Assessing the rock density distribution of a volcano lava dome with a 4-panel scintillator-based muon detector

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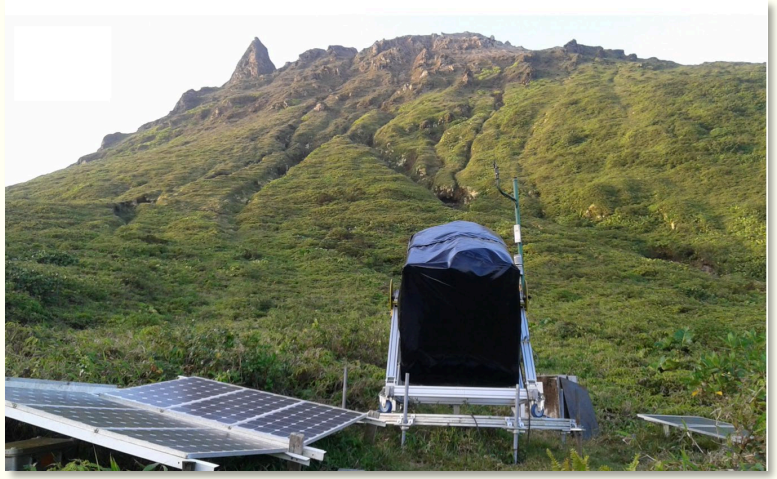
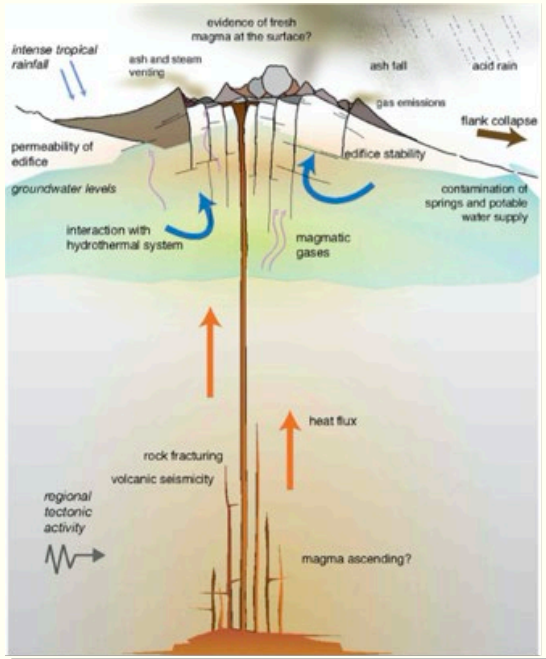
Outline

1. Geophysical context, motivations and challenges
2. Detector technology and available datasets
3. Data processing
4. Reconstruction Performances with Geant4 simulation
5. Application to La Soufrière de Guadeloupe
6. Summary and future work



Geophysical context



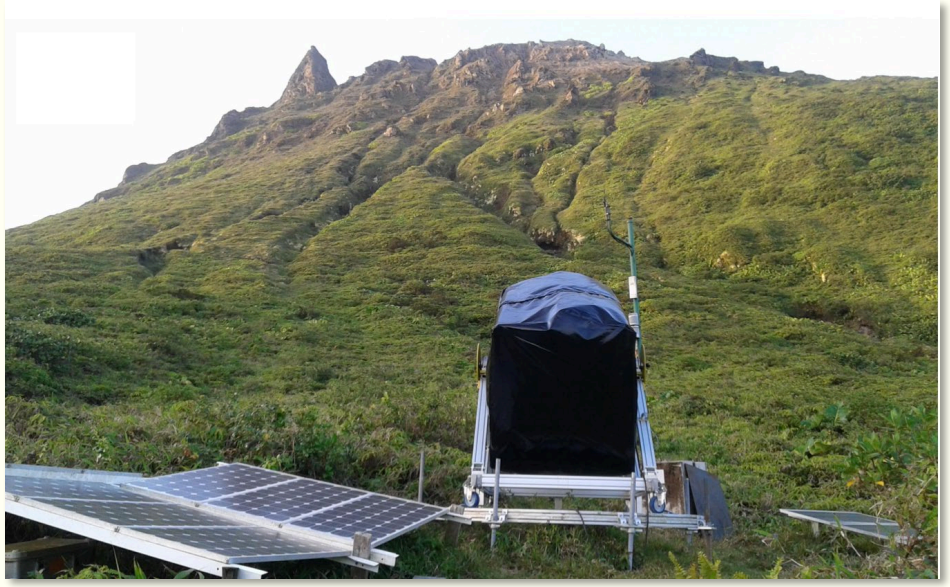
- **Volcanic hydrothermal systems (VHS)** give rise to hydrothermal eruptions, one of the most unpredictable volcanic hazards.
- VHS are also responsible for **highly altered and hot acid liquid saturated rocks**

☞ **Risk of partial flank collapse for volcanic edifices:** critical feature in volcanic hazard

Motivation and challenges

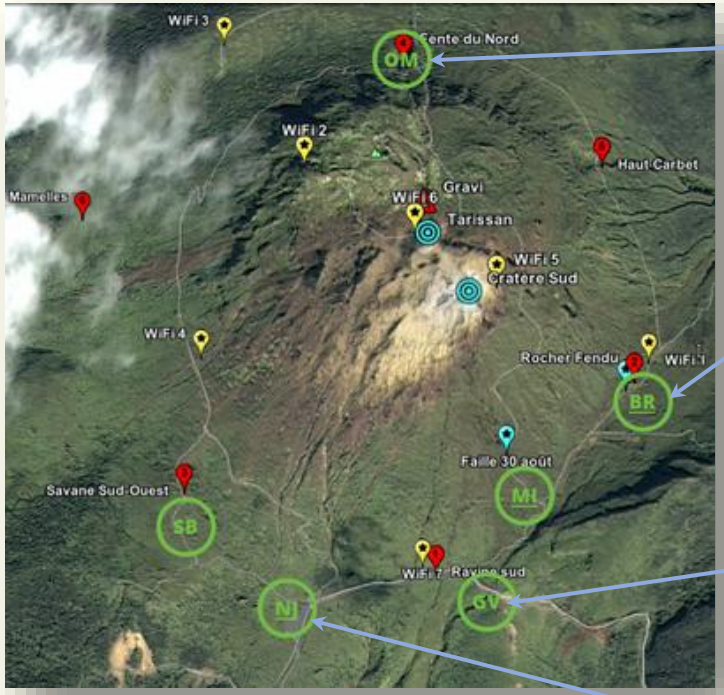
Traditional geophysics provides limited information on dynamics inside volcanic systems

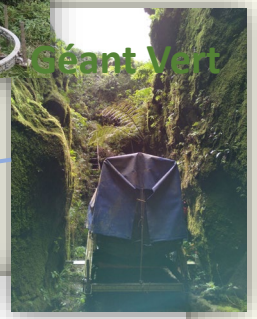
☞ Need for complementary techniques that can track in space and time the inner state of the volcanic system …



☞ **Muons** can give us radiographies of large structures, help us reconstruct their 3D density distribution, and detect temporal variations of density

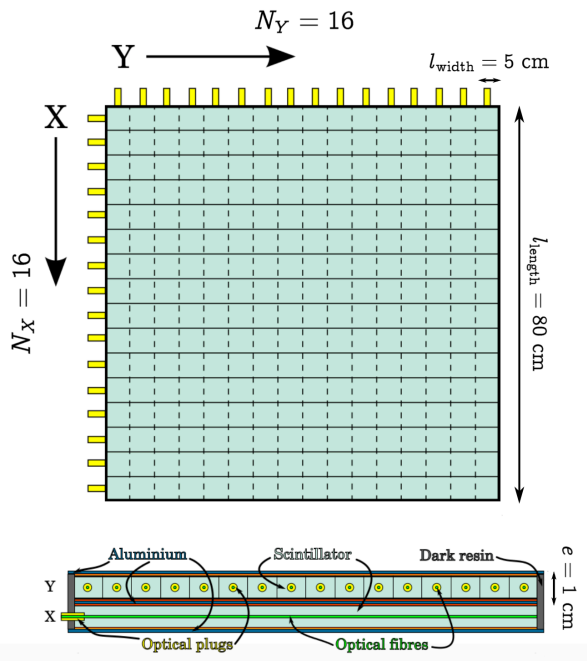
La Soufrière muographers

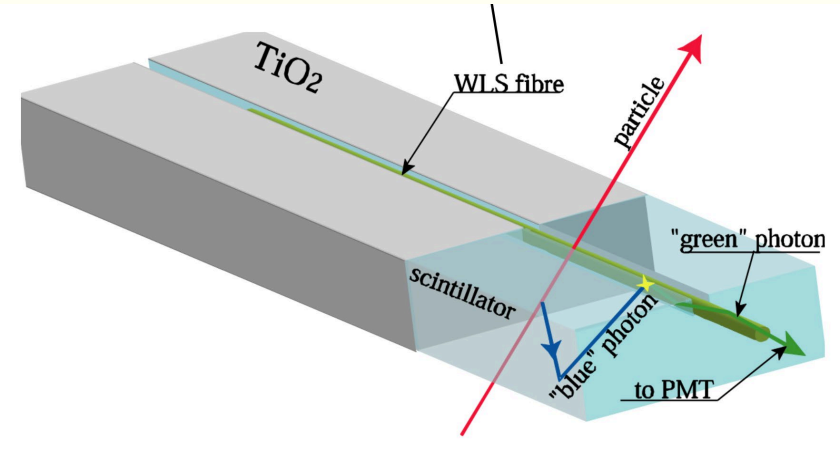


Detectors	Configurations	Run periods
Orange Mécanique	3 matrices (1 v1.1 + 2 v2.0)	2017-2019
Baron Rouge	3 matrices then 4 matrices v1.1	2015-2019 2020-now
 Géant Vert	3 matrices v1.1	2015-2019
Nain Jaune	3 matrices then 4 matrices v1.1	2015-2019 2019-now

Detection technology

Robust particle hodoscopes equipped with 3 or 4 scintillating matrices developed at IP2I, Lyon.





