imaging

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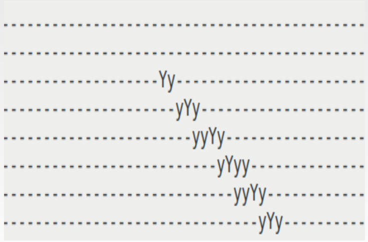
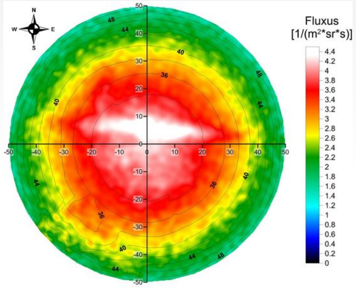
for the **REGARD Det.Phys.Group**

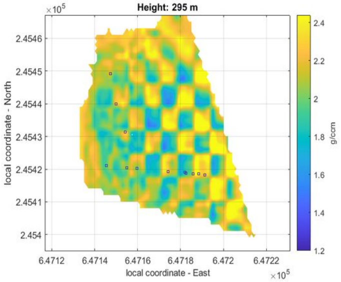
RMKI ELTE Collaboration on Gaseous Detector Research and Development

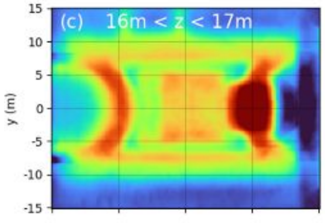
Outline

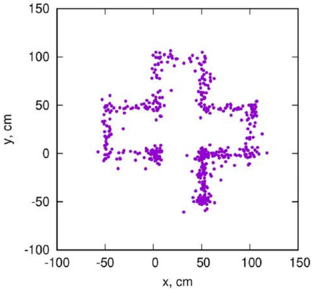
- Detectors for muon tracking
- Raw data and data acquisition
- Triggering, event selection
- Particle tracking
- Detector effects, muon flux
- Angular resolution
- Density-length conversion
- The muogram
- Absorbtion muography, density anomlaies
- Muographic inversion
- Muon scattering tomography
- Imaging via secondaries
- Muometry



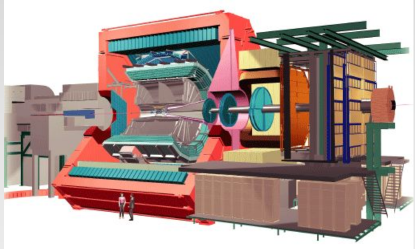




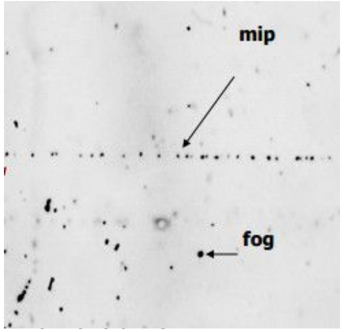


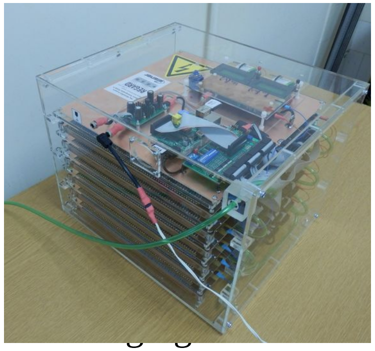


Detectors for Muography



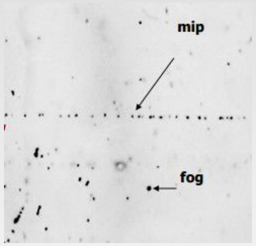
- Muon : charged → particle tracking detectors
- Requirements:
  - Good psoition and angular resolution (~1° , pos/arm)
  - **On Field operation** ! (high humidity, temperature, power consumption, postability, ...)
  - Scalability (large → reduced time req; small: accessiblity)
  - Costefficiency (more det., large sc., industrial app.)
  - Autonom operation for weeks/months (deep mines, volcanoes)
  - Remote access and control (with real-time monitoring)
- Used detectortechnologies:
  Emulsion, Scintillators, Gaseous detectors: MM, RPC, Mod.MWPC
- *Underground: mid flux, low background, rough access*
- *Surface-based: low flux, large background, good access*

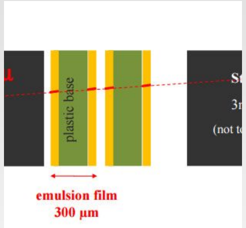




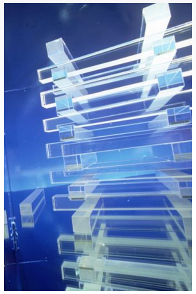
Muography Detectors

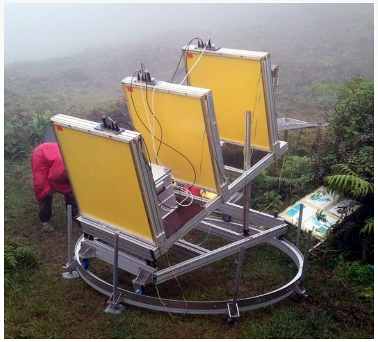
- Emulsion
  solid state, dark grains, 0.001mm
  passive, lightweight, small
  offline reco, transport



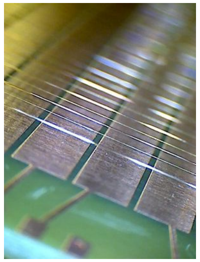
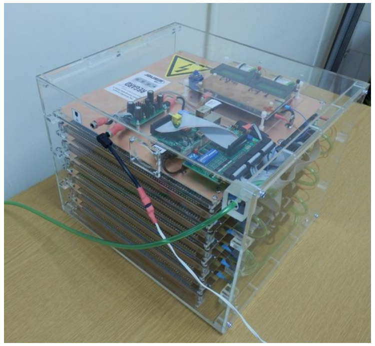


- Scintillators
  plastic scint, PMT, SiPM
  simple, robust, heavy
  low resolution, expensive



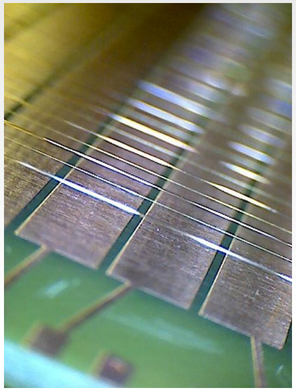


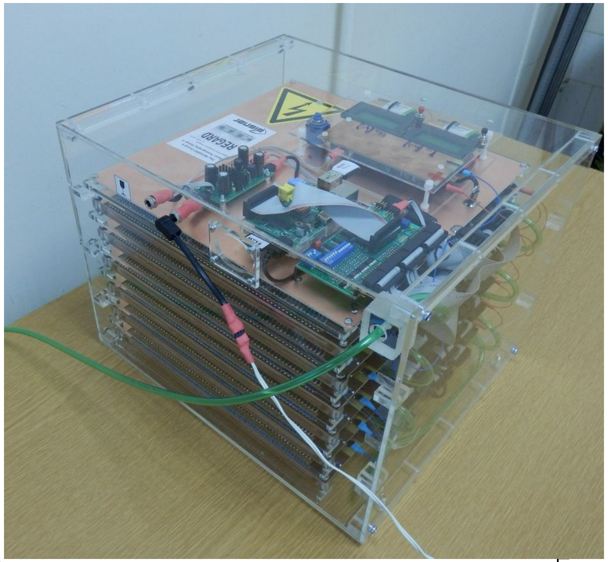
- Gaseous detectors
  ionization, electron avalanche
  precise, cost efficient, lightw
  temp/press var, gas issue
  MM, RPC, Mod.MWPC


Example : Wigner MTL

- MWPC type Gaseous detectors
  Lightweight, High efficiency, High resolution, Multilayer conf, Stable operation, ...
- Physics Process: traversing muon → gas ionization → drift towards the wires → electron avalanche → singal
- Readout: three types of electrodes
  - SenseWires : interconnected : SumSignal
  - FieldWires , Pads/PadWires : Position info
- Digital / Analog readout
  Resolution vs. Cost + Power consumption.
- Trigger: multi-chamber coincidence (eg. 3 of 8)
- DataAcquisition
  Custom boards + RaspberryPi
  Low consumption
- Raw data:
  Event based info, ascii readable files





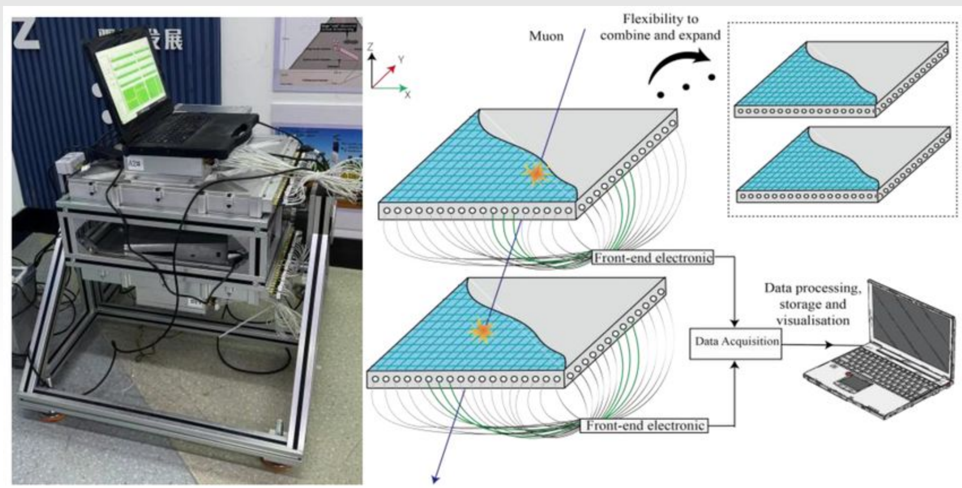
Data Acquisition

- Crucial : performance, cost, consumption, usability
- Timing / Triggering
  - Cumulative (eg.: Emulsion, Dosimeter, Xray pic)
  - Triggered (eg.: HepDet, Scint, GasD)
  - Continuous ?
- Trigger level : hardware, formware, softvare
- Trigger source: External, SelfTrigger
- Dead-time [busy]
- Front-End Electronics
- DAQ control (PIC, RPi, FPGA, ..) [lam,clock]
- BitLevel data → Raw data
- Data throughput, local storage
- Slow control (DCS)
- User Control interface
- [WB]: example schemes

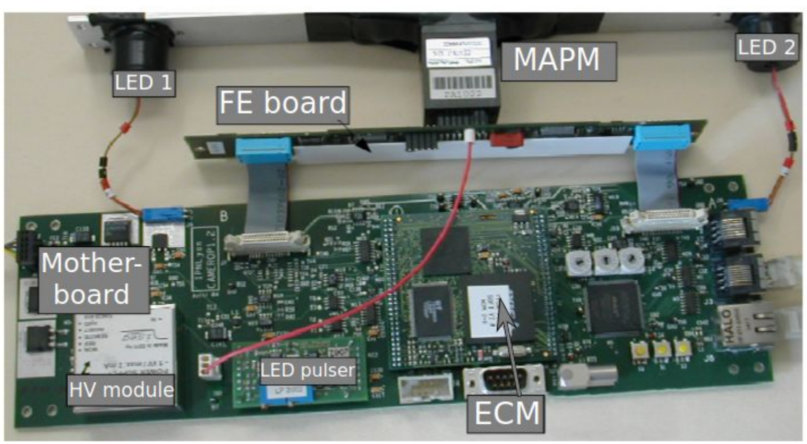
- Custom systems
  (If inherited from HEP technology → shall be optimized..)

