GRAND cosmic-ray search mini-workshop

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Niels Bohr Institute, University of Copenhagen

GRAND Collaboration Meeting
Warsaw, June 05, 2025
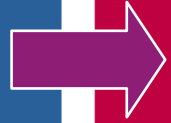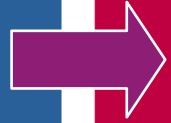
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Raw data collected by GRAND

Raw data collected by GRAND

Selection of cosmic-ray candidates

+

mitigation of background
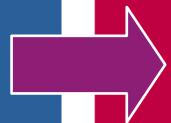
Raw data collected by GRAND

Selection of cosmic-ray candidates

+

mitigation of background

Reconstruction of properties of cosmic-ray candidates *(energy, direction, etc.)*

Raw data collected by GRAND

Selection of cosmic-ray candidates

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mitigation of background

Reconstruction of properties of cosmic-ray candidates *(energy, direction, etc.)*

Distributions of cosmic-ray properties *(spectrum, skymap, mass composition, etc.)*

Raw data collected by GRAND

Selection of cosmic-ray candidates

+

mitigation of background

Jolan + Xishui

Three reconstruction methods:
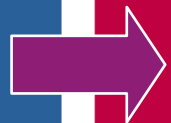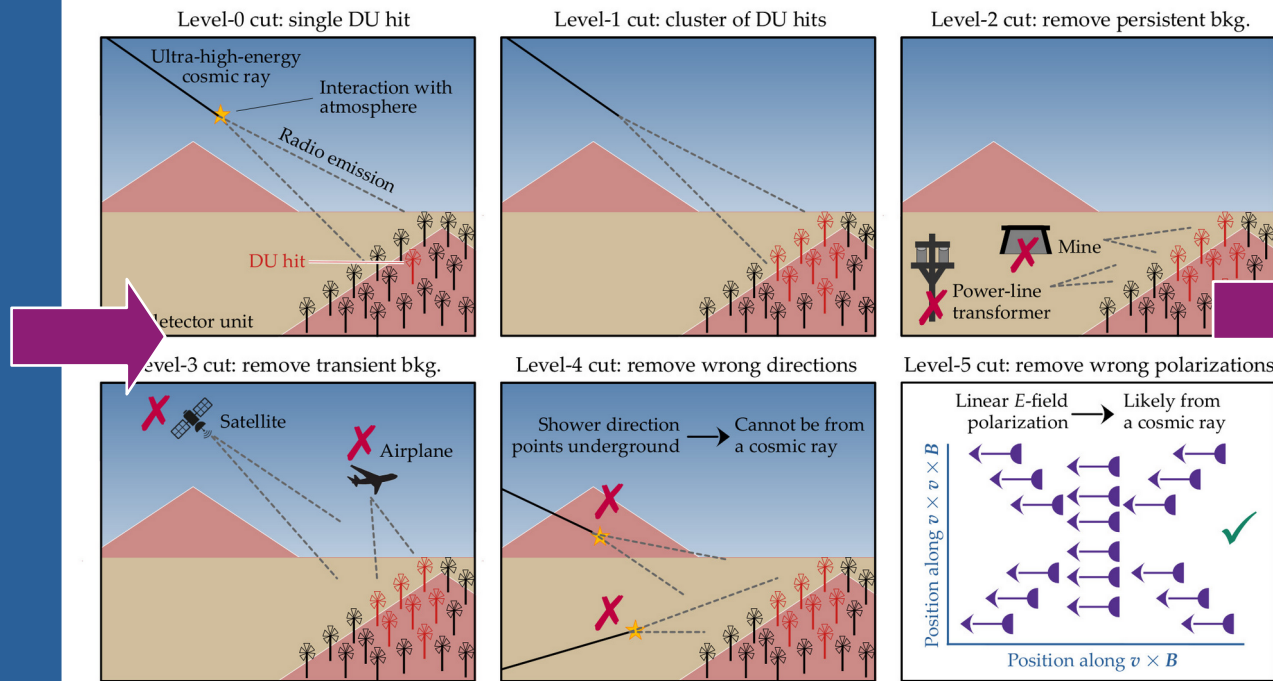Lukas + Kewen
Marion + Pauline
Arsène + Aurélien

Reconstruction of properties of cosmic-ray candidates
(energy, direction, etc.)

Distributions of cosmic-ray properties
(spectrum, skymap, mass composition, etc.)

Raw data collected by GRAND

Level-0 cut: single DU hit

Ultra-high-energy cosmic ray
Interaction with atmosphere
Radio emission
DU hit
Detector unit

Level-1 cut: cluster of DU hits

Level-2 cut: remove persistent bkg.

Mine
Power-line transformer

Level-3 cut: remove transient bkg.

Satellite
Airplane

Level-4 cut: remove wrong directions

Shower direction points underground → Cannot be from a cosmic ray

Level-5 cut: remove wrong polarizations

Linear E-field polarization → Likely from a cosmic ray

Position along $v \times v \times B$
Position along $v \times B$

Reconstruction of properties of cosmic-ray candidates
(energy, direction, etc.)

Distributions of cosmic-ray properties
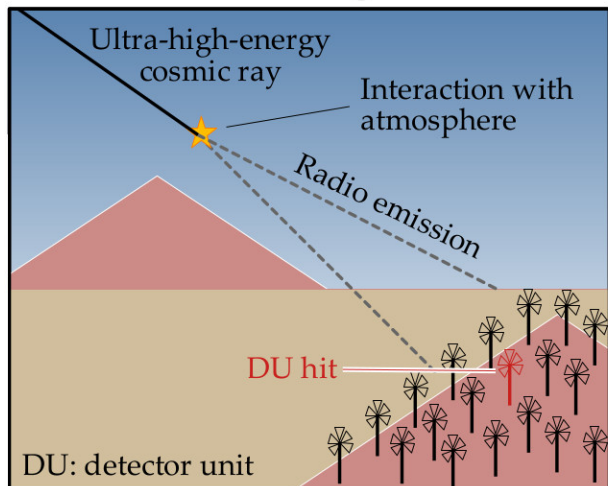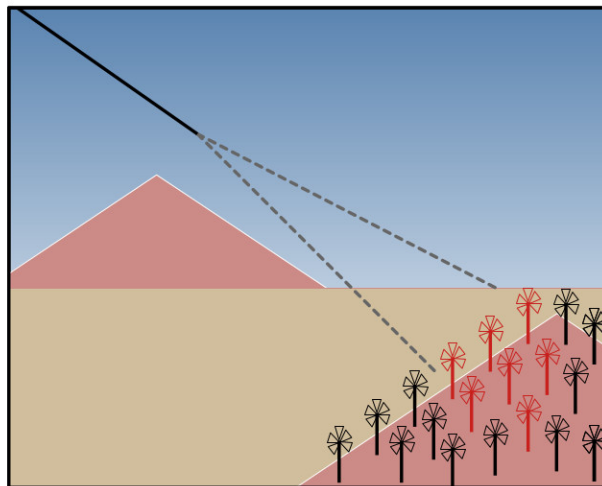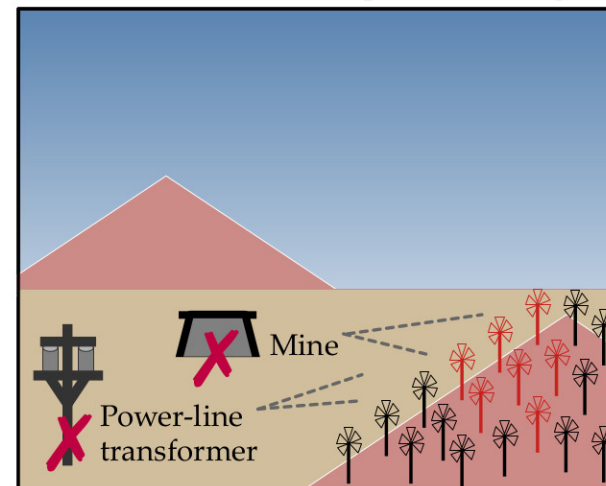(spectrum, skymap, mass composition, etc.)
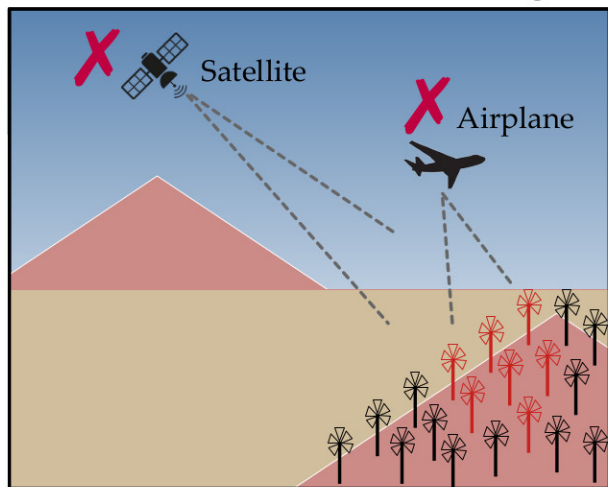
Level-0 cut: single DU hit

Ultra-high-energy cosmic ray
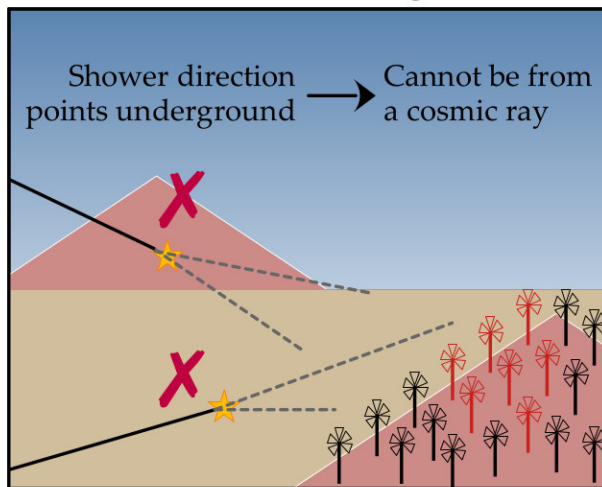
Interaction with atmosphere

Radio emission

DU hit

DU: detector unit

Level-1 cut: cluster of DU hits

Level-2 cut: remove persistent bkg.

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Linear E-field polarization → Likely from a cosmic ray

Position along $v \times v \times B$

Position along $v \times B$

🔍 Search

GRAND ▾

🔍 Find channel

Threads

CHANNELS
- analysis
- articles
- board
- commissioning_data_analysis
- cr_search
- general
- gp300
- hardware
- icrc2023
- icrc2025
- layout
- meeting
- pubcomm
- random
- science
- software
- Add channels

DIRECT MESSAGES
- lukas.guelzow
- clairegd
- arsene.ferriere, aurelien
- playbooks
- kumiko, oma
- kumiko
- lech piotrowski

☆ cr_search ▾ | 👥 36 | 📌 6 | 📄 Weekly huddle (Wednesdays, 14:30 CEST): https://ucph-ku.zoom.us/j/64265154047?pwd=rYUCdFCfydYrLrnH9kW9WbGc7XaGs...

- He requested Lukas to upload these LDFs to Forge and suggested creating a **new dedicated page**.

Conclusion:
- Lukas' noise analysis could provide insights for distinguishing **true events vs background**.
- The team will revisit this in the upcoming **workshop**, possibly using it as groundwork for future classification strategies.

📌 **Pending to-do**

- Everyone: decide which data visualizations (e.g., distributions) are rigorous and safe for ICRC presentation
- Understand the differences between the three reconstruction methods: Lukas + Kewen, Marion + Pauline, and Arsène + Aurélien.
- Lukas: finish testing how the reconstruction changes when artificially removing the notched frequencies
- Lukas, everyone: understand why the reconstruction method of Lukas + Kewen fails on some CR candidates
- @pengxiongma: retrieve and share L1 trigger rates for each DU in January 2025
- @jolan_lavoisier , @tianxs : why do most of the CR candidates you selected have an entry number of 0 or close to that? (Olivier asked this earlier, too.)
- @arsene.ferriere : in Lukas' directional reconstruction, the error on the azimuth is suspiciously small, of ~0.1°. Please clarify how the error on the azimuth and zenith are computed.
- @lukas.guelzow : will provide the identifying numbers of active and inactive DUs in the candidates, to facilitate Pengxiong's attempt to find which DUs were inactive at detection time
- @pengxiongma : will provide information on which DUs were inactive at the time of detection of the top-give candidates of Lukas
- @lukas.guelzow : revisit reconstruction after knowing which DU were inactive at the time of candidate detection
- @marionguelfand, @paulinef : run Lukas' top CR candidates through your reconstruction method (see candidate list in the huddle summary)
- @arsene.ferriere : run Lukas' top CR candidates through your reconstruction method (see candidate list in the huddle summary)
- Everyone: think whether there are specific topics, questions, etc. that you would like us to discuss next week during the CR mini-workshop in Warsaw
- @mbustamante: update Marion + Pauline reconstruction in per-candidate summary plots
- @mbustamante: update summary CR distribution plots for Lukas' new reconstruction results of May 31
- Finalize shortlist of best candidates (CR0, CR3, CR4, CR10, CR31?)