Above '*Super Nain Jaune*' : 4 matrices of 16x16 plastic-scintillator bars of width 50mm, time resolution=10ns + 1 100mm thick lead shielding panel

Main objective

How can we improve precision on 2D muographies and 3D density reconstruction?

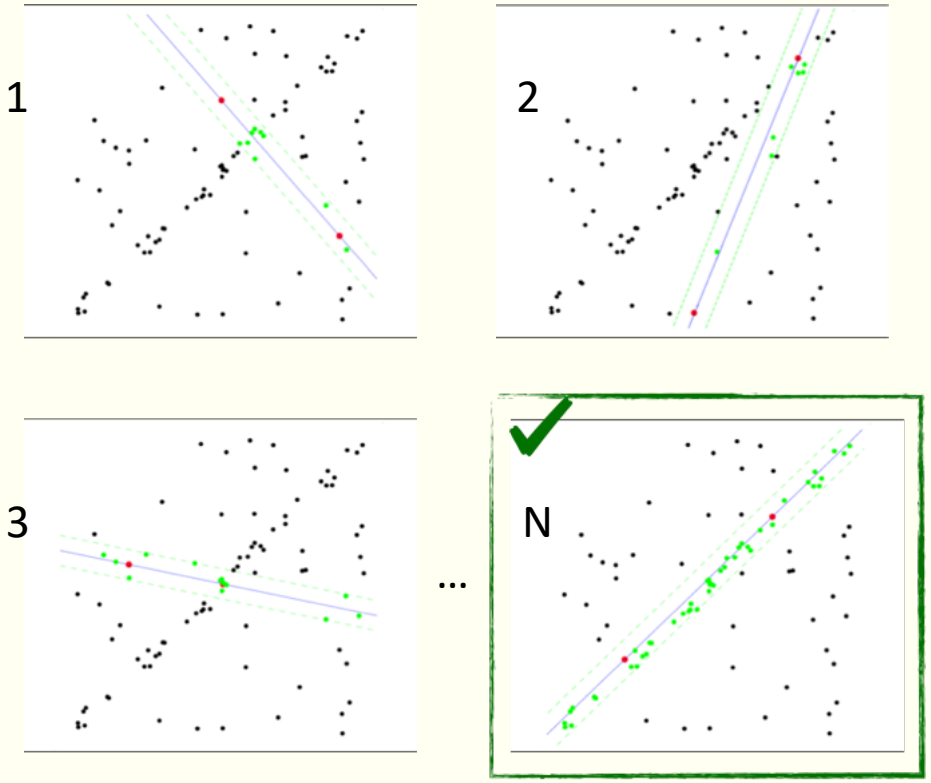
☞ With a **robust processing algorithm** that maximizes the **statistics** of the processed events while maintaining a sufficient **signal/noise separation.**

☞ We have chosen to base this algorithm on a **random sample consensus fit procedure RANSAC** of the raw hits recorded in scintillator bars**.**

Data processing with RANSAC

Random Sampling Consensus

☞ Robust fit method, suited for signal polluted with « ***outliers*** »



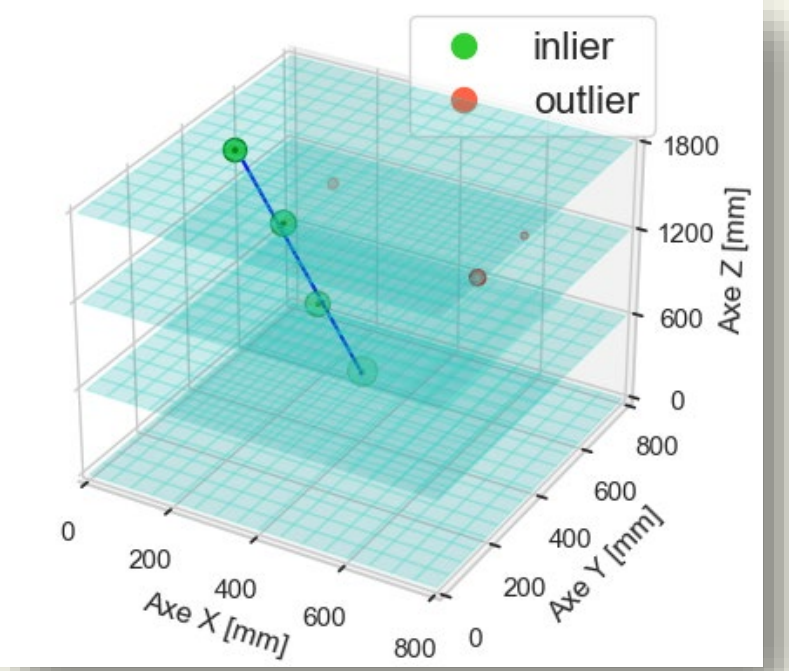
What does RANSAC do?

- Randomly select minimal subset of hits
- Fit an hypothesized model to that subset
- Tag hits that are below a distance ***threshold*** to the model as « ***inliers*** » and tag the rest as « ***outliers*** »
- Iterates N times and selects the best model that maximizes the number of ***inliers.***

Data processing

INPUT

Raw data:
Time and coordinates of hits in each panel



OUTPUT

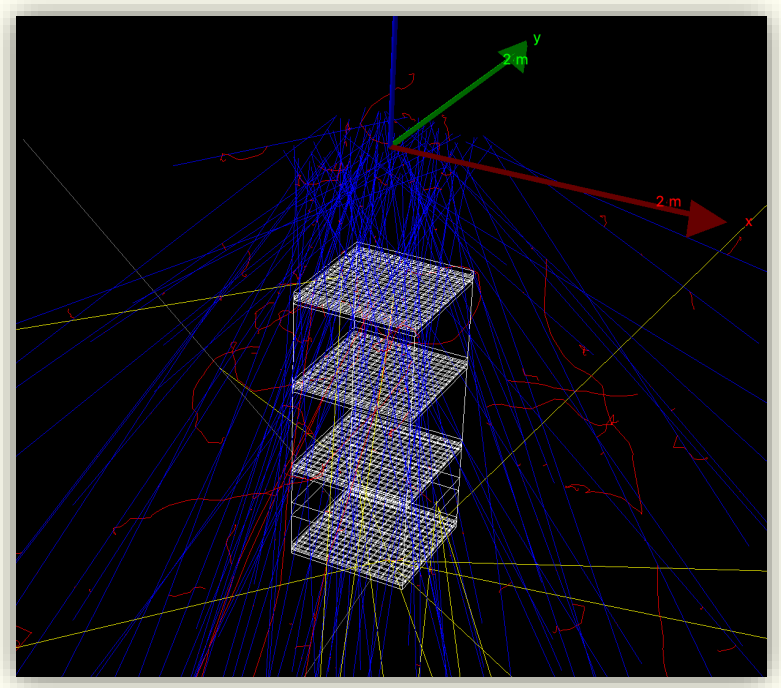
Trajectory model – panel/fit intersections

PROCESSING

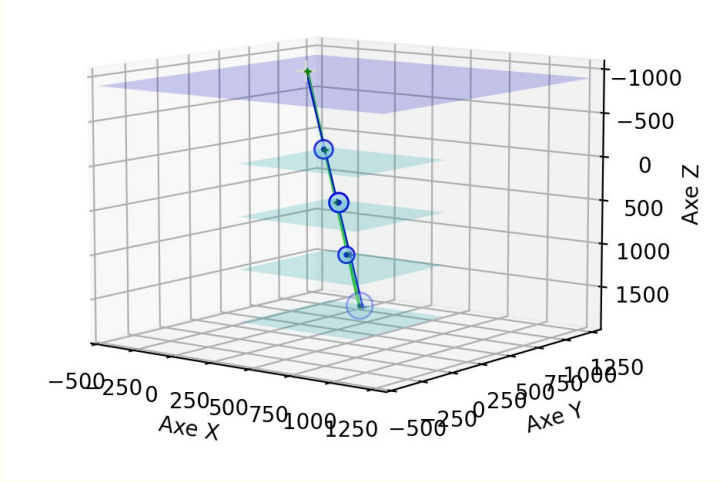
1) Remove event if multiplicity > 10 hits on one panel, time-of-flight < 0
2) RANSAC fit of 3D hits
3) Cut event if less than 3 consecutives inlier hits on panels

RANSAC Performances

- Build a **Geant4 simulation** with 4 matrices of scintillator bars + lead shielding panel.
- Use **Cosmic-Ray Generator (CRY)** to test the simulation output and the RANSAC processing
- Generate particles from a plane surface above the detector placed at zenith $\theta = 0°$ (open-sky)

