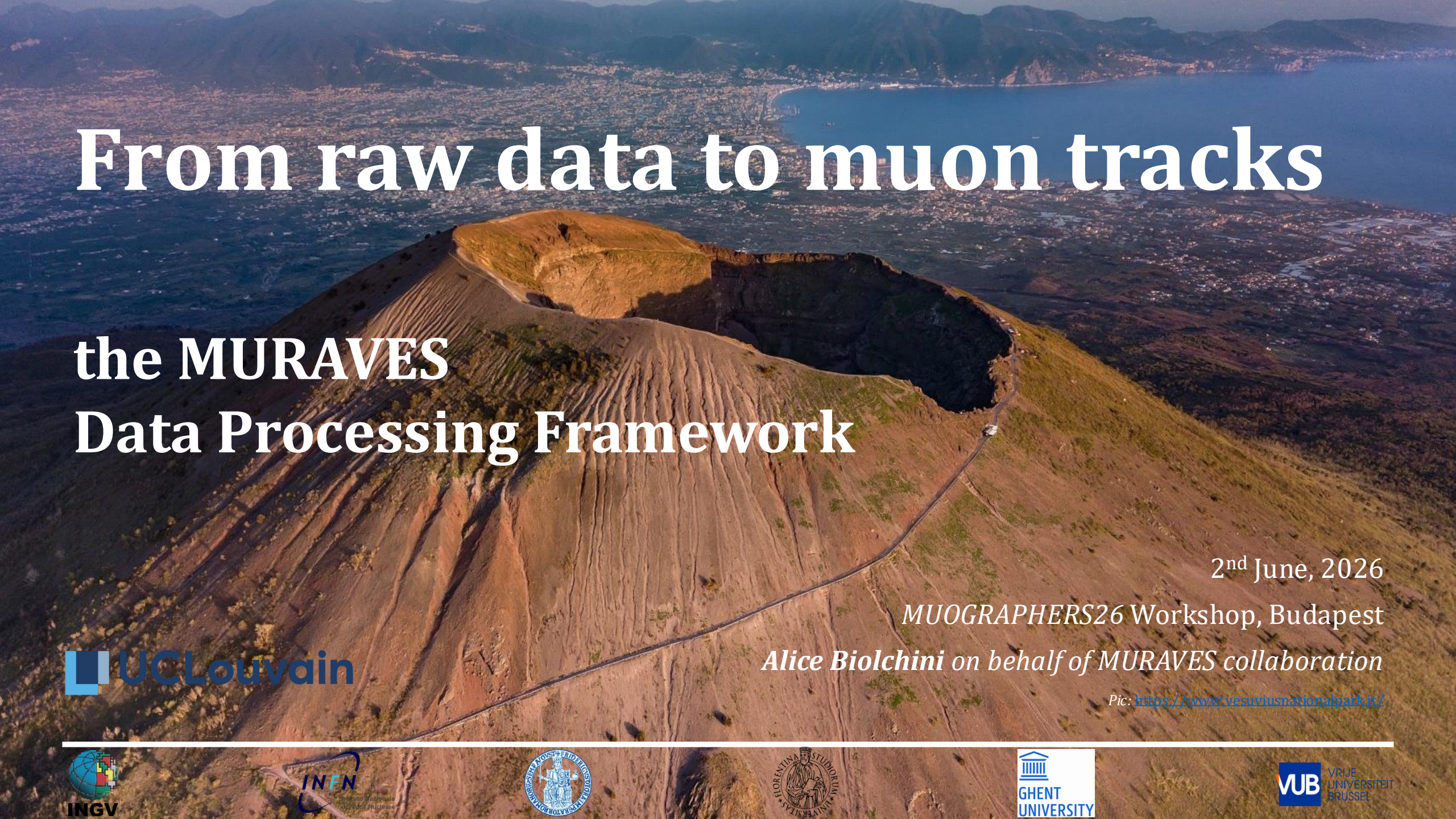
From raw data to muon tracks

the MURAVES Data Processing Framework



2nd June, 2026

MUOGRAPHERS26 Workshop, Budapest

Alice Biolchini *on behalf of MURAVES collaboration*

Pic: https://www.vesuviusnationalpark.it/

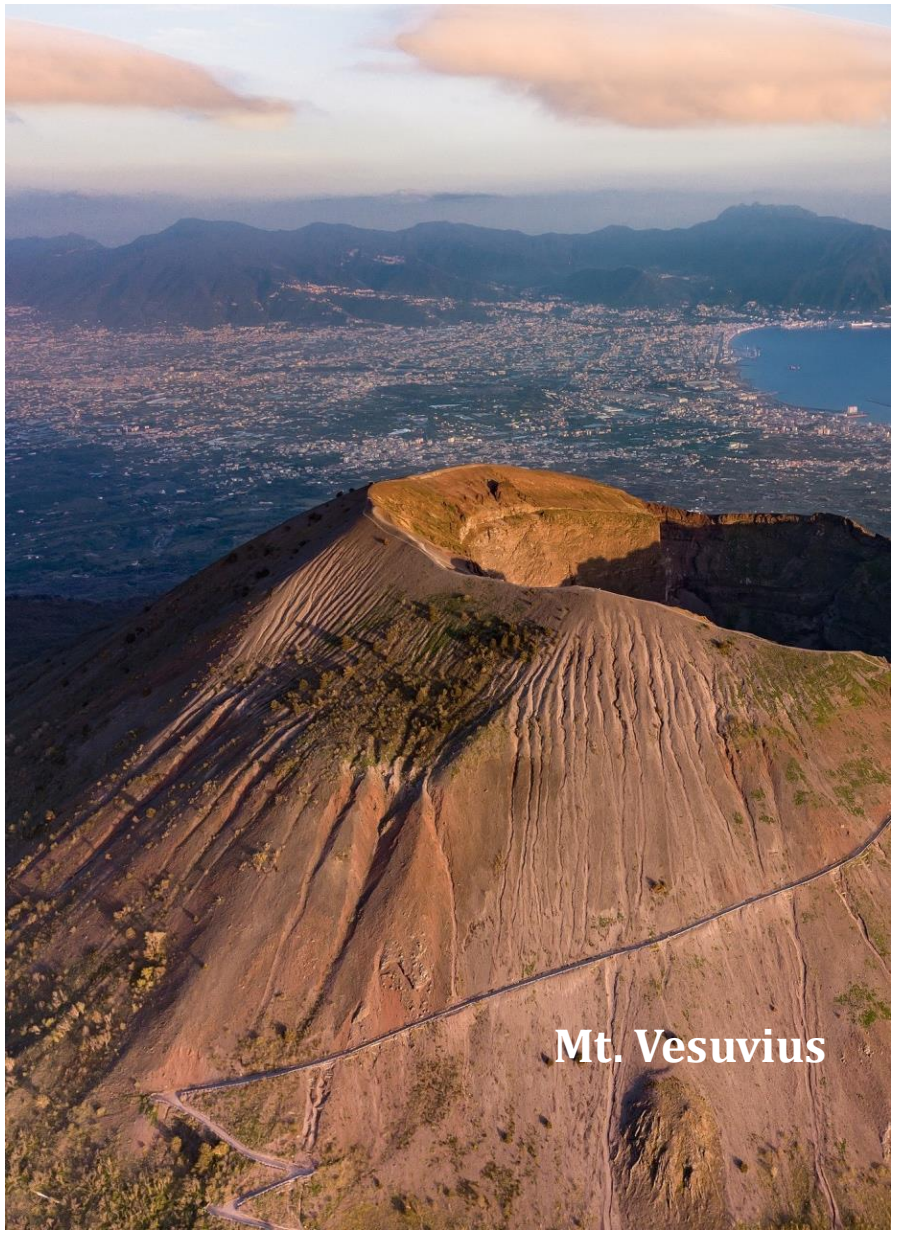
UCLouvain

INGV

INFN Istituto Nazionale di Fisica Nucleare

GHENT UNIVERSITY

VUB VRIJE UNIVERSITEIT BRUSSEL

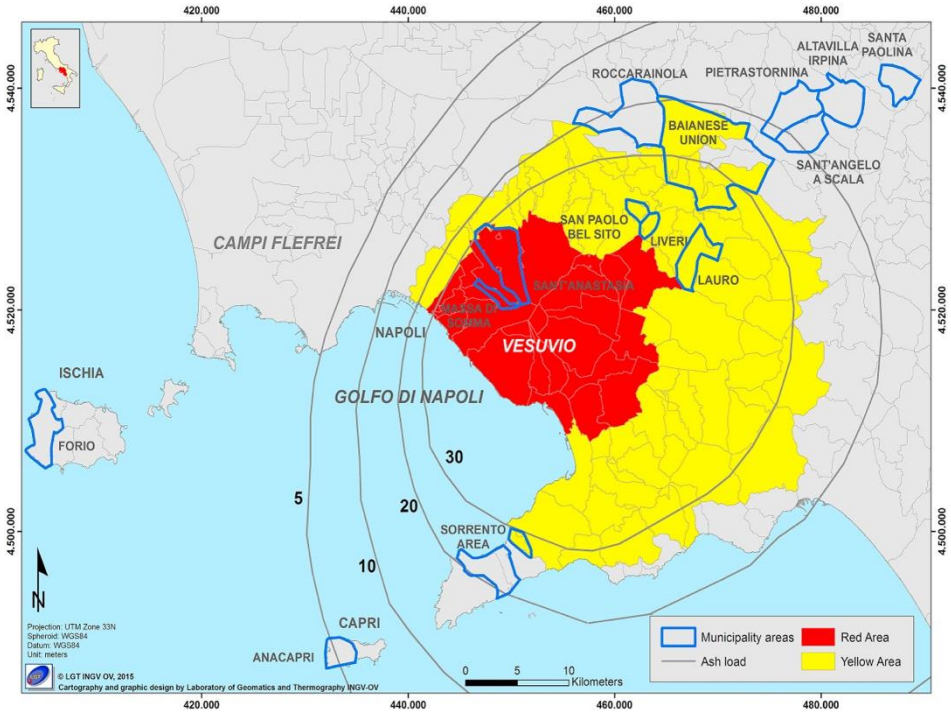


MURAVES (Muon Radiography of Vesuvius)

Active volcano located in Naples (Italy) with **high probability of an explosive eruption.**

54 confirmed eruptions in the last 11,700 years.

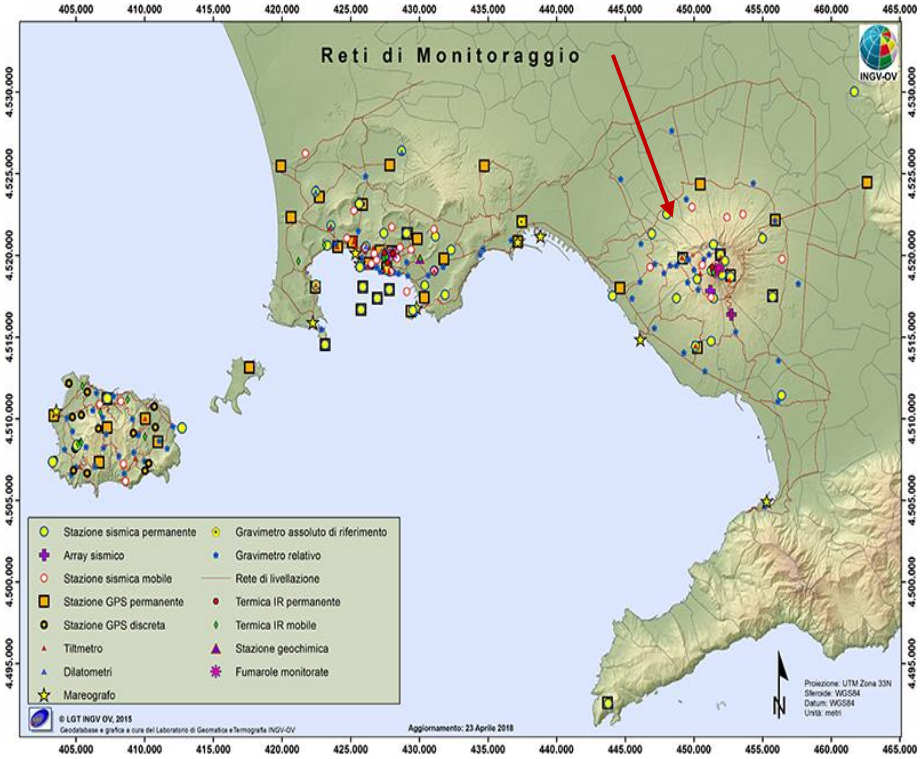
Last eruption occurred in 1944, starting with flowing lava and ending with an explosive eruption.



The red and yellow zones of Vesuvius Emergency Plan. Central circle indicates the limit of 300kg/m² of ash fallout load [1].

Mount Vesuvius

Current days: surrounding highly populated, 0.6 M residents in Red Zone.



Map of monitoring networks of active volcanoes in Campania area

Mount Vesuvius

Current days: surrounding highly populated, 0.6 M residents in Red Zone.

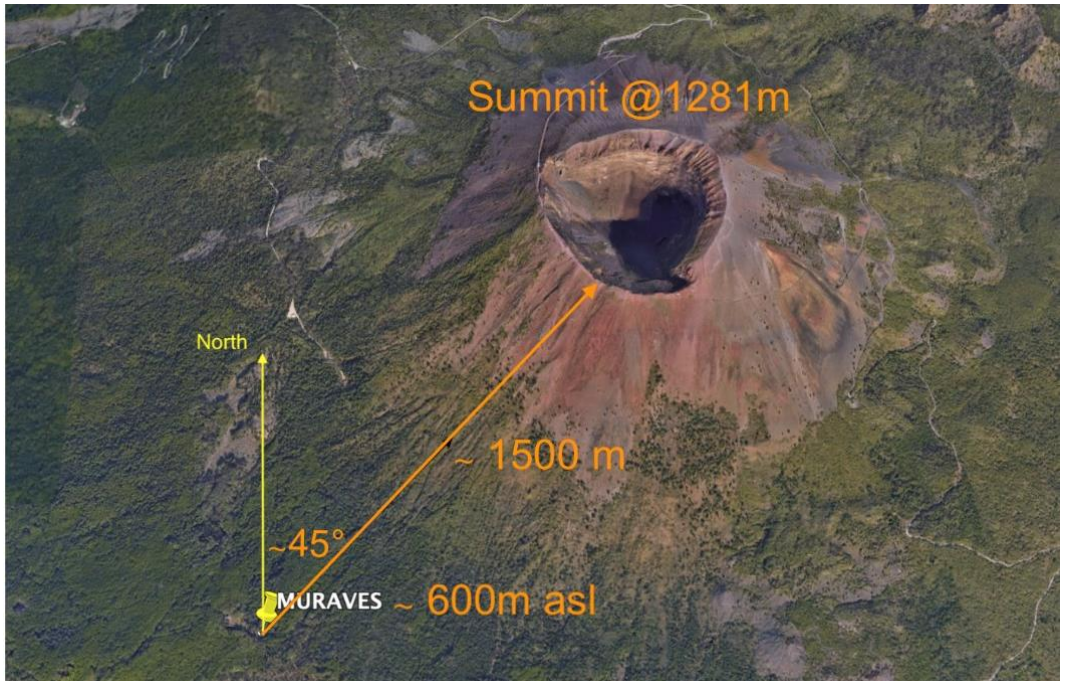
24/7 monitoring from INGV (National Institute of Geophysics and Vulcanology)

The MURAVES Collaboration

- Can muography provide additional information to the current monitoring system?
- Penetrating properties of muons can provide new insights.
- The **MURAVES** (**MUon RAdiography of Mt. VESuvius**) experiment aims to apply muon radiography to the summit of the Vesuvius

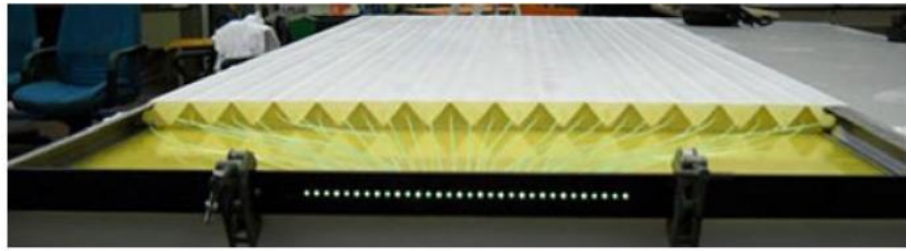
The MURAVES Detector

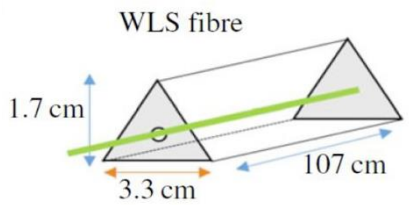
- MURAVES detectors located 1500m away from the volcano crater and ~ 600m asl.

