Arrival Directions of Ultra-High-Energy Cosmic Rays in TA FD

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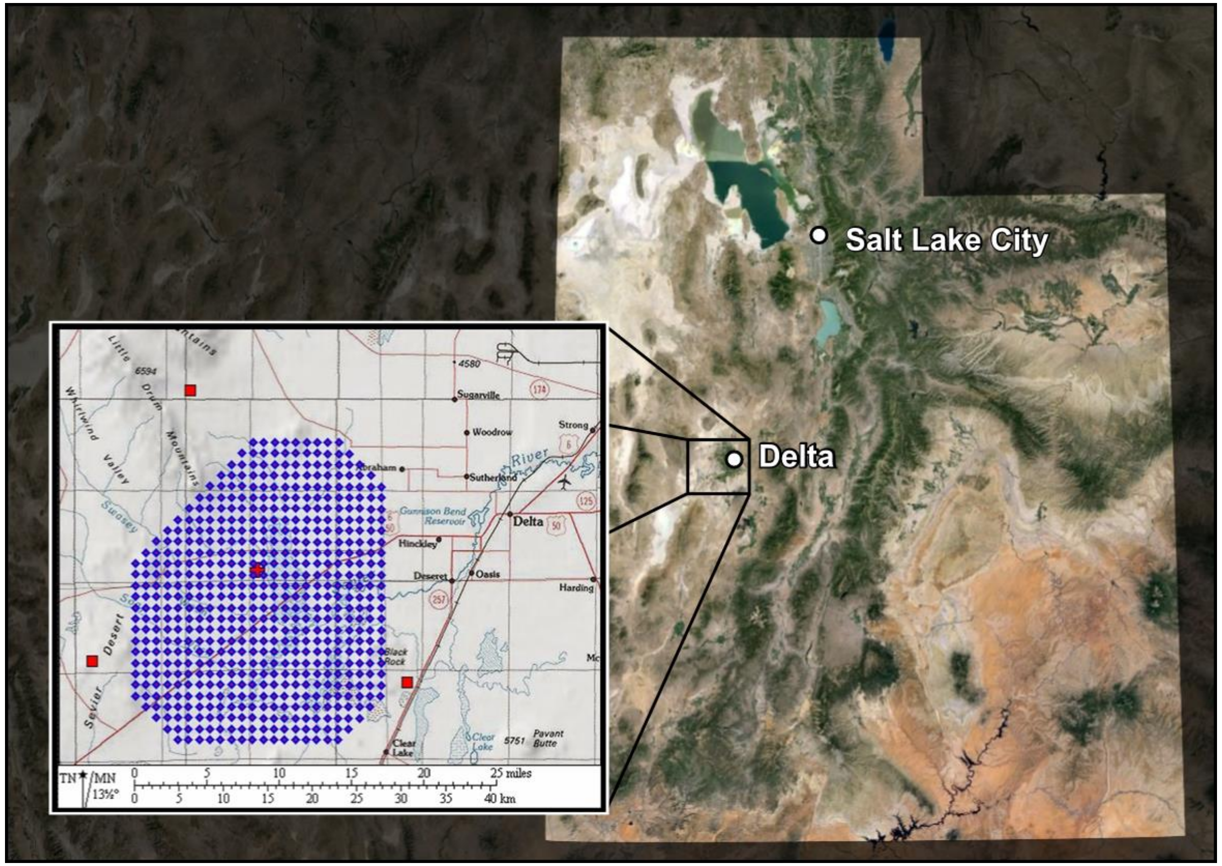
Telescope Array experiment

The Telescope Array (TA) observatory is a hybrid detector system consisting of both an array of 507 scintillation surface detectors (SDs) and 3 **fluorescence detectors (FDs)**.