✔ **10 of 30 tasks checked** • 👥 **18 participants**

Sunday

lukas.guelzow 5:20 PM
I checked the impact of the notch filters today and I don't see any dramatic difference in my reconstructions on simulations.
What I did notice is a slight decrease in the radiation energy which is to be expected if I filter out some frequencies.
I should be able to compensate for this with the energy reference parameter S19 I use to calculate the electromagnetic energy from the radiation energy.

Write to cr_search

B I S H 🔗 </> " ≔ ⋮☰ ℹ️

Run details ⧉   Following

First GP300 CR selection

Identify cosmic-ray candidate events in GP300 data, to be shown at ICRC

Owner   Participants
M @mbustamante ▾   🔴🟠🟣🟡🔵 +11 👤➕

🕐 Update due   [Post update]
   in 4 days

Tasks

▽ Cosmic-ray candidate selection (Jolan, Takashi, Kum... 5 / 5 done

☑ Jolan and Xishui compare CR candidate selection criteria

☑ Hanrui communicates if he has a different list of CR candidates from Jolan's and Xishui's
  If yes, state what are the differences in selection criteria
  H @hanrui_wang

☑ Agree on a single list of CR selection criteria and a single list or CR candidates

☑ Include status of the stations at the moment of detection
  Suggested by Lukas

☑ Assess whether one can use preferentially events with z-polarization available
  Suggested by Tim, indicated by the `adc_input_channels` in the root files. I.e., for 2025March data, the chZ is stored in the ch3 (0-based)

+ Add a task

▽ Reconstruction of CR candidate properties (Mario... 11 / 23 done

☑ Find out which of the CR candidates have Z-channel data saved

Playbook

Practical matters

▶ List of cosmic-ray candidates by Jolan + Xishui available as table on Forge:

   GP300 cosmic-ray candidates to be shown at ICRC 2025: Selection

▶ JSON file merging the reconstructed properties of all the reconstruction methods:

   GP300 cosmic-ray candidates to be shown at ICRC 2025: Reconstruction

▶ All plots and data available on Forge:

   GP300 cosmic-ray candidates to be shown at ICRC 2025: Reconstruction

▶ Plots, data, and plotting scripts on private GitHub repository: plots_grand_cr_properties
(Ask Mauricio for access if interested.)

Current candidate selection criteria

(This is also on Forge, <u>here</u>)

Data: GP300 data from early December 2024 to end of March 2025

Current list of CR candidates obtained by stitching selection criteria of Jolan and Xishui:

1. Reconstruction quality

2. Clustering cut

3. Polarization cut

4. Multiplicity cut

5. Arrival cut

6. Event time cut

7. No high RMS value for channels X and Y

8. SNR cut

9. Remove DU1032, DU1049

10. Visual cut of spread of footprint

11. Visual cut of quality of the trace

Event name	run_no_time	evt_entry	Event name	run_no_time	evt_entry
CR0	20241209_054702	820	CR20	20250115_023750	2
CR1	20241215_180709	0	CR21	20250115_233012	16
CR2	20241219_162205	0	CR22	20250117_115259	83
CR3	20241220_033050	5	CR23	20250117_185153	0
CR4	20241220_033050	13	CR24	20250119_042307	166
CR5	20241222_054623	122	CR25	20250121_225547	0
CR6	20241224_133033	19	CR26	20250122_155158	321
CR7	20241226_113611	68	CR27	20250125_025432	0
CR8	20241226_114408	37	CR28	20250125_034440	50
CR9	20241229_084801	254	CR29	20250128_153832	0
CR10	20250102_003735	2	CR30	20250128_220319	0
CR11	20250102_013241	2	CR31	20250131_065640	47
CR12	20250102_021724	38	CR32	20250131_103628	40
CR13	20250102_073620	117	CR33	20250203_125407	0
CR14	20250102_133014	1	CR34	20250214_031401	3
CR15	20250103_013446	0	CR35	20250215_063517	59
CR16	20250105_041755	78	CR36	20250215_171431	0
CR17	20250111_133346	46	CR37	20250219_010304	0
CR18	20250111_220533	1	CR38	20250304_191440	123
CR19	20250113_140919	4	CR39	20250311_231043	129

Reconstruction methods: overview

We have applied five reconstruction methods to the CR candidates:

▶ Lukas + Kewen, based on E-field reconstruction
   Details: Lukas' talk

▶ Marion + Pauline, ADF based on E-field reconstruction
▶ Marion + Pauline, ADF based on voltage
   Details: Marion's talk ([here](#))

▶ Arsène + Aurélien, based on GNN
▶ Arsène + Aurélien, based on pGNN (PWF bias corrected)
   Details: Arsène's talk ([here](#))

Focused on reconstructing only the CR energy and direction

Event name	run_no_time	evt_entry
CR0	20241209_054702	820
CR1	20241215_180709	0
CR2	20241219_162205	0
CR3	20241220_033050	5
CR4	20241220_033050	13
CR5	20241222_054623	122
CR6	20241224_133033	19
CR7	20241226_113611	68
CR8	20241226_114408	37
CR9	20241229_084801	254
CR10	20250102_003735	2
CR11	20250102_013241	2
CR12	20250102_021724	38
CR13	20250102_073620	117
CR14	20250102_133014	1
CR15	20250103_013446	0
CR16	20250105_041755	78
CR17	20250111_133346	46
CR18	20250111_220533	1
CR19	20250113_140919	4

Event name	run_no_time	evt_entry
CR20	20250115_023750	2
CR21	20250115_233012	16
CR22	20250117_115259	83
CR23	20250117_185153	0
CR24	20250119_042307	166
CR25	20250121_225547	0
CR26	20250122_155158	321
CR27	20250125_025432	0
CR28	20250125_034440	50
CR29	20250128_153832	0
CR30	20250128_220319	0
CR31	20250131_065640	47
CR32	20250131_103628	40
CR33	20250203_125407	0
CR34	20250214_031401	3
CR35	20250215_063517	59
CR36	20250215_171431	0
CR37	20250219_010304	0
CR38	20250304_191440	123
CR39	20250311_231043	129

Candidate by candidate: reconstructed energy

6 top selected candidates: CR0, CR3, CR4, CR10, CR18, CR31
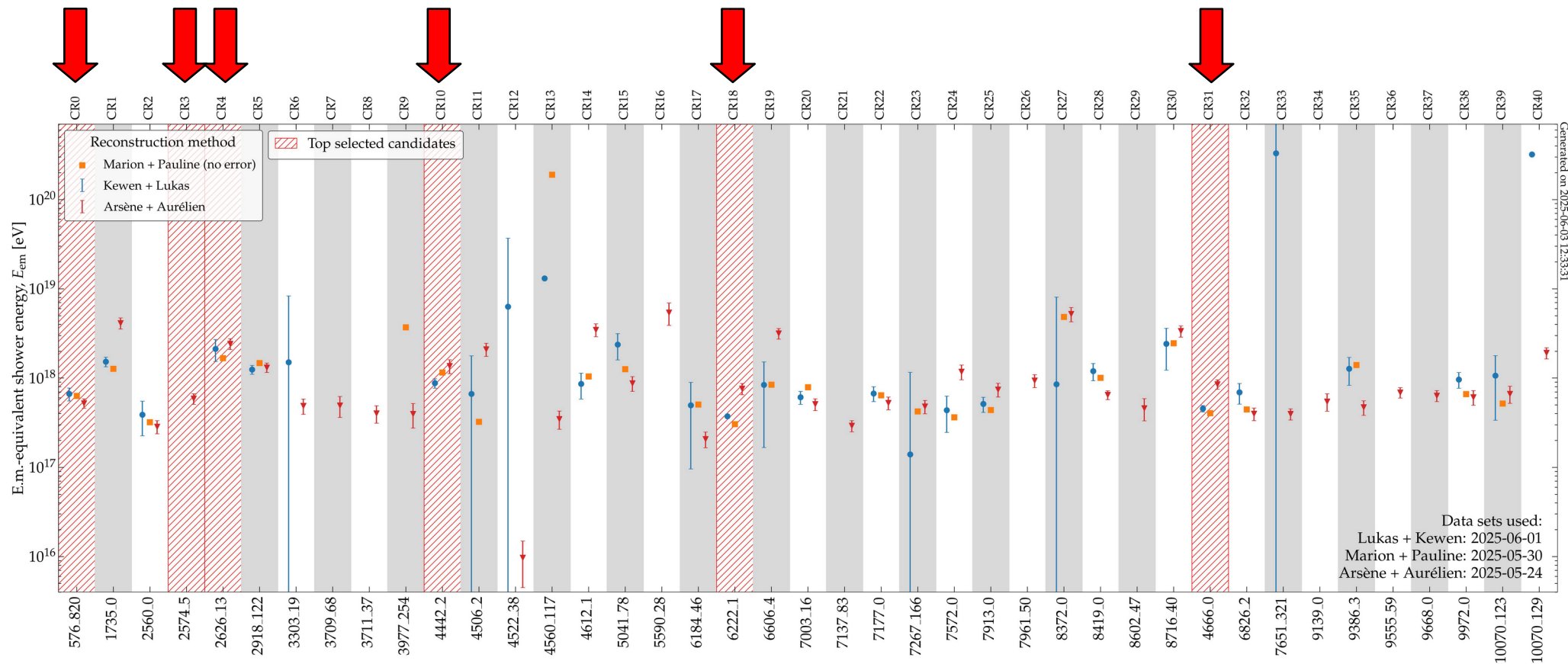
Top candidates are ***not*** outliers in energy

Candidate by candidate: reconstructed energy
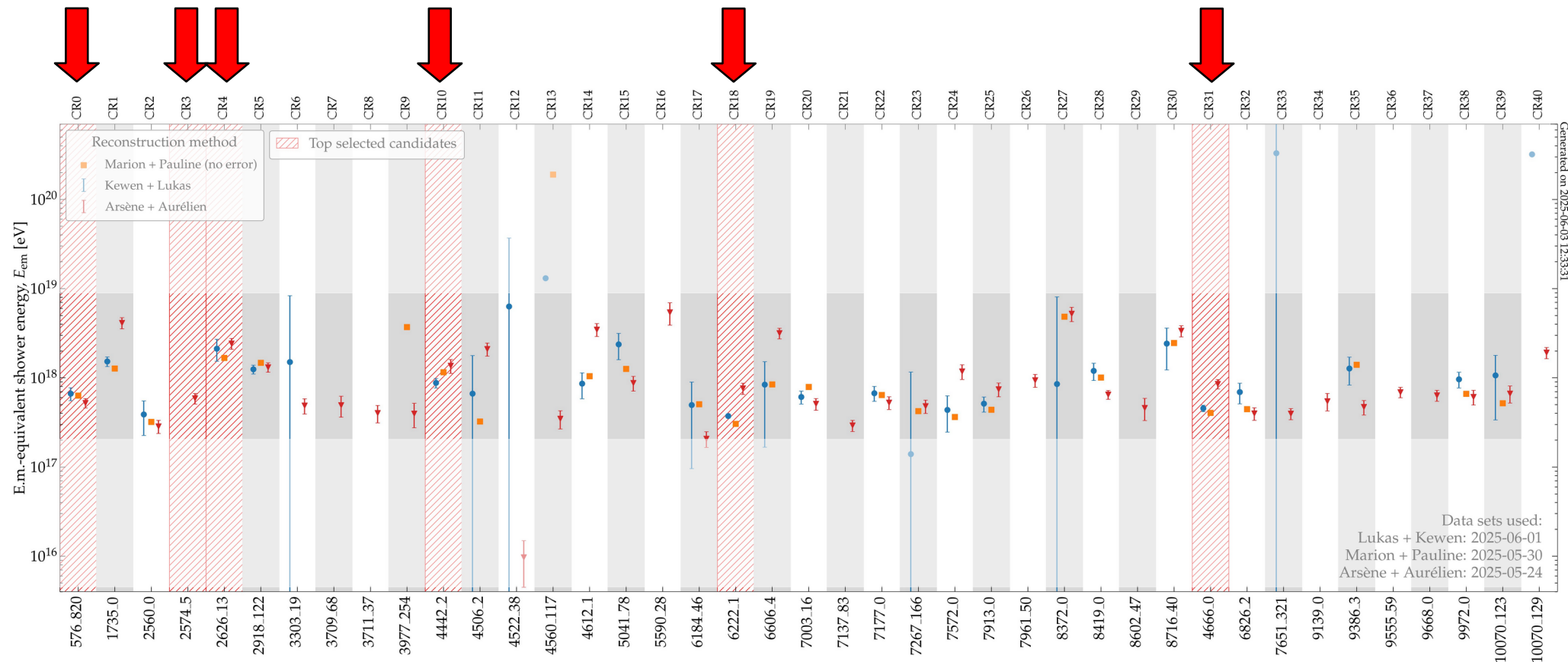
Top candidates are **not** outliers in energy