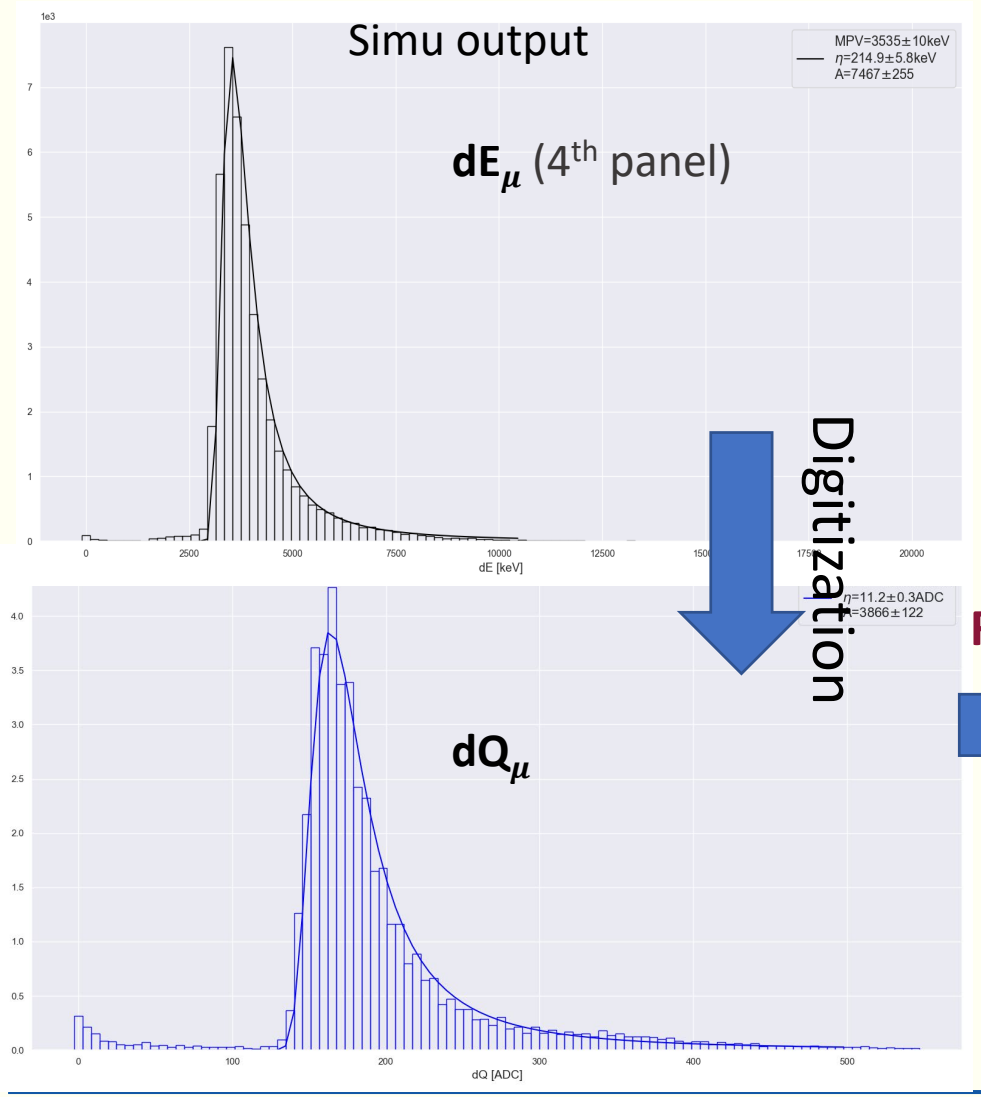


Comparison between **RANSAC** processing and simpler processing procedure based on ***straightness check*** of the particle track.
☞ Compute **angular resolution** $(\Delta\boldsymbol{\theta}, \Delta\boldsymbol{\varphi})$, event counts and **reconstruction efficiency** $\boldsymbol{\epsilon_{reco}}$



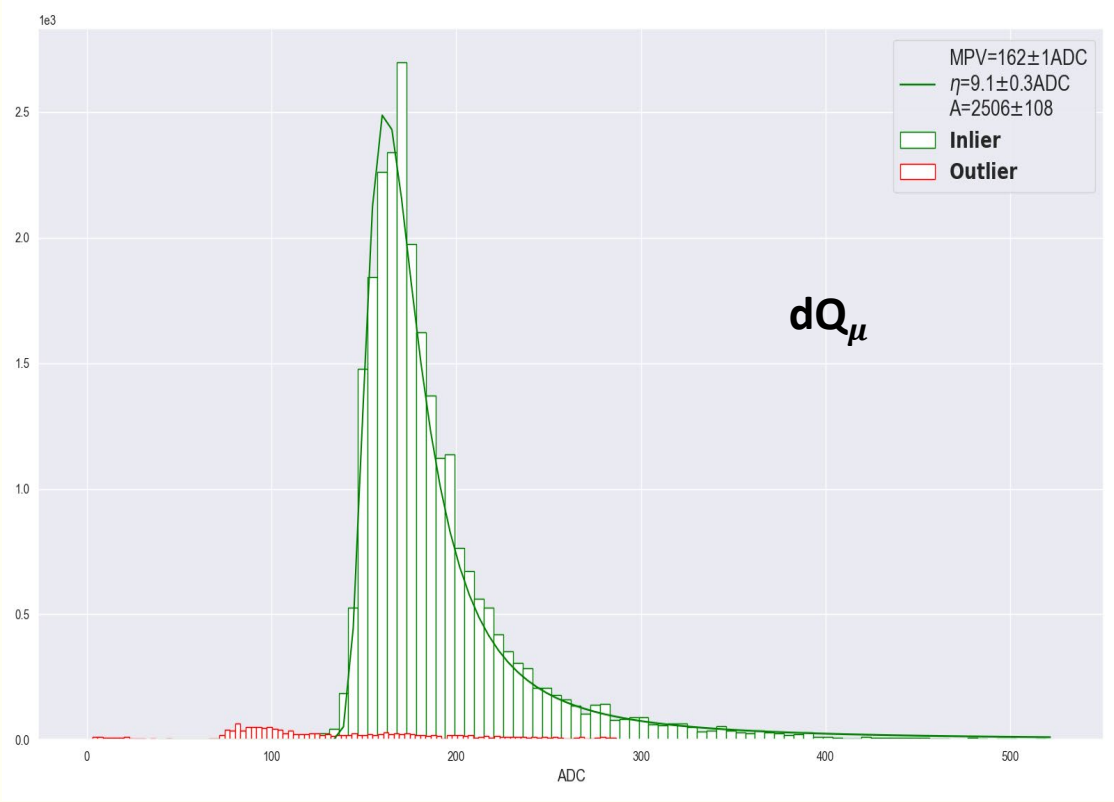
Muon charge signal (simu)

For MC **muon** sample:



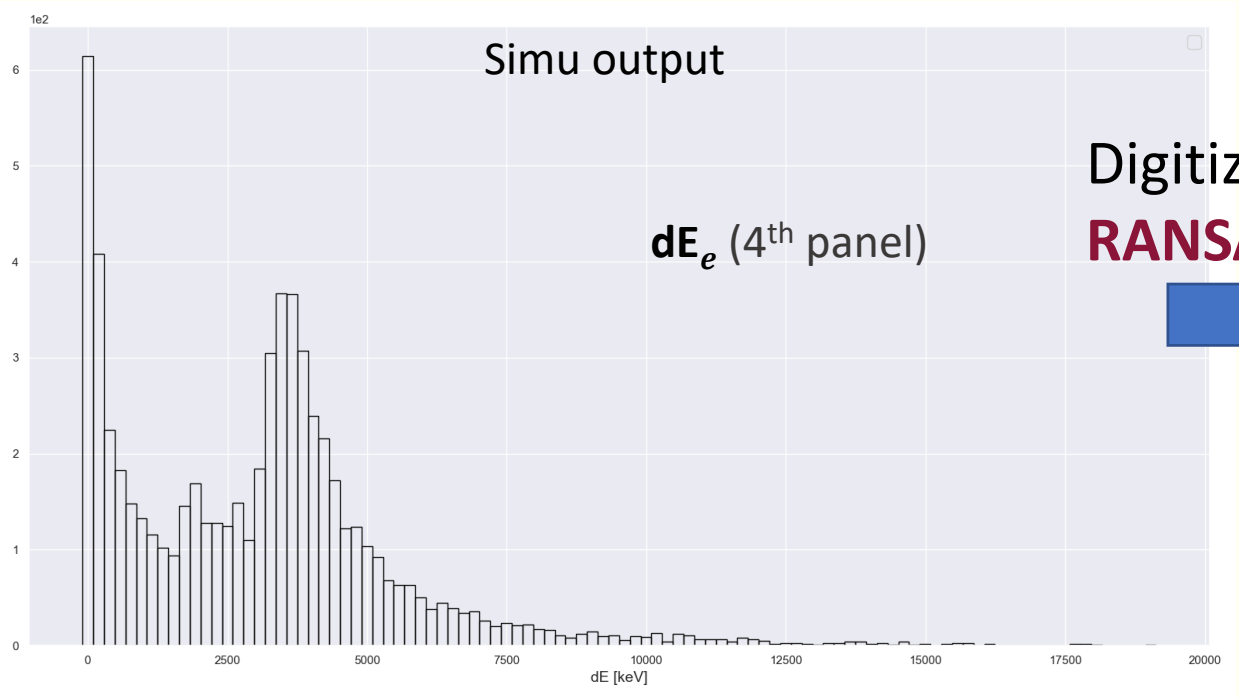
RANSAC

Proportion of **inliers** = **96%** in reconstructed muons

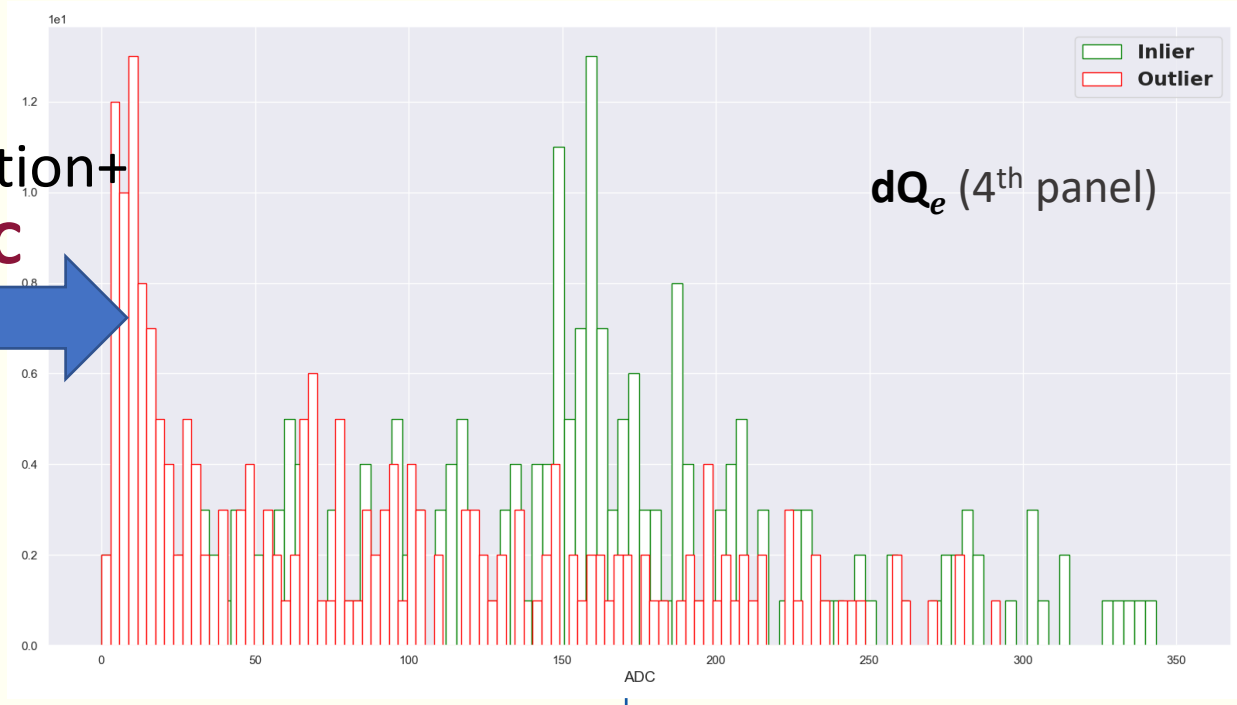


Electron charge signal (simu)

For MC **electron** sample:



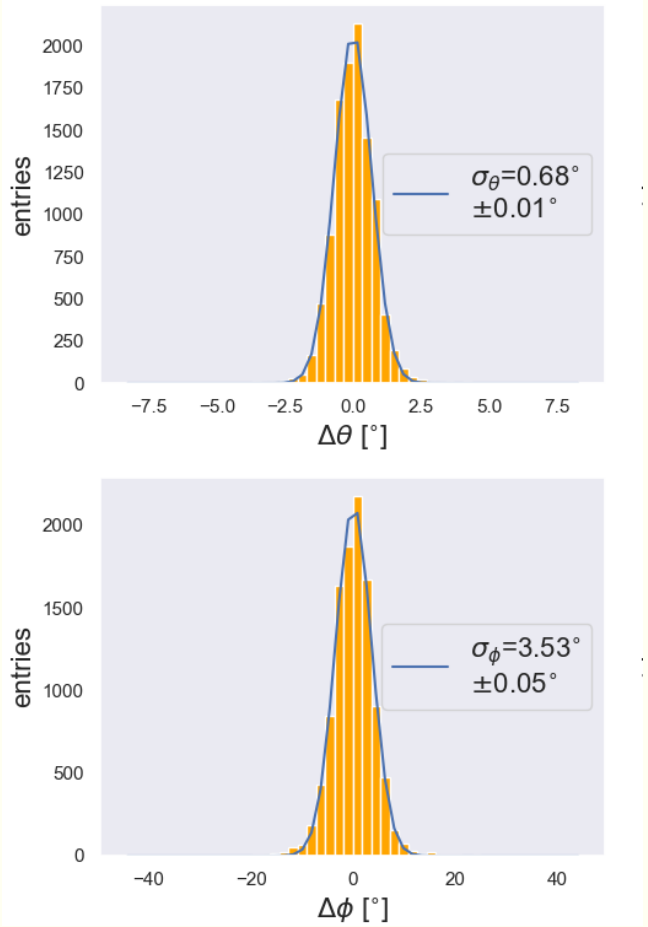
Digitization+
RANSAC



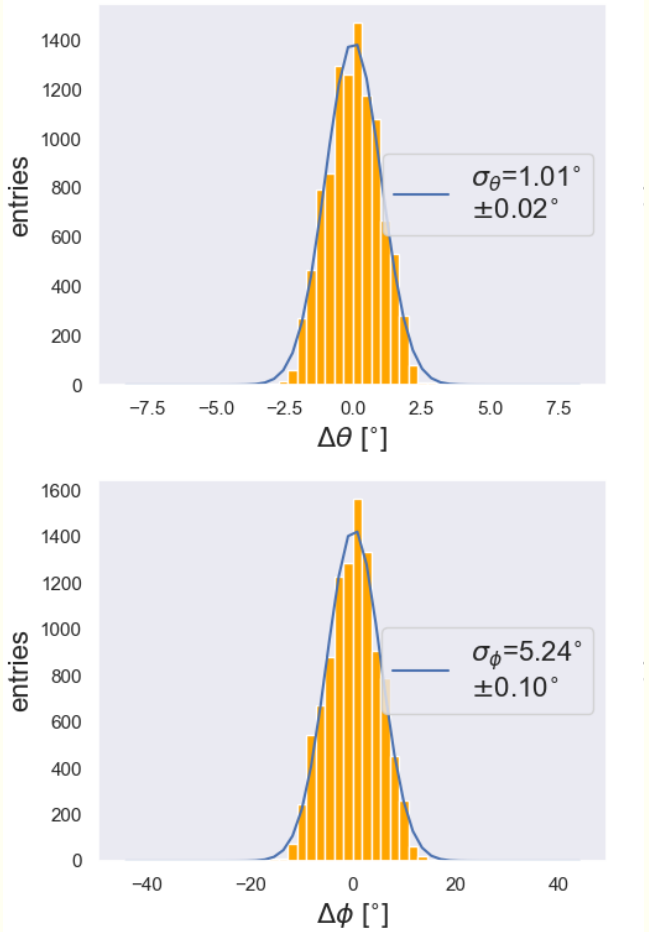
Ratio **outliers**/**inliers** $= \mathbf{0.85}$
in reconstructed events

Angular resolution (MC muon)