Credit: Telescope Array collaboration

How a fluorescence detector 'sees' an EAS

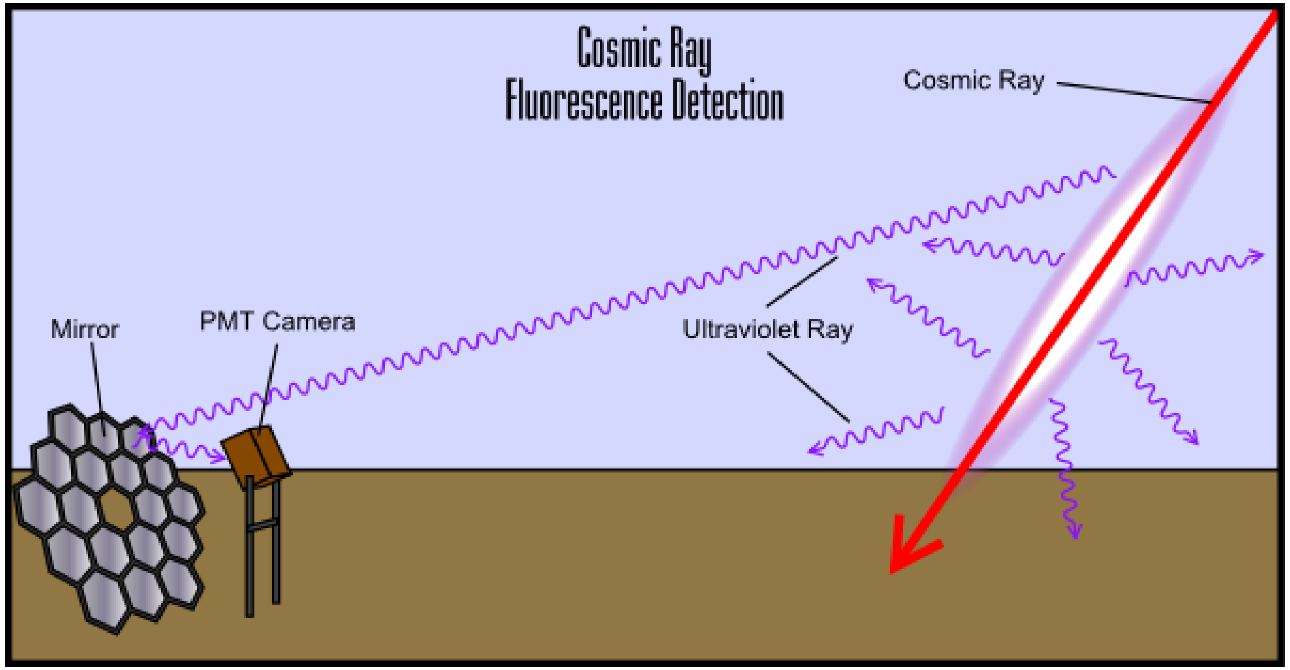


Fig. 1. Fluorescence light from the EAS is collected by the mirror and focused onto the PMT camera.