Candidate by candidate: reconstructed zenith angle
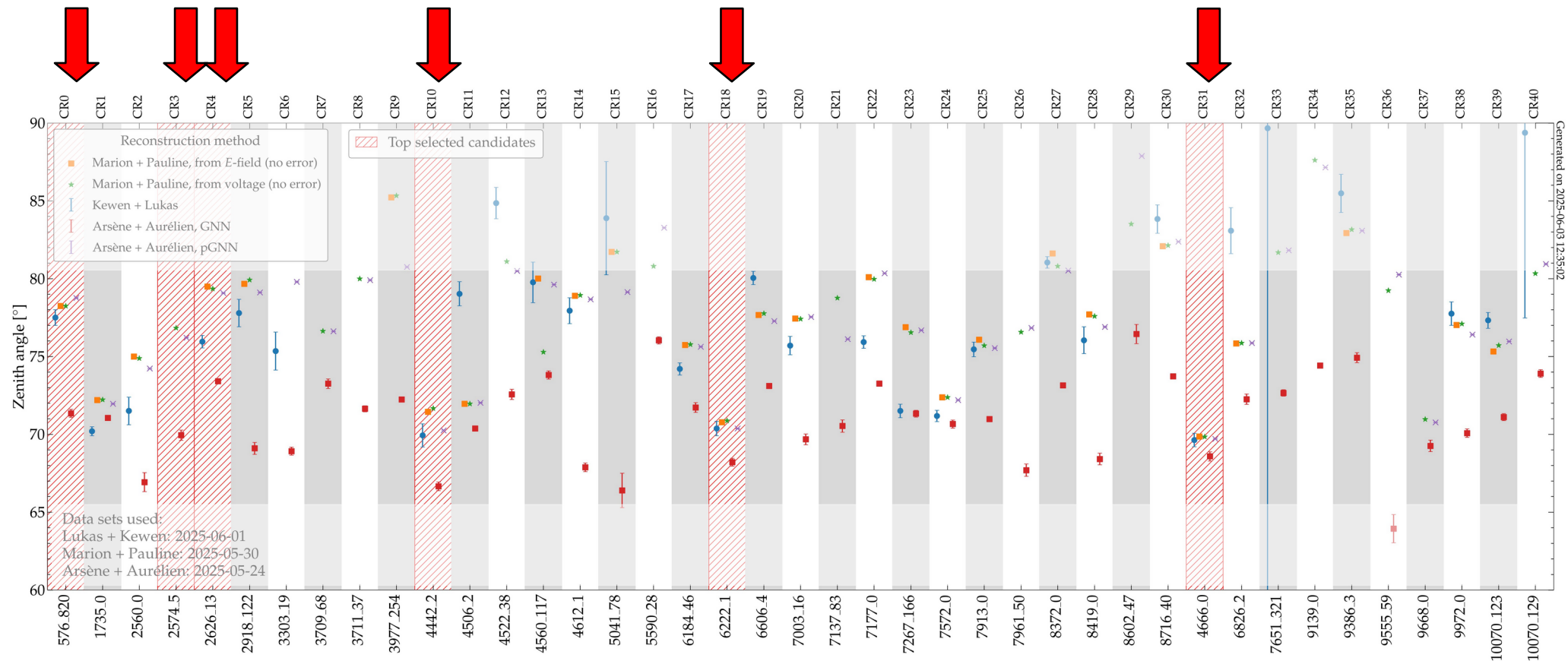
Top candidates are ***not*** outliers in zenith

Candidate by candidate: reconstructed azimuth
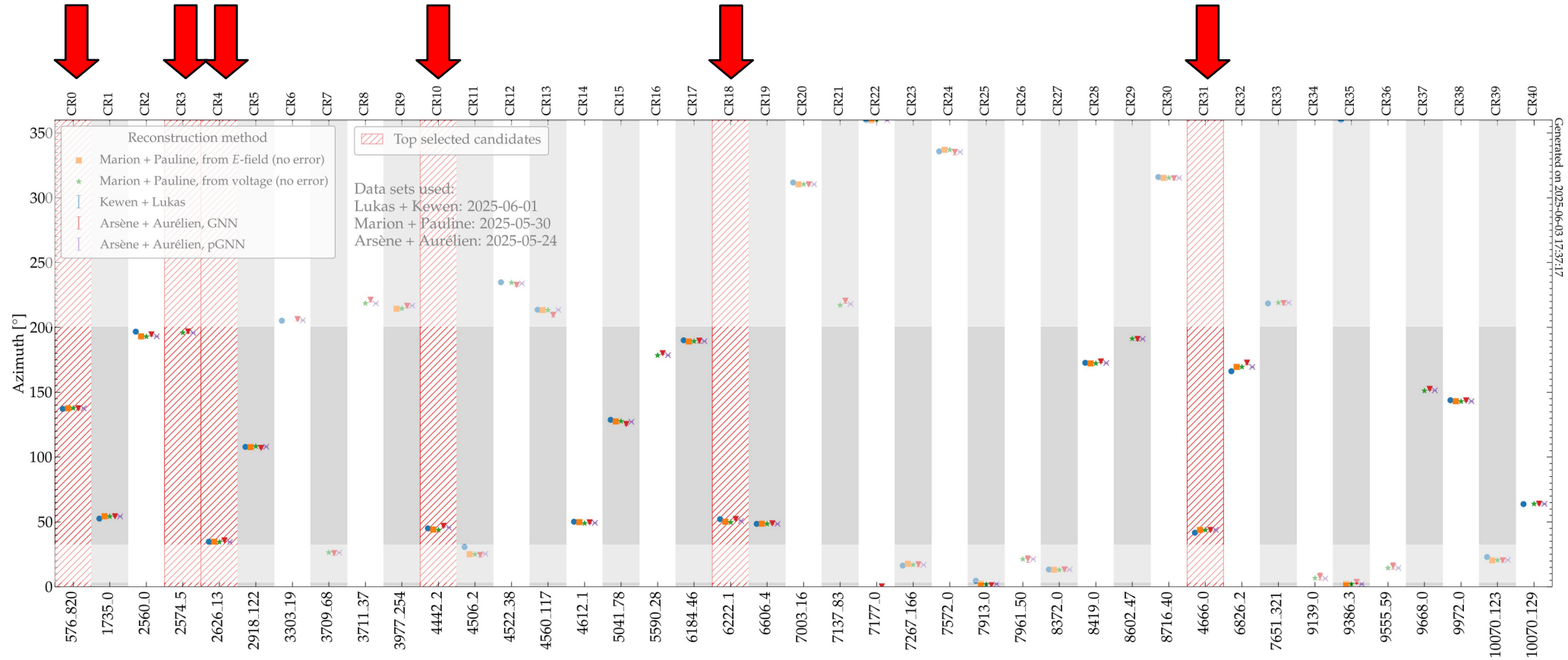
Top candidates are *not* outliers in azimuth

What should we show at the ICRC?

(1) **Short list of featured candidates:** Out of the full list of (~40) candidates, which 1-5 are most likely to be cosmic rays? These are the candidates to show. Validate the ones we have.

(2) **Which reconstruction method:** Should we show the result of a single reconstruction method? Of all of them? If all, how (limited time, slide space)?

(3) **Additional CR properties:** What information other than energies and directions, if any, do we want to show? Lateral distribution functions? Voltage? Polarization? Too early?

(4) **Distributions of CR properties:** What do want to claim, if anything, about the distribution of the properties of the full list of candidates, *i.e.*, of their energies and directions?

LDFs of top candidate CR0

(Run 576 , Event 820): $E_{em}^{rec} = 0.74 \pm 0.13$ EeV, $d_{max}^{fit} = 100 \pm 534$ km

$\theta = 77.5°$, $\phi = 137.3°$, $\alpha = 122.1°$, $\chi^2/\text{ndf} = 1.61$
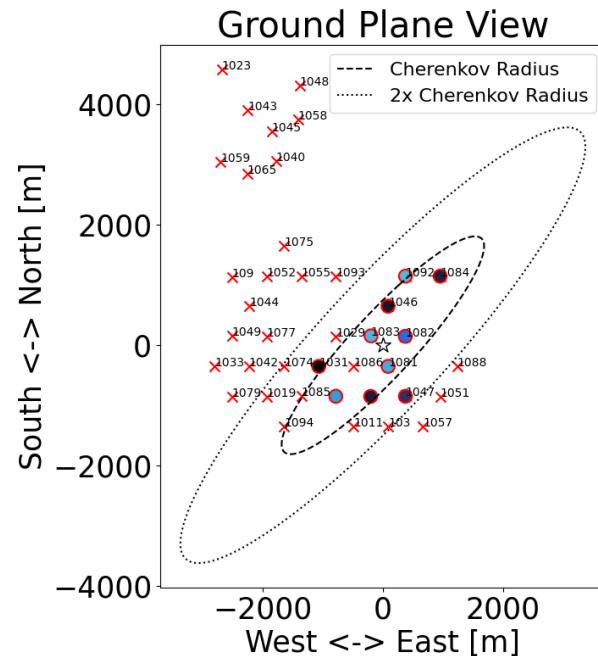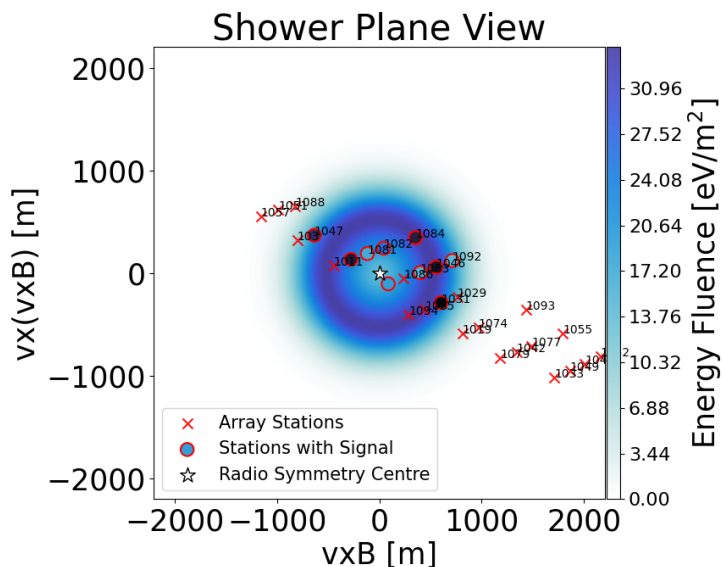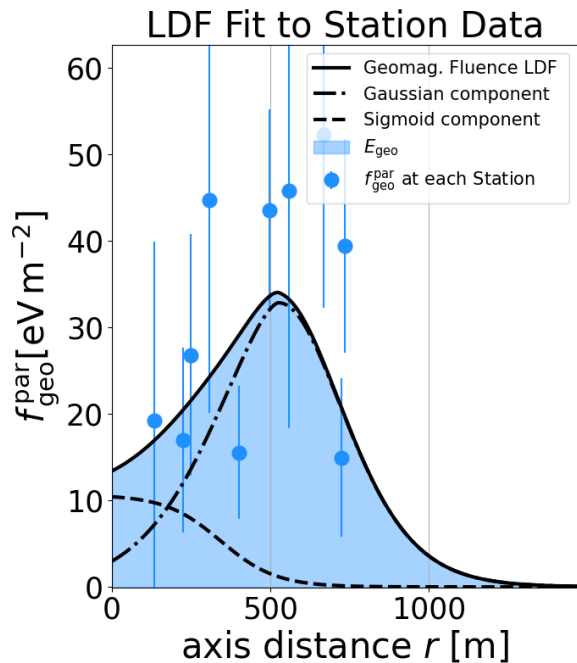
Results from Lukas