RANSAC



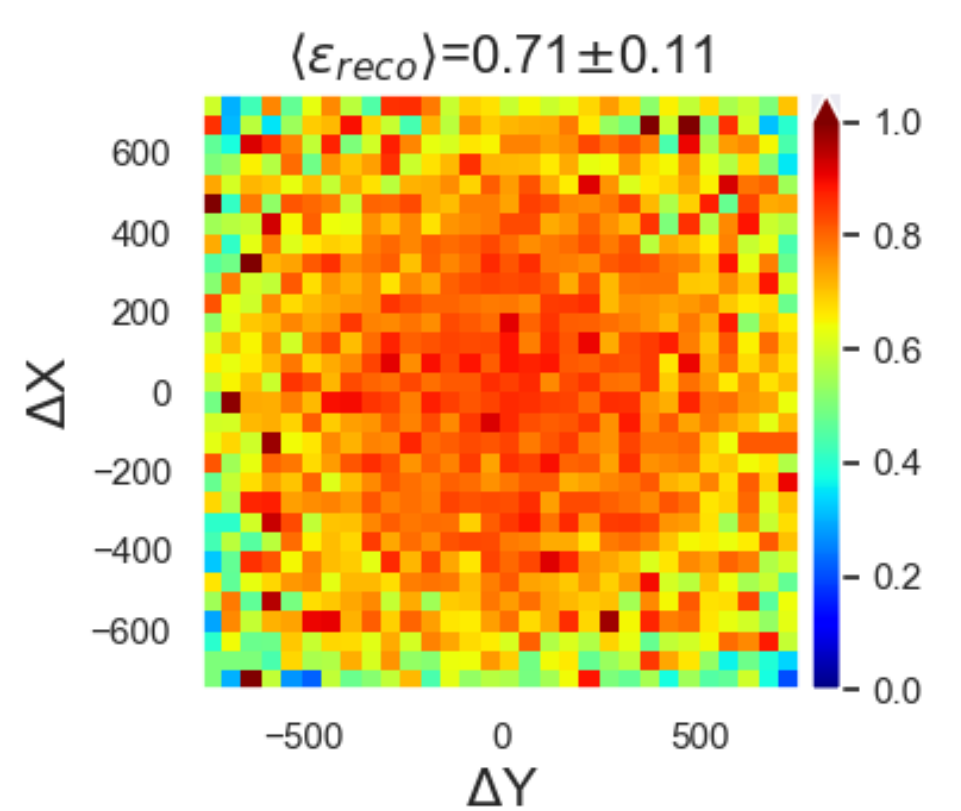
Straightness check



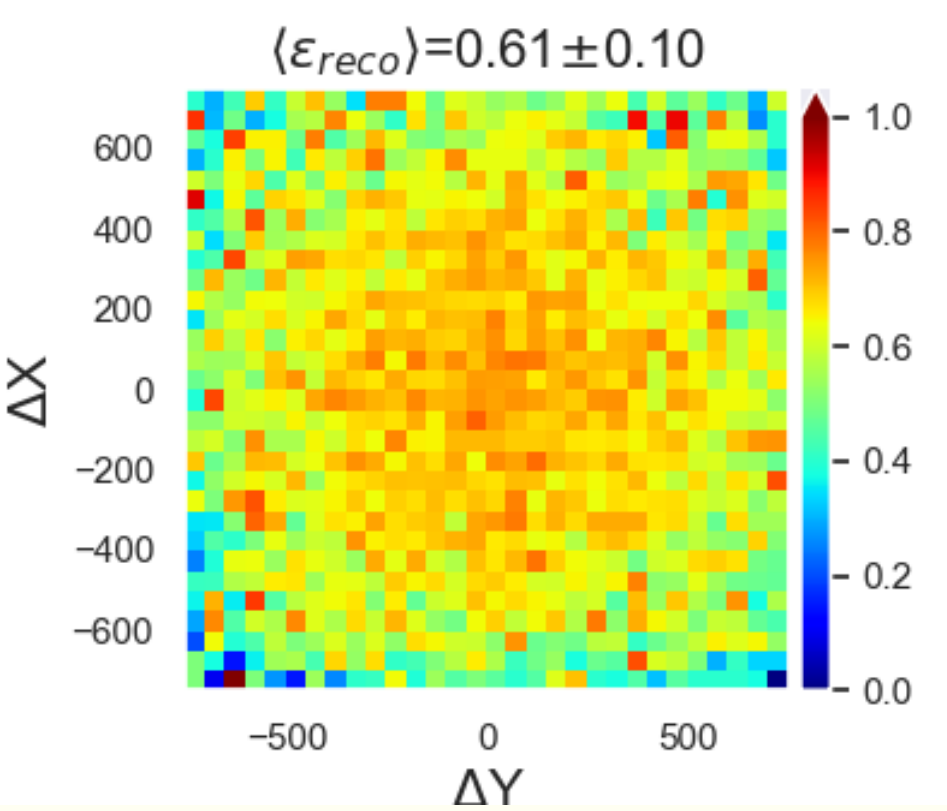
☞ **RANSAC** improves by 30% the zenith and by 33% the azimuth angular resolutions for MC muons (open-sky case)

Reconstruction efficiency (MC muon)

RANSAC



Straightness check



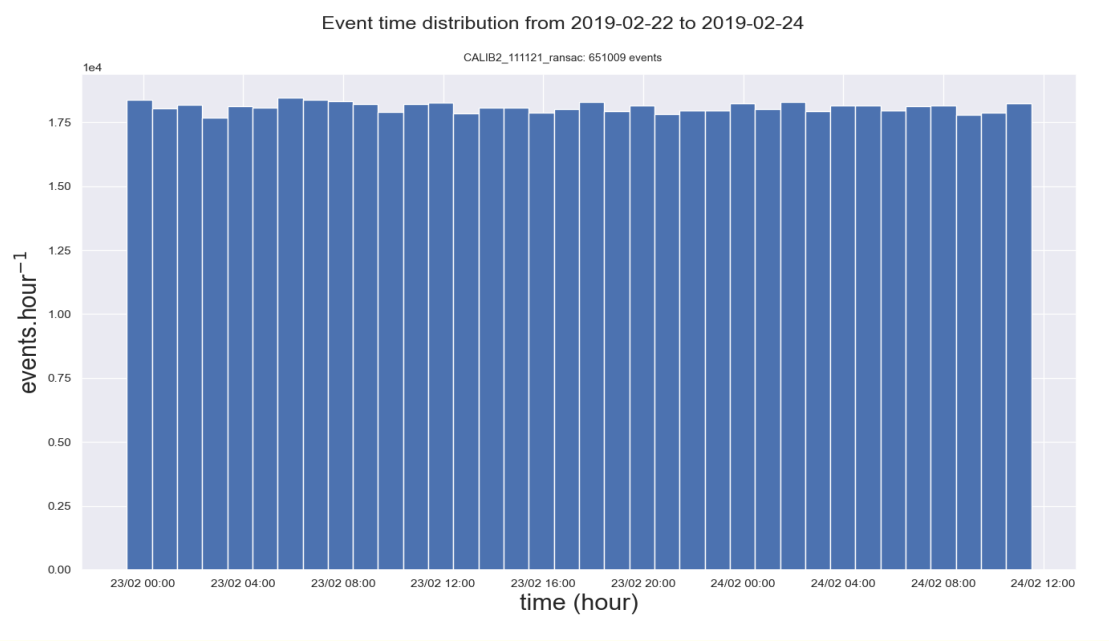
☞ **RANSAC** increases by 10% the mean muon reconstruction efficiency

Reconstructed event rate

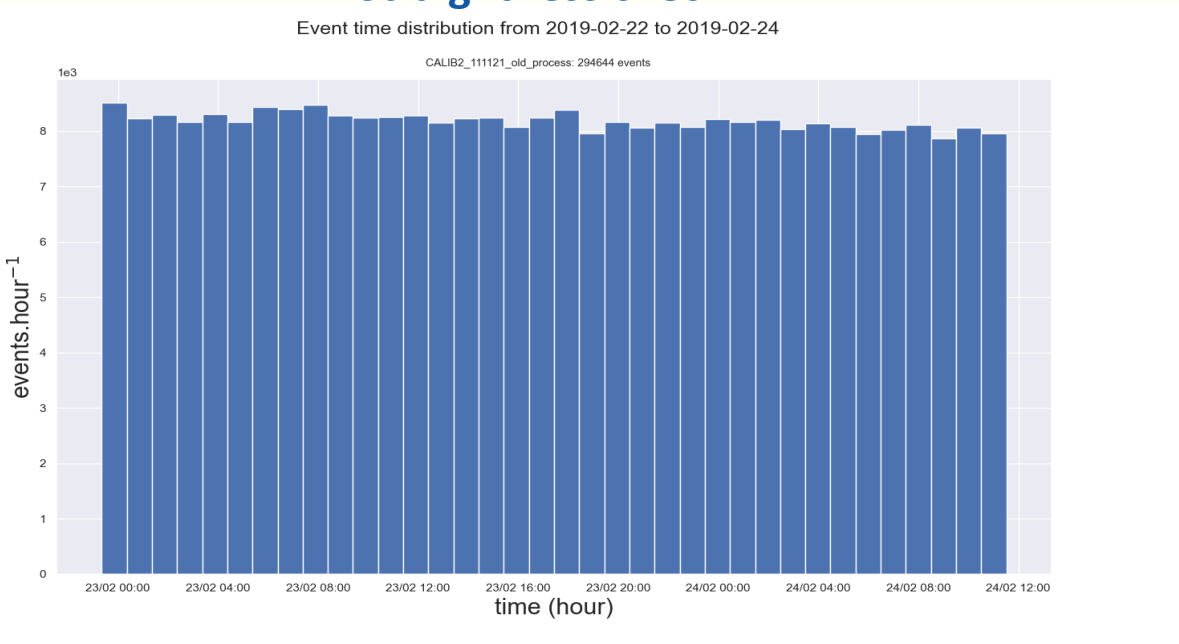
☞ For MC muon sample, **RANSAC** increases by **13%** the reconstructed muon rate.

☞ For a data open-sky run (below), **RANSAC** increases by **54%** the event rate.