Credit: Telescope Array collaboration

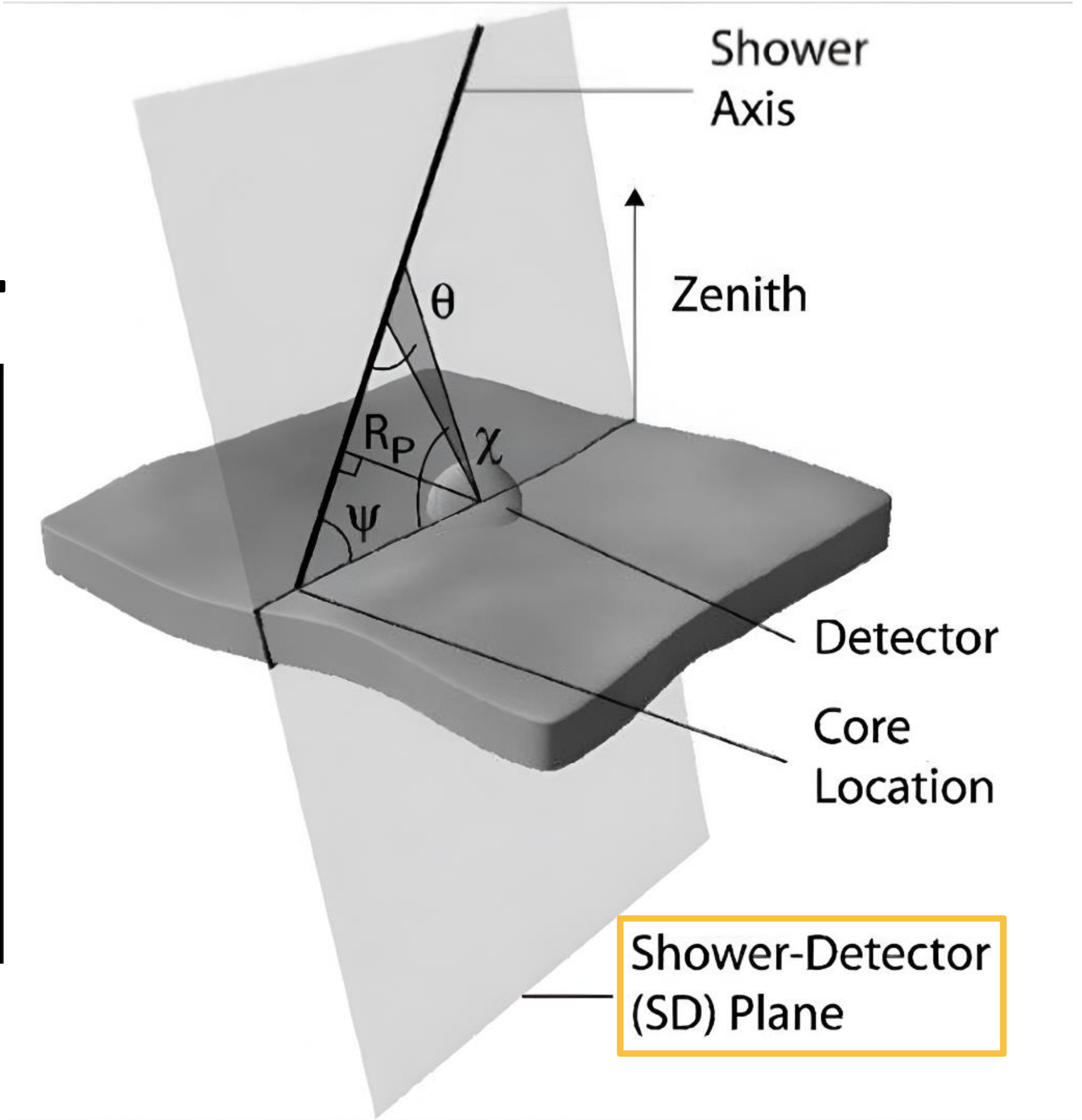


Fig. 2. Shower−Detector Plane (SDP) contains the detector and the shower axis.

Goal & Key Clarification

- **Primary Goal**: Enhance the angular resolution associated with **the normal to the Shower-Detector Plane (SDP)**.
- **Critical Distinction**: This work focuses **NOT** on **the detector's angular resolution for cosmic ray arrival directions in mono-mode**, but rather on the resolution of the SDP's orientation itself — a fundamental parameter for shower geometry reconstruction in stereo-mode.