Cosmic ray candidates: some examples
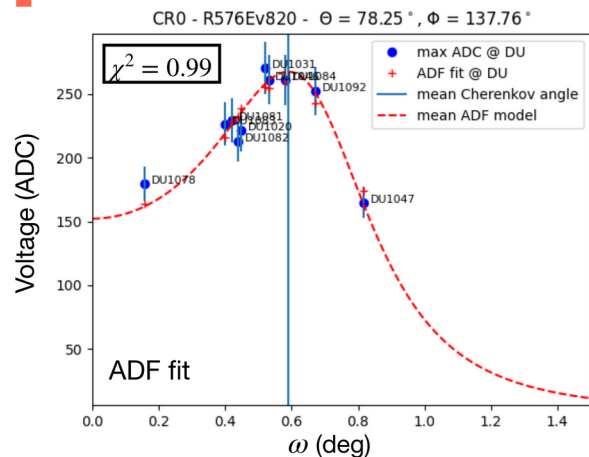
Cherenkov angle:
Fixed parameter of the ADF model computed with semi-analytical toy model (prior to the fit)
Depends on Xsource position and atmosphere model only
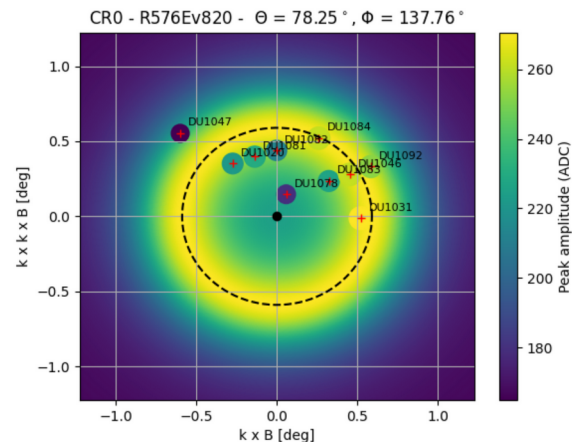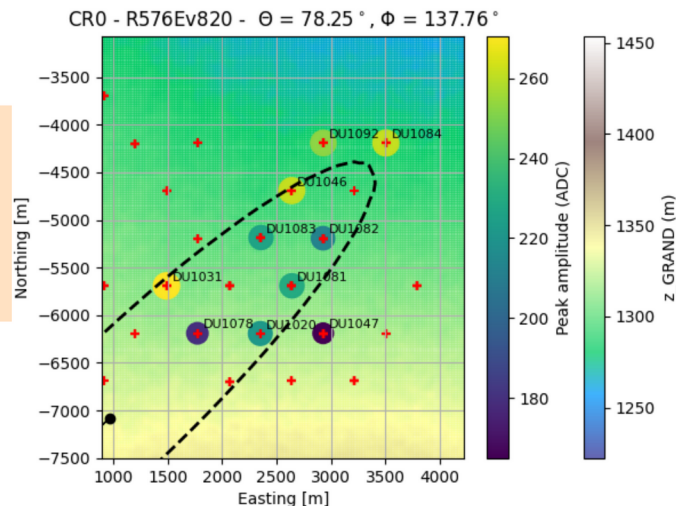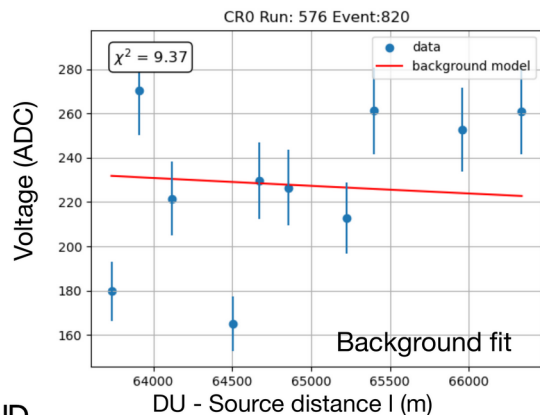
LDFs of top candidate CR3

(Run 2574 , Event 5): $E_{em}^{rec} = 0.82 \pm 0.25$ EeV, $d_{max}^{fit} = 69 \pm 475$ km
$\theta = 74.0°$, $\phi = 195.5°$, $\alpha = 133.1°$, $\chi^2/\text{ndf} = 7.94$
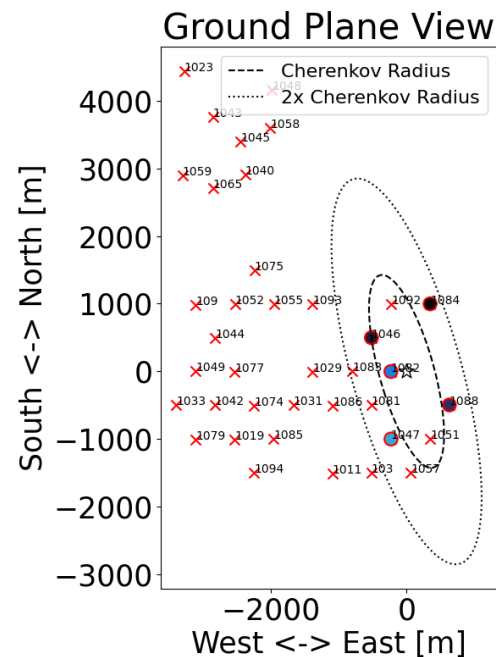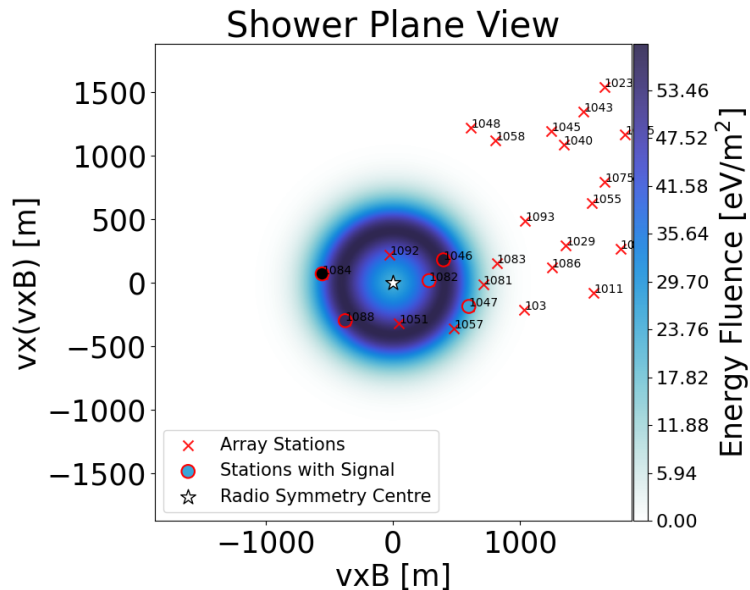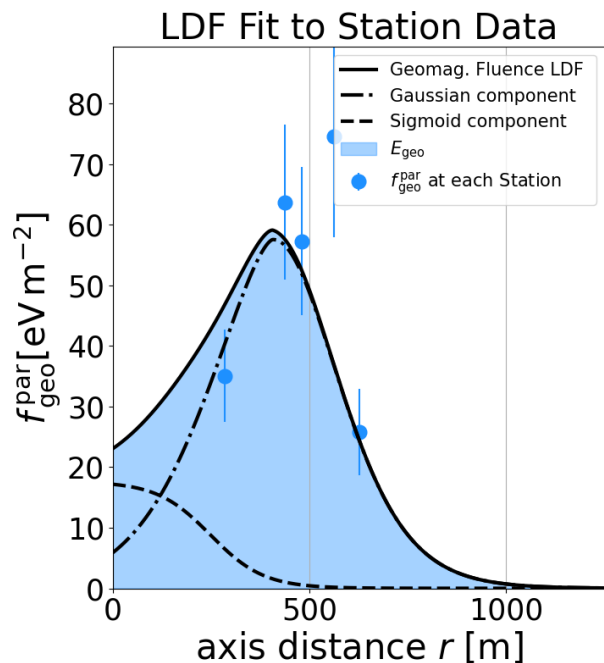
Results from Lukas

Cosmic ray candidates: some examples
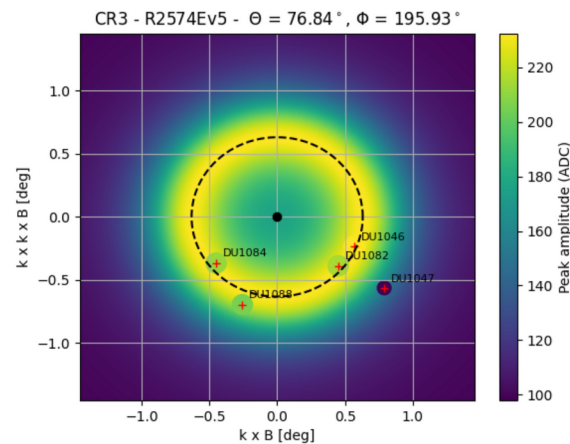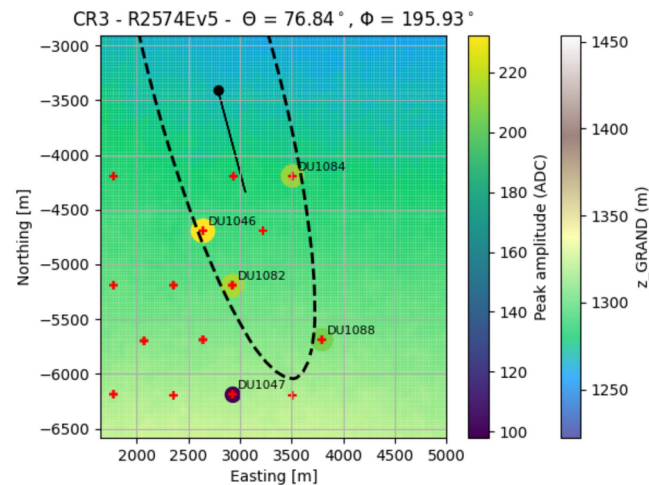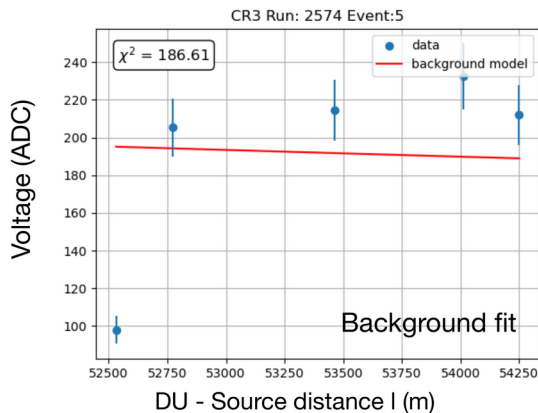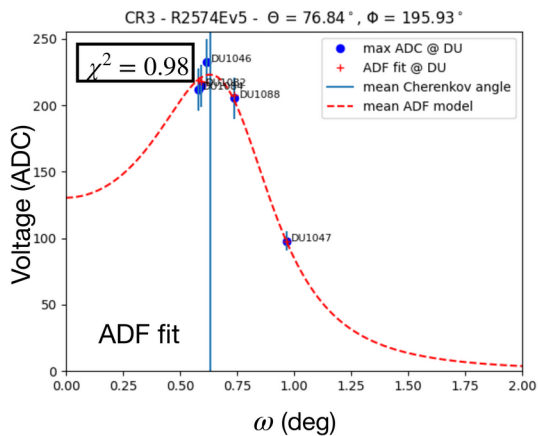
LDFs of top candidate CR4

(Run 2626 , Event 13): $E_{em}^{rec} = 2.05 \pm 0.10$ EeV, $d_{max}^{fit} = 84 \pm 7$ km