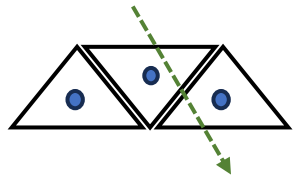


MURAVES tracking layer

- Trackers are made of 64 triangular adjacent scintillator bars;
- Scintillator light is collected via optical fiber and later read out by Silicon Photomultipliers (SiPM)







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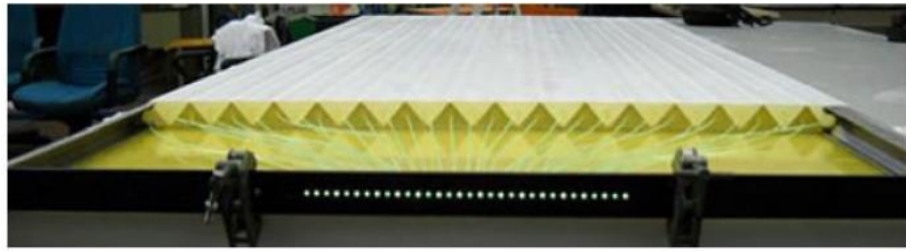
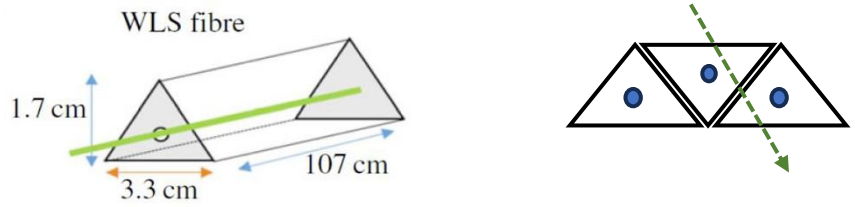
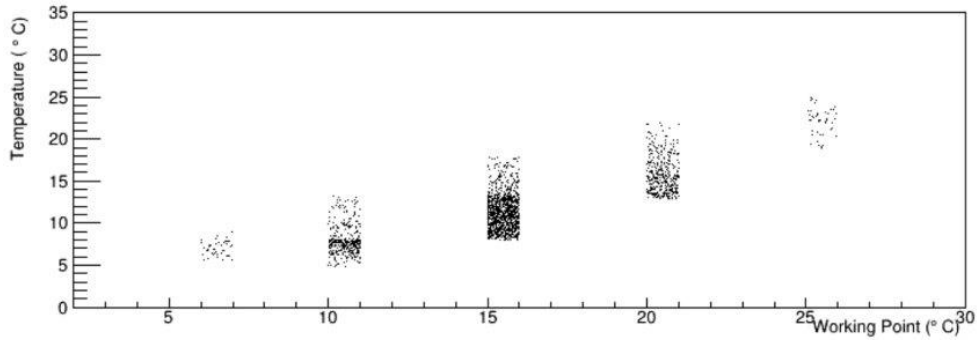




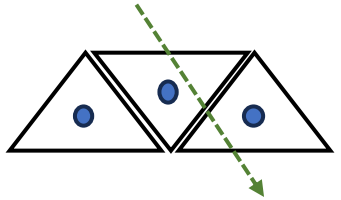
- SiPM gain depend on temperature
- Every 32 SiPMs installed two Peltier cells

  (*thermoelectric cooling*)
- Three main Working Points (WPs) : (15, 20, 25)ºC

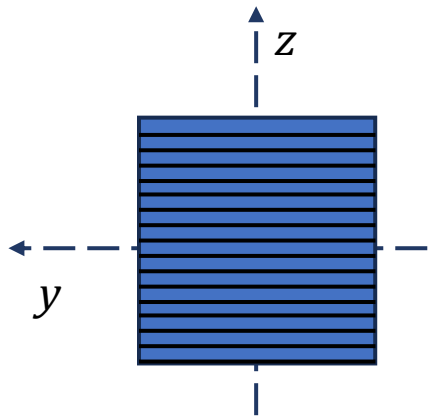


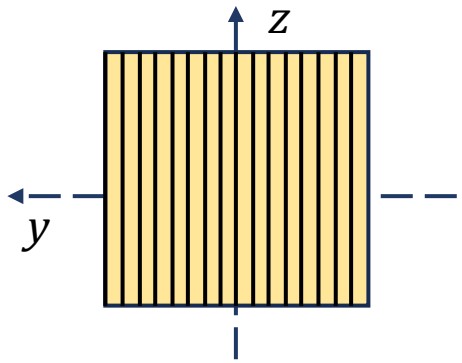
MURAVES detection plane

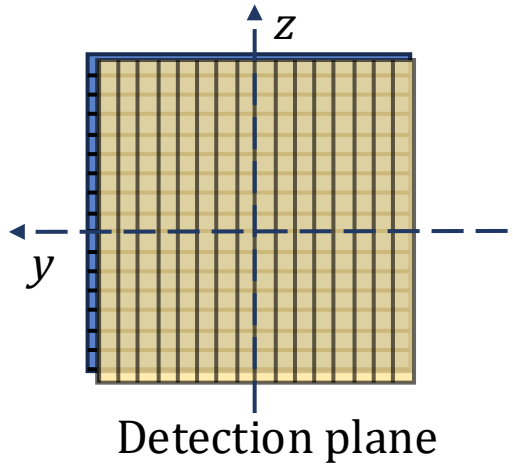
- Two layers arranged sequentially form a detection plane (bars in one layer perpendicular to those in the other)



64 bars per layer



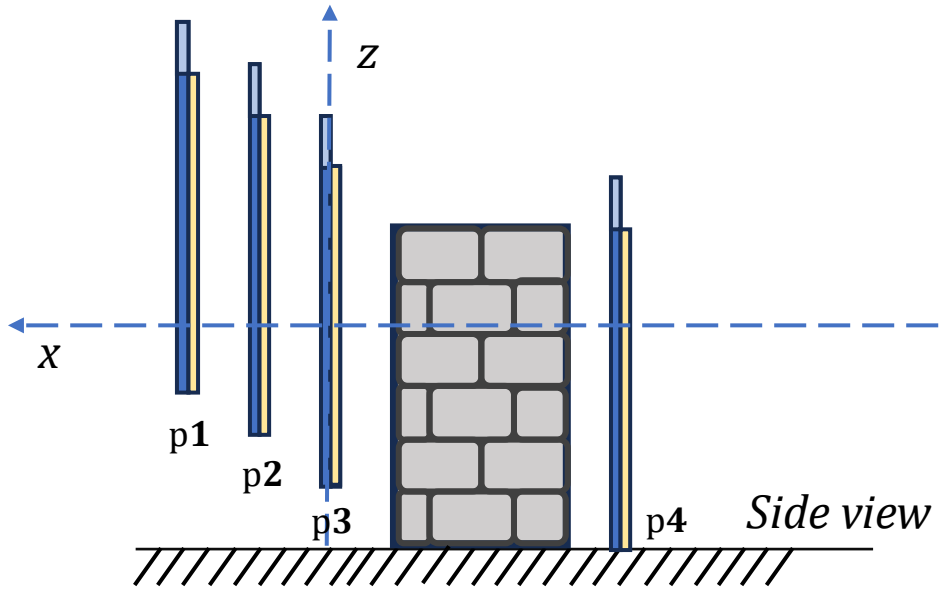


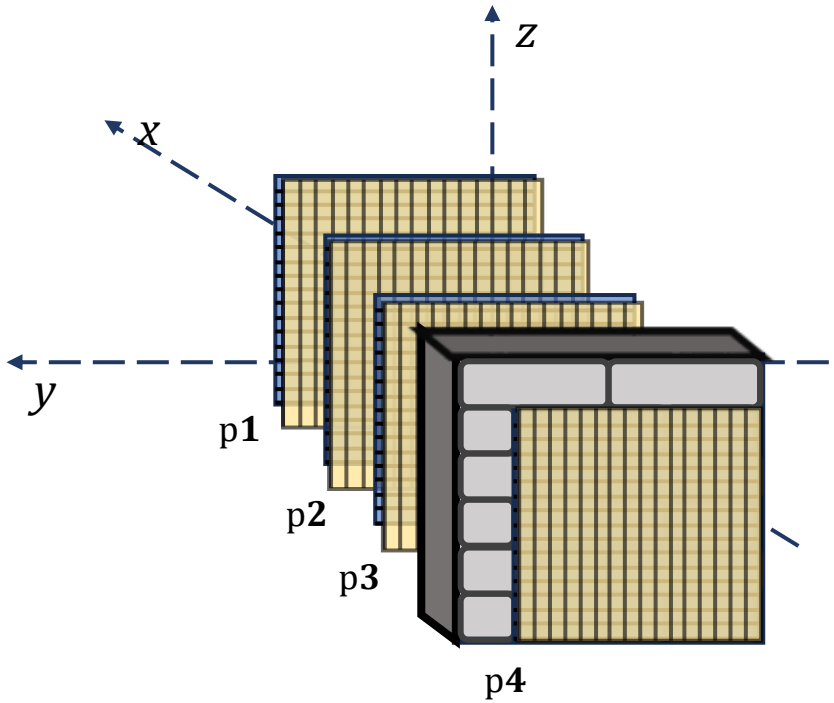


MURAVES hodoscope

- Two layers arranged sequentially form a detection plane (bars in one layer perpendicular to those in the other)

- A single hodoscope is composed by:
  - 4 planes of 1 m^2 active area each
  - ~60 cm of lead block in between two downstream plane





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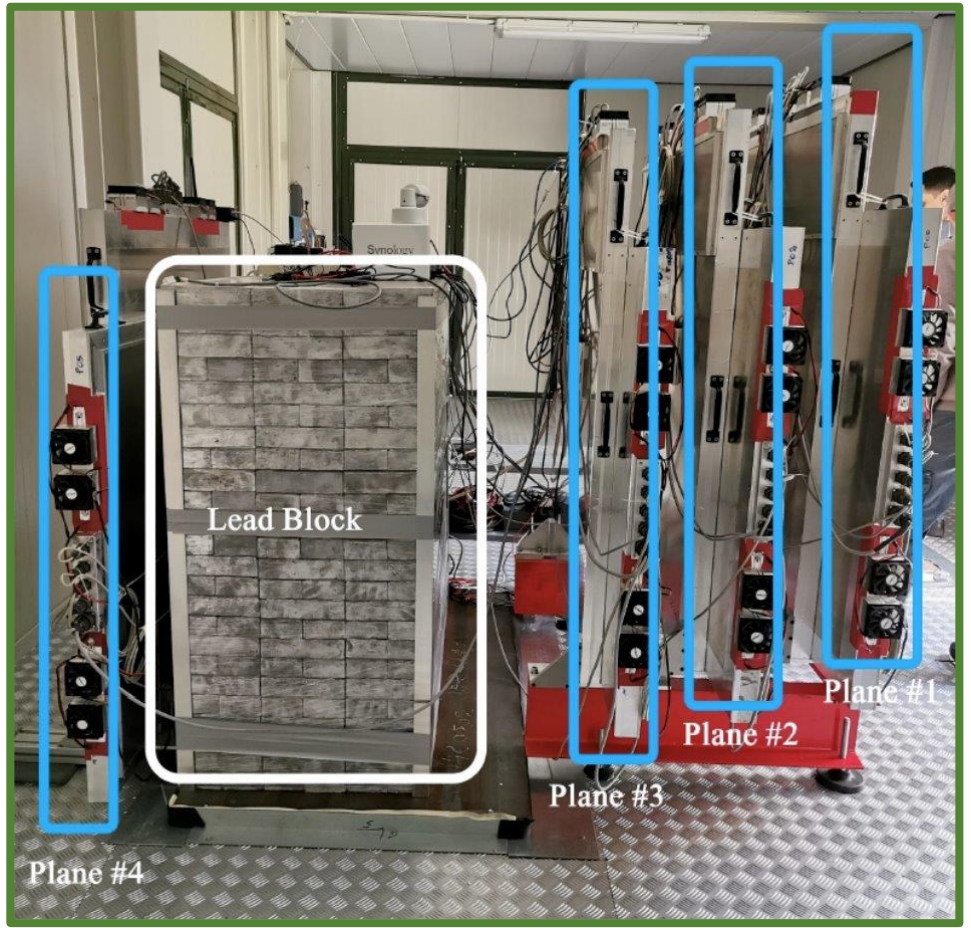
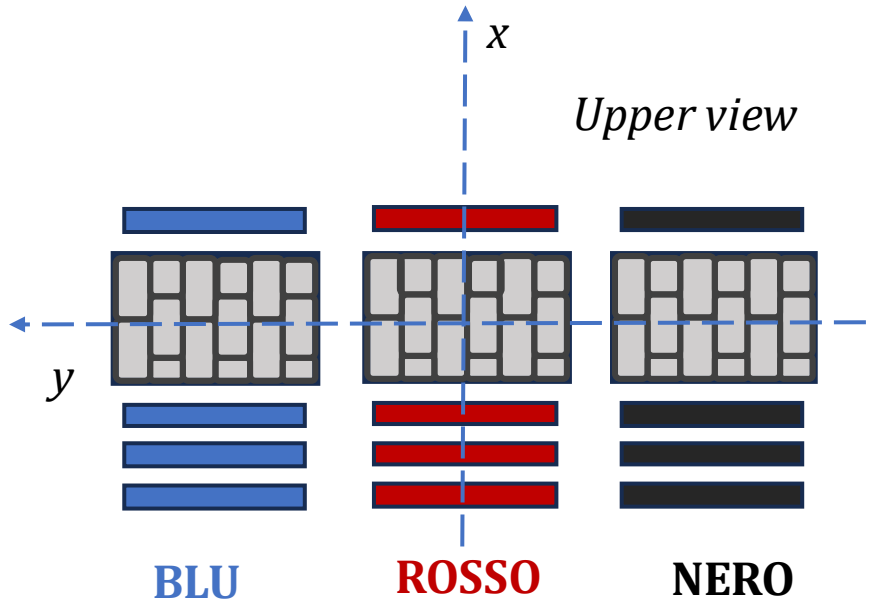