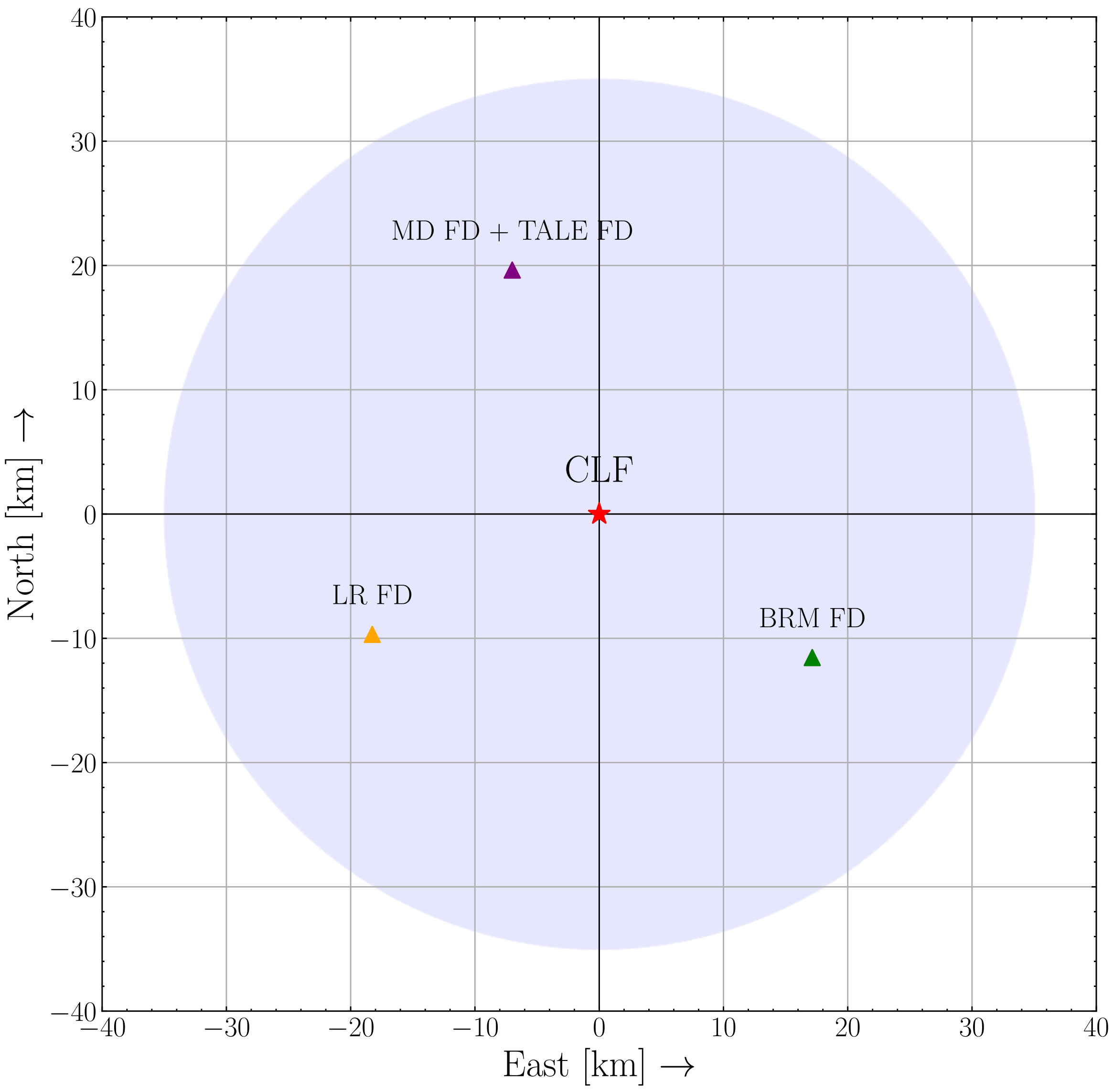


Fig. 3. Core location distribution of Monte Carlo showers. Uniform distribution within the circle of 35 km radius from the CLF location.

Monte Carlo Simulation

The analysis was performed on ***protons*** generated by $\boldsymbol{CORSIKA-77550}$ with $\boldsymbol{QGSJet\ II-04}$ with the following parameters:

$\mathbf{18.5 < \log_{10} E_0 < 20.0}$

Slope of the primary energy spectrum in CORSIKA: $\mathbf{-1.0}$

Slope of the primary energy spectrum after reweighting: $\mathbf{-2.7}$

Zenith angle of the shower axis: $[\mathbf{0.0°}; \mathbf{65.0°}]$

Azimuthal angle of the shower axis: $[\mathbf{-180.0°}; \mathbf{180.0°}]$

Core position: uniform distribution within the circle of **35 km radius** from the CLF location

Detector: ***LR*** (monocular mode)

EAS Reconstruction Code: $\boldsymbol{TA\ Java\ 2023}$ (TA collaboration) simulates detector response and reconstructs shower parameters