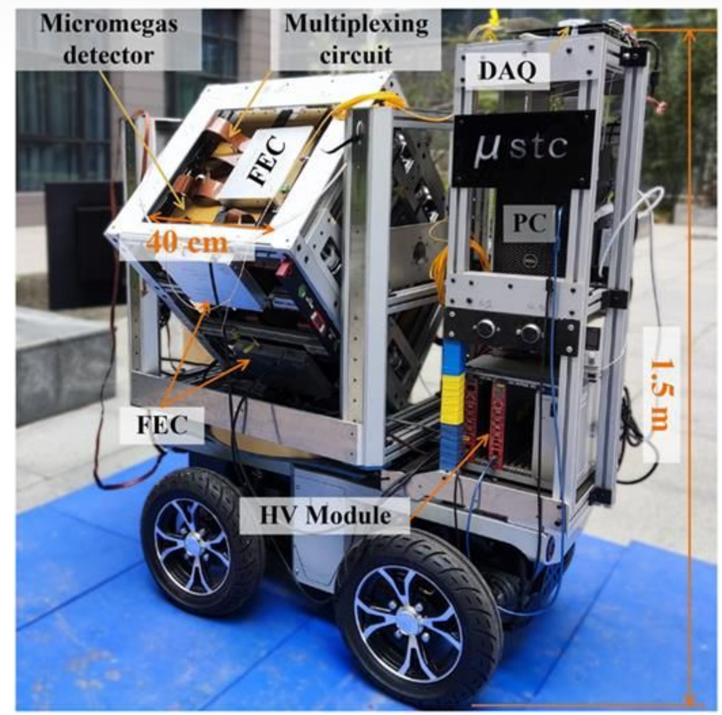
Data Acquisition

- **Examples**
  Tomovul, SMO, Scint+SiPM+FPGA, RPC-calice, MM-uTPC,



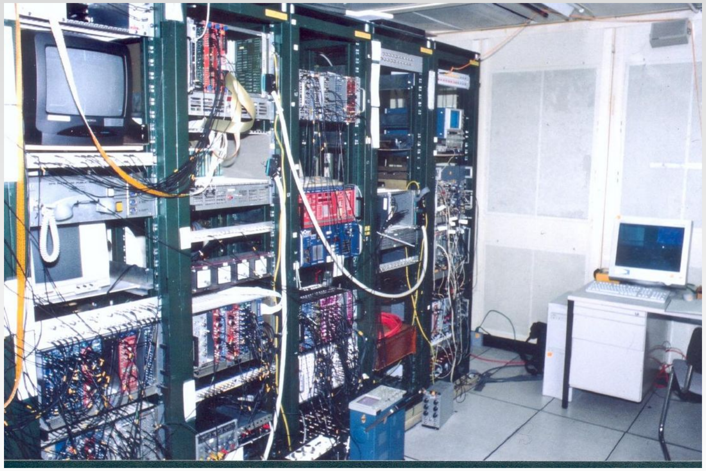
(a) (b)

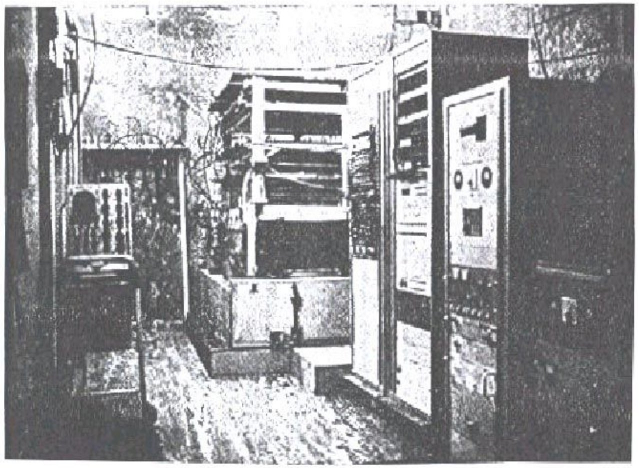


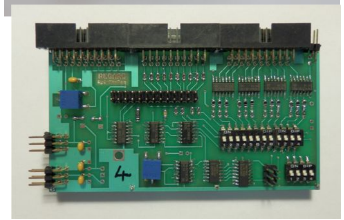


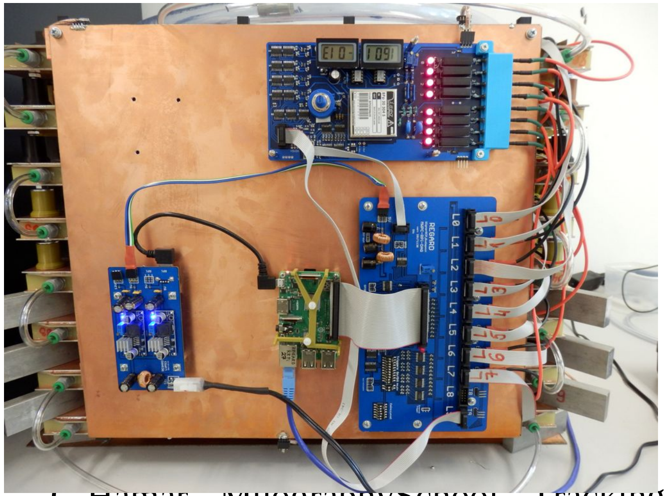
Example : RPi DAQ

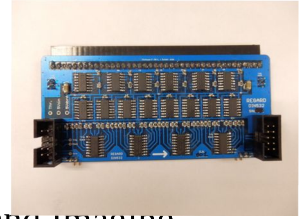
- RapberryPi microcomputer (low cost)
  ARM CPU + Broadcom
  Periferals: USB, HDMI, **GPIO**, …
- DataStorage + Access + Control
  OS eg. Raspbian linux
- GPIO pins (10MHz) adaptable
  for any custom protocol
- FEE: Digital: Preamp+Discrimination
  → ShiftReg : chainable, simple
  power < 5mW/ch
- Trigger : N-fold coincidence for layers

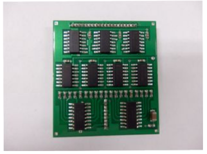






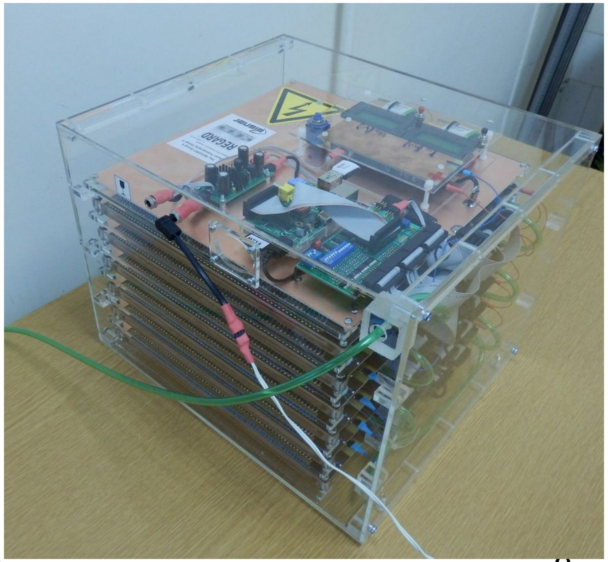






Particle Tracking

- Multilayer configuration
- Layer: 2 dim / 1+1 dim / 1 dim [WB] pros/cons?
- Position info
  Digital / Analog   + Cell-shape
- [WB]: standard, triangle, drift circles
- TPC → 3 dim → 2+1 (as layers)
- Muon : Straight trajectory
  Simply fit a line?
  [WB]: Let us calculate it
- Performance (Efficiencies)
  does it change over time?
- Data based evaluation
- Event based analysis



Simple Particle Tracking

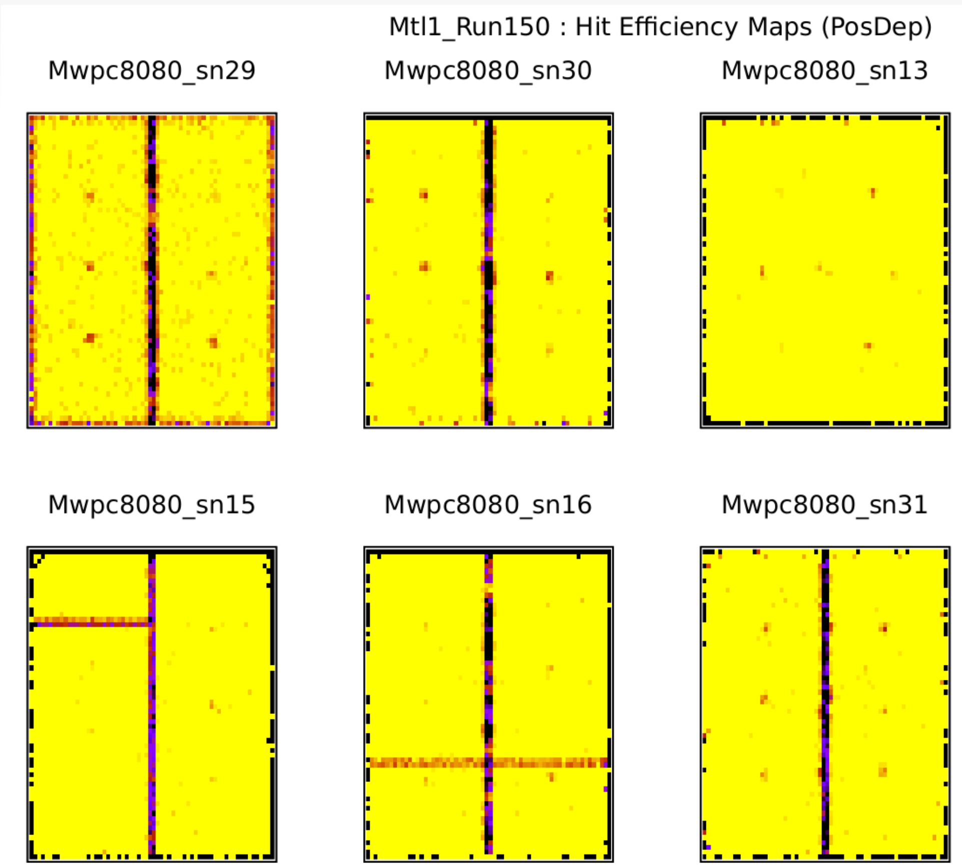
- Muon tracking = fitting a linear trajectory for the hits (enough?)
- Clusterization of hits
  (issue of large clusters, delta-electrons, merged ones, ..)
- Standard combinatorial tracking algorithm (min. chi2)
- Hough transform
- Kalman filter