The MURAVES Detector

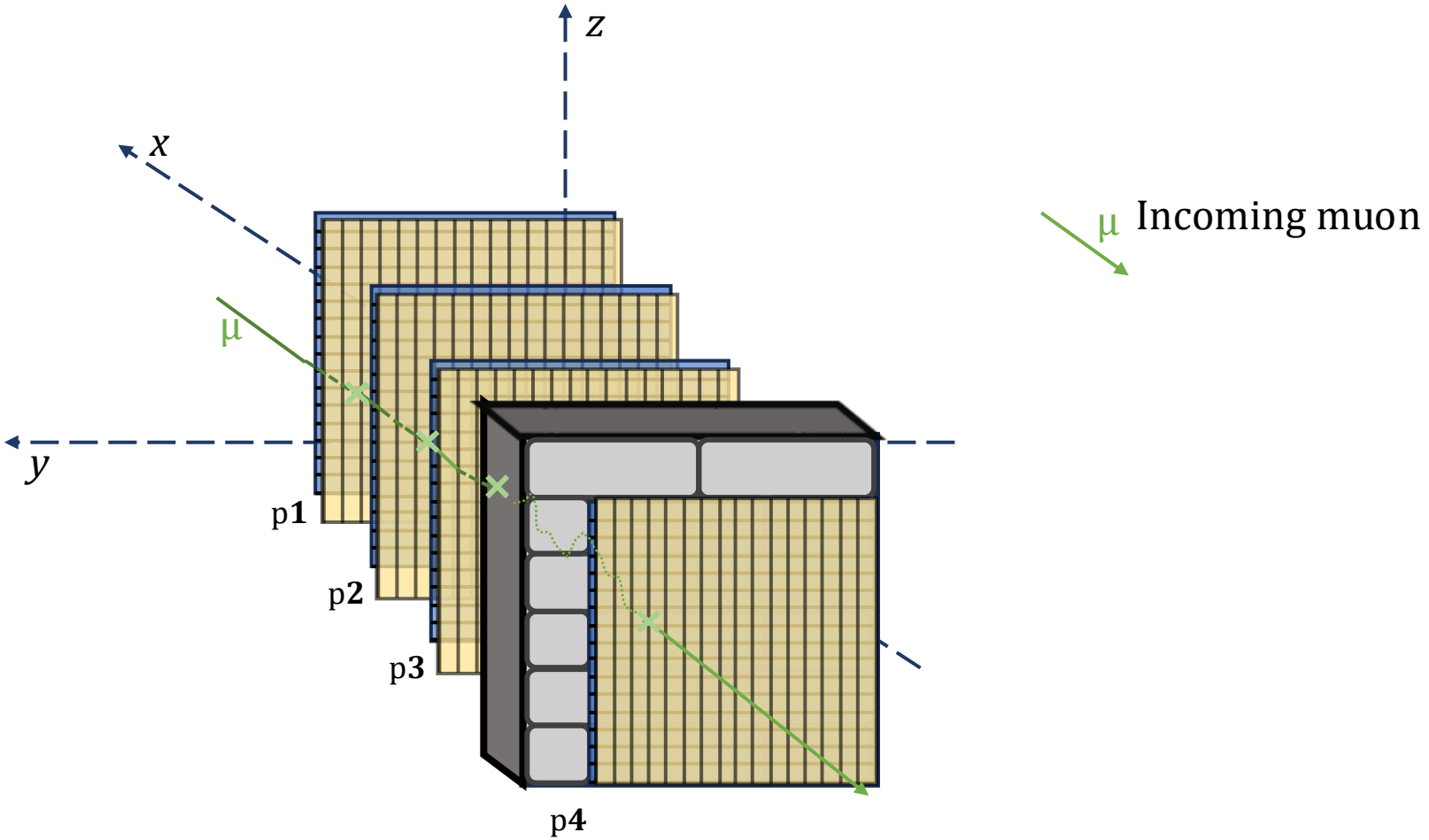
- Two layers arranged sequentially form a detection plane (bars in one layer perpendicular to those in the other)

- A single hodoscope is composed by:
  - 4 planes of 1 m^2 active area each
  - ~60 cm of lead block in between two downstream plane

- MURAVES telescope is composed by 3 identical muon trackers: **NERO** **ROSSO** **BLU**.

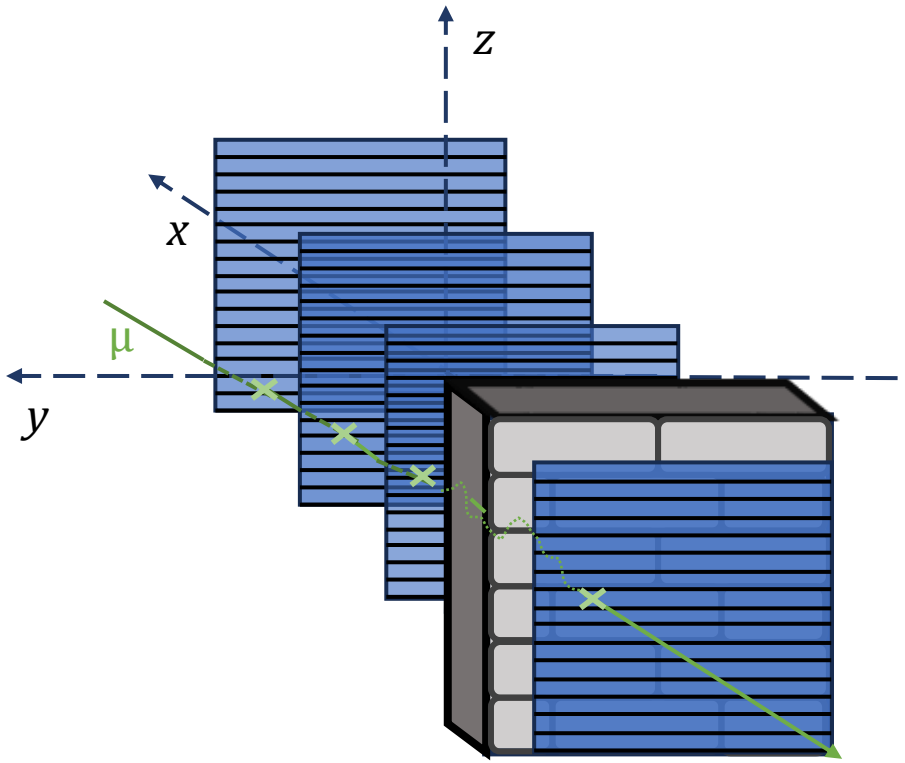


Tracking

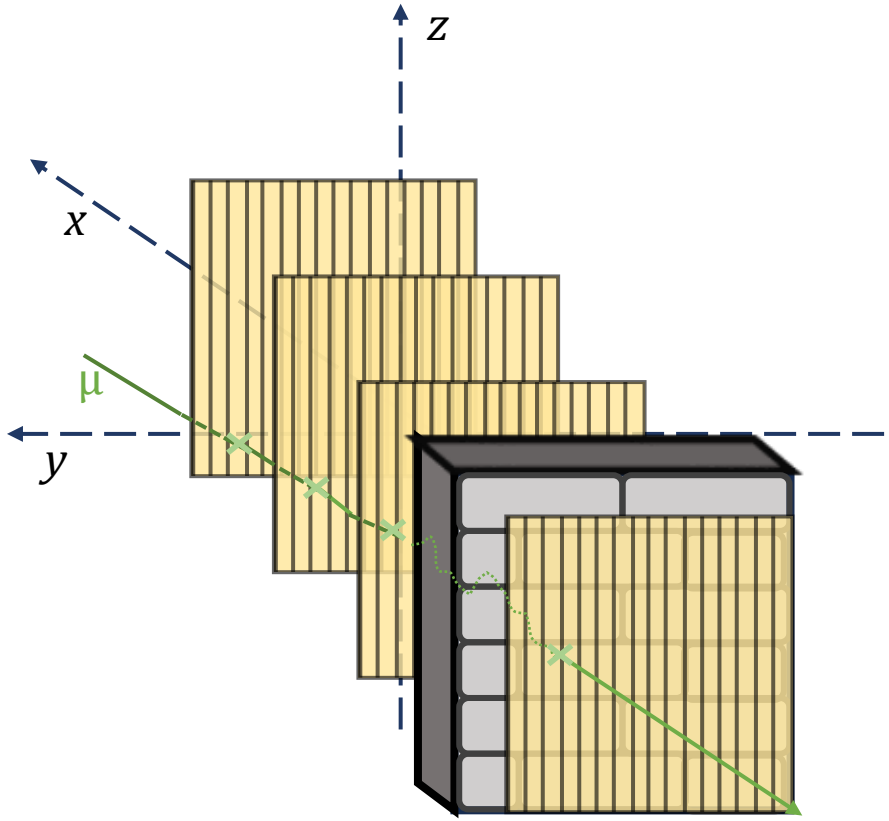


Tracking

μ Incoming muon



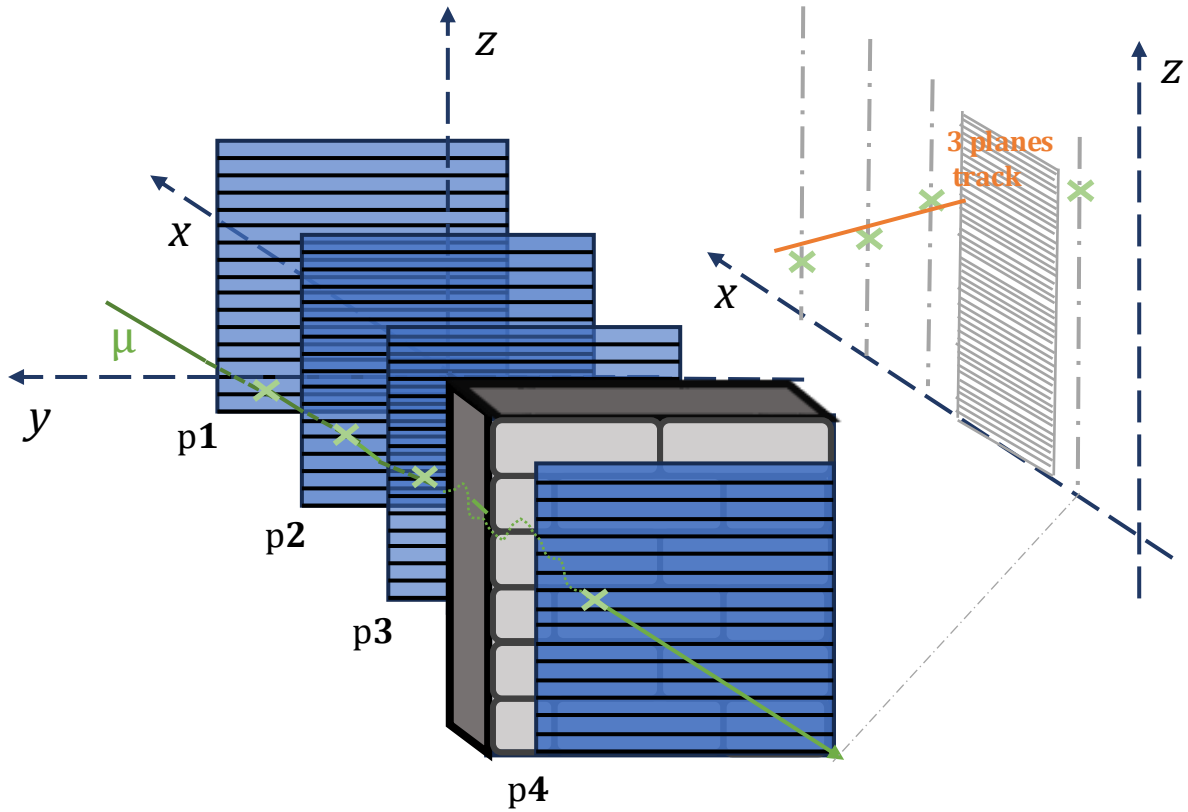
2D track on *xz* plane
(bars aligned to y axis)



2D track on *xy*
(bars aligned to y axis)

Tracking

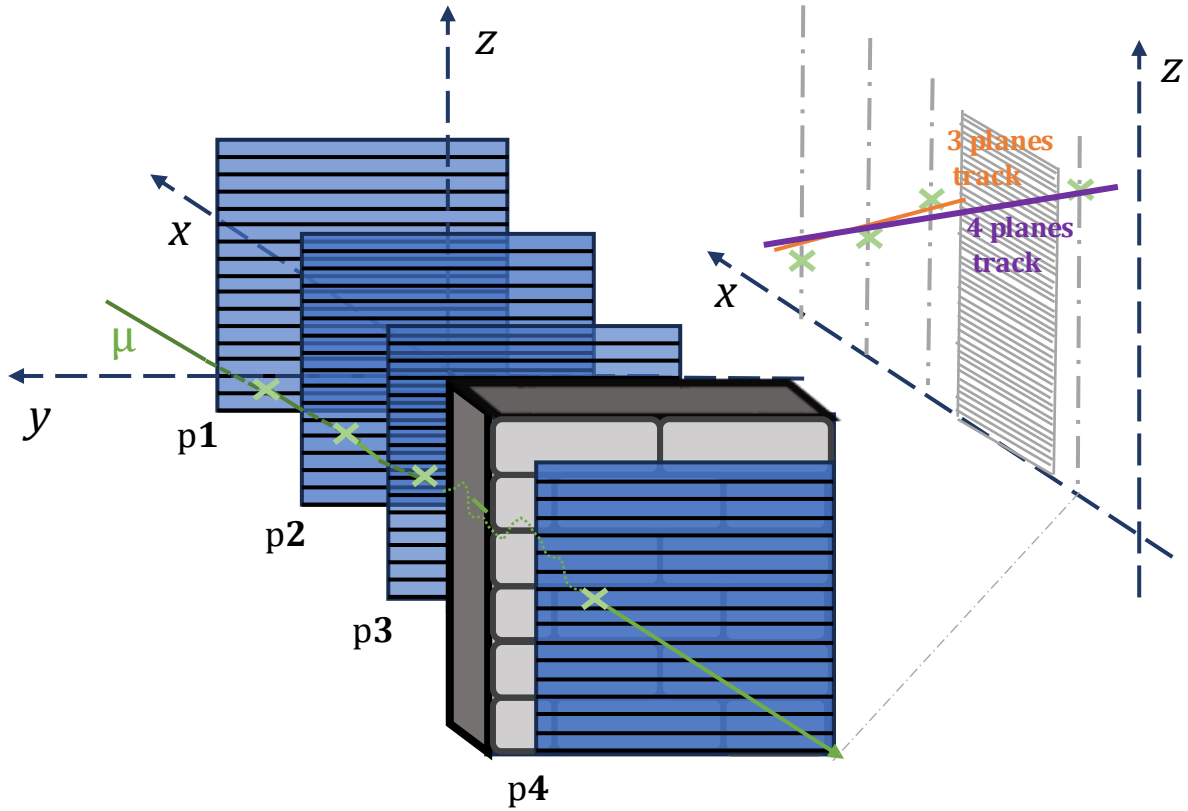
μ Incoming muon



- Linear min $\mathcal{X}^2$ fit to hits of the first 3 planes
  → 3p track
- $\mathcal{X}^2$ is info on track quality
  → $\mathcal{X}^2_{3p}$

Tracking

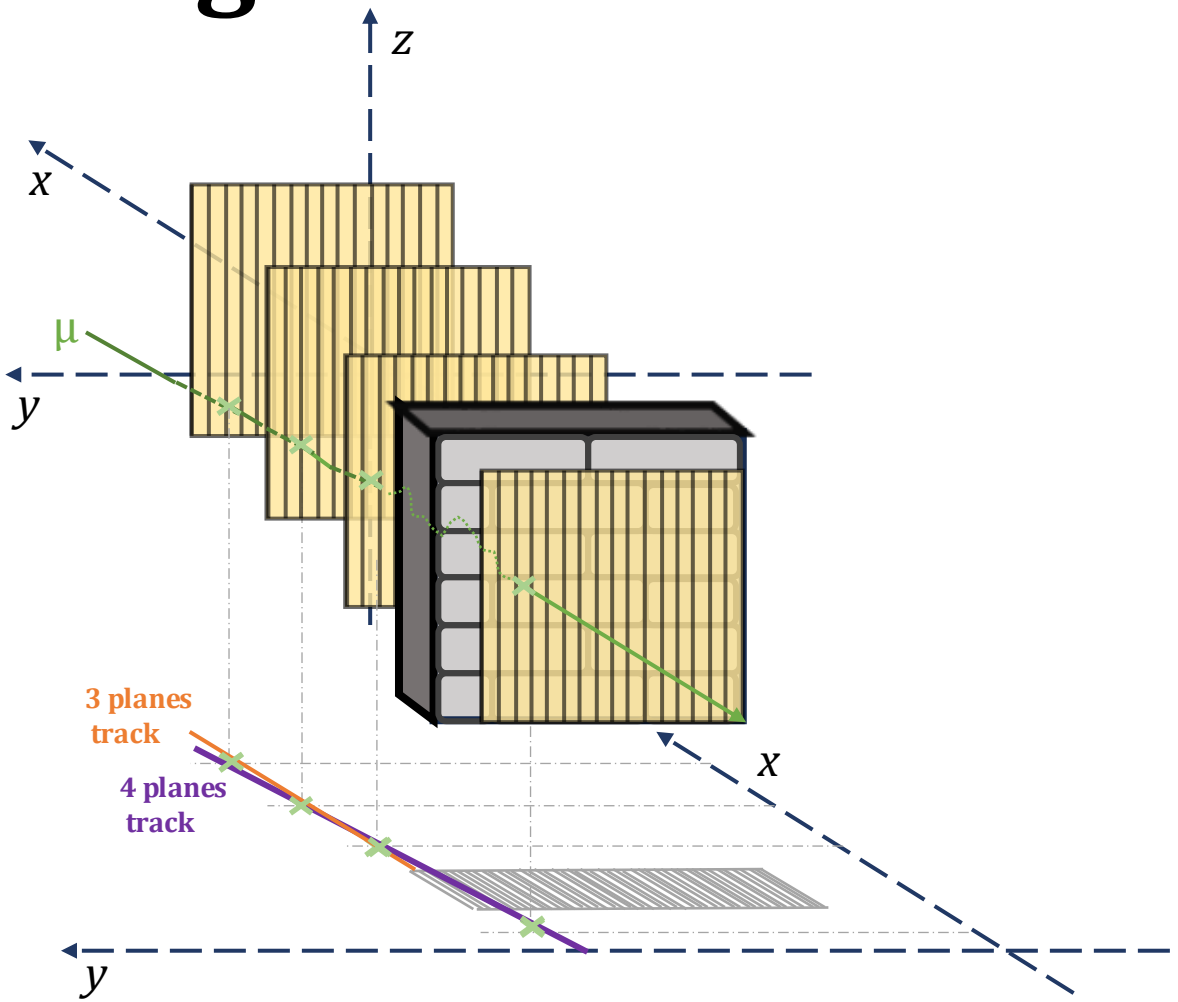
μ Incoming muon



- Linear min χ^2 fit to hits of the first 3 planes
  → 3p track
- χ^2 is info on track quality
  → χ^2_{3p}