$\boldsymbol{TA\ Java}$ output: **27** geometric and shower profile parameters

Number of reconstructed events before quality cuts: $\mathbf{242374}$

Quality Cuts

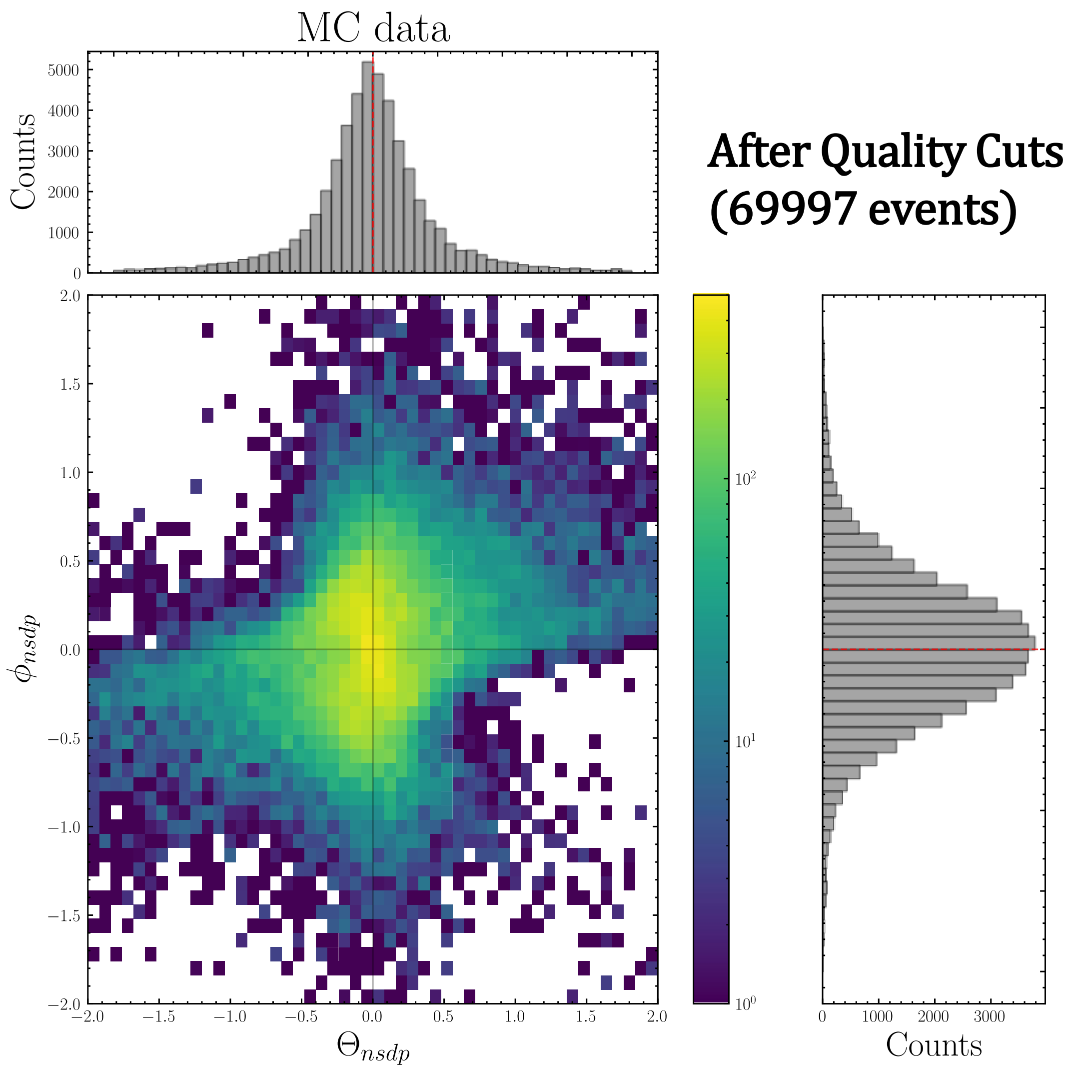


Fig. 4. Accuracy of the initial SDP normal reconstruction. $(\theta_{nsdp}, \phi_{nsdp})$ – the differences between the reconstructed coordinates of the normal **before our improvement** and the true (Monte Carlo) values. Based on **69997 quality-passed** events.

Quality Cuts	events	f (%)
Reconstructed events	86234	—
Number of PMTs > 10	85891	99.6
Track length > 10°	85738	99.8
Time extent > 2 μs	85452	99.7
R_p > 0.5 km	83771	98.0
Minimum viewing angle > 20°	68560	81.8
Ψ angle < 120°	66504	97.0
Geometrical χ^2/ndf < 10	56247	84.6
$X_{\max}$ inside FOV	30179	53.7
Zenith angle < 55°	28959	96.0
Core distance from CLF < 25 km	28932	99.9
Energy > $10^{17.2}$ eV	28269	97.7
Total retention fraction	—	37.8

Table 1: Summary of the quality cuts. The number of events passing each successive selection criterion is described, together with the corresponding retention fraction f of hitherto-passing events.