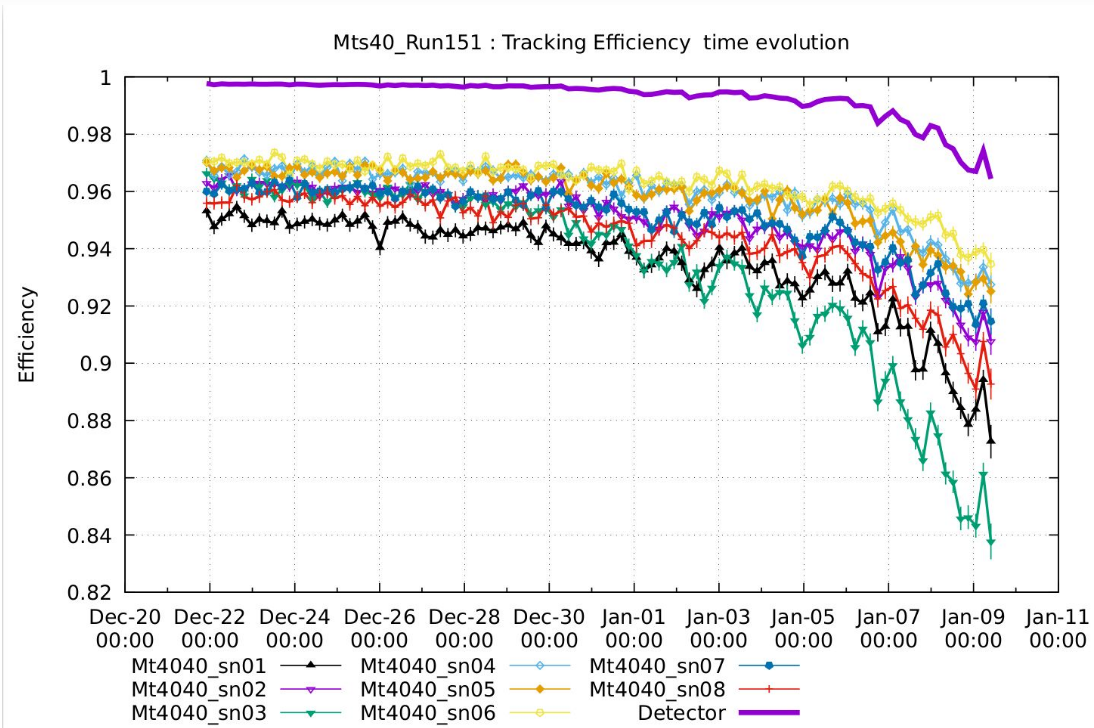
```
EventId : 917 (2025-03-01_11:14:34) dt=52402
................................................................   ----------------------------------------------------------------
................................................................   ----------------------------------------------------------------
Xx..............................................................   ----------------------------------Yy----------------------------
......xxXx......................................................   ------------------------------------yYy-------------------------
..............xxXxx.............................................   --------------------------------------yyYy----------------------
......................xxXxxx....................................   -----------------------------------------yYyy-------------------
..............................xxXxx.............................   -------------------------------------------yyYy-----------------
......................................xxXxx.....................   ----------------------------------------------yYy---------------
THP: 11.5 oC, 44 %, 1002 mbar
Adcs:  0  0  0  0  0  0  0  0
Track : 0 : TrackMain  (p: min 6/8)
        TrackX : Points:  6 , Slope:  -1.2008 , Position:  325.04 , Khi2/ndf:  0.871
        TrackY : Points:  6 , Slope:  -0.3655 , Position:  379.91 , Khi2/ndf:  2.089

EventId : 935 (2025-03-01_11:14:37) dt=35177
.............xXxx...............................................   --------------------------------------------------------yyYy----
....xxxxxxxxxxXx................................................   -----------------yyyyy-----------------------yyyyyyyyYy---------
....xxxxxxxxXx..................................................   ---------yyyy--------yyy------------------------yYy-------------
.......xxXxx....................................................   ---------yy---------------------------------yYy-----------------
......xxXx......................................................   --------yy------------------------------yYy---------------------
....xxXxxx......................................................   ------------------------------------yYyy------------------------
...xXx..........................................................   --------------------------------yYy-----------------------------
.xXx............................................................   ----------------------------yYy---------------------------------
THP: 11.5 oC, 44 %, 1002 mbar
```

Detector Performance

- Calculating / monitoring performance is essential !
- Using same data for performance checks
- Trigger efficiency, Tracking efficiency, Gain, Resolution, ...
  wrt. Local Position, Angle of Incidence, Time, …
- Statistical and systematical uncertainties (subspace projections)





Flux Calculation

- Muography requires the angular-**differential Flux** $F(\Theta, \phi)$
- Flux definition

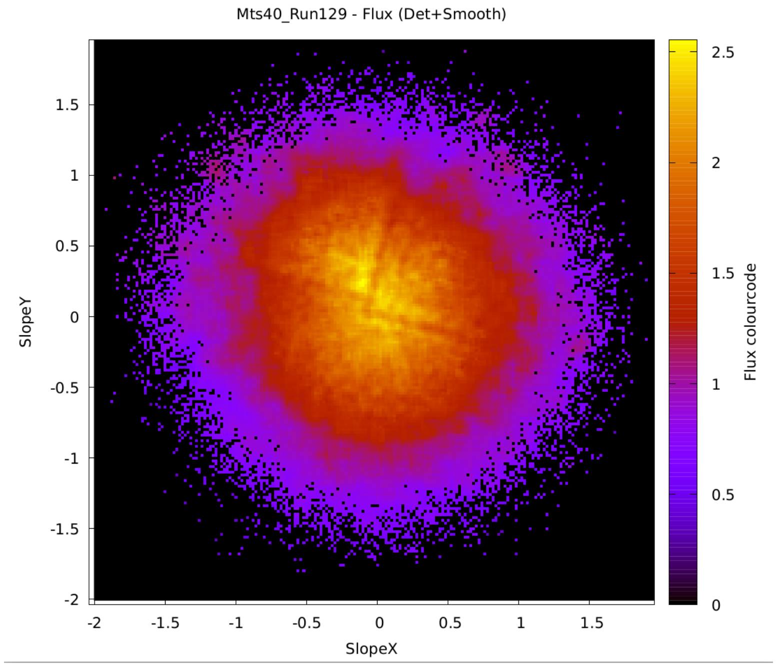
  N.Tracks ? Muon or nor, Background
  Efficiency ? Dependencies, TimeEvolution
  Time ? DeadTime
  Area ? PerpendicularArea, Tracking params
  Solid-angle ? Binning, Jacobian

  [which shall be considered differential/non-uniform ?]

$$F = \frac{N/\epsilon}{t \cdot A \cdot \Omega}$$

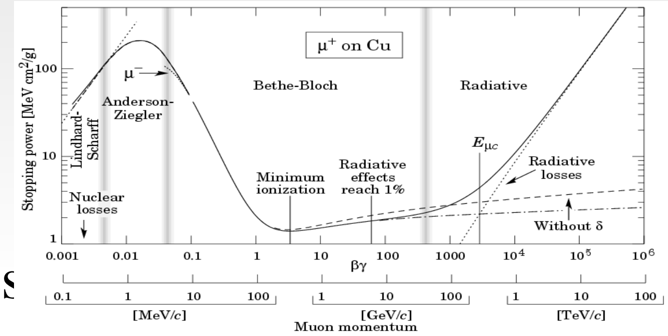
- Binning driven by goals and statistics
- Uncertainties : **Statistical** , Systematic

  bin-by-bin: Poisson → √n
- Required time ~ week-month

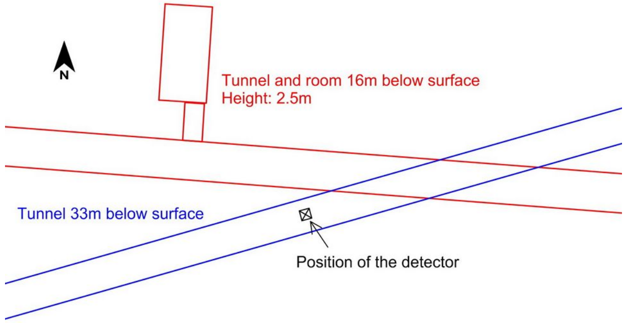


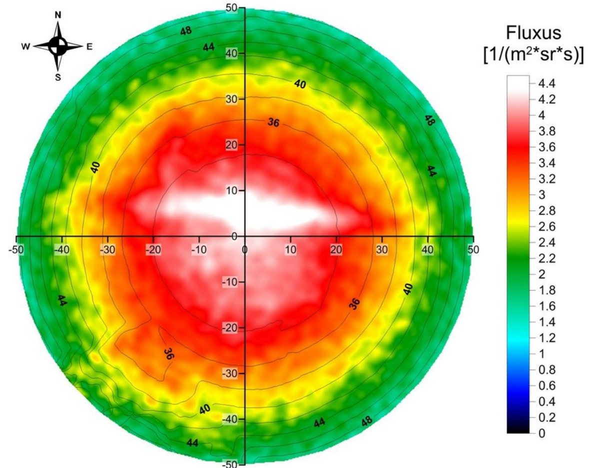
Density Length

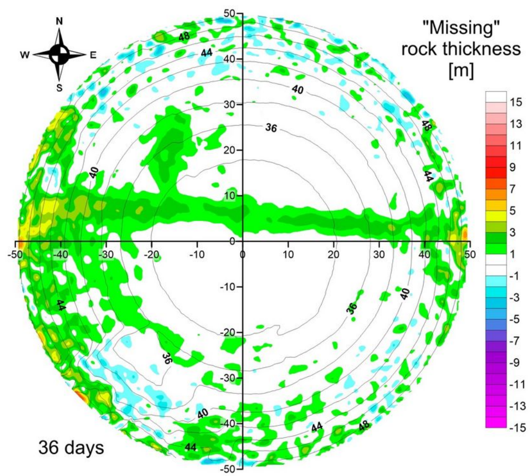
- Muon Flux ⇔ DensityLength
  (most simplified quantity : Opacity , not recommended)
- Muon energy spectrum
  Few parametrizations exists (how could it be measured?)
- Expected muon flux:
  Smooth energy loss (Bethe-Bloch)
  DensityLength, Zenith, Energy spectrum, +?
  [WB]: Let's calculate it together



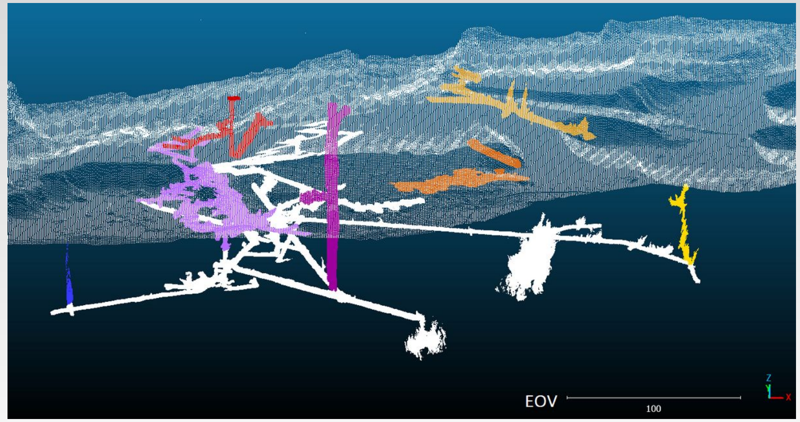
- Surface and underground survey for known structures
  + geological info for densities
- Comparing measured and expected/calculated values can reveal the anomalies or density-maps