- Linear min χ^2 fit to hits of the first 3 planes
  → 4p track
- χ^2 is info on track quality
  → χ^2_{4p}

Tracking



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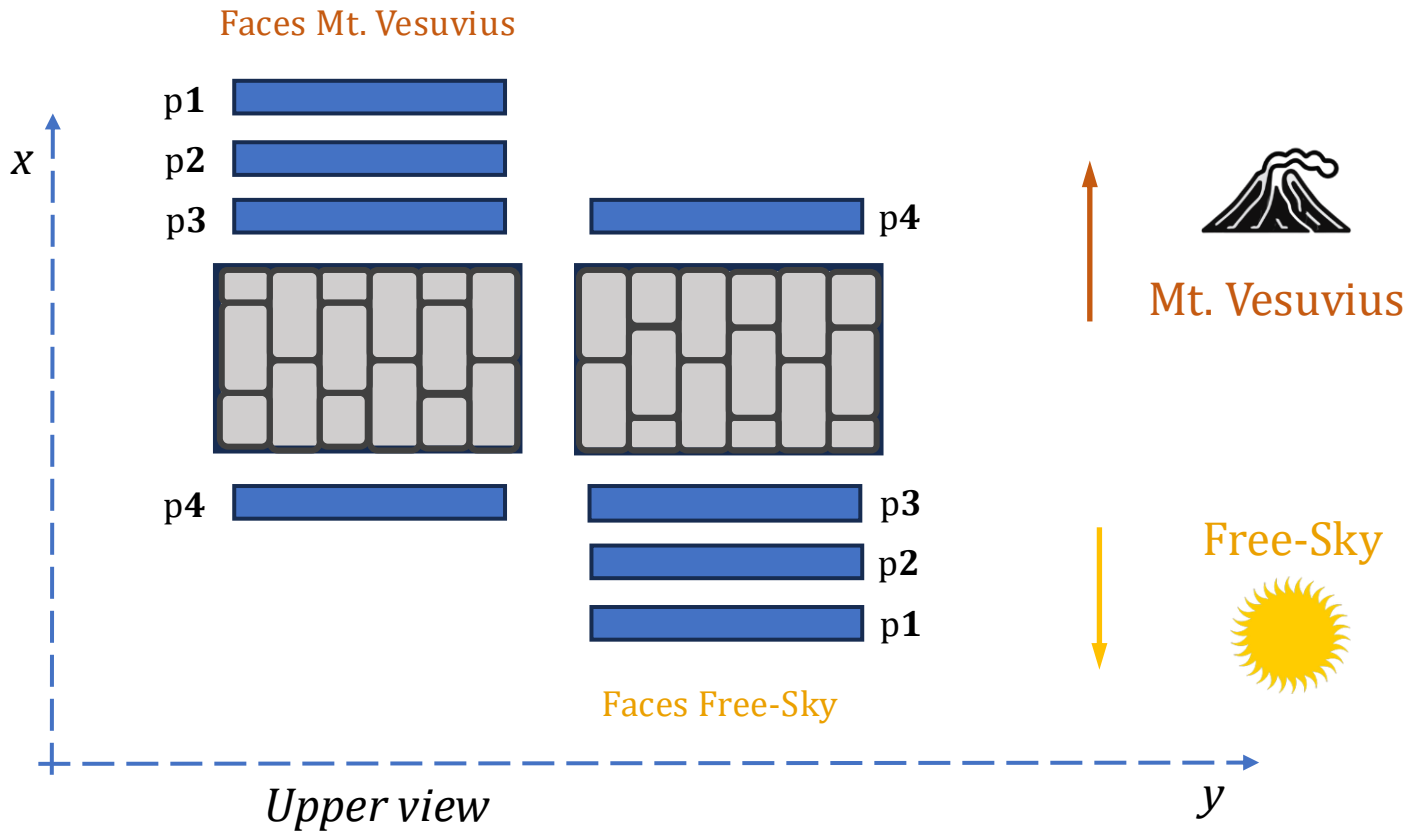
  → 4p track
- χ^2 is info on track quality
  → χ^2_{4p}

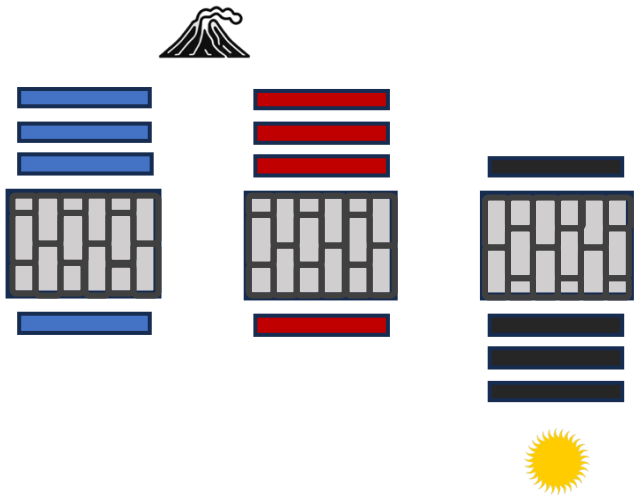
The MURAVES Data taking

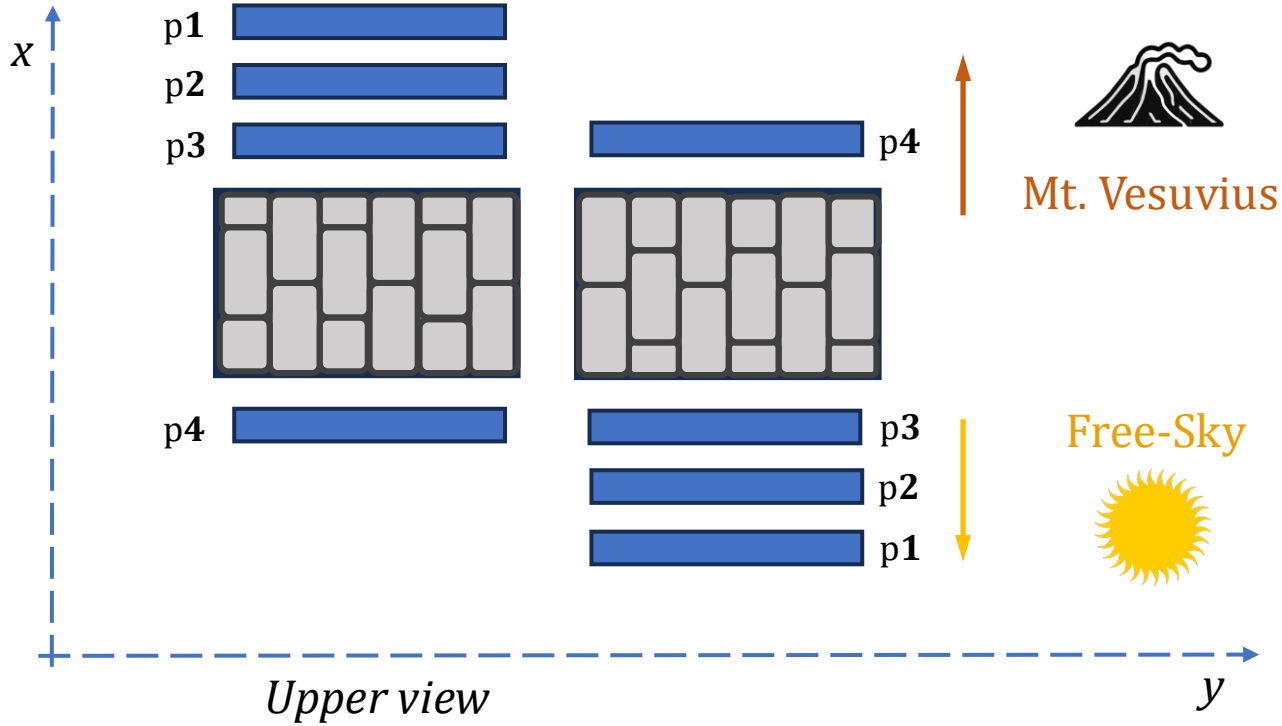
- 2 installation positions:
  - Facing Free Sky (FS)
  - Facing Mt. Vesuvio



The MURAVES Data taking

- 2 installation positions:
  - Facing Free Sky (FS)
  - Facing Vesuvio
- 2 hodoscopes face Mt. Vesuvius
- 1 hodoscope faces FS





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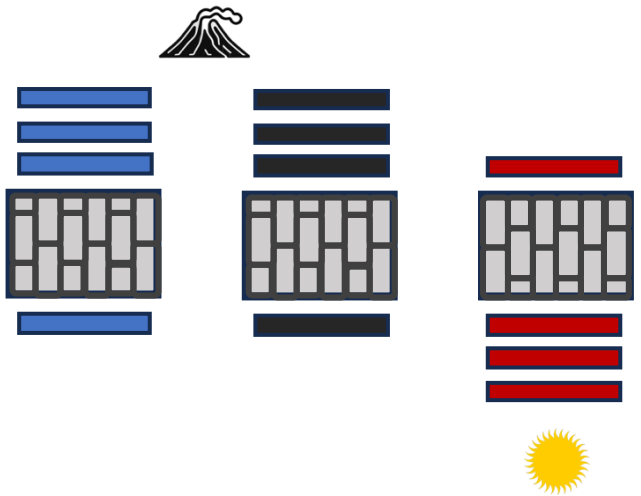

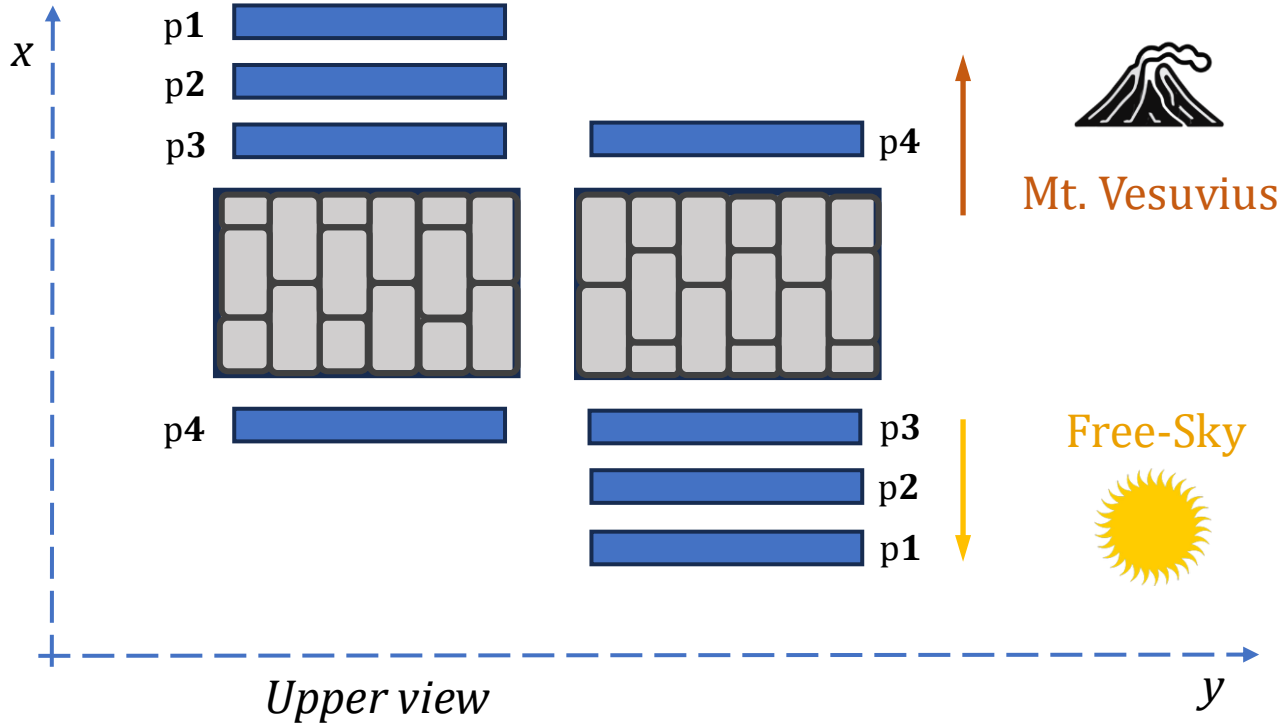

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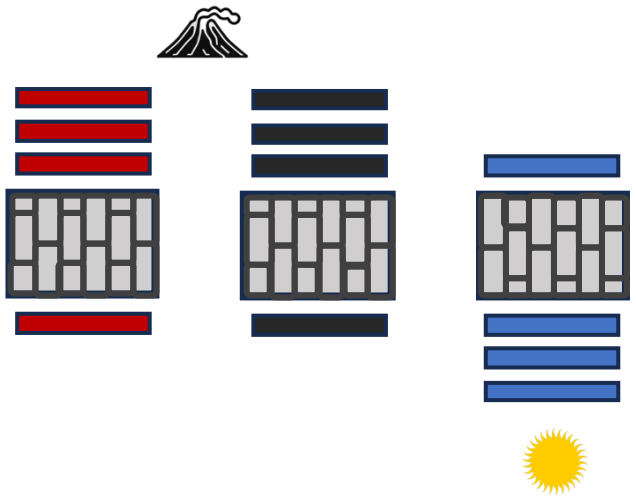
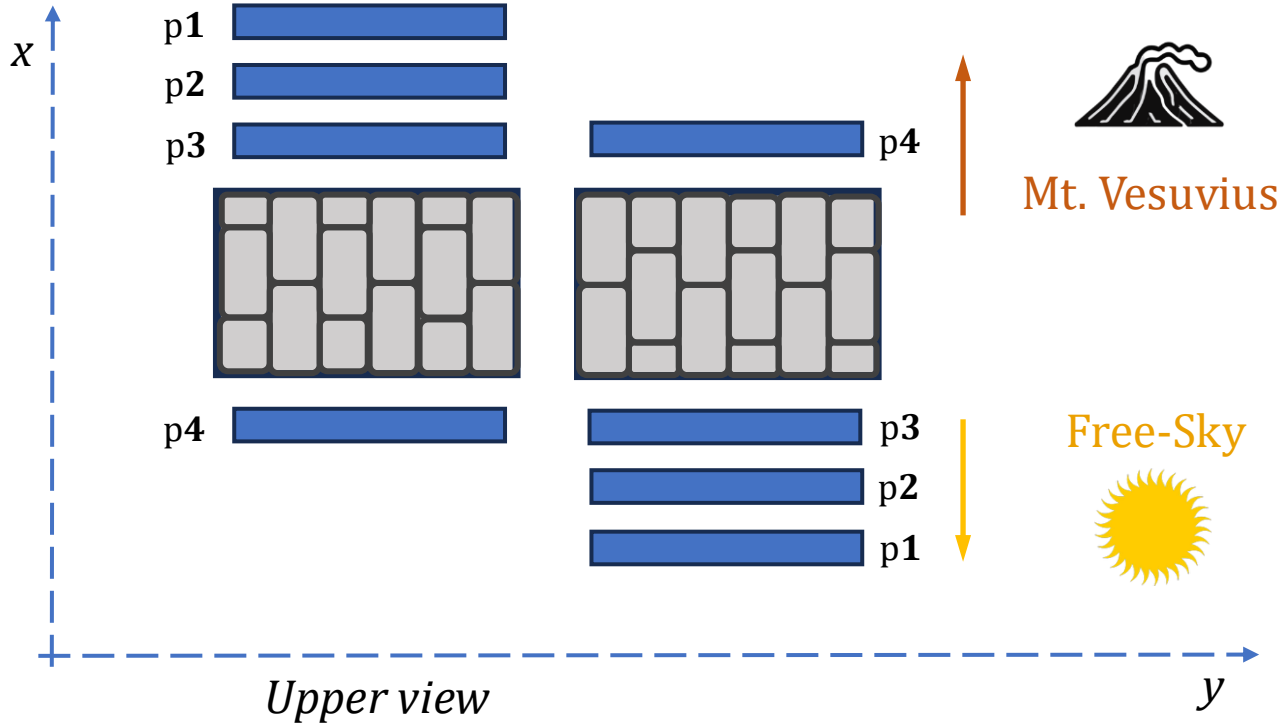