The **quality cuts** were taken from arXiv:1511.07510v3 (p. 9, table 1)

Number of events after quality cuts: **69997**

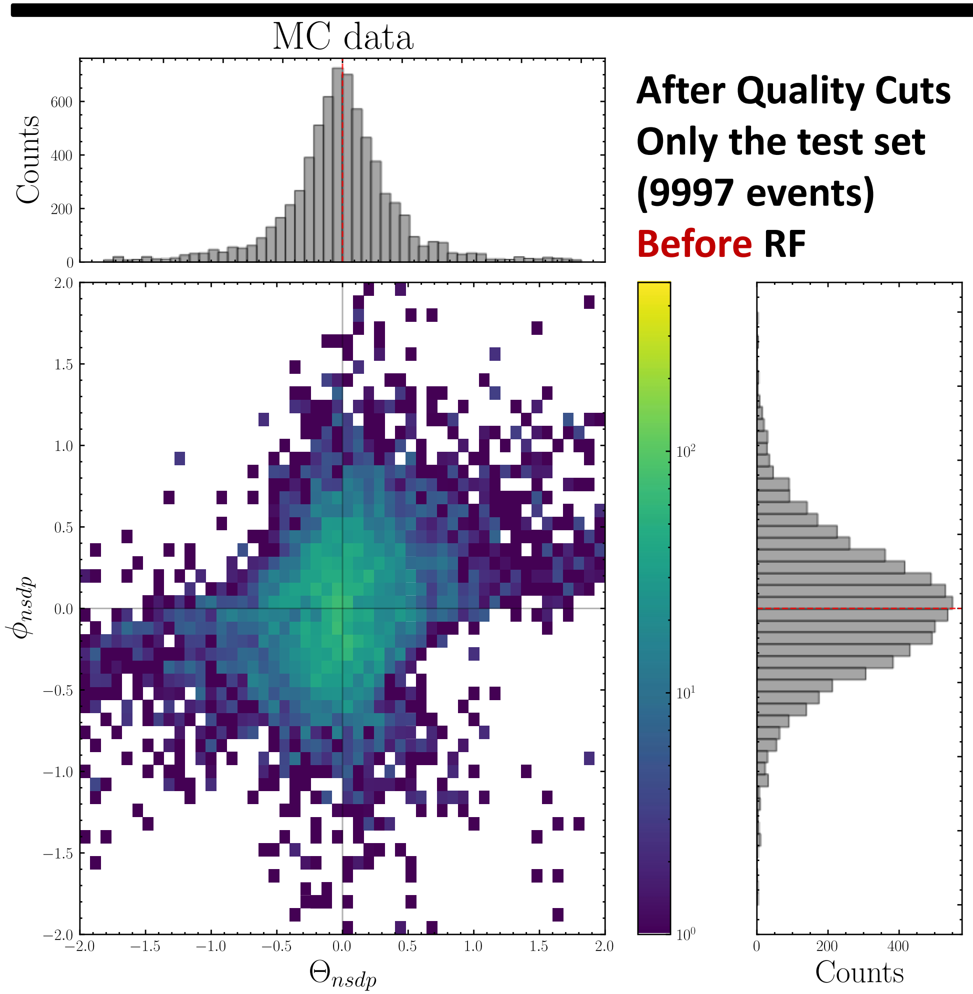
Methods Used in the Analysis

- For our task, the **RandomForestRegressor** model from the **scikit-learn** library (Python) was used within the **MultiOutputRegressor** wrapper.