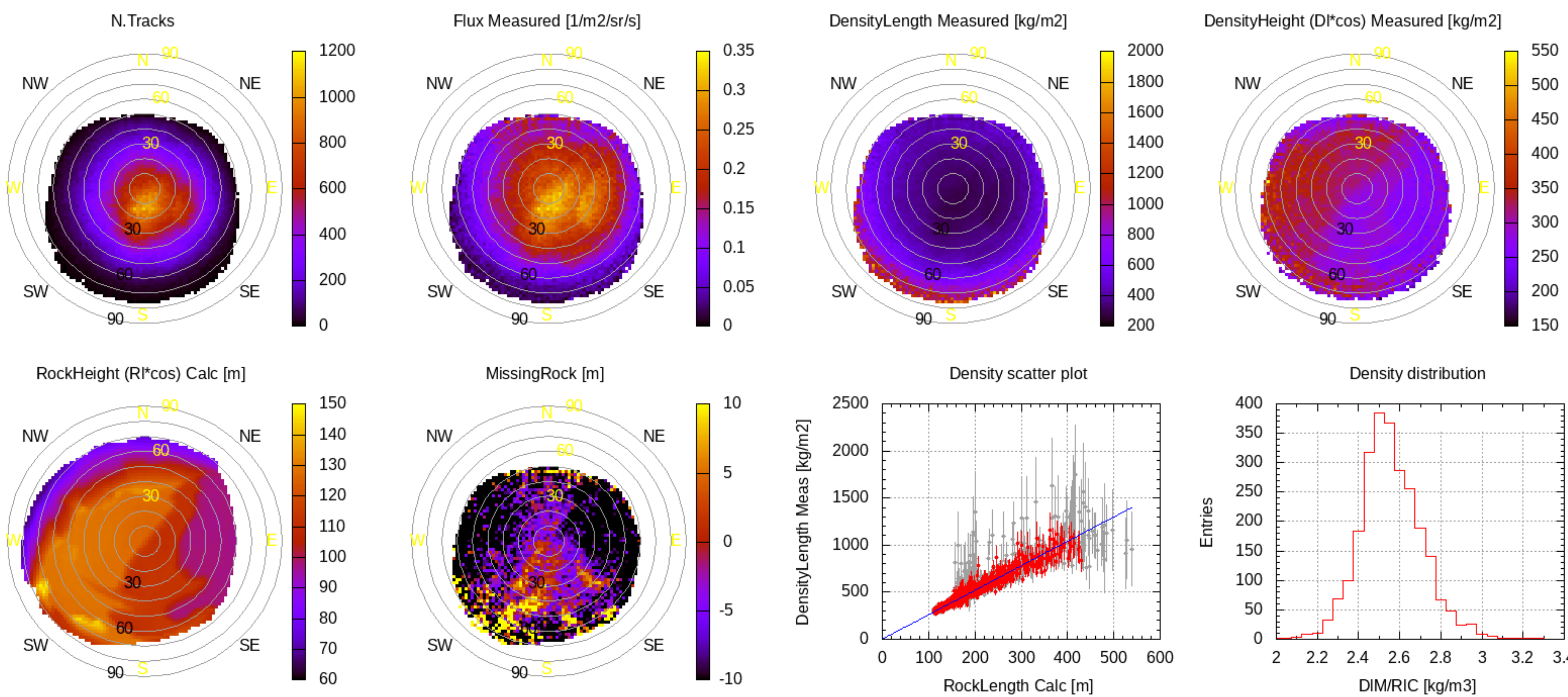






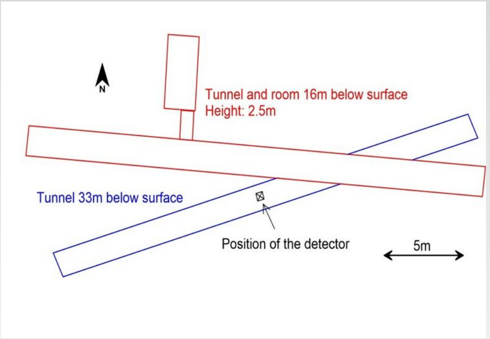
Example : Muogram

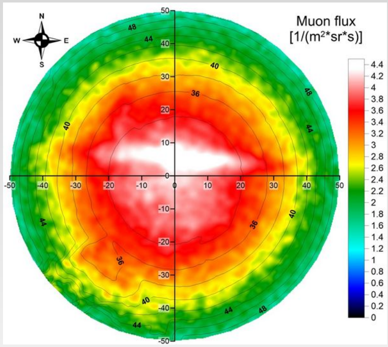




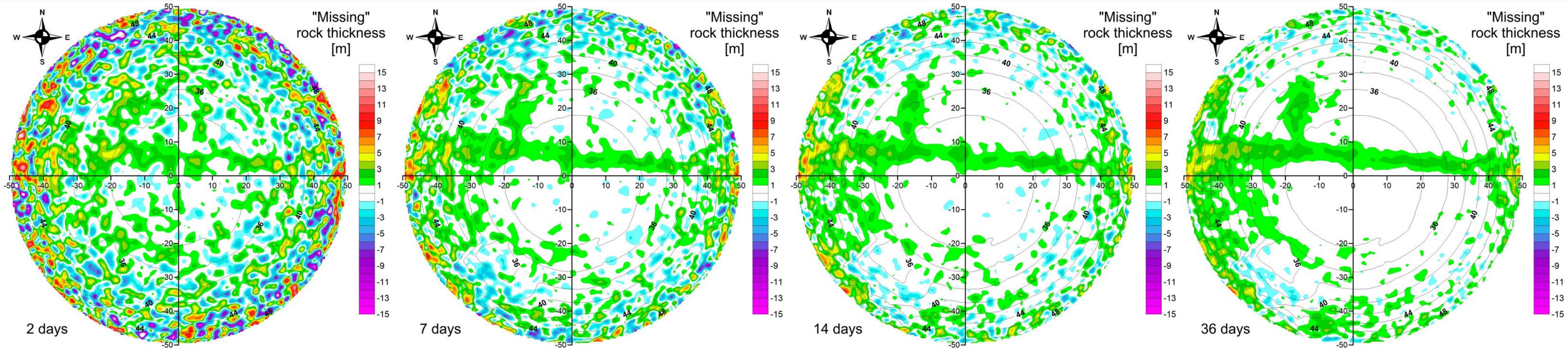
Example : Statistics

Tunnel under the Castle of Buda

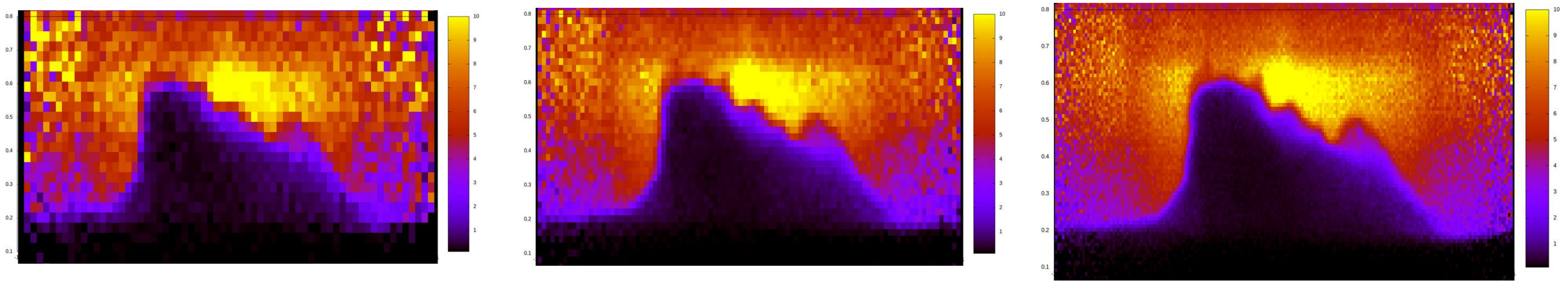




Lab-1
Lab-2

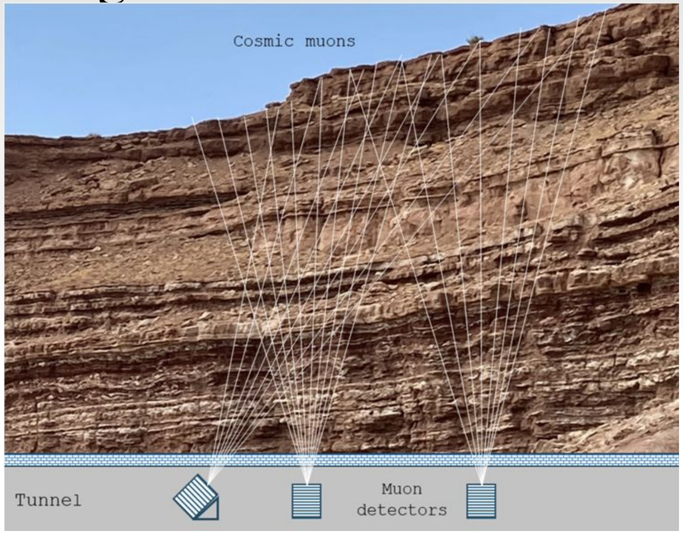


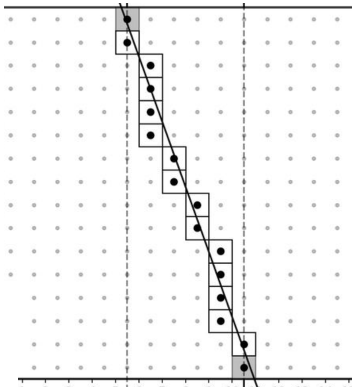
Castello di Mussomeli : a castle on a hill in Sicily

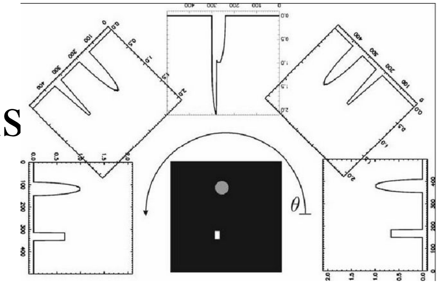


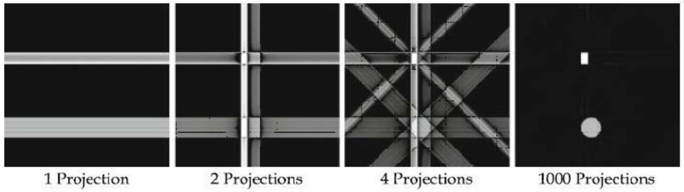
Muographic Inversion

- Three dimensional density imaging
  requires multiple muograms, and volumtric reconstruction
- Medical imaging (CT) : huge statistics, 360° around target
- Muography : few points, limited statistics
  → extra info, geo assumptions, limitations, …
- Direct model and Inversion
  - voxelization : constant density within a voxel
  - measurement points : only a few
  - rays : muon path
  - linearized model : density length
  - full survey as matrix
    Voxel D → measured DL aolng rays
  - matrix inversion ?
- Bayesian approach to overcome stability
- Main issue:
  artefacts
  deformations
  reliability