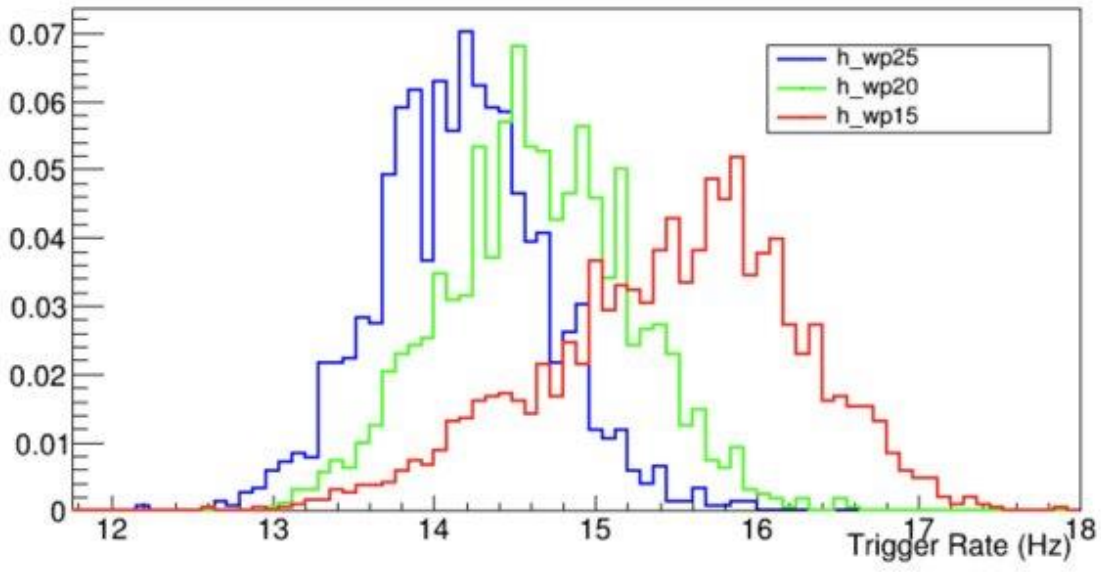


The MURAVES Data taking

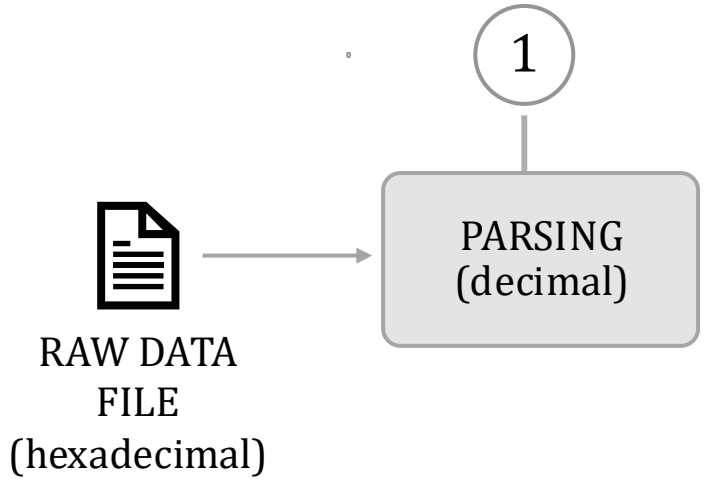
- **Trigger logic**:
  - OR of all 64 channels belonging to a same layer
  - AND of all 6 layers of the 3 planes before lead for each layer

- **Runs:**
  - packages of 40 000 triggering events.

- Runs organized by
  - hodoscope
  - Working Point (WP) temperature

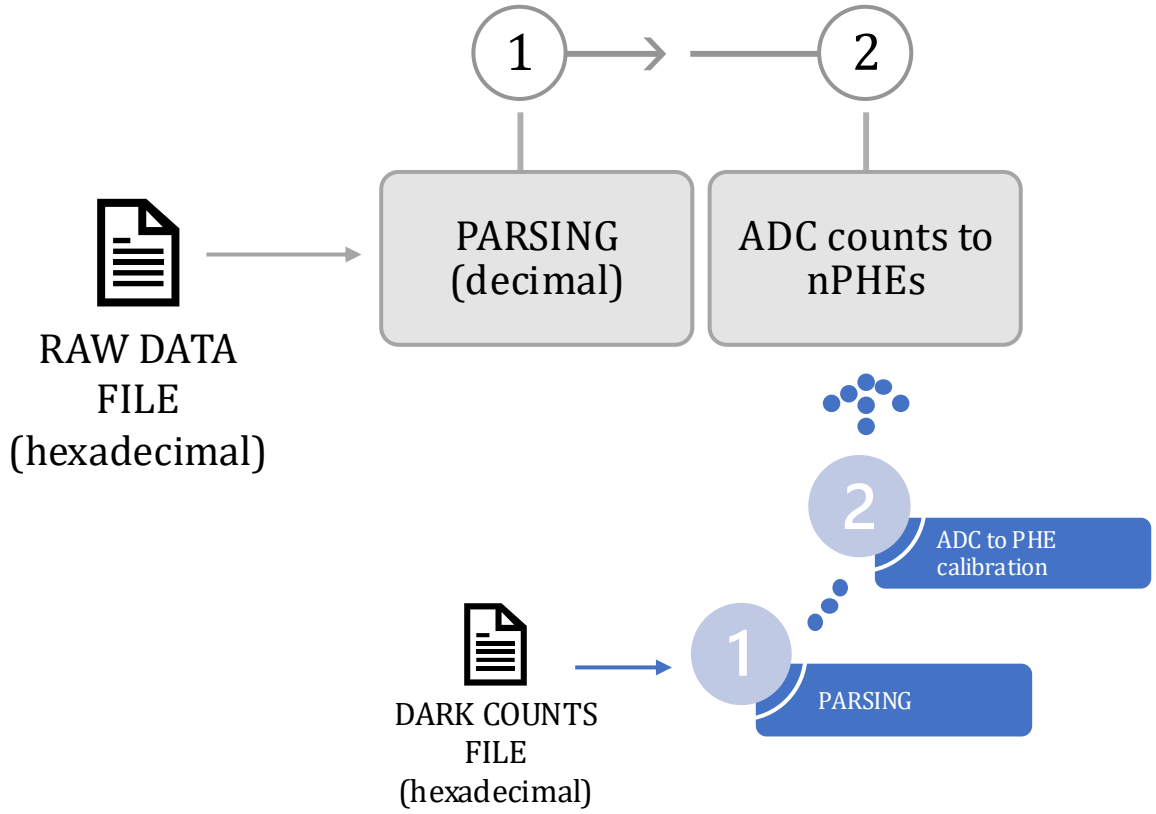


Data reconstruction pipeline



- ADC conversion
- Initial data quality checks
  - Trigger rate
  - Data structure
  - Bit shift / missing-bit frequency

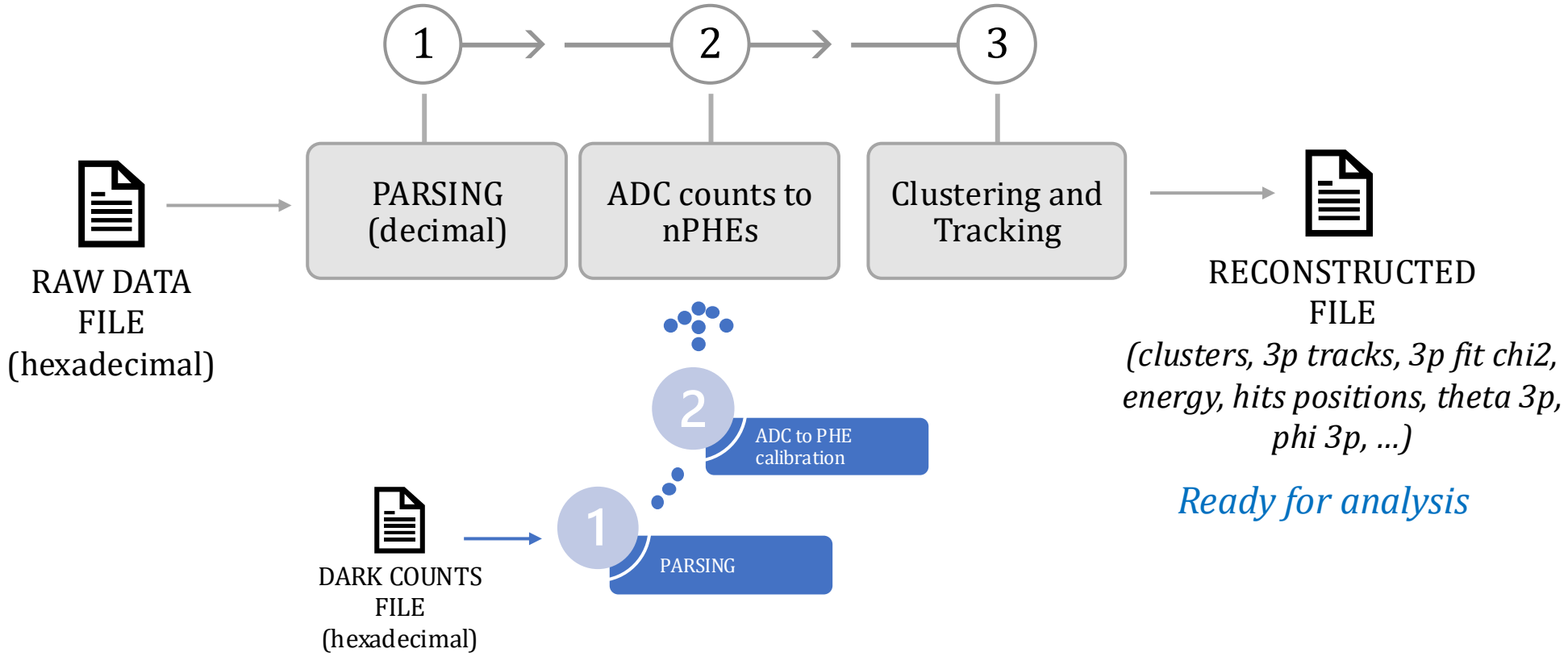
Data reconstruction pipeline



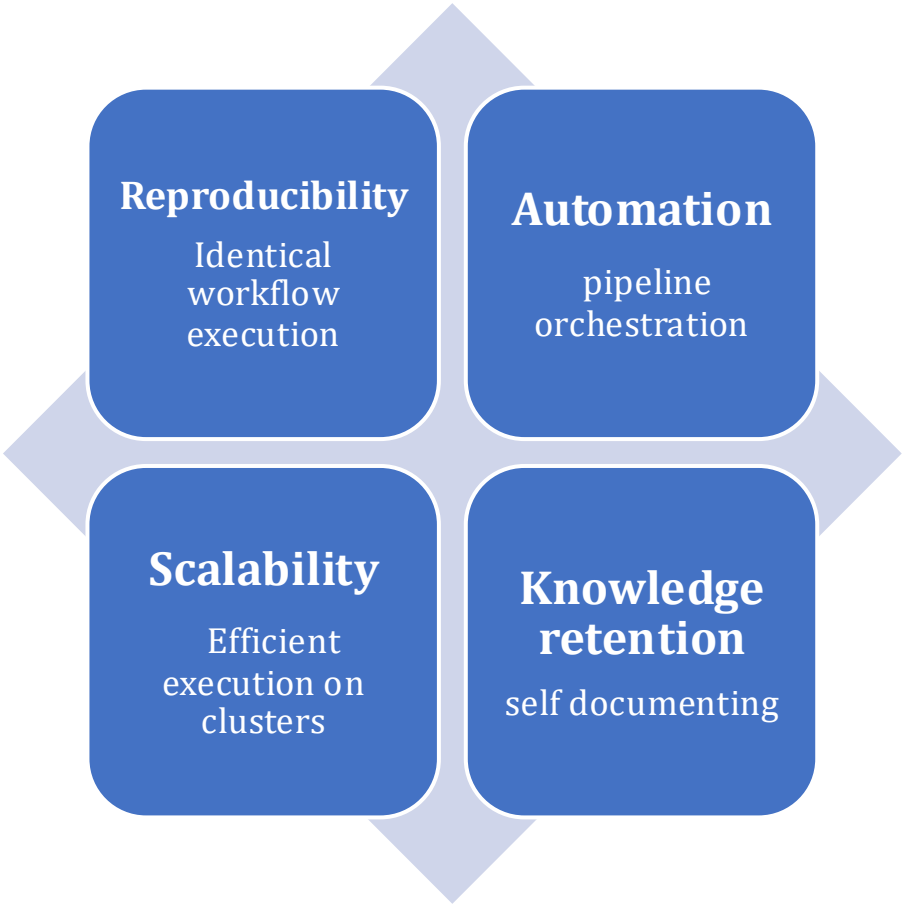
- Raw data files contains signals in ADC counts
- Secondary pipeline needed to find ADC to Energy conversion

- Dark counts runs are parsed and used to find
  - Pedestal peak
  - 1 photoelectron value
- ADC to PHE calibration:
  ADC counts to 1PHE of energy released