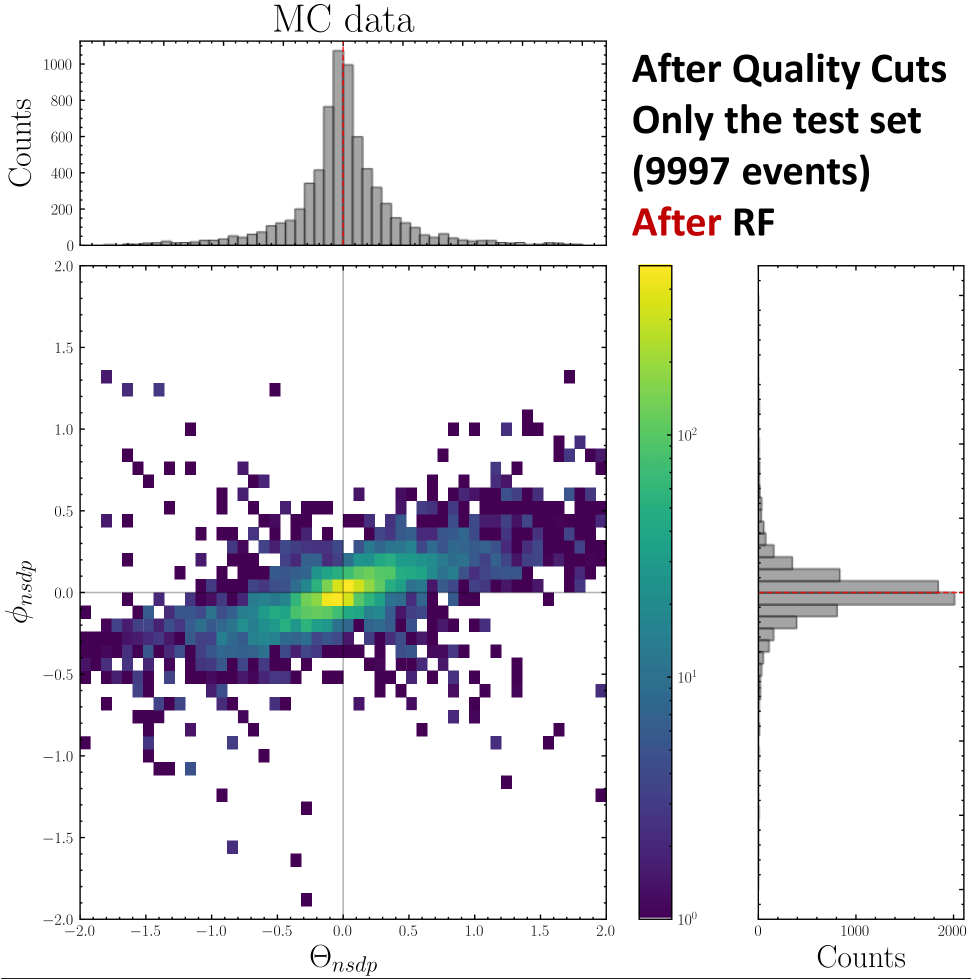
- The model was trained on **the output of the TA Java 2023 program that passed the mentioned quality cuts**.

- The model was trained to predict **the difference between the true and reconstructed normal to the SDP**, scaled by a factor of 10^6 to prevent rounding errors.

Results



After Quality Cuts
Only the test set
(9997 events)
Before RF



After Quality Cuts
Only the test set
(9997 events)
After RF

Fig. 5. Accuracy of the initial SDP normal reconstruction. $(\theta_{nsdp}, \phi_{nsdp})$ – the differences between the reconstructed coordinates of the normal **before our improvement (RF)** and the true values.
Based on **9997 quality-passed test** events.

Fig. 6. Accuracy of the final SDP normal reconstruction. $(\theta_{nsdp}, \phi_{nsdp})$ – the differences between the reconstructed coordinates of the normal **after our improvement (RF)** and the true values.
Based on **9997 quality-passed test** events.