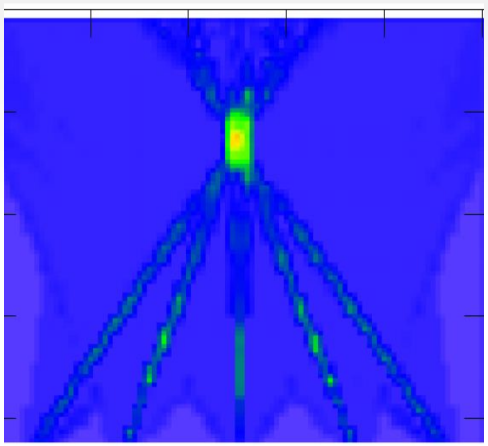


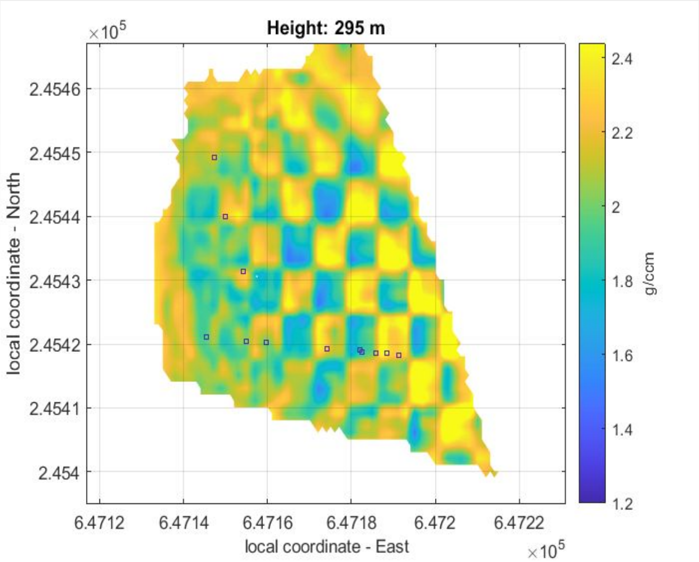


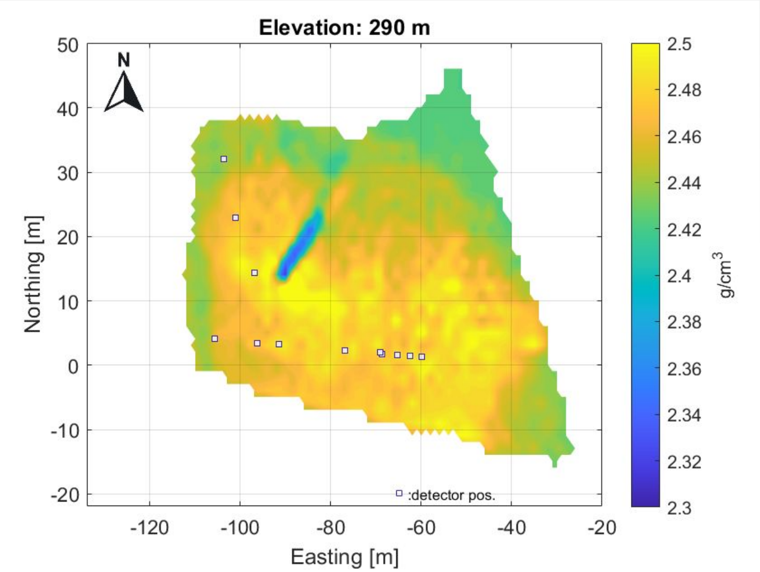
Muographic Inversion

Pratical issues and examples

- Solution evaluation
  Model calculation, Synthetic data, Chess-board test,
  Fisher info, Artefact identification, ..



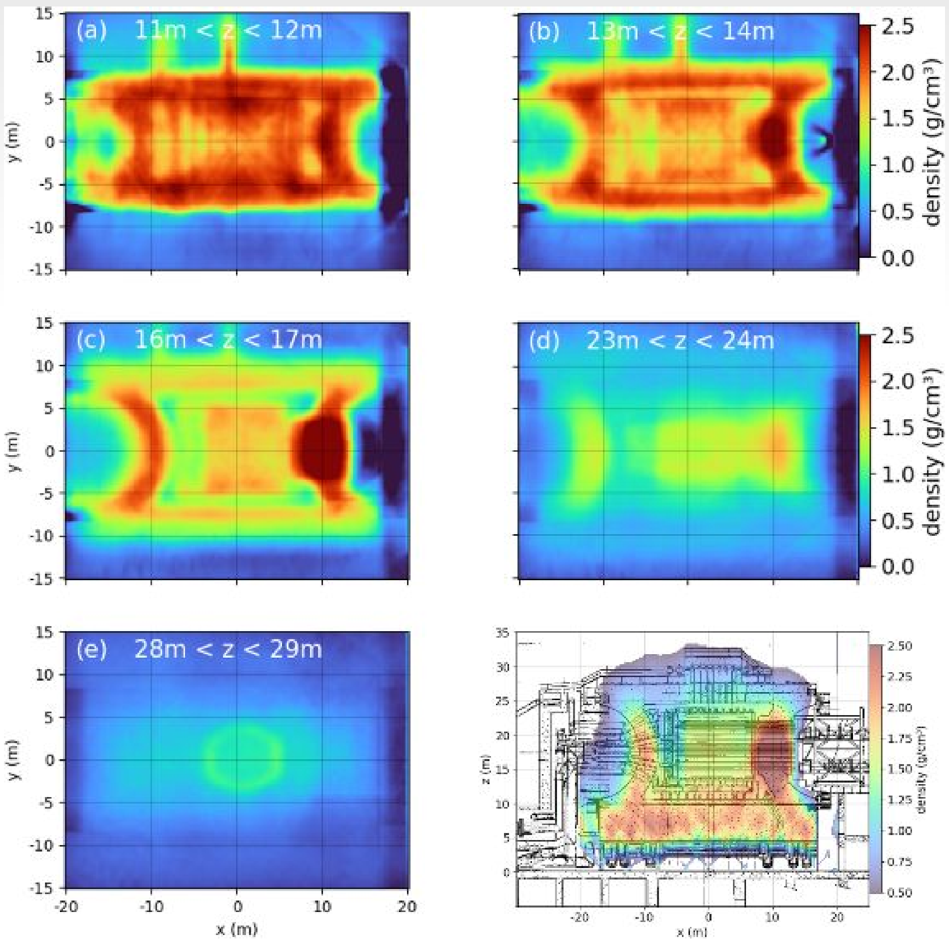


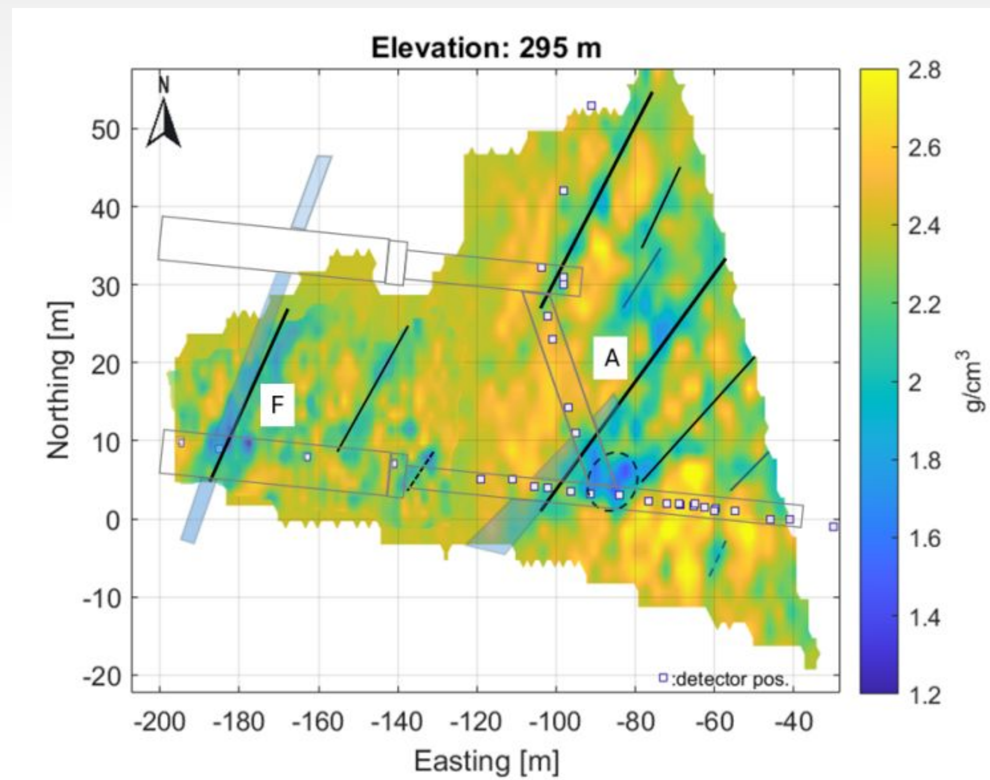


- Non-bayesian methods, ML-boosted algorithms
- Limitations and requirements
  acessibility issues, statistics vs points, otpimization, priors, ..

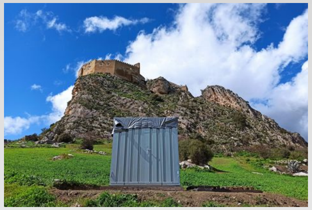
Example : Inversion

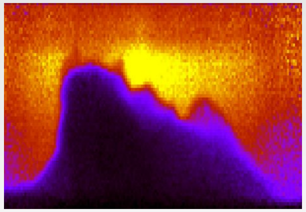
- Applicability: basically everywhere .. :)
  Example: industrial structure: reactor imaging
  Example: geological formation: fracture zones in a hill



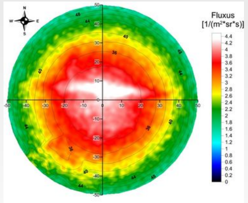


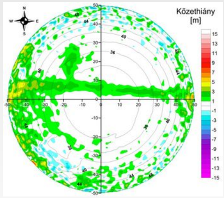
Alternative Muography



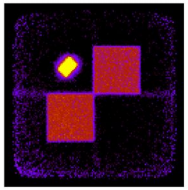


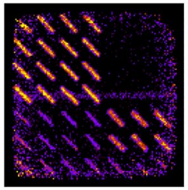
- **Muography** (Classical / Absorption):
  Absprption of cosmic muons → decreases flux through materials
  Directional detection : muogram → density map of hills
  Geophysics, mining, araeology, industrial app., meteorology, ...
  (volcanoes, caves, tunnels, pyrimids, ...,...)



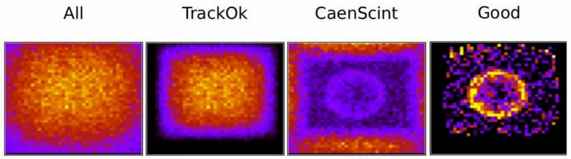


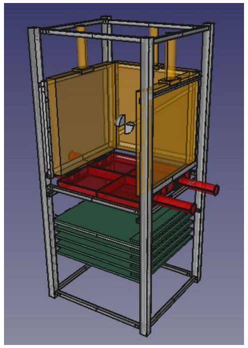
- **Muon Scattering Tomography**
  Multiple scattering on high-Z materials
  Two tracklets : scattering image → high Z materials
  Hidden objects, Homeland security, Cargo inspections, ...