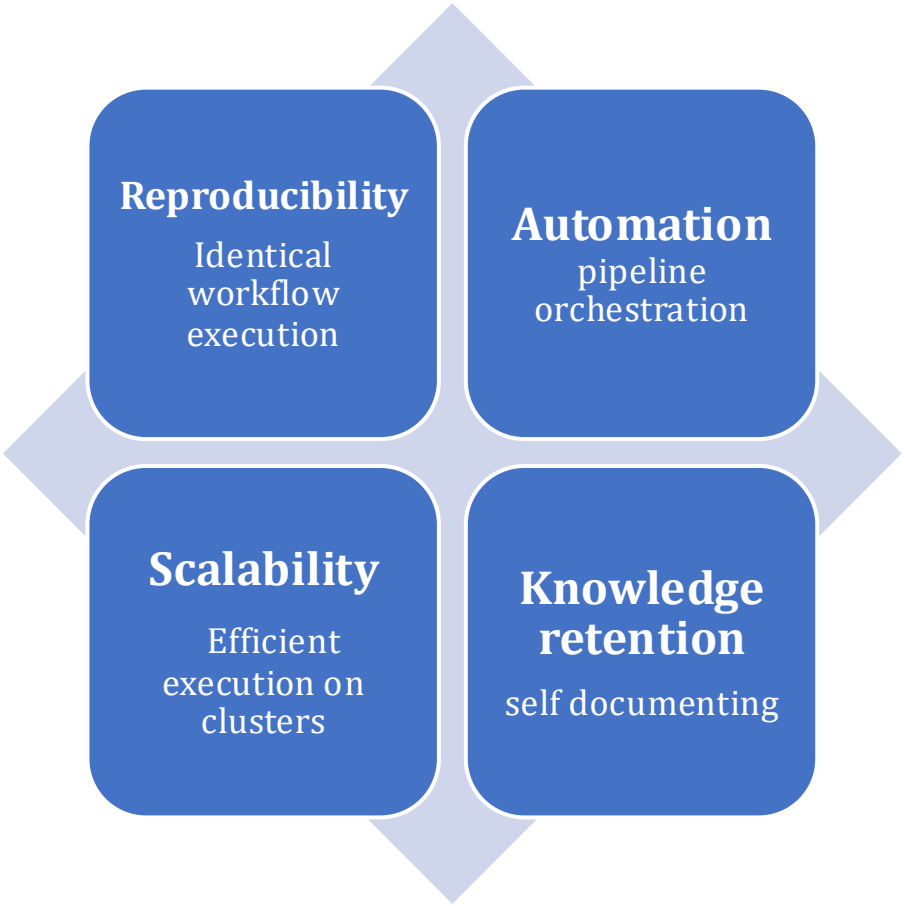
Data reconstruction pipeline



Workflow management system



Workflow management system

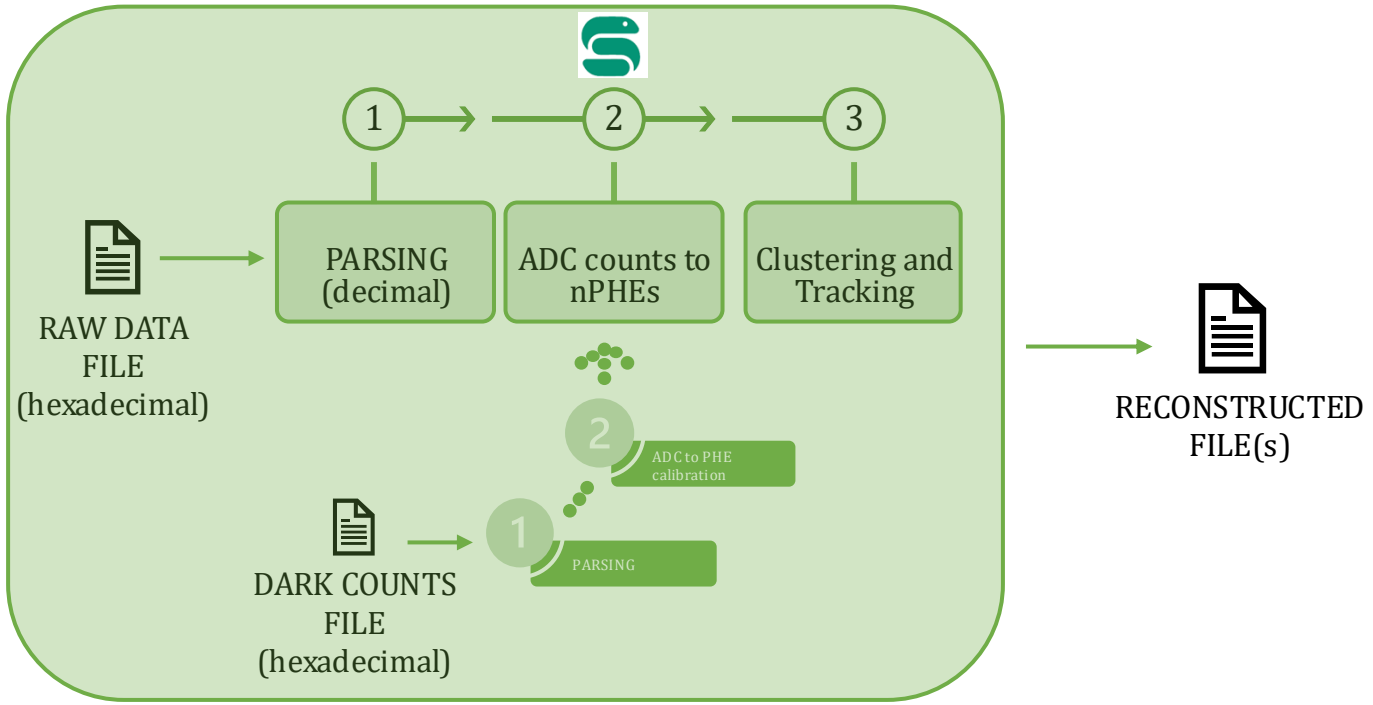


snakemake

- **Clear and simple**
- **Automatic job parallelisation**
- **Integration with workload management systems (qsub, condor, ...)**
- **Previous experience with the software**

Pipeline execution

"Go, Snakemake!"

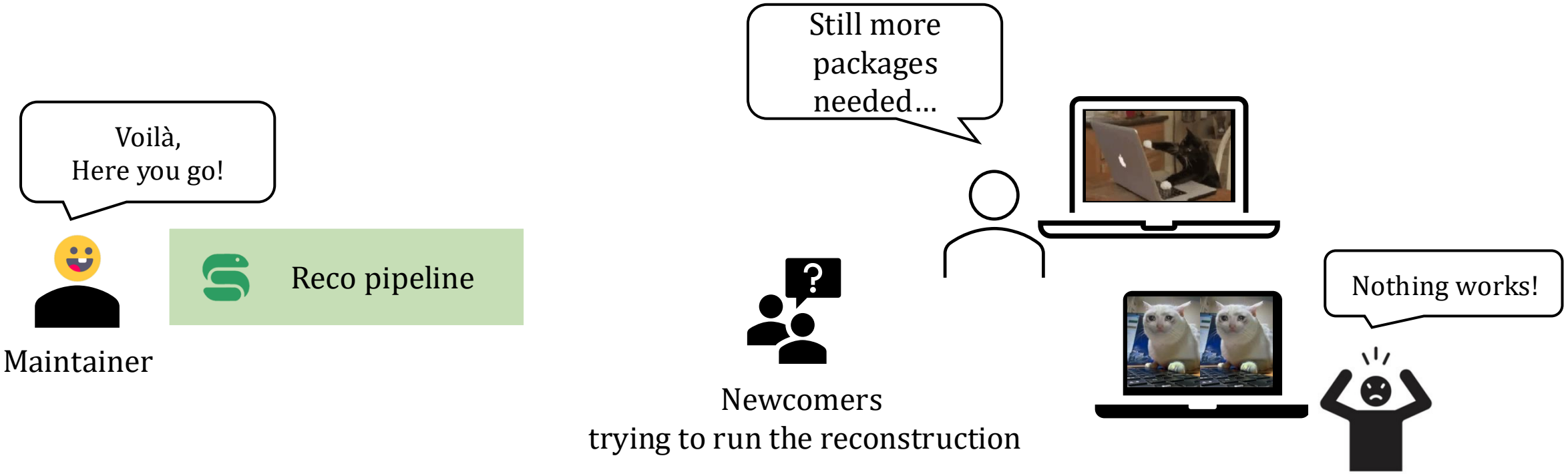


User experience

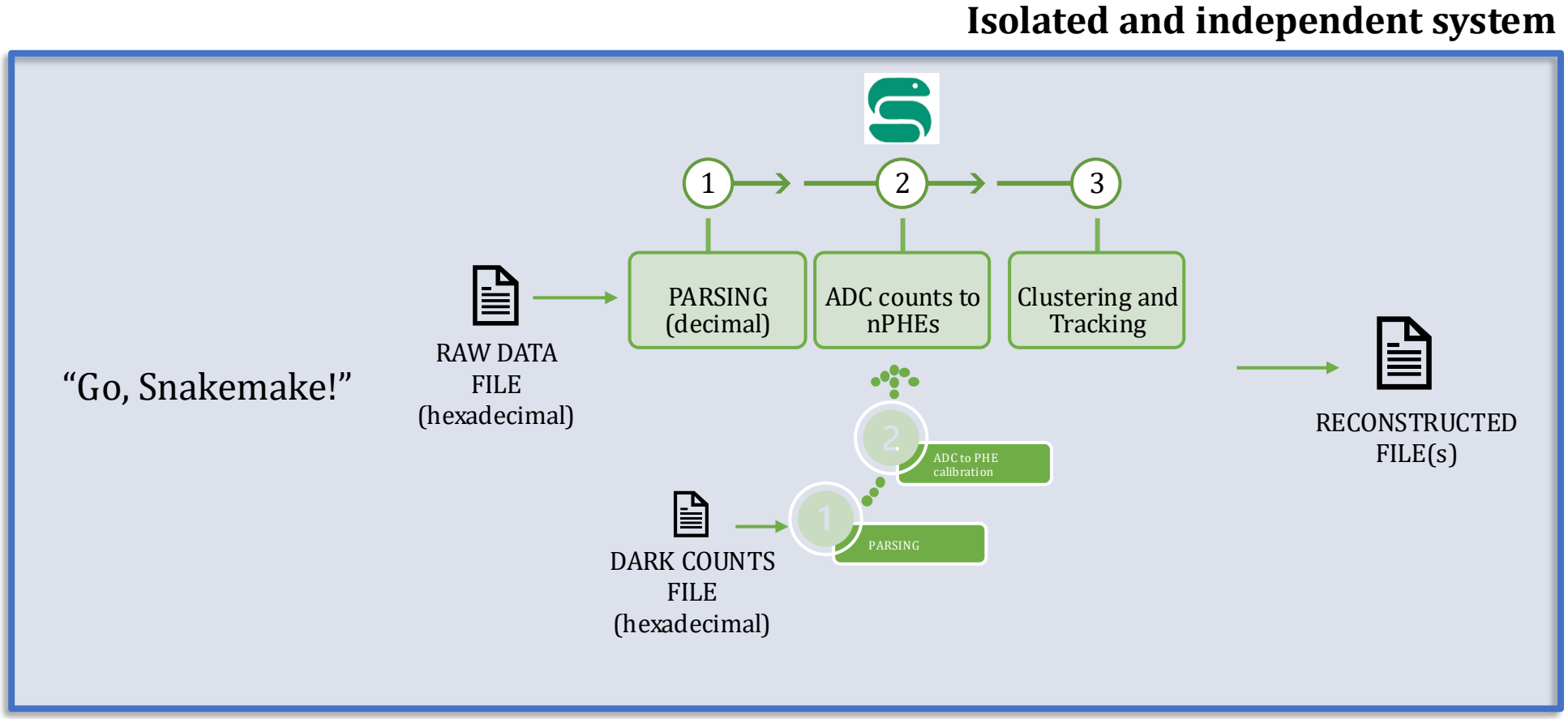
Maintainer

Reco pipeline

User experience



Container


Isolated and independent system
"Go, Snakemake!"
RAW DATA FILE (hexadecimal)
1
PARSING (decimal)
2
ADC counts to nPHEs
3
Clustering and Tracking
RECONSTRUCTED FILE(s)
2
ADC to PHE calibration
1
PARSING
DARK COUNTS FILE (hexadecimal)

Container

Isolation

Environment isolated from host system

Portability

consistent across any system

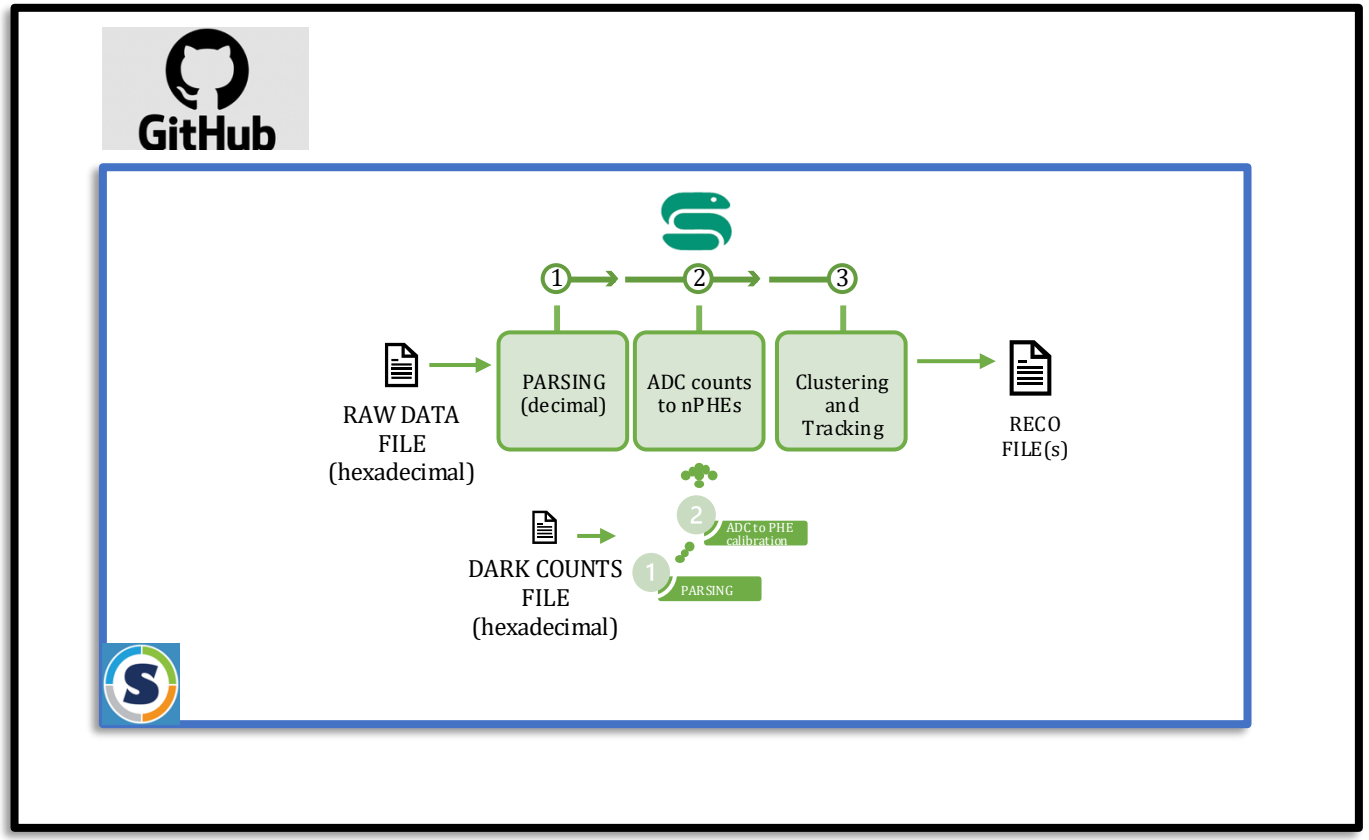
Happy users

- A container is an immutable image
- It always starts from the same initial state