$\theta = 76.0°$, $\phi = 34.7°$, $\alpha = 80.5°$, $\chi^2/\text{ndf} = 0.53$

Results from Lukas

Cosmic ray candidates: some examples

ADF fit

Background fit
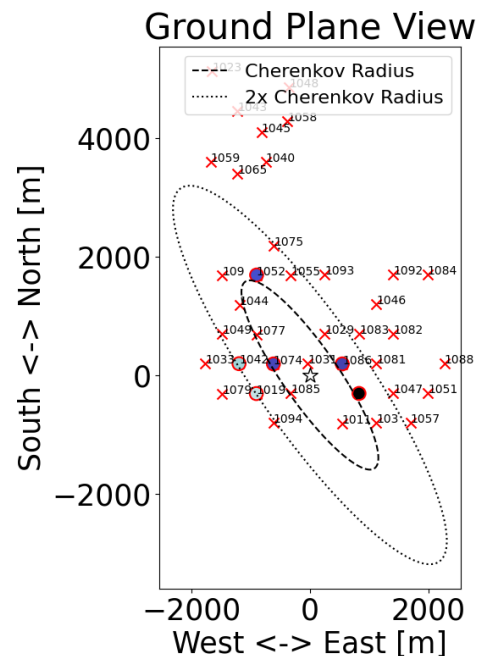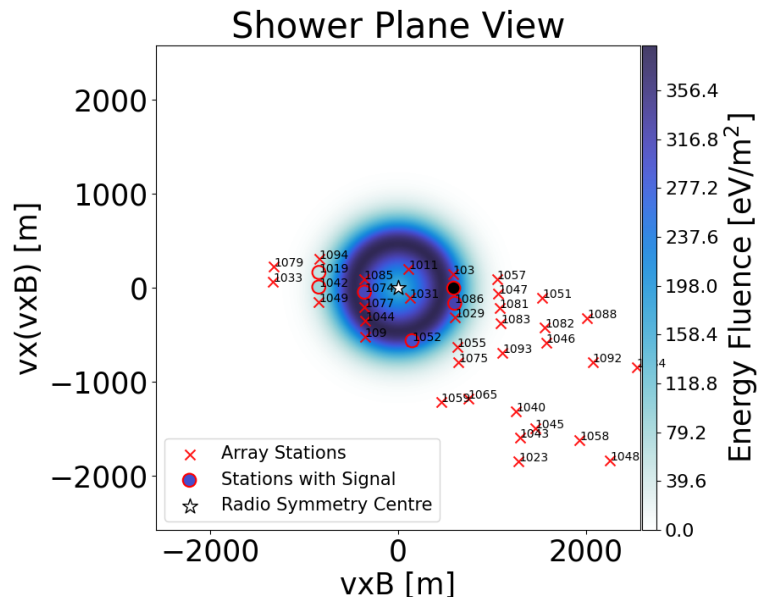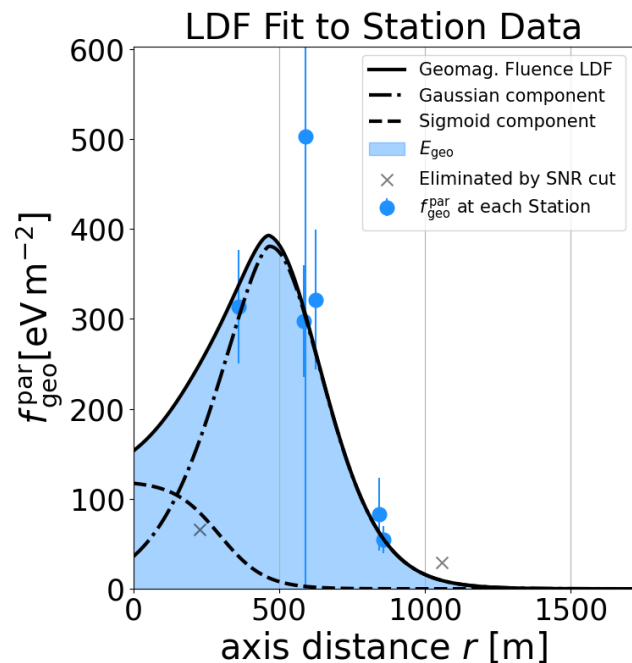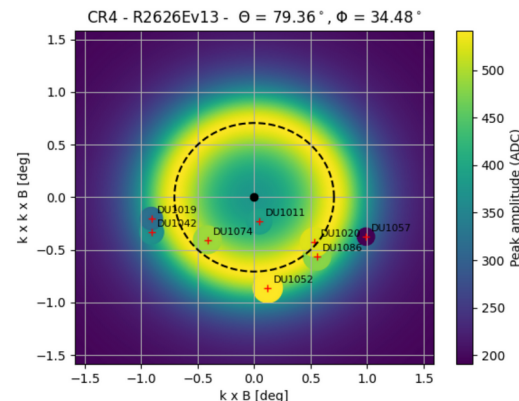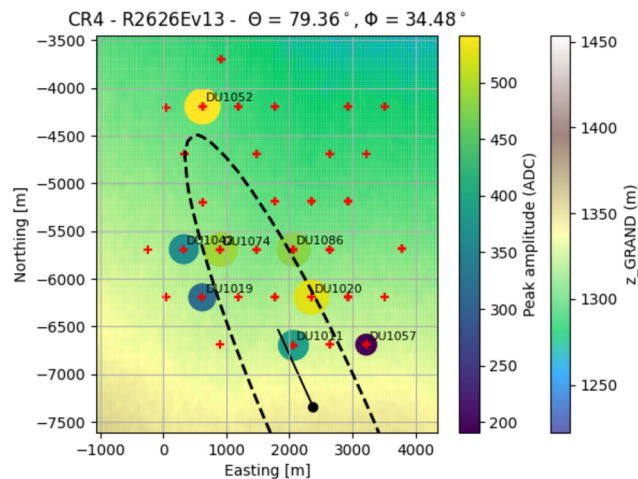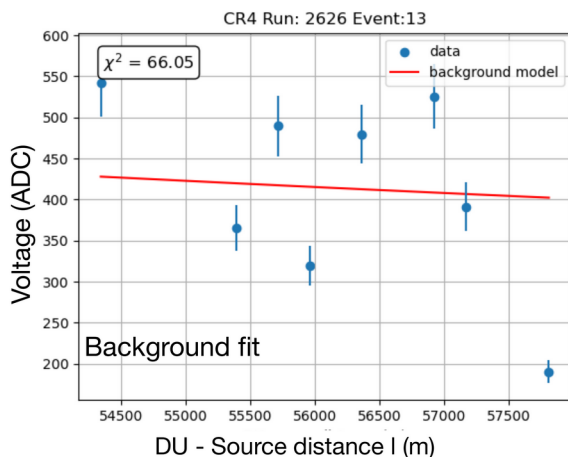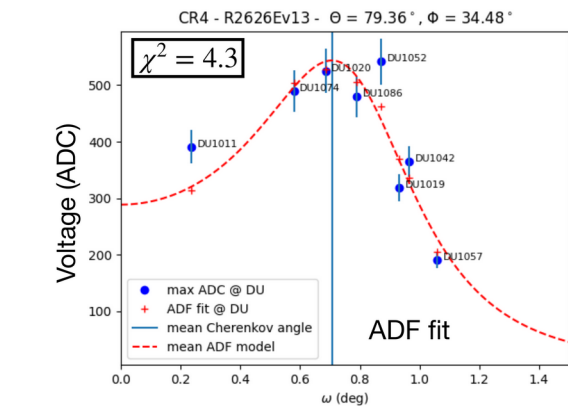
We have some very convincing events

LDFs of top candidate CR10

(Run 4442 , Event 2): $E_{em}^{rec} = 0.90 \pm 0.12$ EeV, $d_{max}^{fit} = 30 \pm 18$ km

$\theta = 69.9°, \phi = 45.0°, \alpha = 89.2°, \chi^2/\text{ndf} = 1.68$
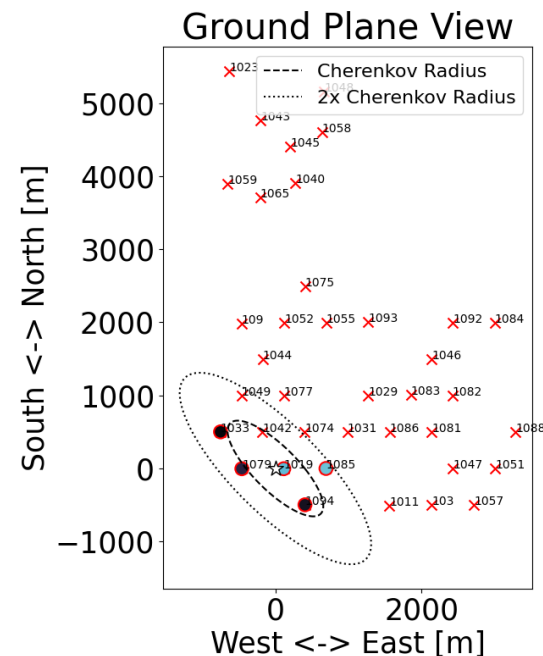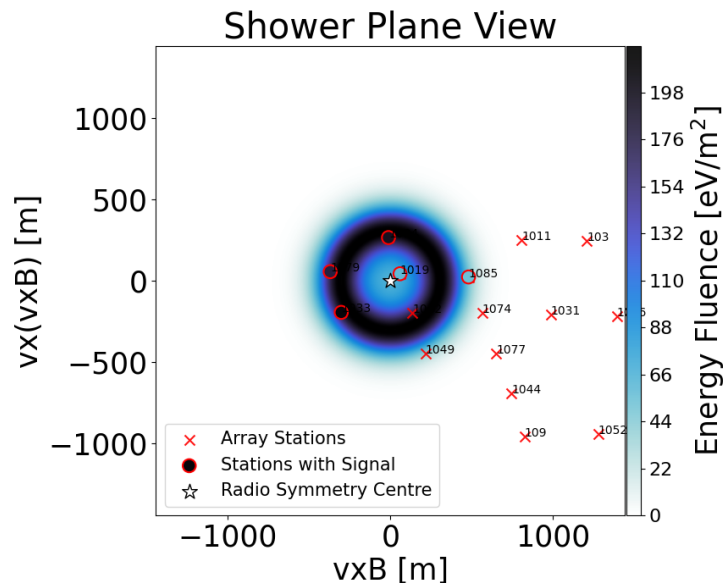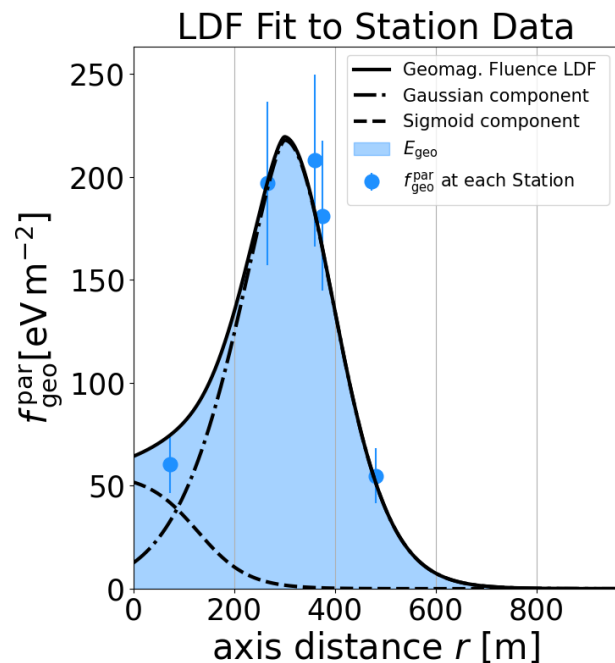
Results from Lukas

LDFs of top candidate CR18

(Run 6222 , Event 1): E_{em}^{rec} = 0.38 ± 0.02 EeV, d_{max}^{fit} = 32 ± 17 km

θ = 70.4°, ϕ = 52.1°, α = 91.2°, χ^2/ndf = 0.62
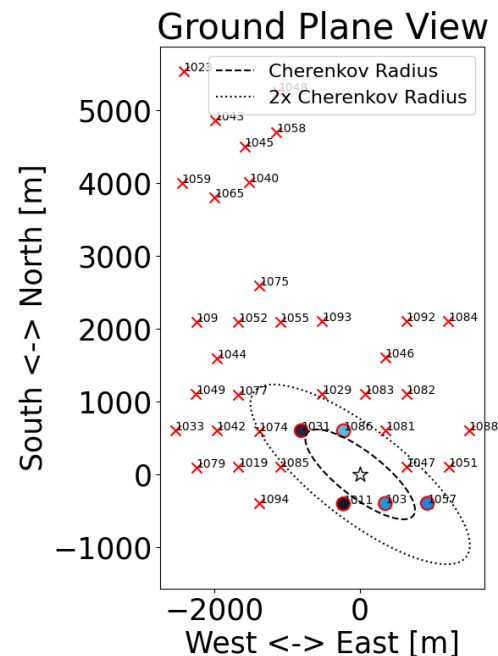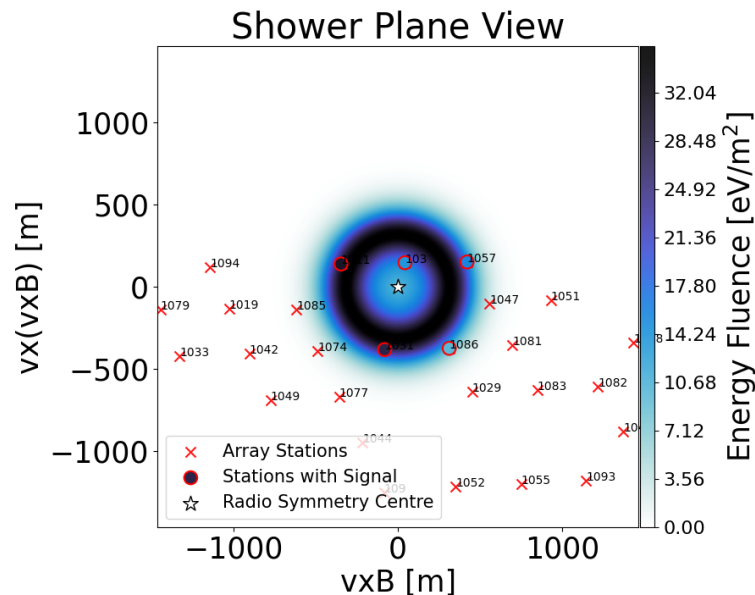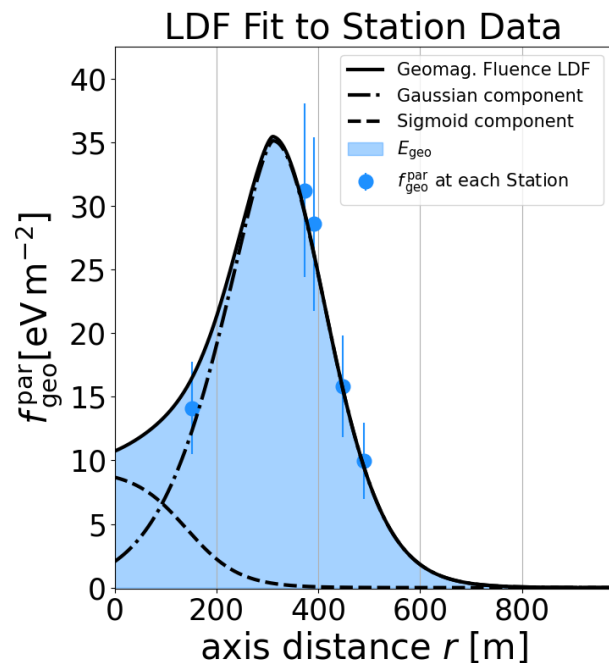
Results from Lukas