- **Muon induced secondaries**
  Secondaries can be produced in small targets
  Spectra depends on the material conposition
  → nondestructive inspection





- **Muometric positioning**
  Straight trajectory of muons
  Underground absolute localization where GPS cannot be used

Muon Scattering Tomography

- Charged particle : Coulomb scattering in the high field of the nulceus
- Multiple Coulomb Scattering

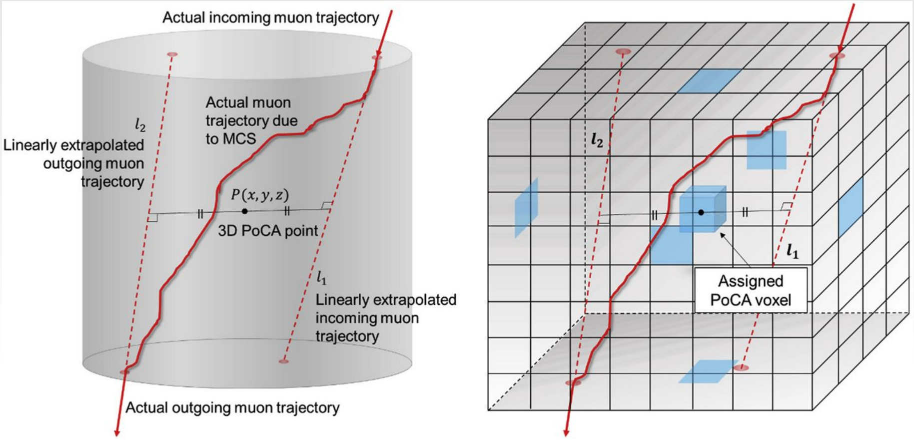
$$\sigma_\theta = \frac{13.6MeV}{p}\sqrt{\frac{x}{x_0}}\left[1+0.038\,ln\left(\frac{x}{x_0}\right)\right]$$

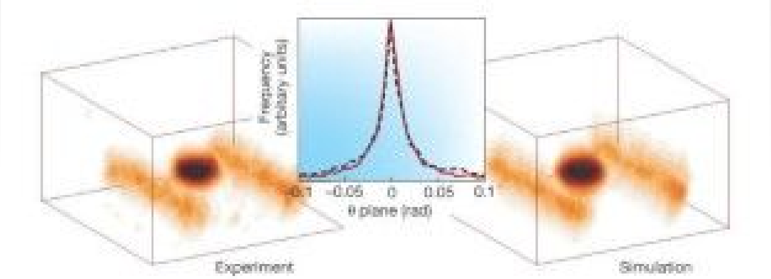
- Sensitive for **high-Z** materials
- Required statistics is way lower than classical muography
- Scanned object ~ few meters (truck, cargo)
- Resolution ~ cm scale
- Can reveal internal or hidden structures
  Cargo inspection, Homeland security,
  Nuclear strucure/reactor/waste inspection

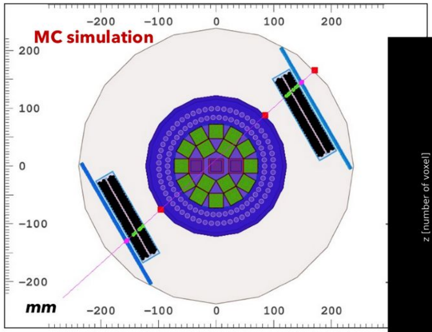
- Tracking and Imgaing:
  Tracklets on both side of the volume (incoming and outgoing tracks)
  High angular resolution is required (high density FEE or spaceous setup)
  Reconstruction algorithm (layered, PoCA, UTRec, Direct comp.)
  Momentum information could aid reco?
- Practical issues: enclosing materials, limited time
- What is actually needed ?

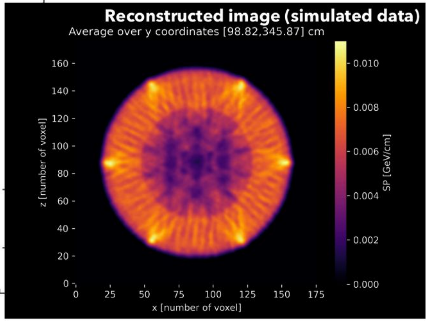
Example MST

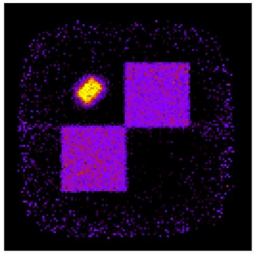
- Size + Readout + Reconstruction
  Reco? (layered, PoCA, UTRec, Direct comp.)



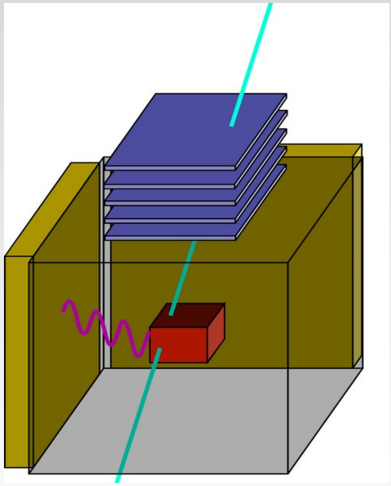




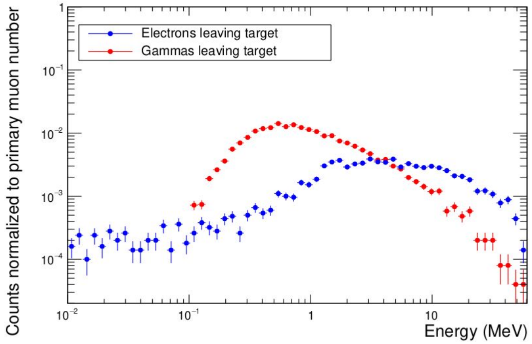


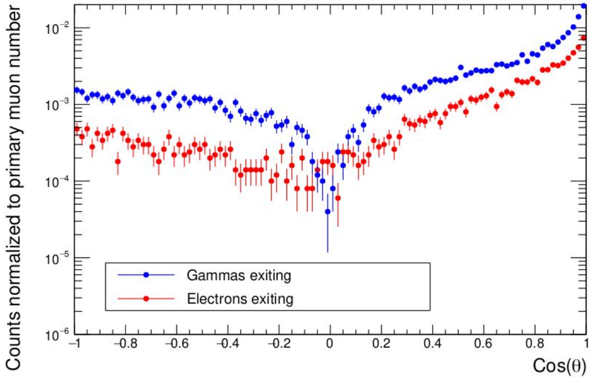


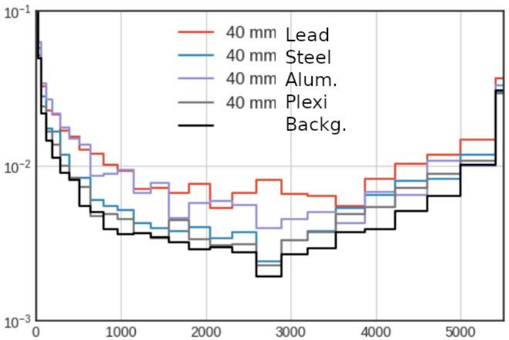
Imaging via Secondaries



- Traversing muons induce radiation of secondaries
  their spectra highly depends on the traversed material
  → Material identification even for low-Z
- Muon tracker : high resolution, scalable
- Secondaris: mostly low energy electron and gamma
  Measure spectra, low E-cut, muon sep.
  Detectors: HPGe, Plastic Scint., NaI, .. ?
- Advancements
  e/g identification : e/g ratio highly depends on material (Lead: 00.3,Polyst.: 33.5)
  direction of secondary : muon separation, skin effect
  combined system : muon scattering and absorption, momentum meas?
- Issues: secondaries shall escape the target but be detectable
- Simulation becomes most important
- Imaging: simple projection, angular info for tomography, adv in combined setup

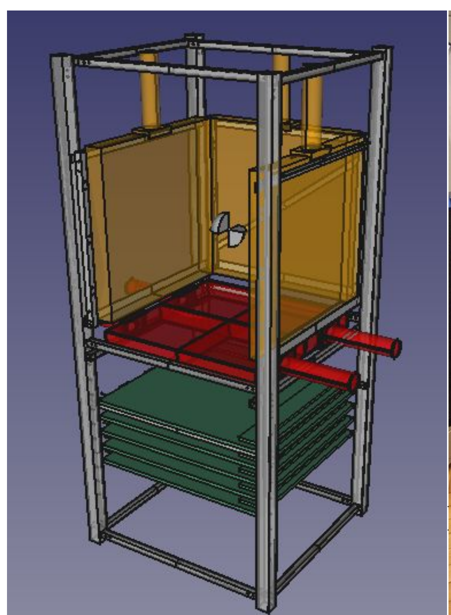


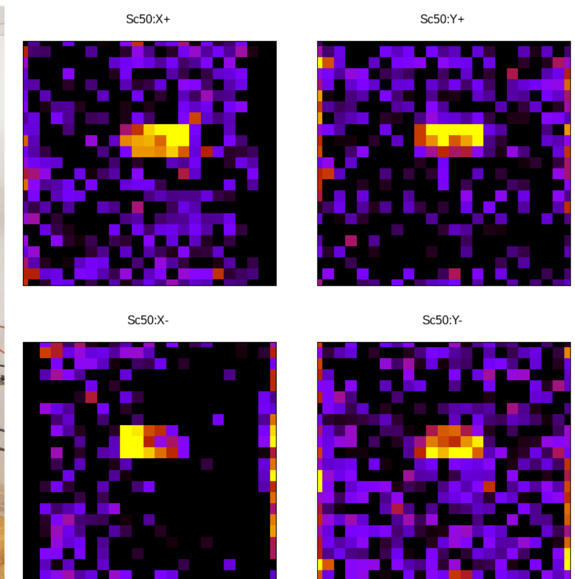




Imaging via Secondaries

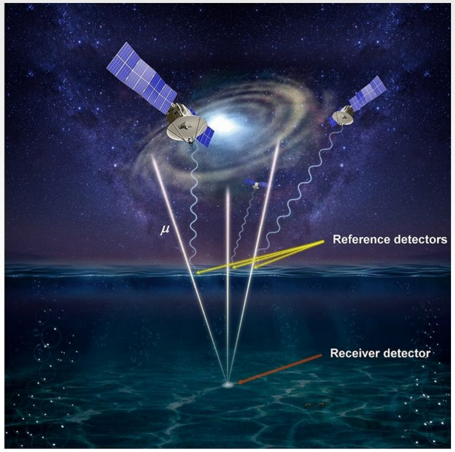
Novel method only a few groups are involved
simulation and experimental works

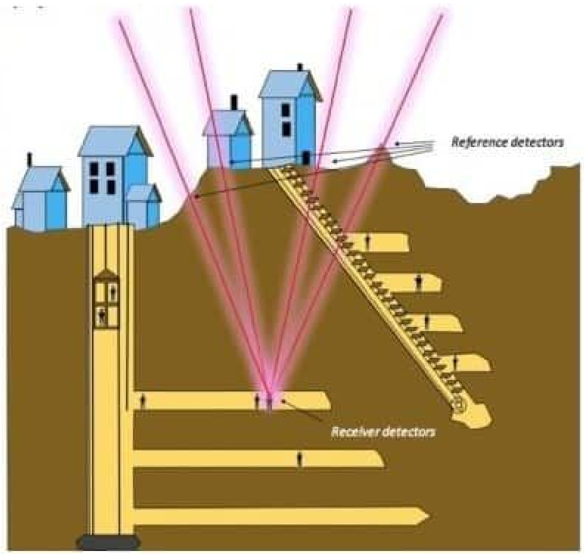




Muometry

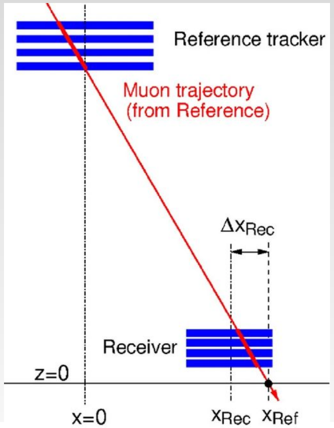
- Muon **long straight trajectory**, deep penetration into Ground
  - Coincidence of two detectors → both on line of trajectory
  - Two (or more) referece → **Localization in 3D**
- Info
  Time of arrival : distance towards unit
  Muon direction : direction of unit
- Practical applications
  Underground (or subaquatic) **absolute** localization
  where no GPS/GNSS data is present/usable
- Applicability in :
  - Mine: map tunnels
  - Underground localization
  - Disaster recovery: locate humans under remains
  - Monitoring inter-building movements
  - …
- Time consumption increases with the depth,
  decreases with active area
- More Reference trackers: large coverage,
  faster position update, better depth reco.