SINGULARITY

DOCKER

Documentation and versioning



GitHub

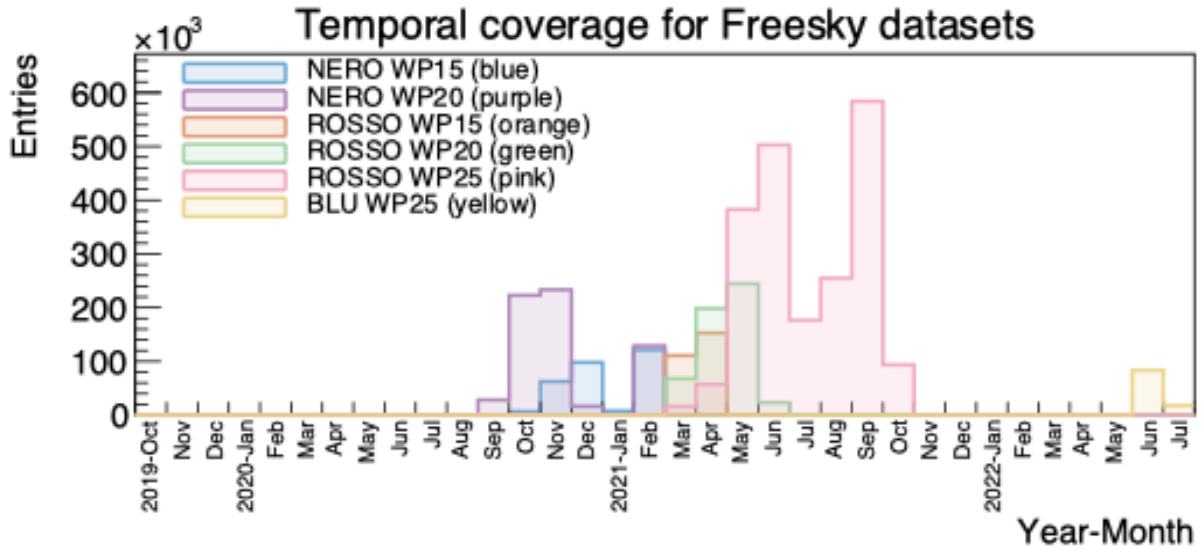
- Versioning and releases track updates
- Metadata of the output file have:
  - latest repo release at production
  - reconstruction parameters

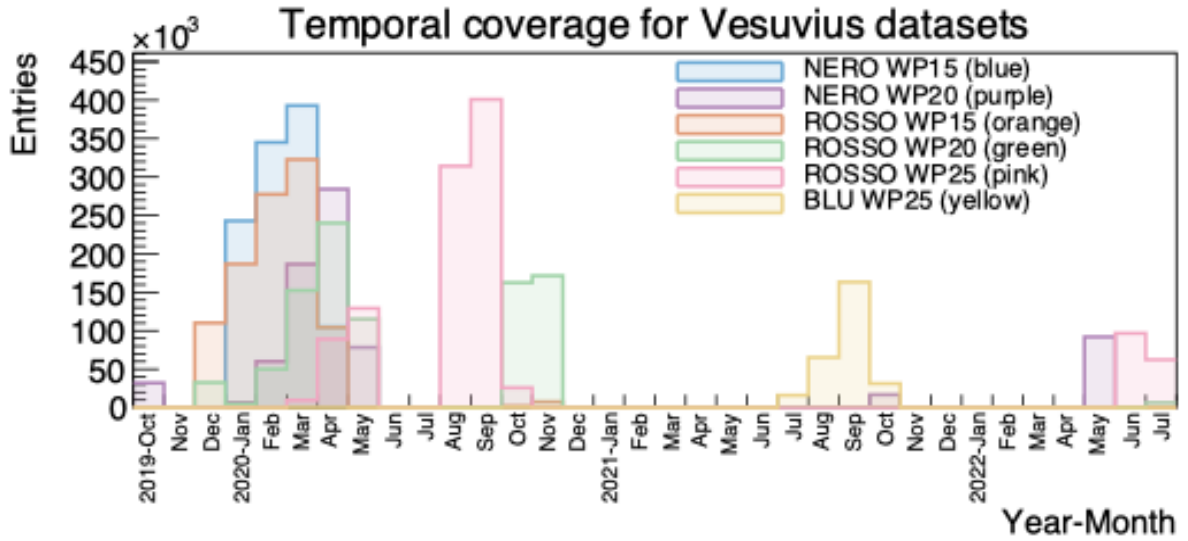
Collected data

- Data were collected
  October 2019 → July 2022

- Today: preliminary imaging of **NERO WP20**

Credits to Yanwen Hong



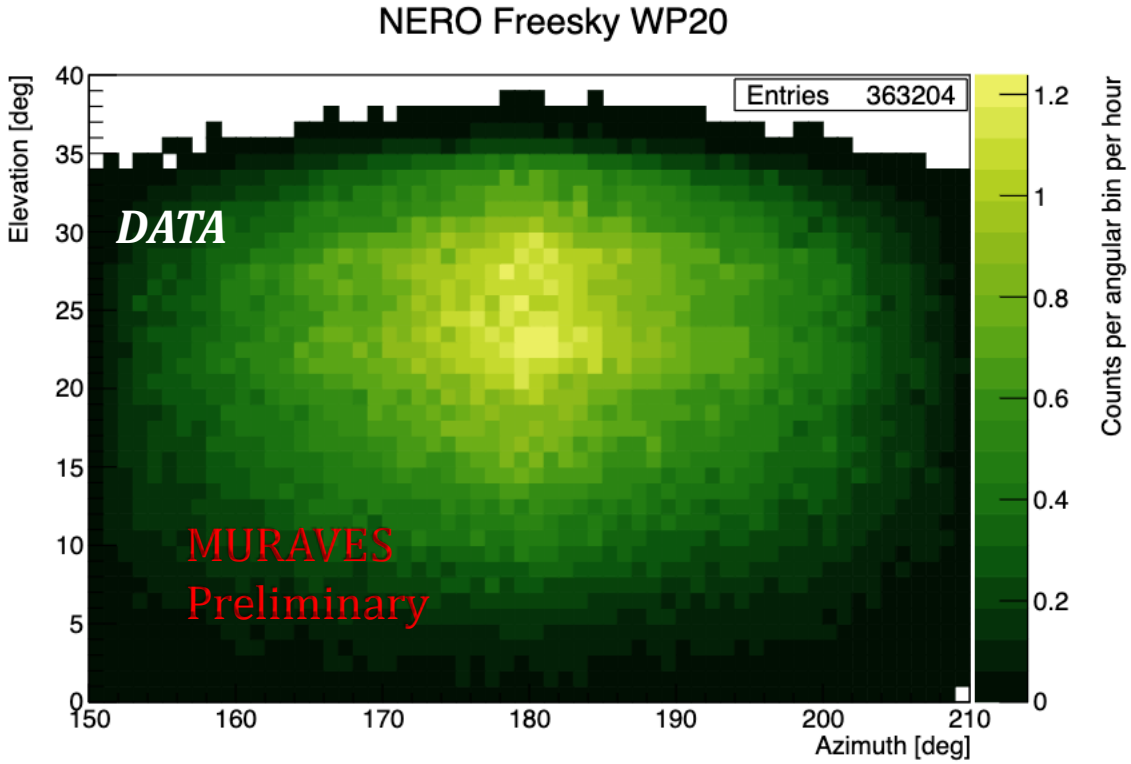


Free-Sky imaging from reconstructed muon tracks

Credits to Yanwen Hong

- Considering only tracks with hits on all 4 planes
- Selection on chi2 of 3 plane track :

$$\chi^2_{3p\,(xy)} \,\&\, \chi^2_{3p\,(xz)} < 2$$

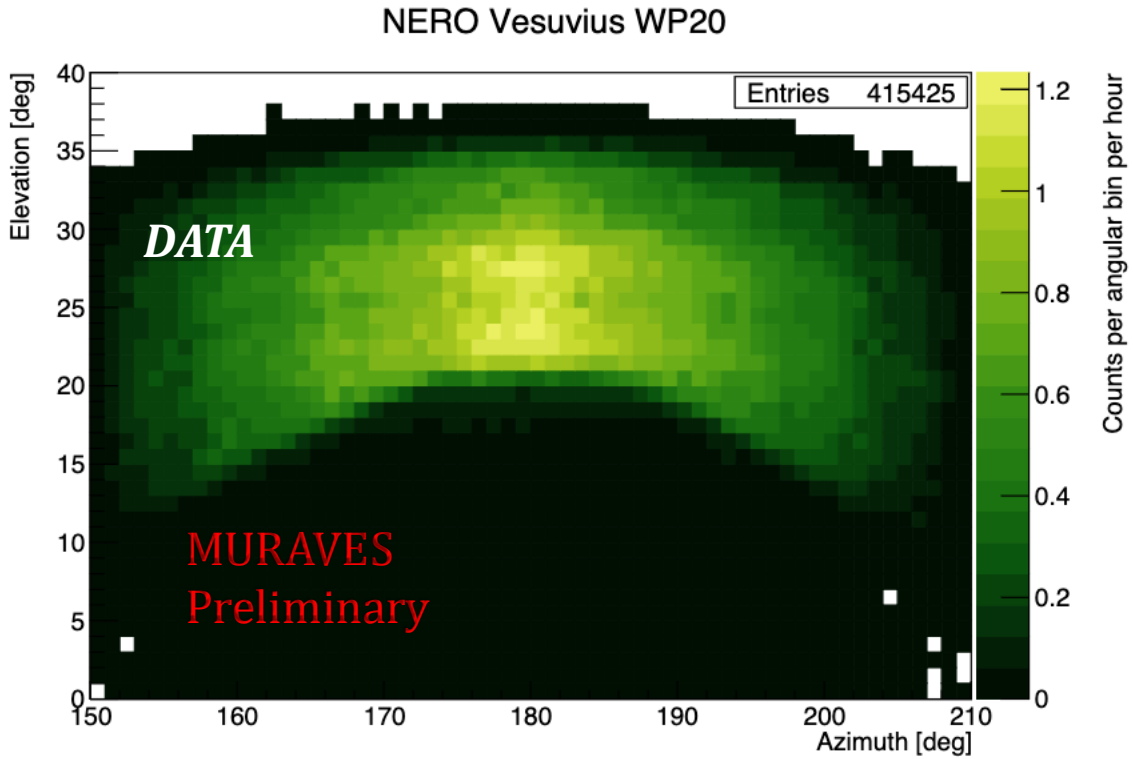


Vesuvius summit imaging from reconstructed muon tracks

Credits to Yanwen Hong

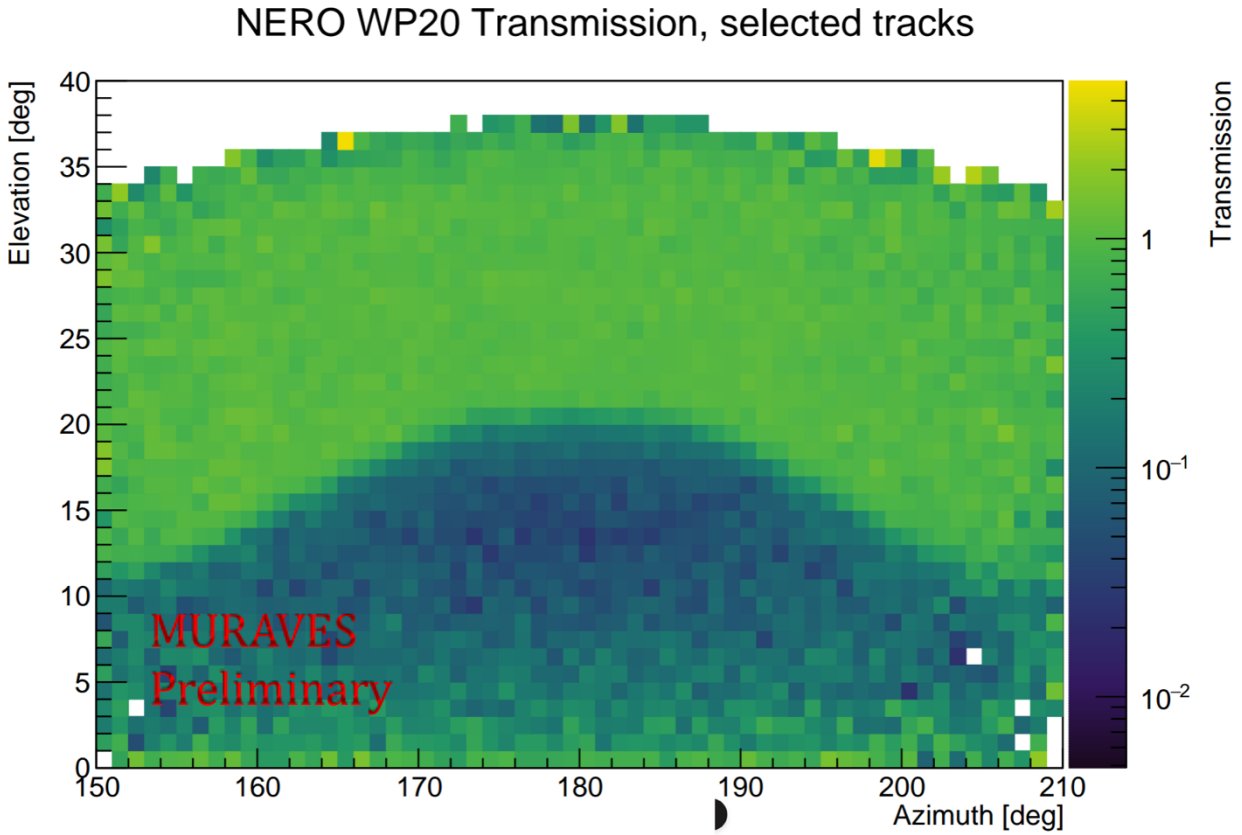
- Considering only tracks with hits on all 4 planes
- Selection on chi2 of 3 plane track :

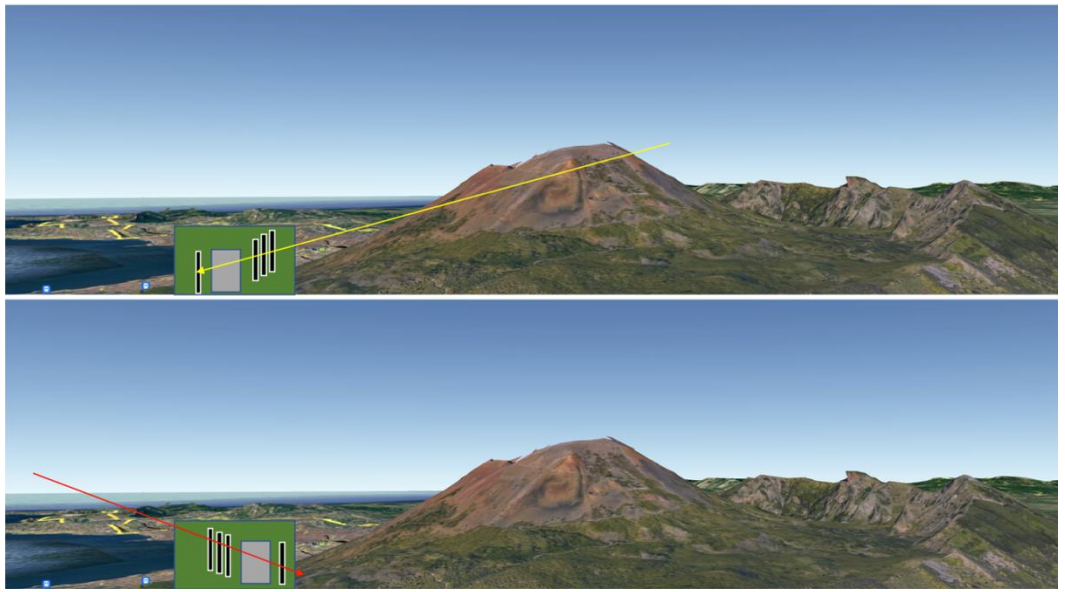
$$\chi^2_{3p\,(xy)} \,\&\, \chi^2_{3p\,(xz)} < 2$$



Transmission on Vesuvius summit

Credits to Yanwen Hong





$$T(\theta,\phi) = \frac{N_\mu^v(\theta,\phi)/\Delta t^v}{N_\mu^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^v \cdot S_{eff}(\theta,\phi)\int_{E_{min(\rho)}}^{\infty}\Phi(\theta,\phi;E)dE}{\epsilon^{fs}\cdot S_{eff}(\theta,\phi)\int_{E_0}^{\infty}\Phi(\theta,\phi;E)dE}$$

Summary and conclusions

- **New reconstruction framework** for maintainability, reproducibility, and software portability

- **Preliminary images** with reconstructed datasets:
  - Free- Sky and Vesuvius summit images for **NERO WP 20** selected with **3-plane χ^2 selection**
  - Transmission plot shows muon radiography of the Vesuvius summit
  - Further analysis needed to extract meaningful quantities

- Ongoing **simulation studies** and **data analysis strategies** will be presented on Wednesday
  Don't miss **Adithyan's on Wednesday**!