LDFs of top candidate CR31

(Run 4666 , Event 0): $E_{em}^{rec} = 0.46 \pm 0.04$ EeV, $d_{max}^{fit} = 37 \pm 10$ km

$\theta = 69.6°$, $\phi = 41.8°$, $\alpha = 88.5°$, $\chi^2/ndf = 1.81$
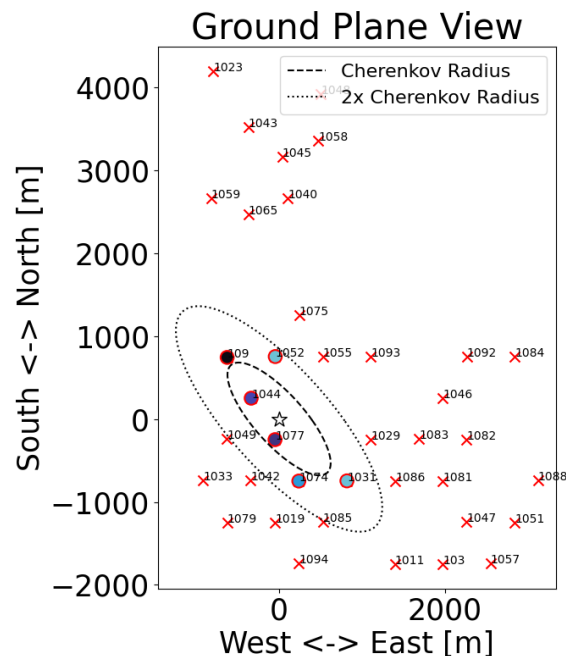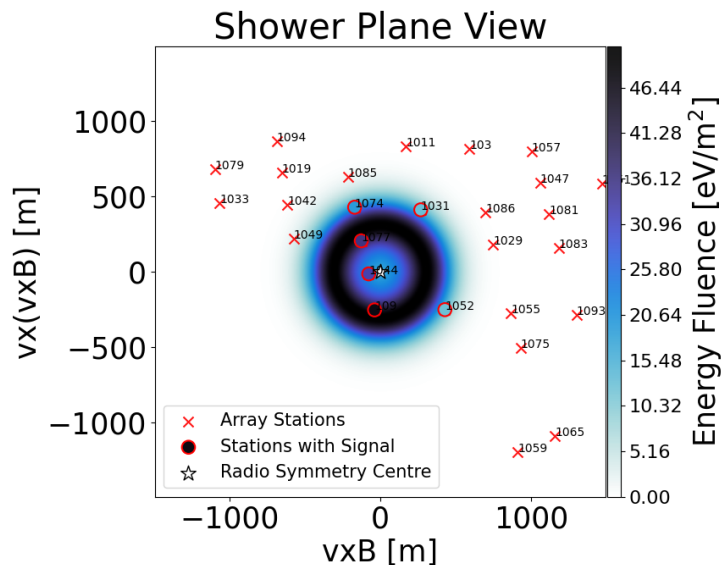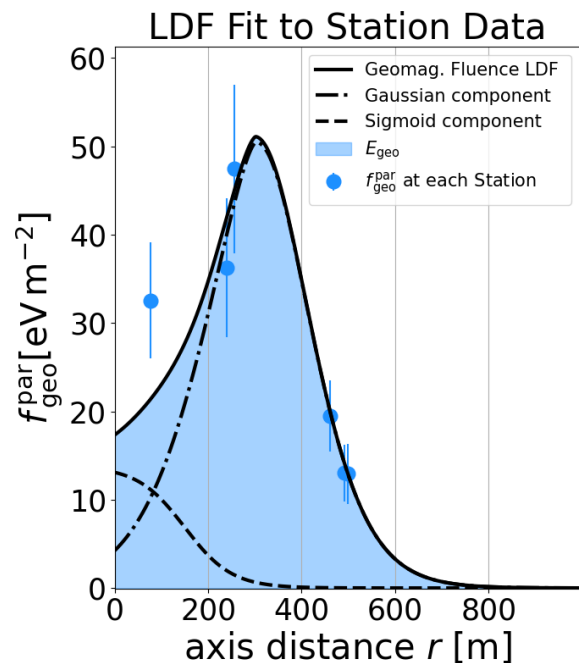
Results from Lukas

Noise event examples

(Run 10070 , Event 541): $E_{em}^{rec} = 1.34 \pm 133.05$ EeV, $d_{max}^{fit} = 64 \pm 2851$ km
$\theta = 73.1°$, $\phi = 197.6°$, $\alpha = 133.5°$, red. $\chi^2 = 5.31$
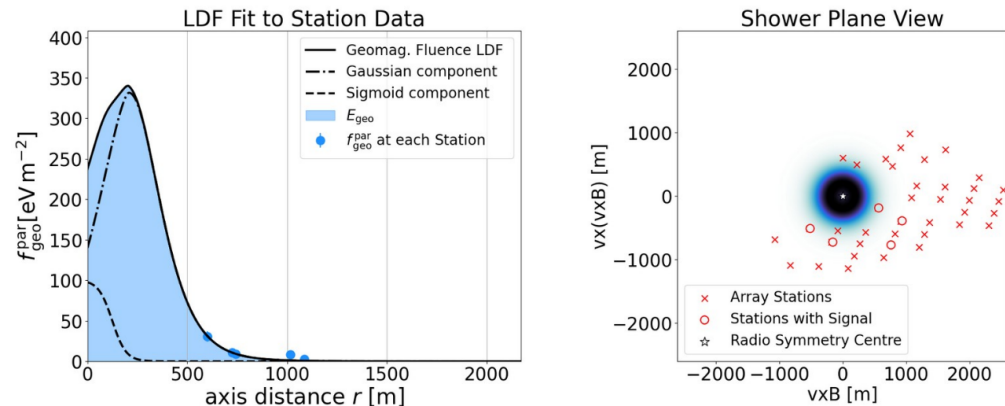
(Run 10070 , Event 415): $E_{em}^{rec} = 16.52 \pm 0.00$ EeV, $d_{max}^{fit} = 475 \pm 0$ km
$\theta = 89.1°$, $\phi = 298.0°$, $\alpha = 77.9°$, red. $\chi^2 = 9.89$
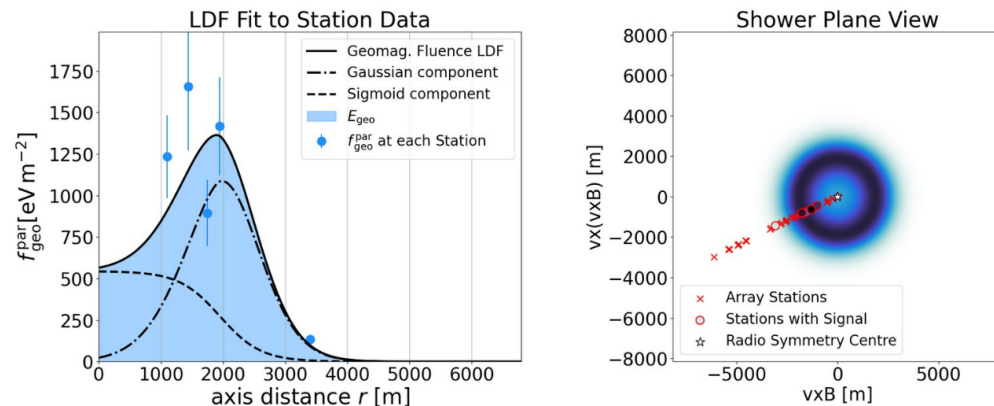
(Run 10070 , Event 273): $E_{em}^{rec} = 1.25 \pm 7198.16$ EeV, $d_{max}^{fit} = 223 \pm 273730$ km
$\theta = 83.8°$, $\phi = 220.0°$, $\alpha = 117.2°$, red. $\chi^2 = 48.22$
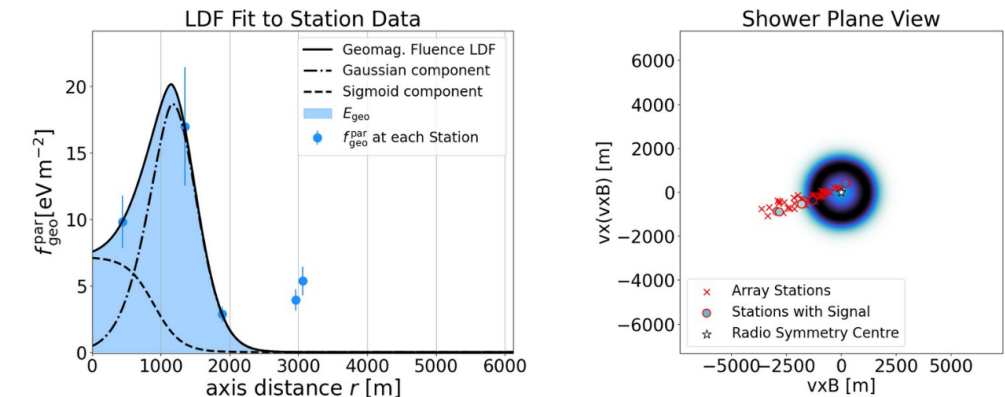
(Run 10070 , Event 675): $E_{em}^{rec} = 1.97 \pm 0.92$ EeV, $d_{max}^{fit} = 209 \pm 451$ km
$\theta = 85.6°$, $\phi = 297.4°$, $\alpha = 81.4°$, red. $\chi^2 = 5.77$
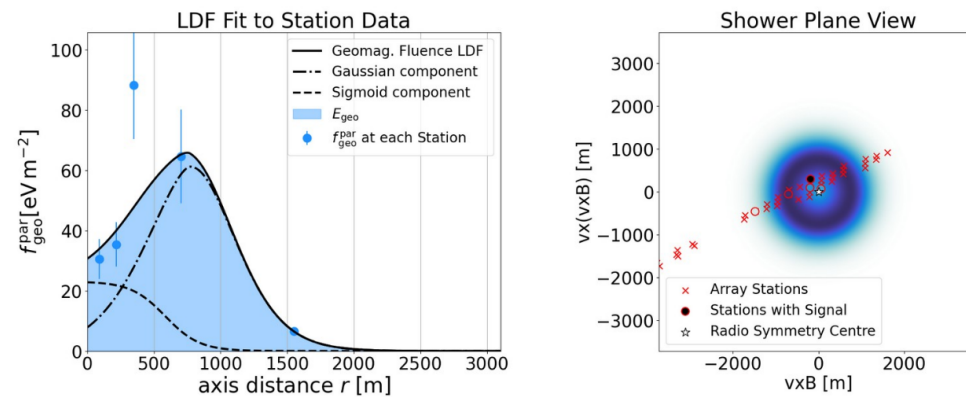
Impact of notch filters on LDF reconstruction