RANSAC



Straightness check

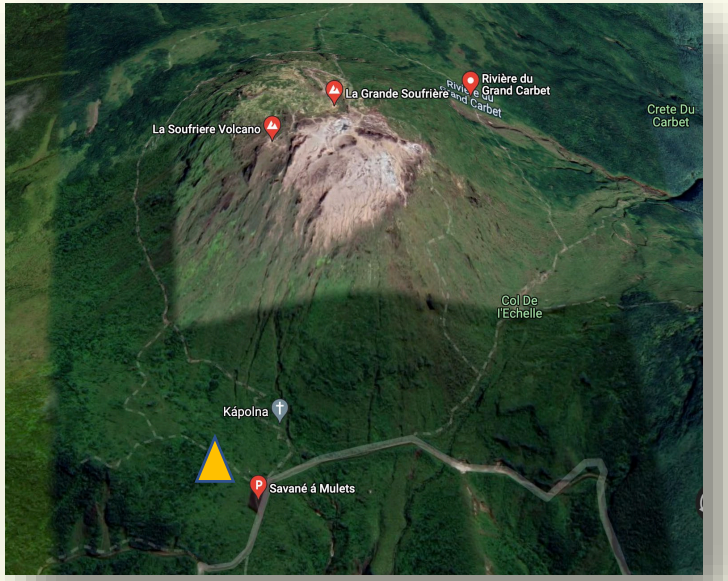


Tomography results

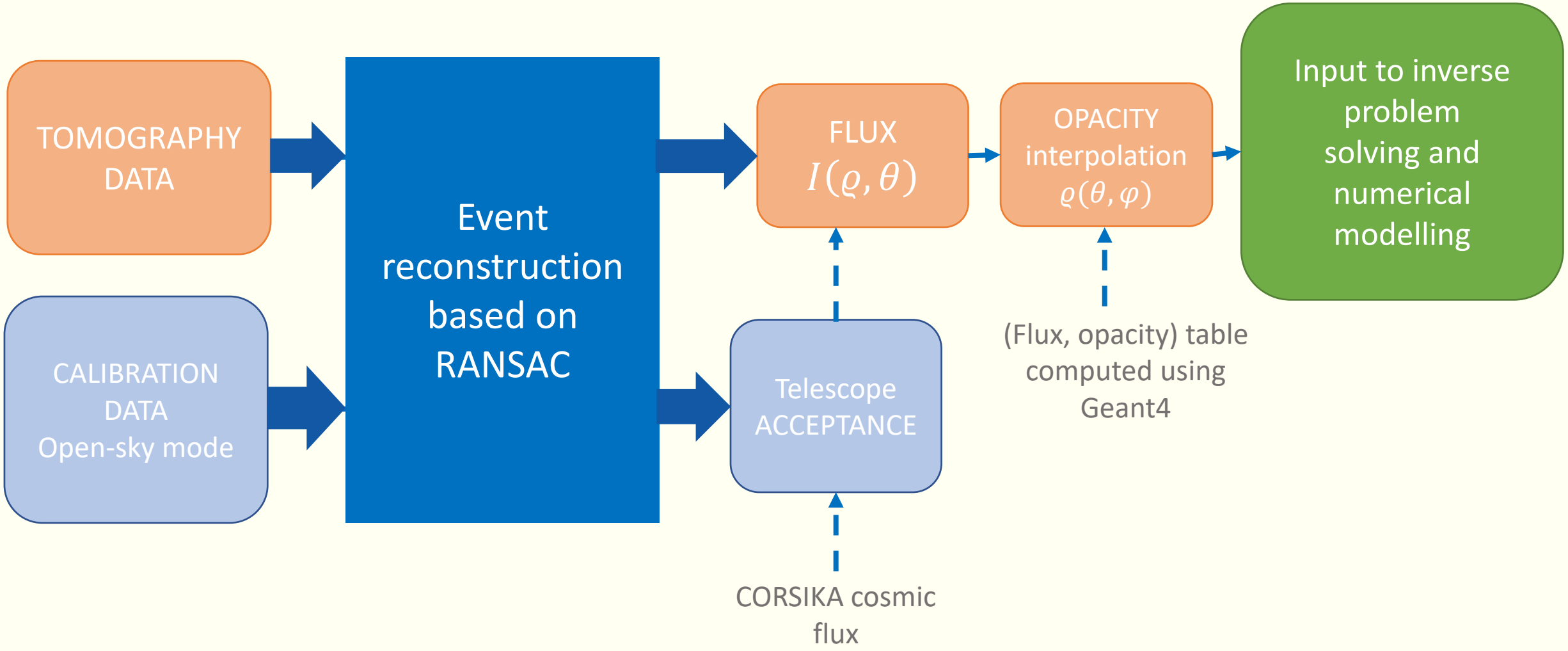
Detector : Super Nain Jaune

Location : La Soufrière South parking

Run duration : 145 days (02/19->08/19)



Full data processing outline

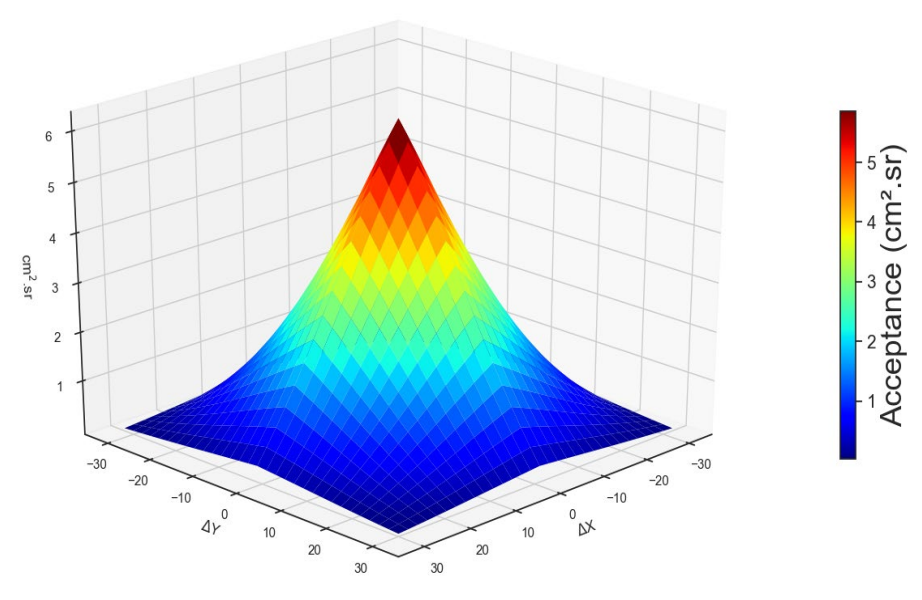


Experimental Acceptance (data)

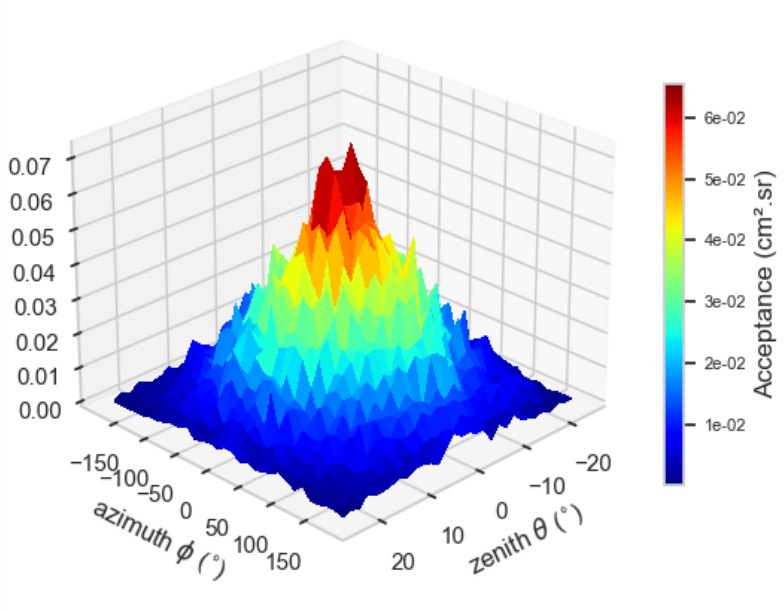
Computed along each detector line-of-sight (θ, φ):

$$\mathcal{T}(\theta, \varphi) = {}^{N(\theta,\varphi)}/_{\Delta T * \phi_{corsika}}$$

where $N(\theta, \varphi)$ is the measured open-sky event count at (θ, φ), ΔT is the run duration, and $\phi_{Corsika}$ is the CORSIKA open-sky integral flux.