Thanks for your attention. Any questions?

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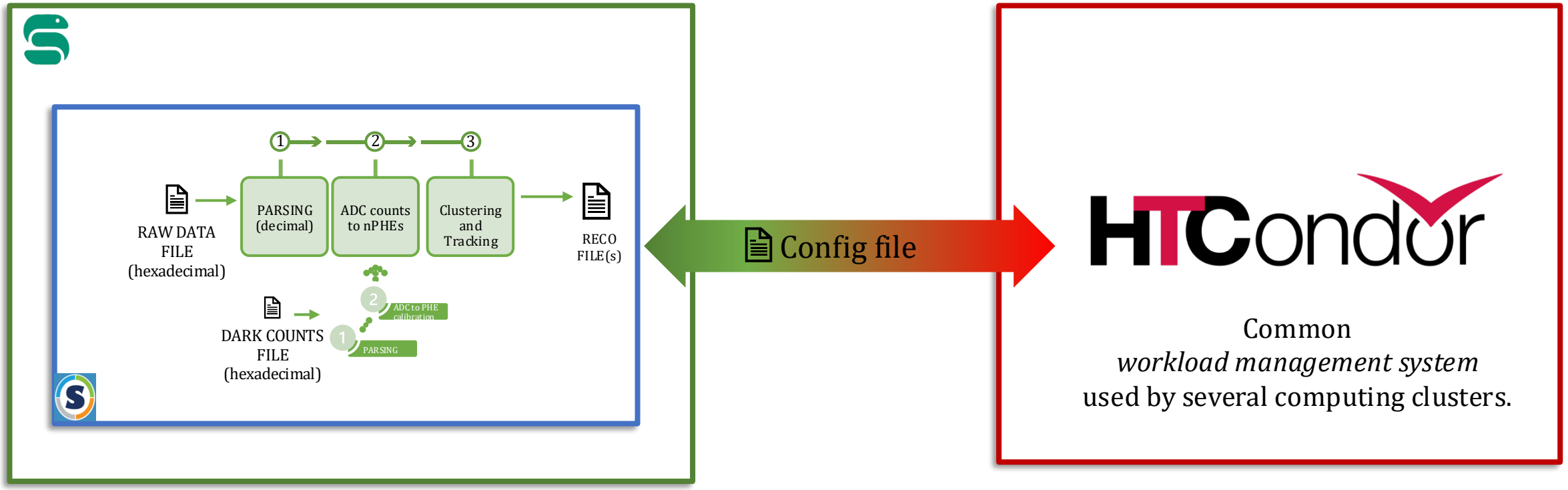
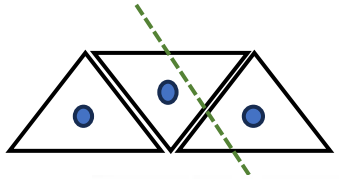
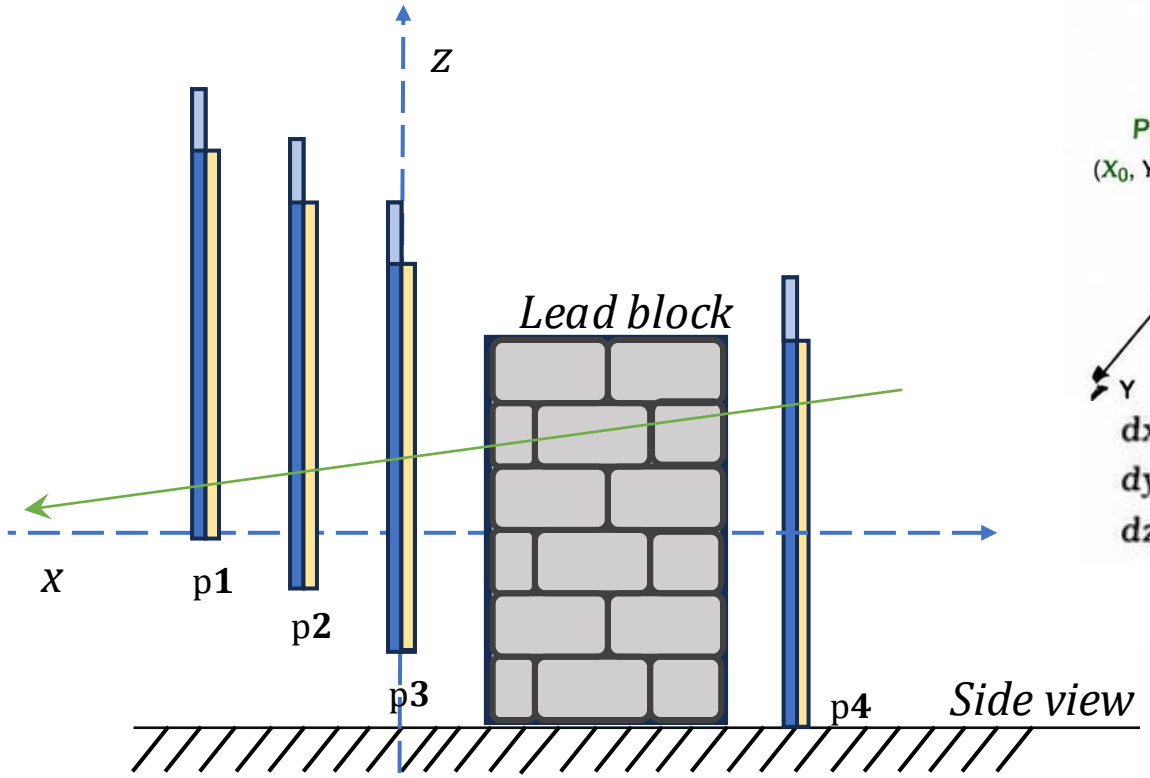
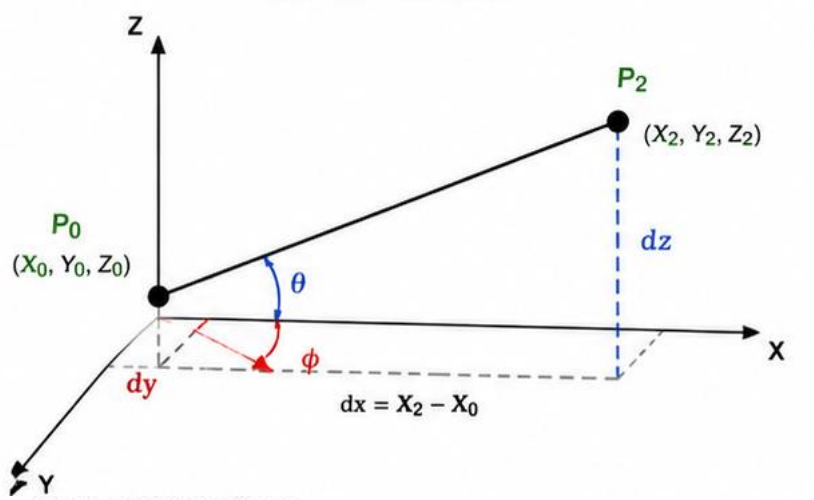
Intensive production



Tracking



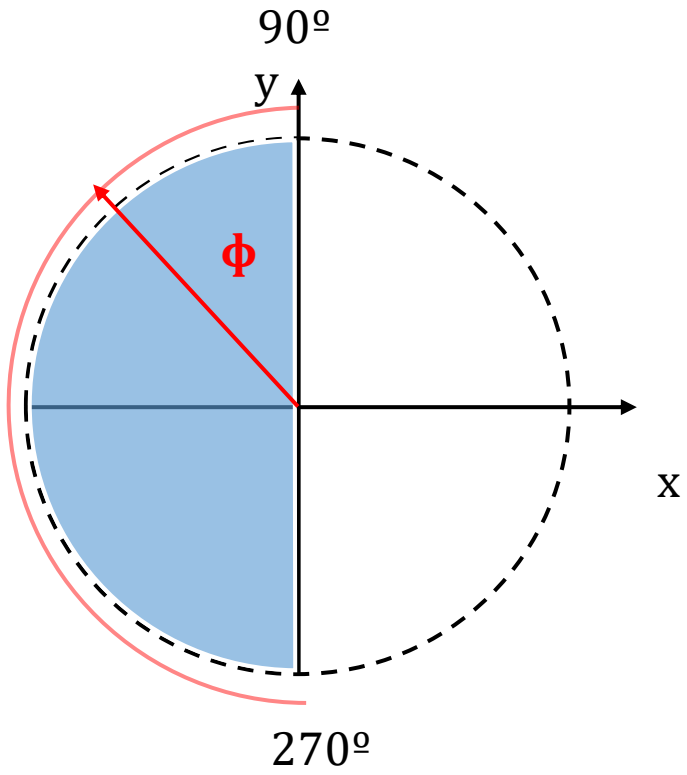


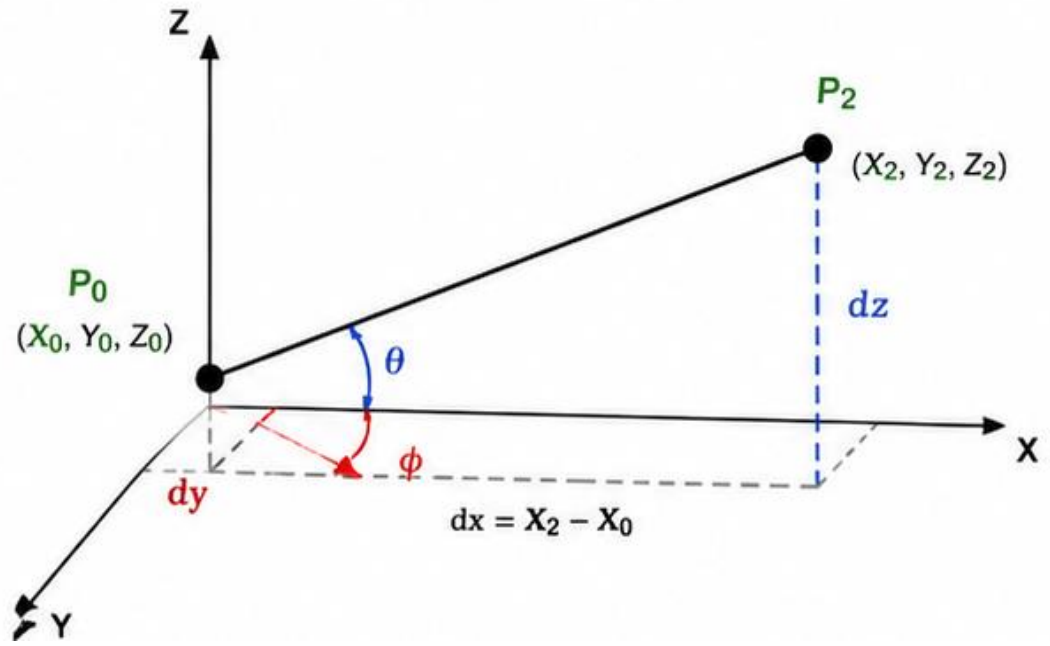


$$dx = X_2 - X_0$$
$$dy = slope_{xy} \cdot dx$$
$$dz = slope_{xz} \cdot (X_0 - X_2) = -slope_{xz} \cdot dx$$

- $\theta = \text{atan}\left(\frac{|dz|}{\sqrt{dx^2 + dy^2}}\right)$
- ϕ depending on the case

Angles definition



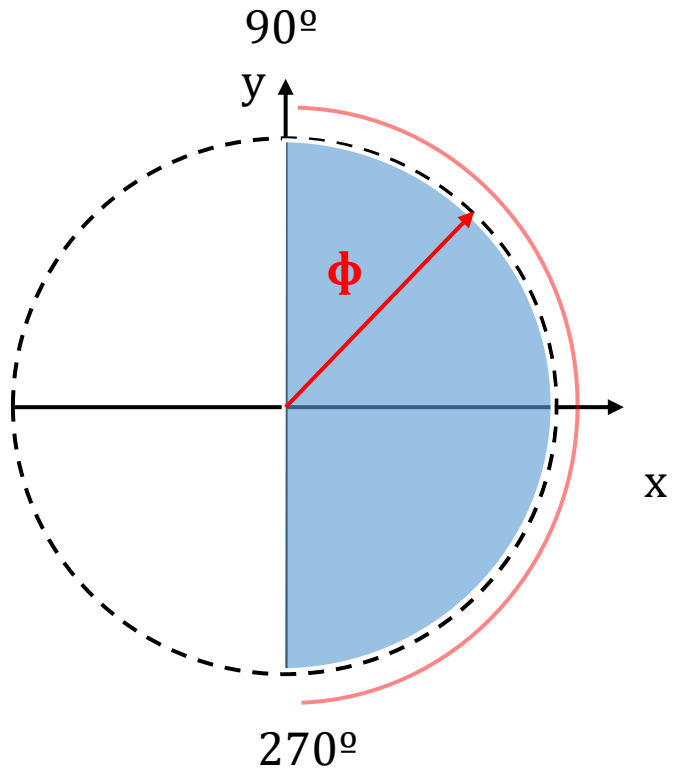


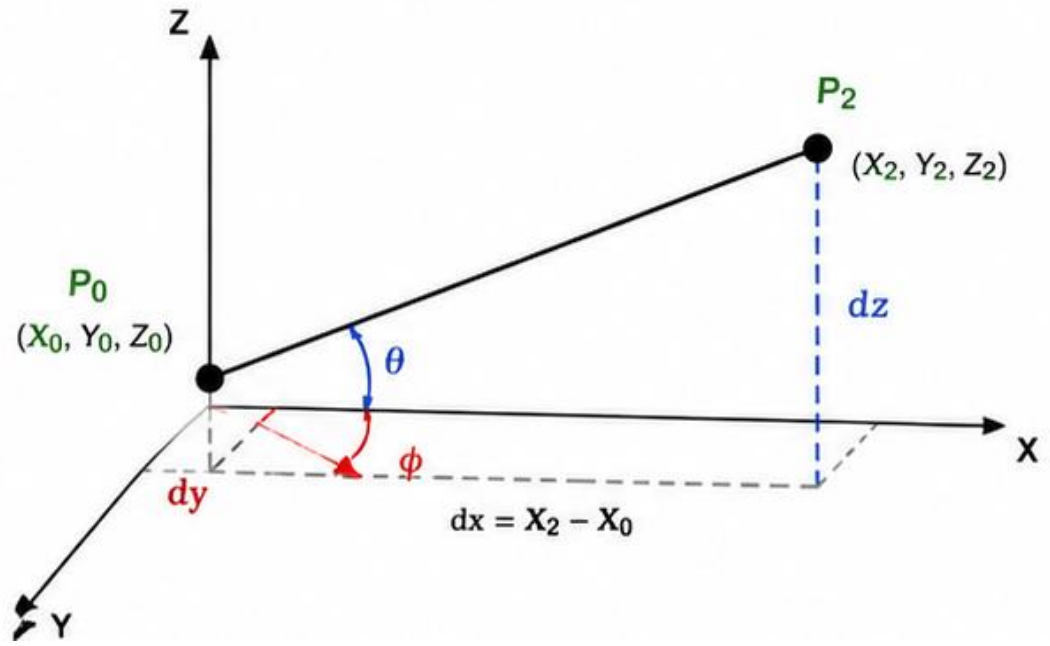
dz > 0 $\Phi = \text{atan}(\text{slope}_{xy})\ 180/\pi + 180$ º

- ✅ **Forward-Downward muon candidate**
- ❌ **Backward-Upward muon (low probability)**

ϕ in Muraves field of view: [90 - 270] º

Angles definition





dz < 0

$\Phi = \text{atan}(\text{slope}_{xy})\ 180/\pi + 180$ º

- ✗ **Backward-Downward muon**
- ✗ **Forward-Upward muon**

ϕ outside Muraves field of view: [0-90] º OR [270-360] º