Results from Lukas

GP300 simulations unfiltered   Filtered at 39, 119, 133, 137 MHz
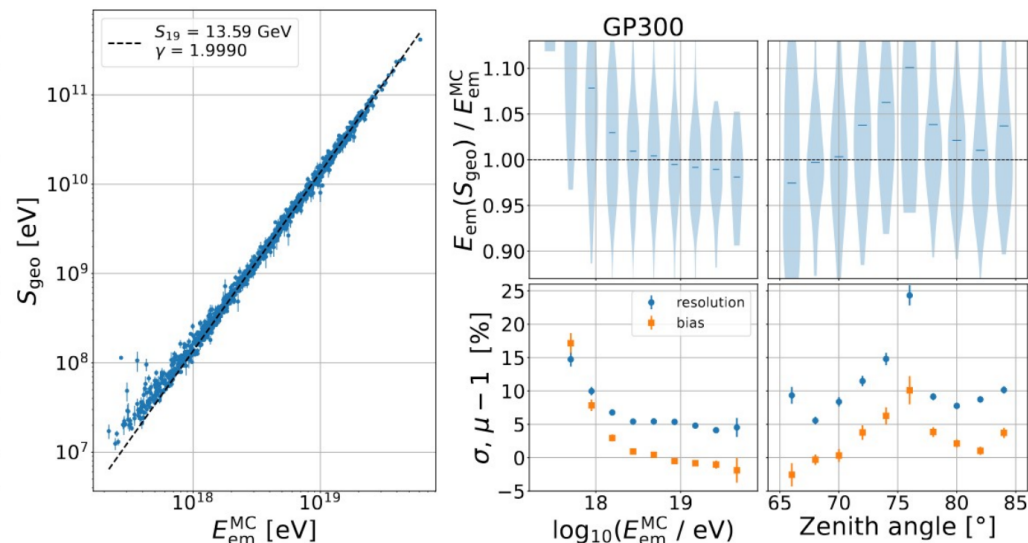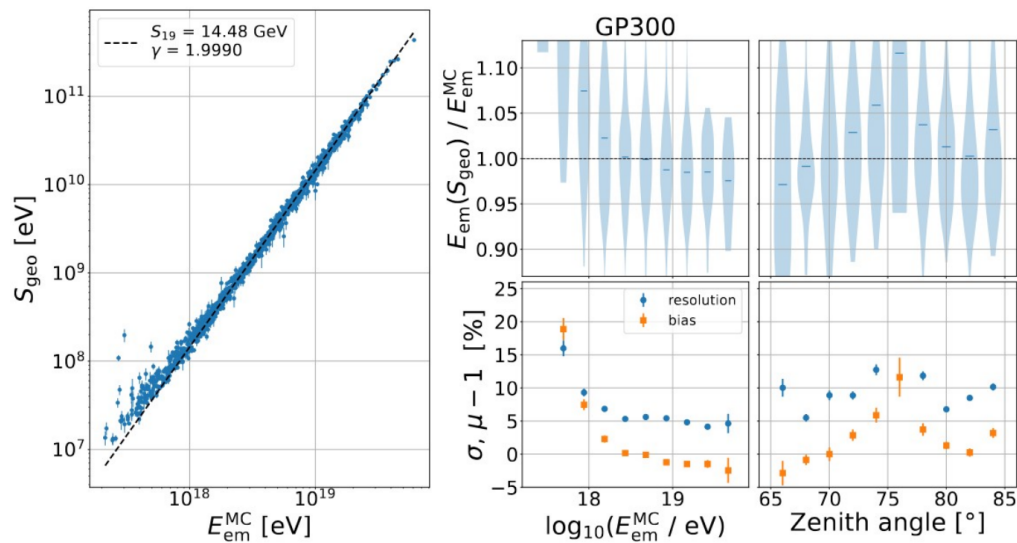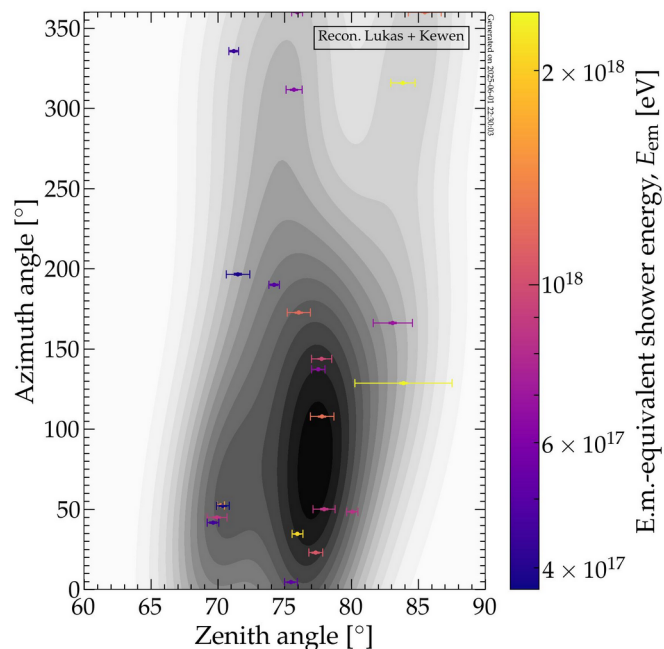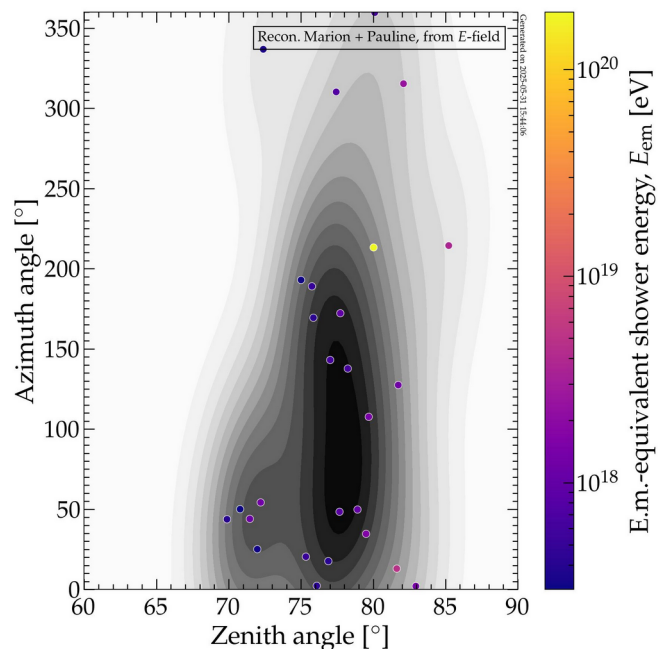
Joint 2D distributions

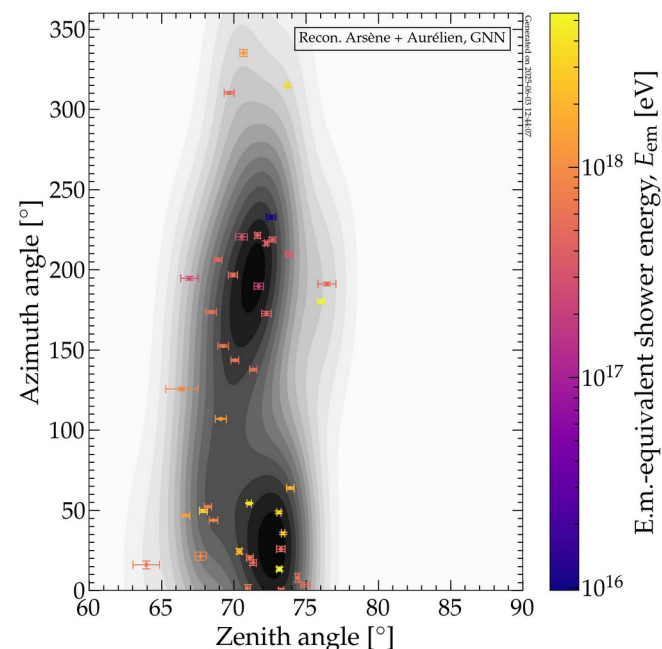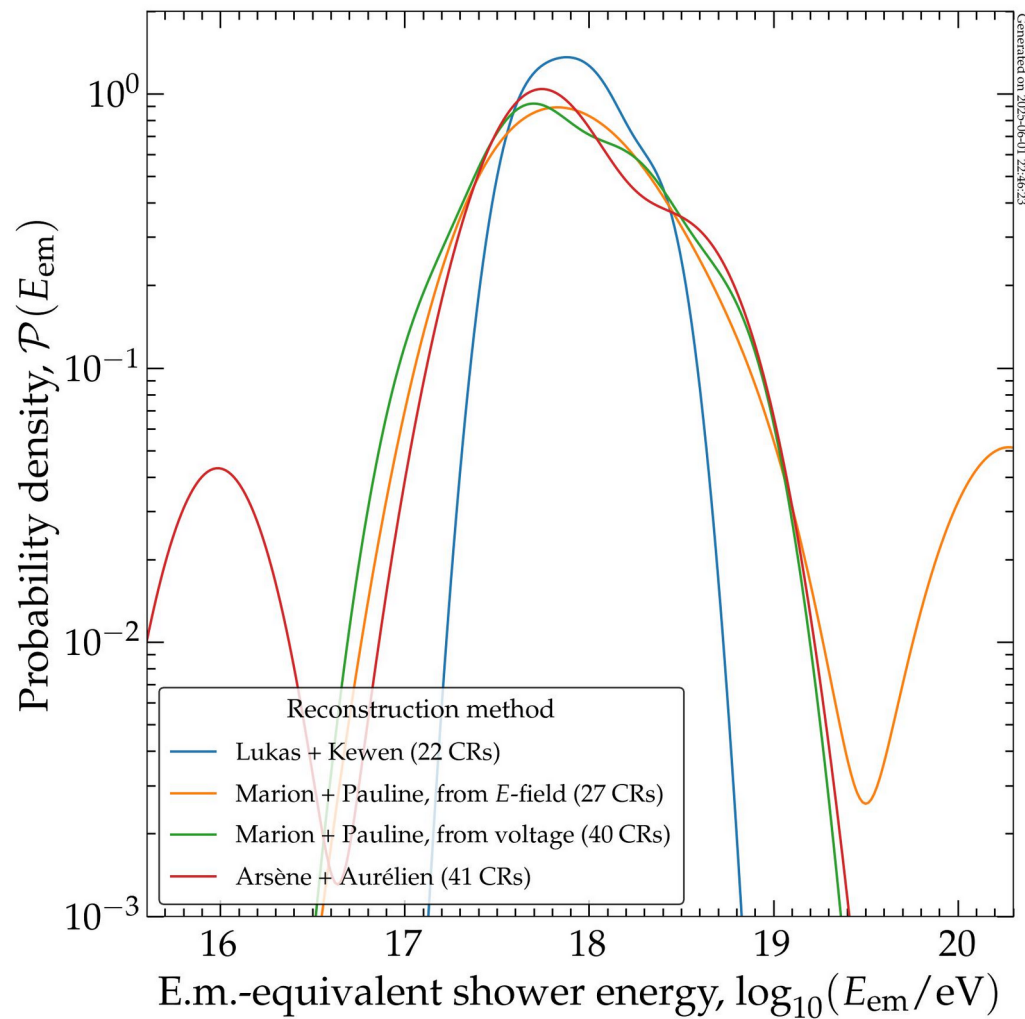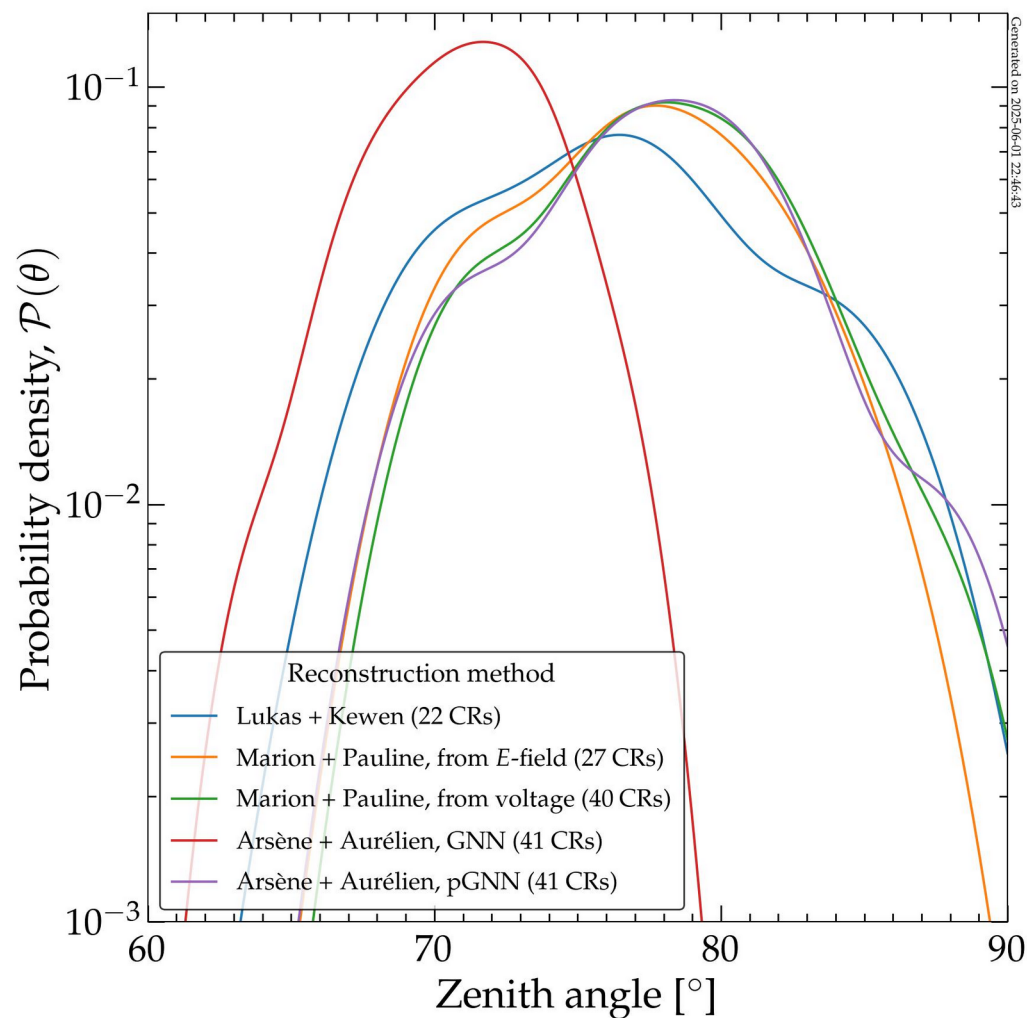*E.g.*, in azimuth *vs.* zenith, from different reconstruction methods:

Distributions produced using different reconstruction methods broadly agree
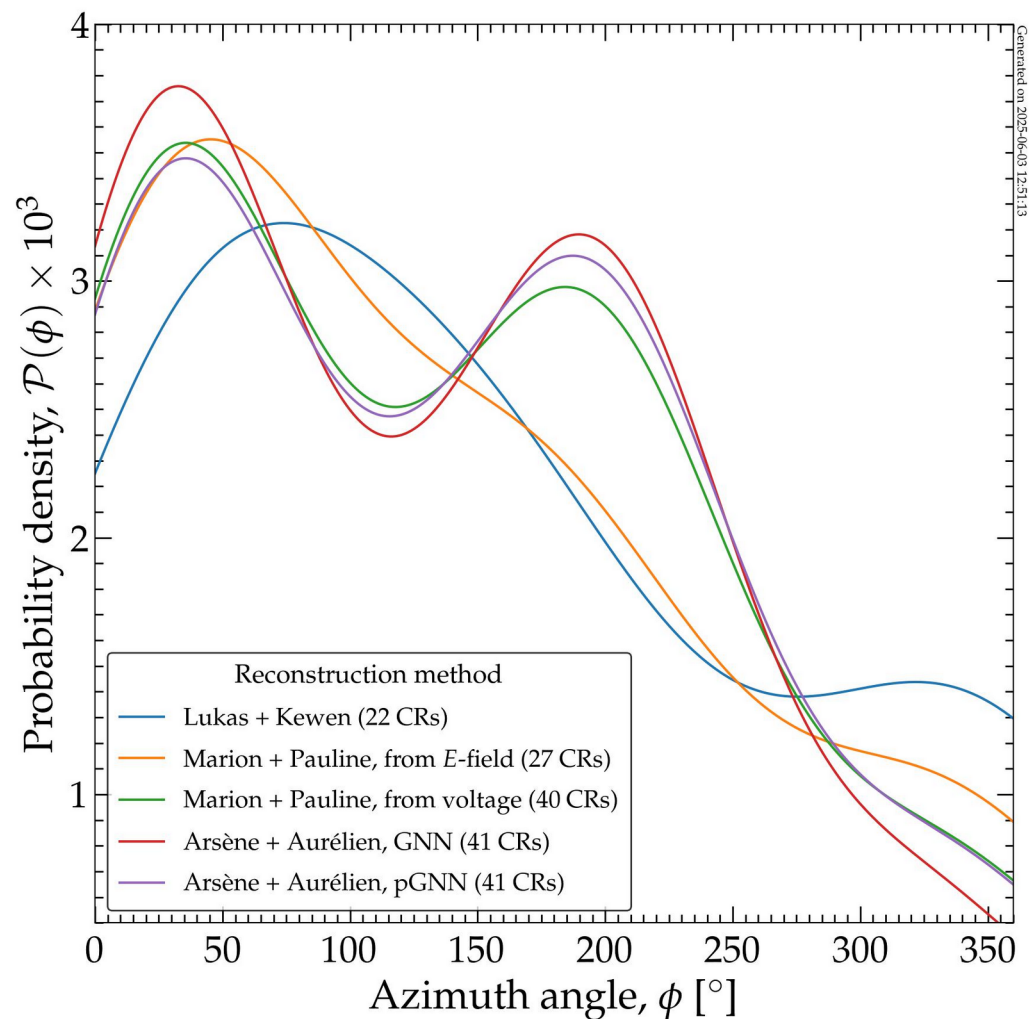
Many more 2D distributions available on Forge ([here](#))

1D distributions of reconstructed energy
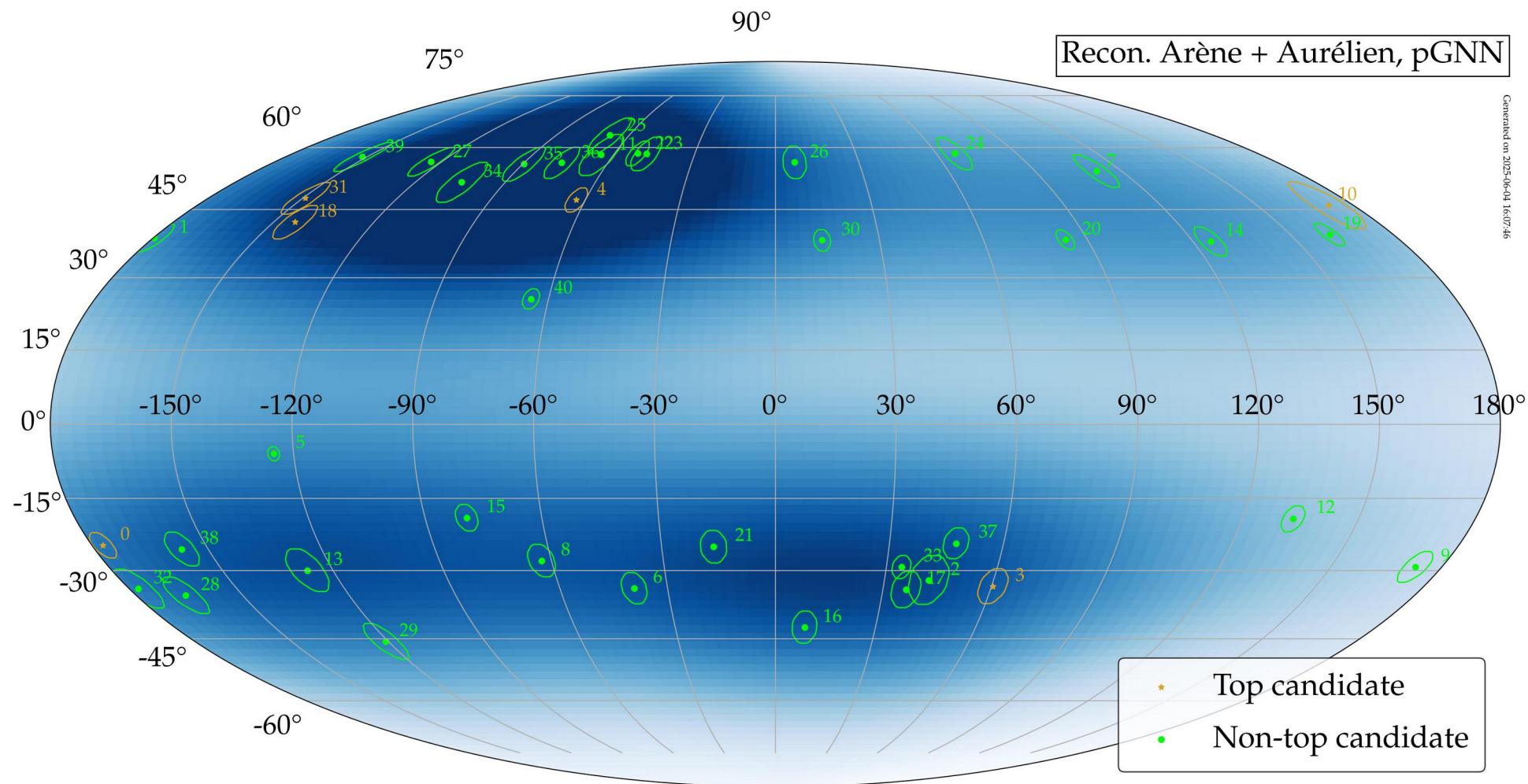
1D distributions of reconstructed zenith

1D distributions of reconstructed azimuth

First (<u>very</u>) preliminary CR skymap

Recon. Arène + Aurélien, pGNN

Generated on 2025-06-04 16:07:46

Top candidate
Non-top candidate

30

First (<u>very</u>) preliminary CR skymap

Recon. Arène + Aurélien, pGNN

Generated on 2025-06-04 16:07:46

Warning:
do *not* take this seriously until we improve our CR selection and reconstruction!

Do not show this plot outside the Collaboration

★ Top candidate

● Non-top candidate
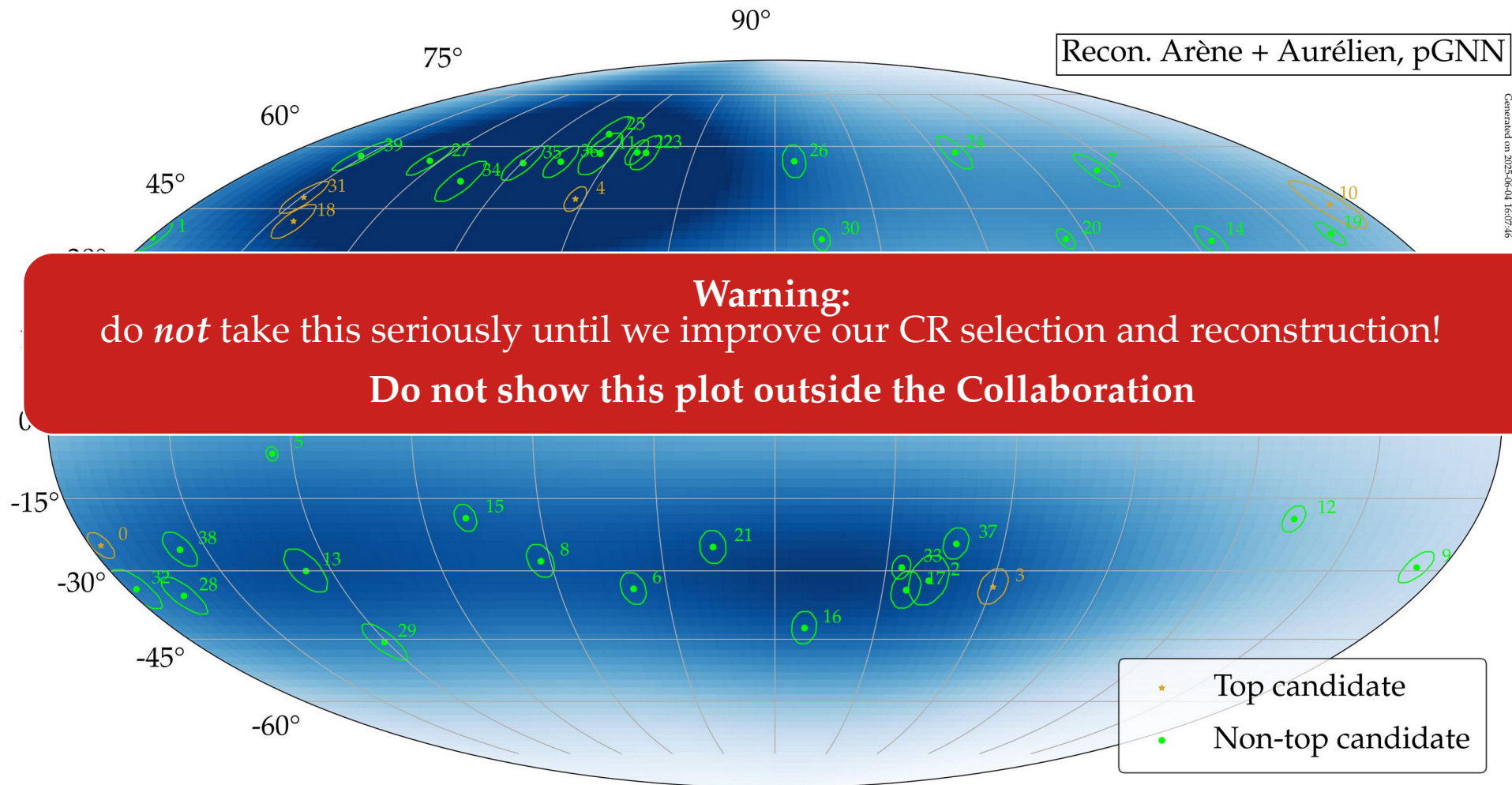
Additional items missing for the ICRC

▶ Understand if the errors in reconstructed energy and direction are accurate

▶ If a reconstruction method (*e.g.*, Marion + Pauline) does not currently output reconstruction errors, extend it (we cannot show data points without error bars)

▶ Decide what visuals we show on slides and proceeding

▶ Be ready to answer these questions:
  ▶ What is the statistical significance of candidate CRx being a real cosmic ray?
  ▶ How sure are we that we have identified all of our sources of background?
  ▶ How many cosmic rays do we expect to see in GP300? (Sei's work)

Future CR pipeline (post-ICRC)

Candidate selection and reconstruction

Critical:

▶ Develop a single, unified set of CR candidate selection criteria
▶ Merge the candidate selection and candidate reconstruction steps
▶ Use DCx simulations based on the real array layout (which can vary over time)
▶ Include information about active/inactive status of all DUs at any one time
▶ Use DCx with global trigger algorithm
▶ Include information about what firmware version was used in the DUs at any one time

Important:

▶ Stop relying on visual inspection of traces and footprints when selecting CR candidates
▶ Once mature, add the reconstruction methods to GRANDlib

To infer CR spectra, arrival distribution, mass composition

▶ Write methods to unfold from shower properties to cosmic-ray properties
(primary particle energy, direction, *etc.*)
▶ Have a fully characterized irreducible background (*i.e.*, noise that survives the cuts)