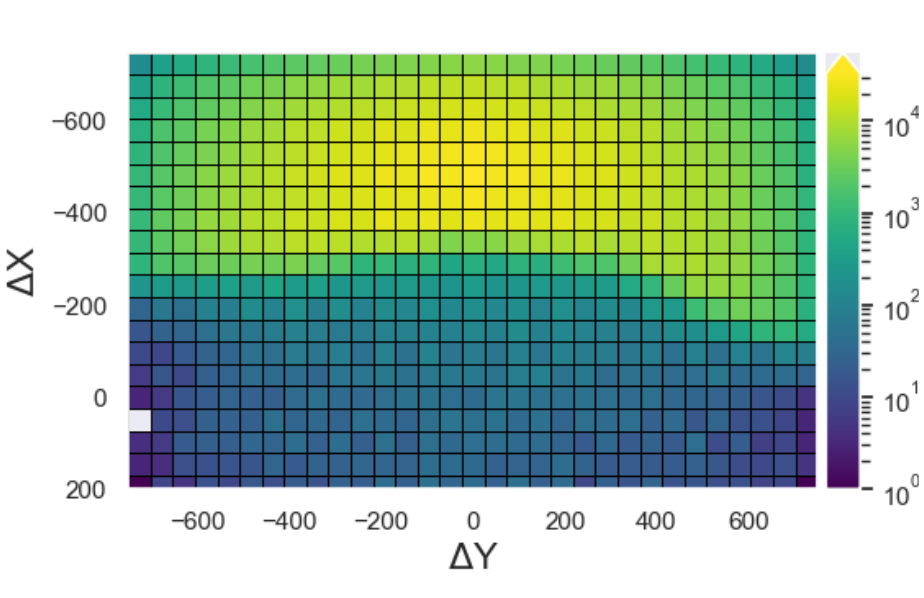
Theoretical acceptance

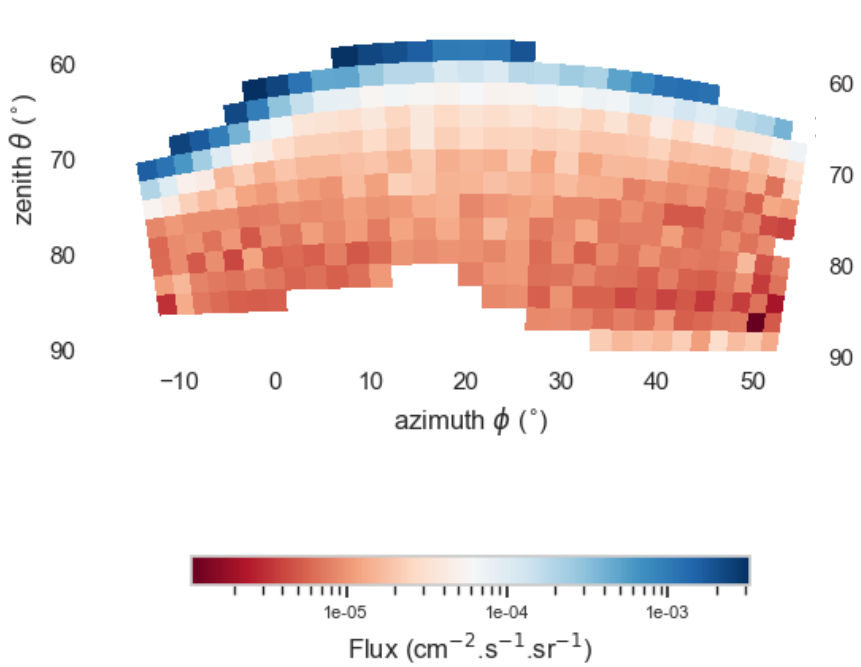


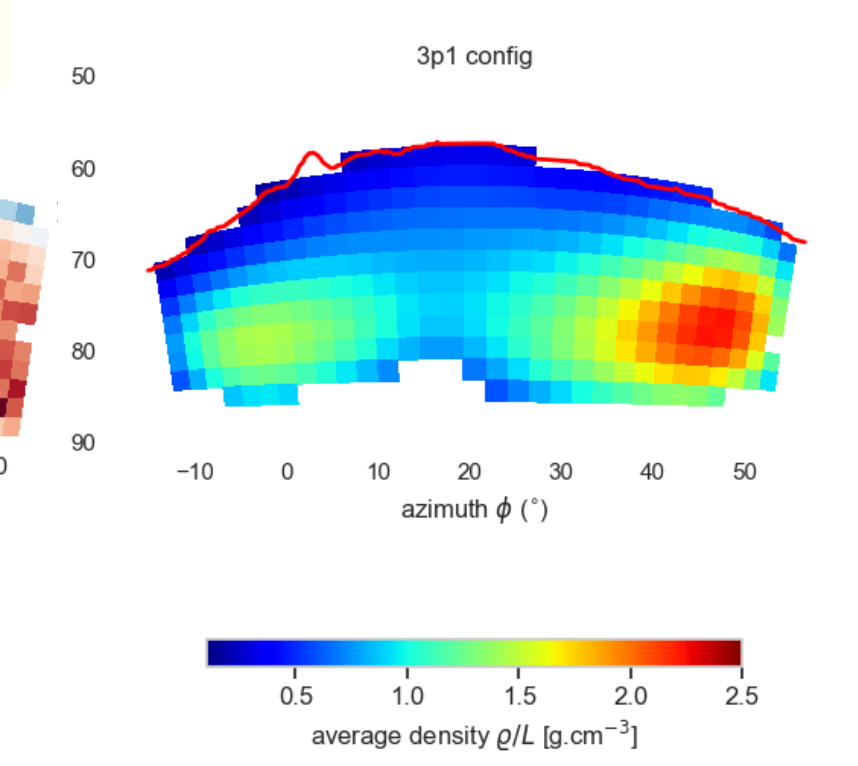
Experimental acceptance

From hits map to average density

Event count N → **Outgoing flux I** → **Average density $\overline{\rho}$**







3 panels sub-configuration

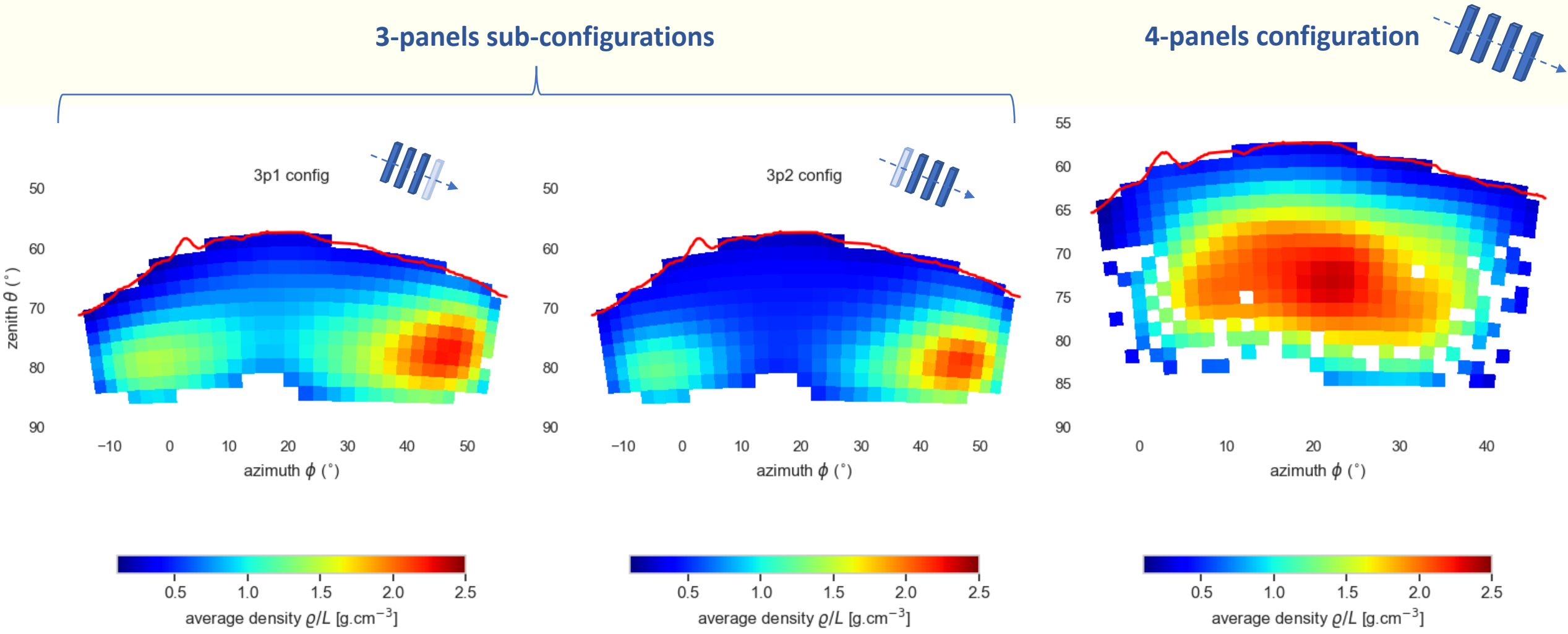
$$I(\varrho,\theta) = \frac{N(\varrho,\theta)}{\Delta T \times \mathcal{T}}$$

$$\overline{\rho} = \varrho / L$$

Average density (data)

3-panels sub-configurations

4-panels configuration



Summary

We have implemented a RANSAC based processing algorithm, that brings significant advantages to muon data processing compared to a non-fit processing method:

- 30% gain in muon angular resolution
- 10% gain in muon reconstruction efficiency
- 13% increase in the event count (simu), 54% for an open-sky run (data)

Main drawback: It doubles the processing time (~2min for 10^5 MC events on 8 Go CPU)

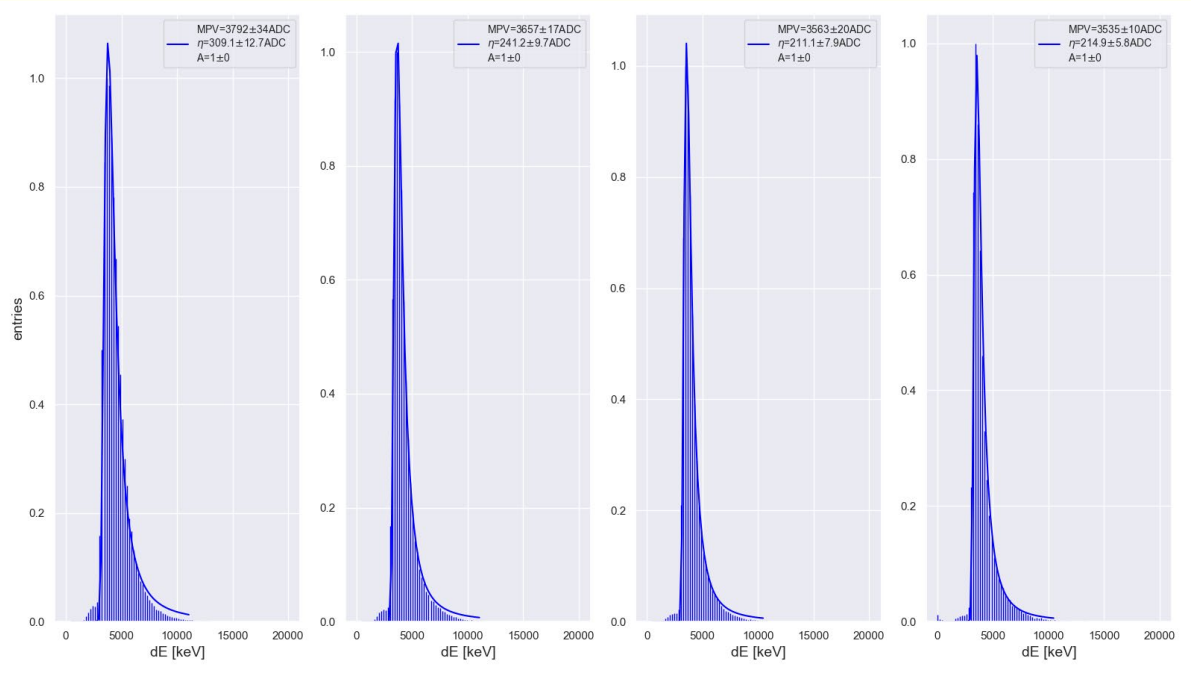
Future analysis

- Cross-check analysis results for simultaneous telescope data taking periods
- Refine the detector response in the G4 simulation
- Tackle data inversion for 3d density modelling
- Couple muons to other geophysical dataset e.g gravimetry data (Rosas-Carbajal et al., 2017)