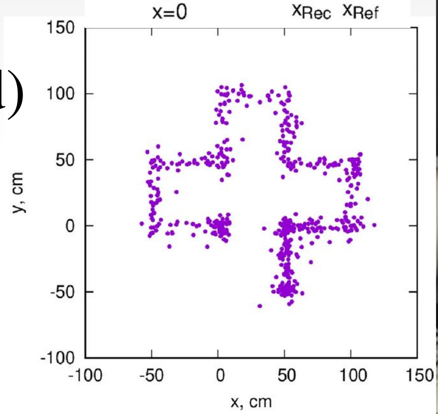


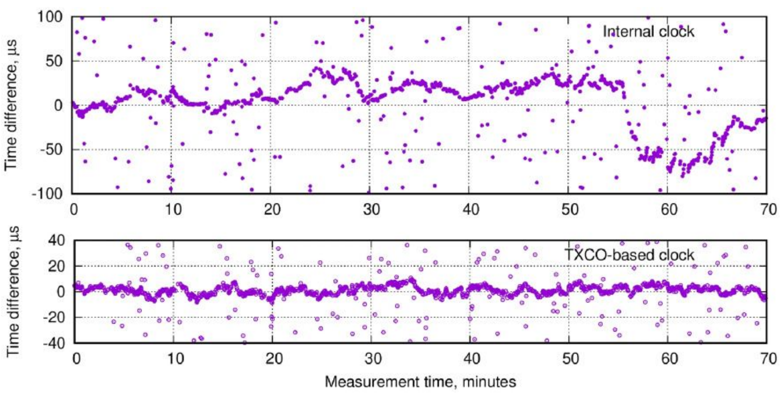


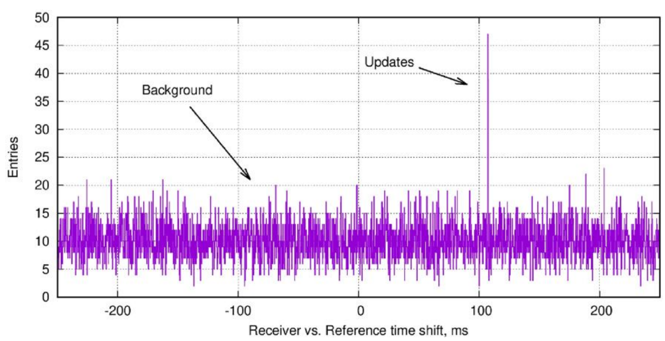
Muometry

- Tracking : standard
- Main issue : coincidence recognition
  huge background from other muons
  [WB] : lets estimate signal over noise
  need for proper time resolution
  and synchronization
- Localization precision
  multiple scattering along path (in the ground)
  limitations → statistics, update rate

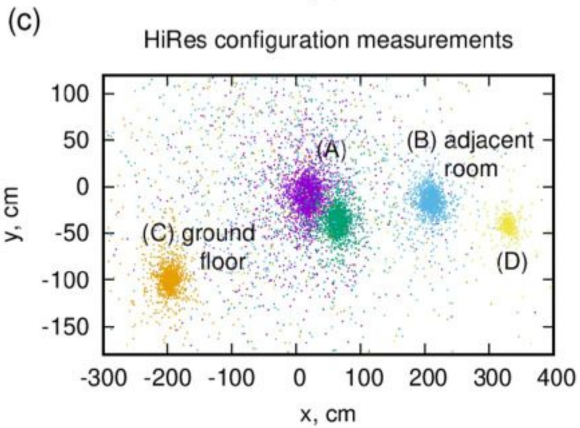


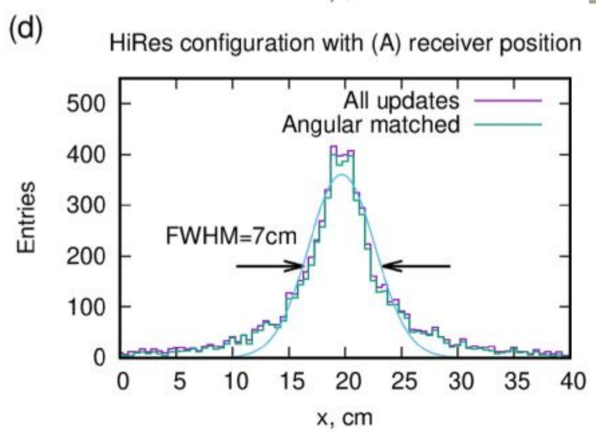






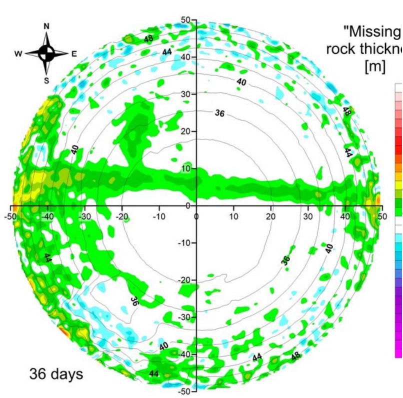
Hama

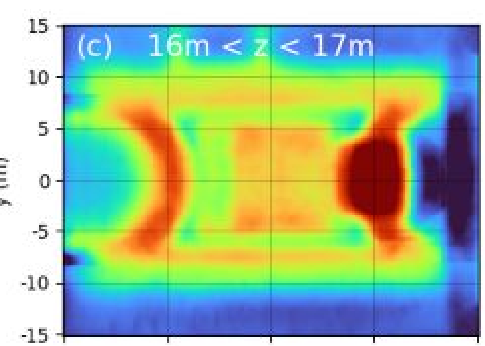


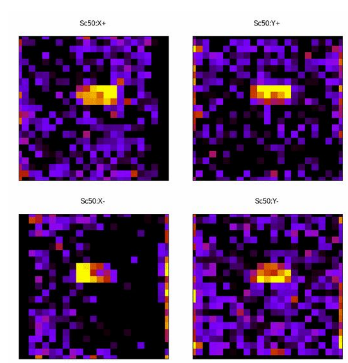


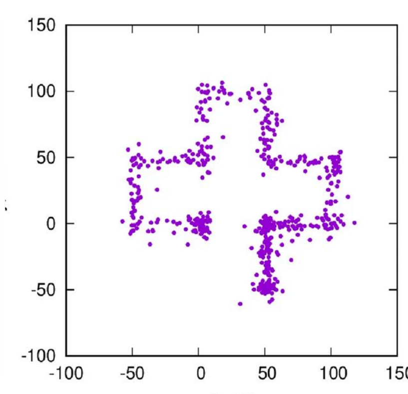
Summary

- Muography requires tracking detectors
- Goals shall define the system for DAQ and analysis
- Event based analysis : triggering, event selection
- Performance monitoring : same data could be used
- Muon flux : statistic and systematic uncertainties
- Density-length conversion : parametrization, calc., no golden
- Classical (absorbtion) muography : density map, anomalies
- Muographic inversion : 3d reconstruction, artefacts
- Muon scattering tomography : hidden materials
- Imaging via secondaries : low Z material id.
- Muometry : positioning without GPS









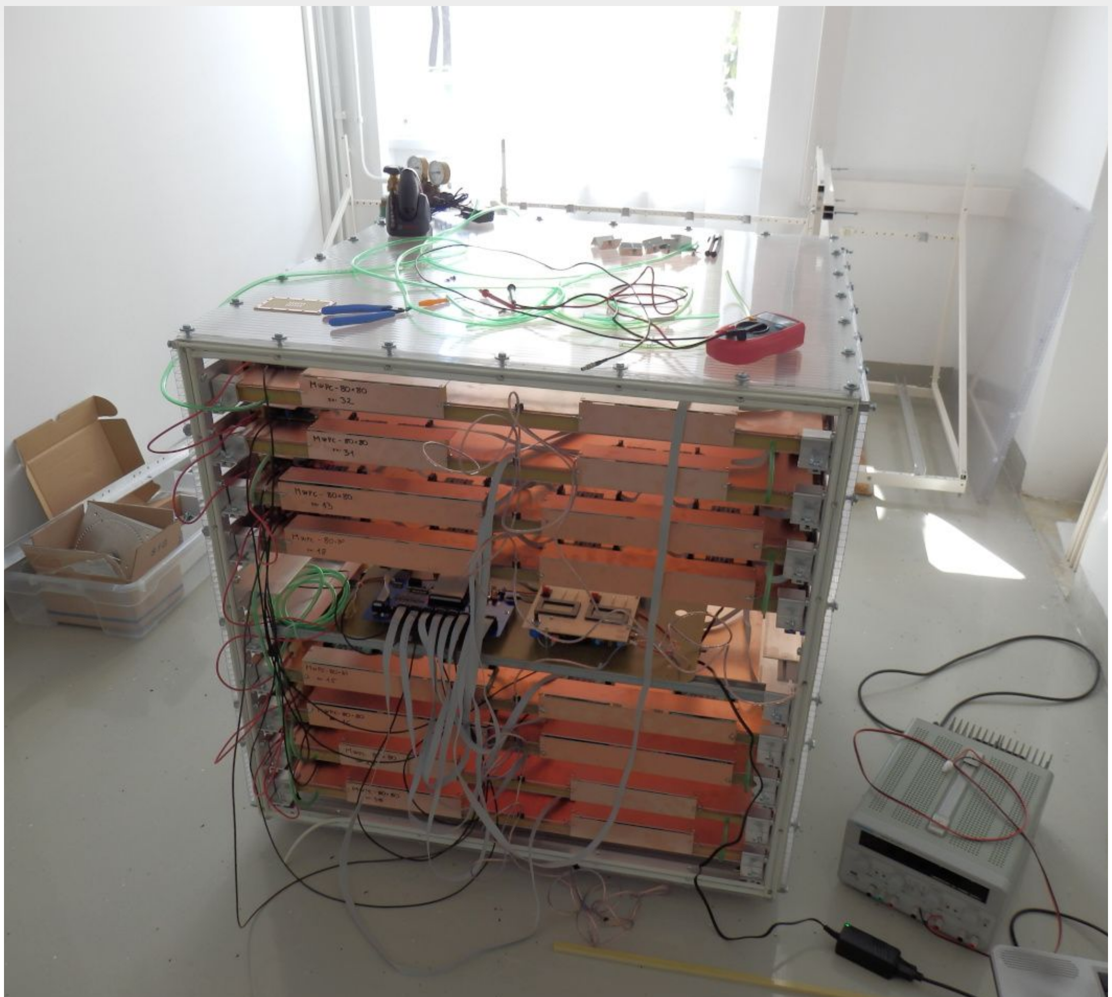
Laboratory Excercises

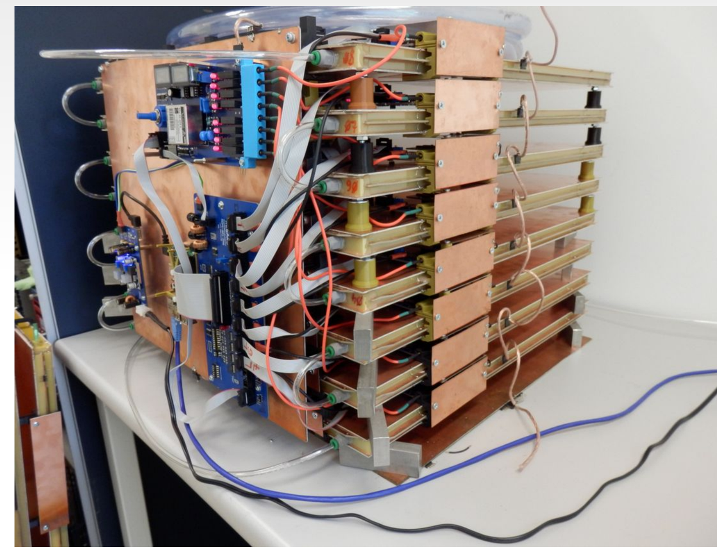
- **Basics of MWPC** [hardware lab] (lc: Richárd Nagy, Lab: Lab-110-StudentLab)
  Operational excercise with a small Multi-Wire Proportional Chamber:
  MWPC internal structures, Gas supply, Oscilloscope operation, Detection of beta source with MWPC; Measure Landau distribution, Measure GasGain vs HighVoltage.
- **MWPC as Tracker** [hardware lab] (lc: Bence Rábóczki, Lab: Lab-092-MARI]
  Oparational excercise with a multi-layered MWPC based Muograph tracker:
  MWPC structure, Muograph tracker setup, Oscilloscope operation, Detection and Tracking of cosmic muons; Measure Efficiencies and Gain vs HighVoltage.
- **Muograph operation** [hardware+software] (lc: Boglárka Stefán, Lab-001-TERI)
  Operational excercise and verification of a Muograph tracker:
  Muograph tracker structure, DataAcqisition, Detection and Tracking of cosmic muons; Measure differential cosmic flux, inclined operation, verify consistency wrt inclination.
- **MuonScattering measurements** [hardware+software] (lc: Gábor Nyitrai, Lab-003-HubaG)
  Opration of a muon scattering experiment with twelve MWPC layers:
  MuonTracker structure, MuonScattering feaures, Tracking of cosmic muons, identification of tracklets and scattering; Measure few iron and lead targets, image targets via tracklet scattering.
- **Exposure calculation** [software calculation] (lc: Nicolas Viaux, Office-101A)
  Calculate the direct problem for muographic imaging:
  Define the direct problem, include detector effects, estimate imaging capabilities for simple grometry, estimate time of exposure for tunnel detection.
- **Basics of Geant4 simulation** [software simulation] (lc: József Szűcs, Office-101B)
  Running and understanding a Geant4 simulation for muography:
  Introduction to Geant4 simulation framework, Physics list, Particle generators, Detection layers; Run simulation for a simple geometry with an underground tunnel, estimate detectability.
- **Muographic Inversion** [software calcualtion](lc: László Balázs, Office-103A)
  Baysian inversion for muon tomography reconstruction:
  Define the tomographic inversion, Baysian approach, 2d/3d reconstuction, MatLab implementation, Issue for muography; Run and investigate inversion artefacts for 2D model for detecting an underground tunnel.
- **MuonScattering reconstruction** [software combined] (lc: Zahraa Daher, Office-101)
  Simulation and reconstruction of muon scattering experiment:
  Softwar frameworks for simulation and analysis, Geant4 simulation, Main effects and issues for various reconstruction algorithms; Run and image iron and lead targets in a muon scattering setup, estimate capabilities.

Backup Slides

Portable Muographs

- **Large-size Muograph**
  Based on Modified MWPChambers,
  Mostly used for easier-access sites (see later)
  Eight layers of 80x80 cm^2 or 50x50 cm^2





Can be manually carried if needed :)

Raw Single Event

- Event based readout and analysis
- Recorded data (for each event)
  - Event Id
  - TimeTag (DateTime, + high res. TimeDiff)
  - For each layers:
    -- Hit positions (two directions, zero suppressed)
    -- SumSignal (adc)
    -- Trigger info
  - HvInfo
  - Environmental info
  - Readout check info

```
Event 1040000 ,   2025-03-03_18:31:25 ,  dt :  20877
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Adc :    1484     2088     2324     2960     2576     2268     2536     3860
THP :   T= +13.25 oC, H= 55.0%, P= 1003.0 mBar, ThpId: 0
Counter :        +1 (193)
Pattern :       Triggered on :  0 1 1 1 1 1 1 1 0 0 0 0 (ok)
Check :   ok    ok    ok    ok    ok    ok    ok    ok    ok
HV:  UIseg: 1624 , UMon: 1616 , IMon:   39.1
```
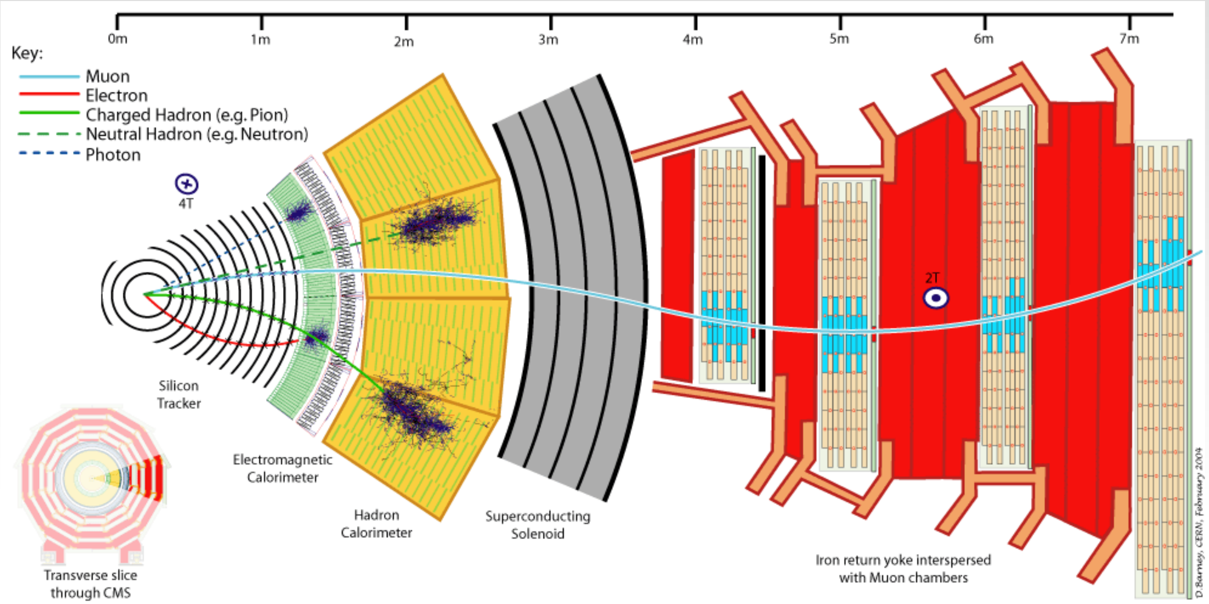
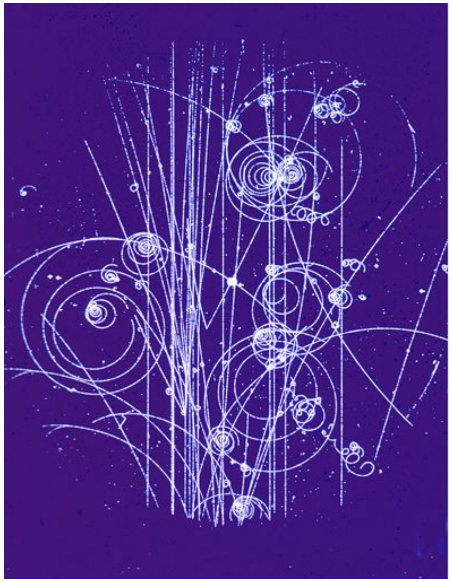

Detectors for High Energy Physics

- Bubble Chambers
- Scintillators
- Silicon D.
- Gaseous D.

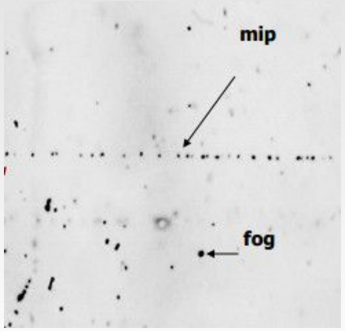
- **Tracking**
- Calorimeter
- Identification

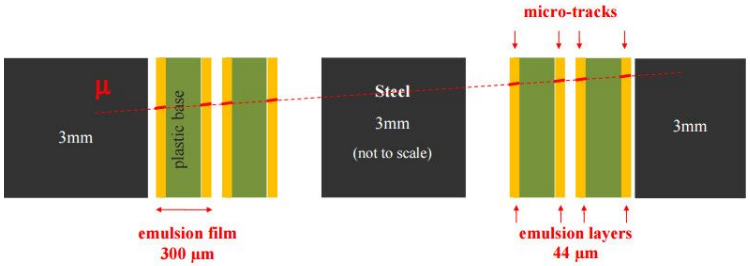




Emulsion Detectors

- Nuclear emulsion films (AgBr in gelatine)
  (like in OPERA experiment)
- INFN Sez. Napoli
- Spatial resolution ~ 1 μm
- Ionization → black grains on the film layers
  approx 35grains/100μm
- Multiple layers of micro-tracks
  → 3 dim tracking
- Automatised scanning system
- Portable (lightweight)
  No power needed for operation
- Tracking only offline





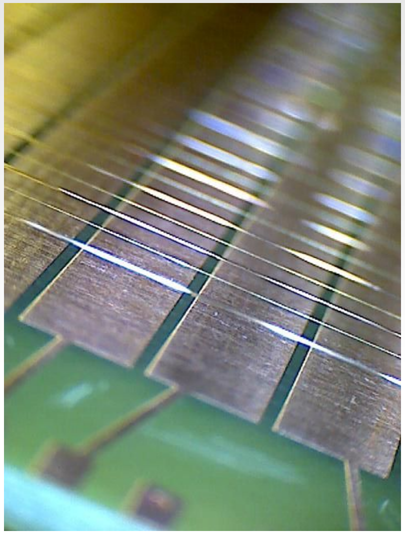
Scintillators for Muography

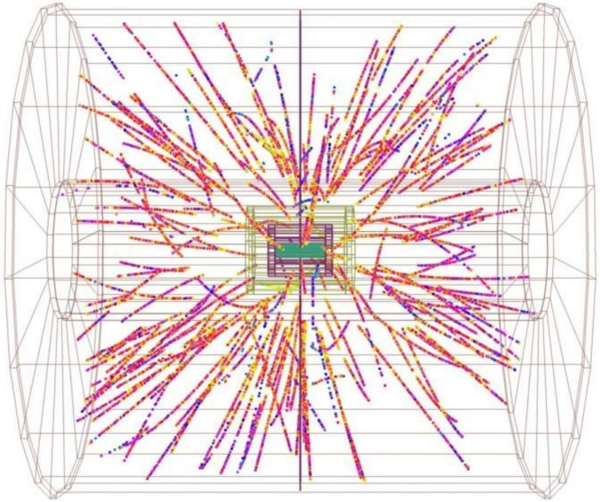
- Array of plastic scintillators
- Excellent time resolution (reject backward particles?)
- Spatial resolution ~ 2-5 cm
- Readout :
  PAMT : reliable, moderate power, high cost/channel
  SiPM : new, low power, temperature control, dark current
- Few layers (cost!) → simple coincidence
- Simple operation : widely used
- Volcano muography
- Japan, Italy, France

Gaseous Detectors : Why?

- First **electronic** tracking devices
- **Large** volume is possible
- Low material budged
- Sub-mm **tracking** (even in 3 dim)
- **Cost efficient** construction
- Known technology
- Moderate **electronics**
- **Various structures**

- Particle **identification** possibility
- Usability for **photon** detection





Gaseous Detectors
Main technologies and types

- Geiger-Müller counter
- Spark Chamber, Parallel P.Ch.
- **Resistive Plate Ch.**, MRPC

- Proportional chamber
- **Multi-Wire Prop.Ch.**
- Drift chamber
- **Time Projection Ch.**

- MicroPattern Gas.Det.: RD51
- HoleType: GEM, TGEM, Cobra
- MeshType: **MM**, bMM
- SingleLayer: uPIC, Well
- Combined: InGrid

- + Photon Detection
- + Liquid material