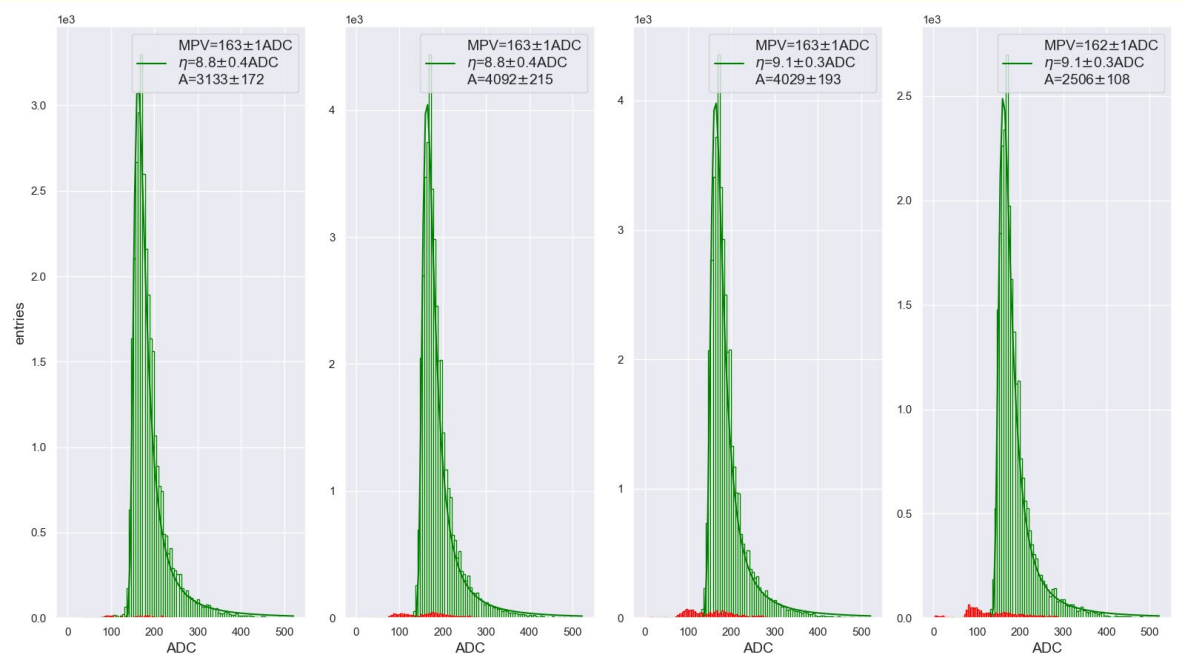
Back-up slides

Muon charge signal in panels (simu)

dE_μ for all panels
Simu output (before **RANSAC**)



dQ_μ
RANSAC output



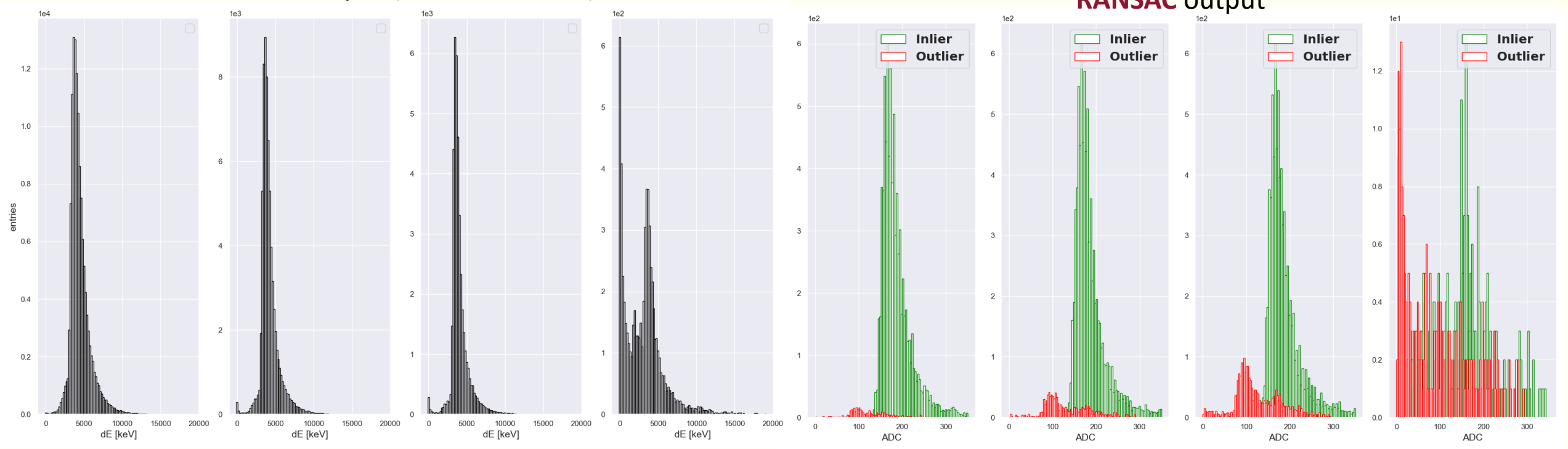
Proportion of **inliers** = **96%**
in reconstructed events

Electron charge signals in panels (simu)

For CRY **electrons:**

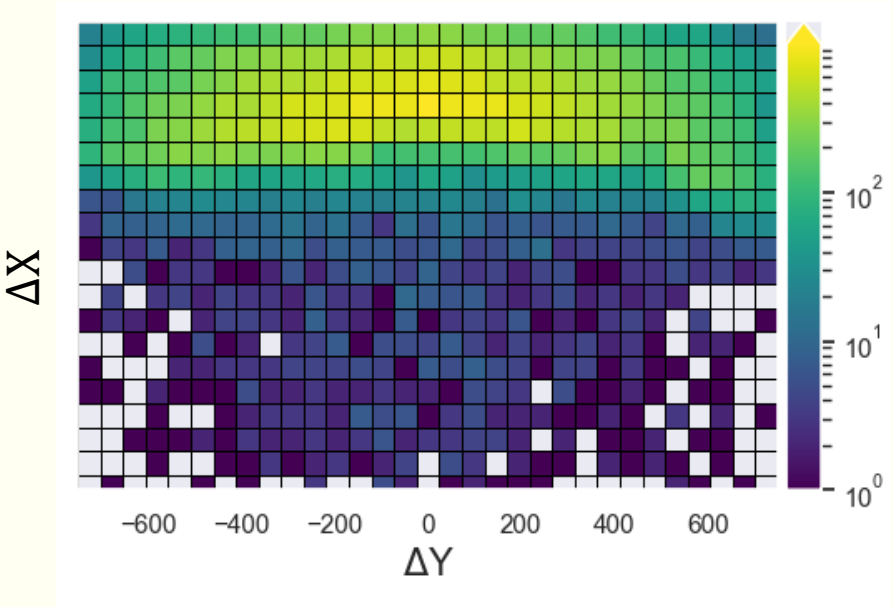
dE$_e$ for all panels
Simu output (before **RANSAC**)

dQ$_e$
RANSAC output

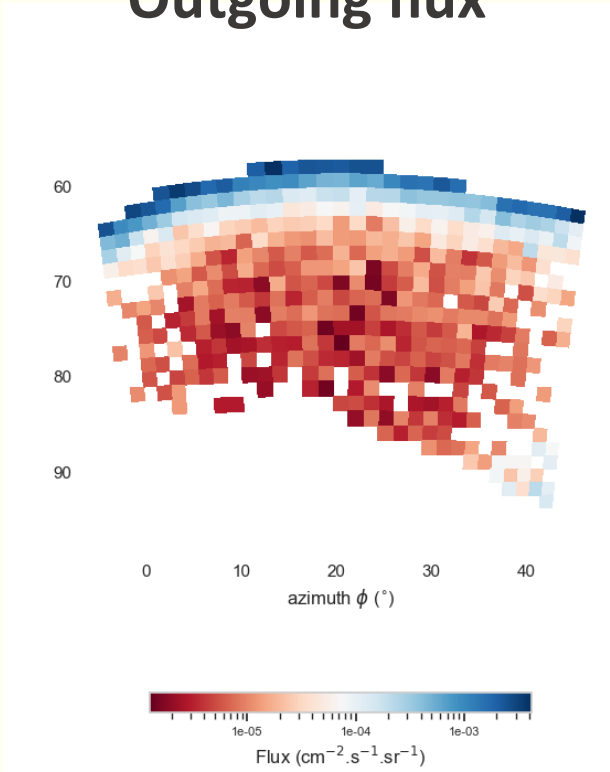


From hits map to average density

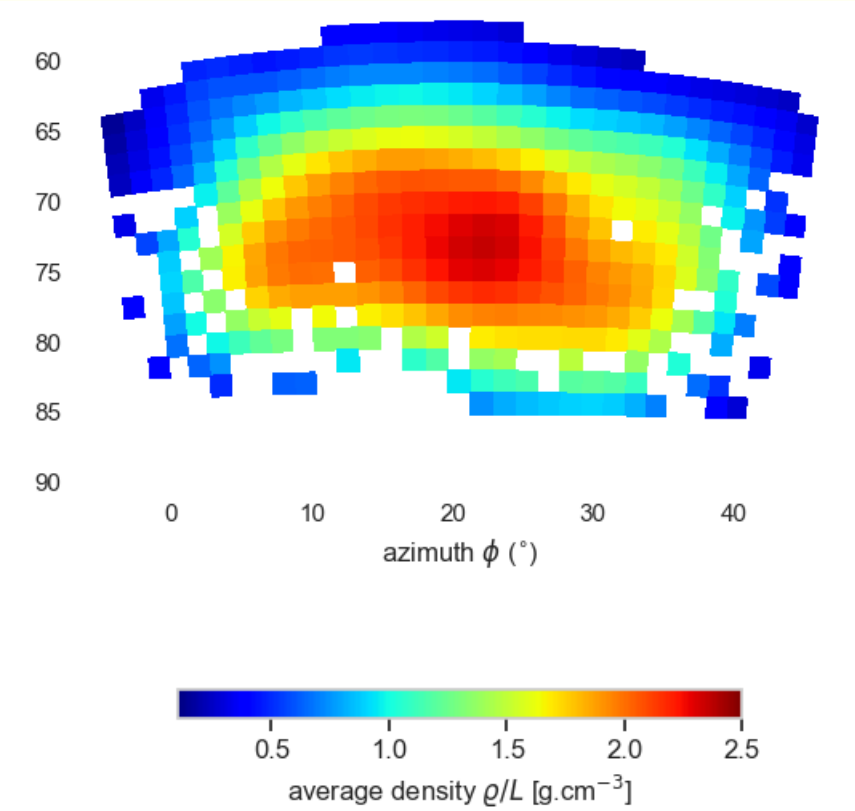
Number of detected particles



Outgoing flux



Average density



4 panels configuration