Results

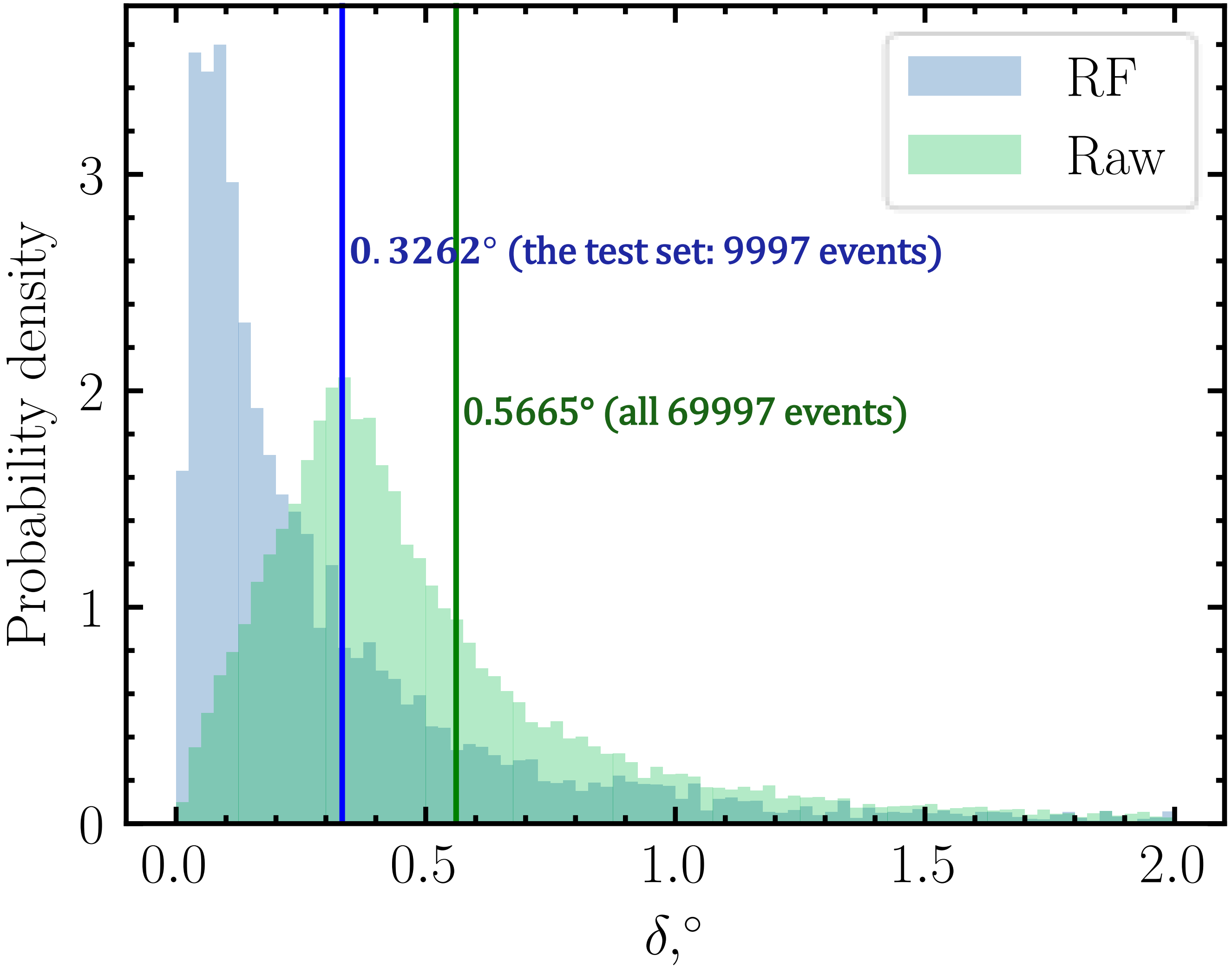


Fig. 7. Distribution of the angular error $\boldsymbol{\delta}$ for the $\boldsymbol{n_{SDP}}$. Comparison of the reconstruction accuracy before (Raw) and after (RF) applying the Random Forest method.

- δ – the angular distance between the true and the reconstructed n_{SDP}
- $\sigma_{68} = \mathbf{0.5665°}$ before RF

  $\sigma_{68} = \mathbf{0.3262°}$ after RF

Interestingly, $\boldsymbol{\Delta MAE}$ of the azimuthal angle of the n_{SDP} $(\phi_{nsdp}) \approx \mathbf{1.0°} - \mathbf{1.3°}$.

However, $\boldsymbol{\Delta MAE}$ of the zenith angle of the n_{SDP} $(\theta_{nsdp}) \lesssim \mathbf{0.1°}$.

ΔMAE – reduction in the mean absolute error after applying the RF.

Results

Raw (all 69997 events)

RF (the test set: 9997 events)

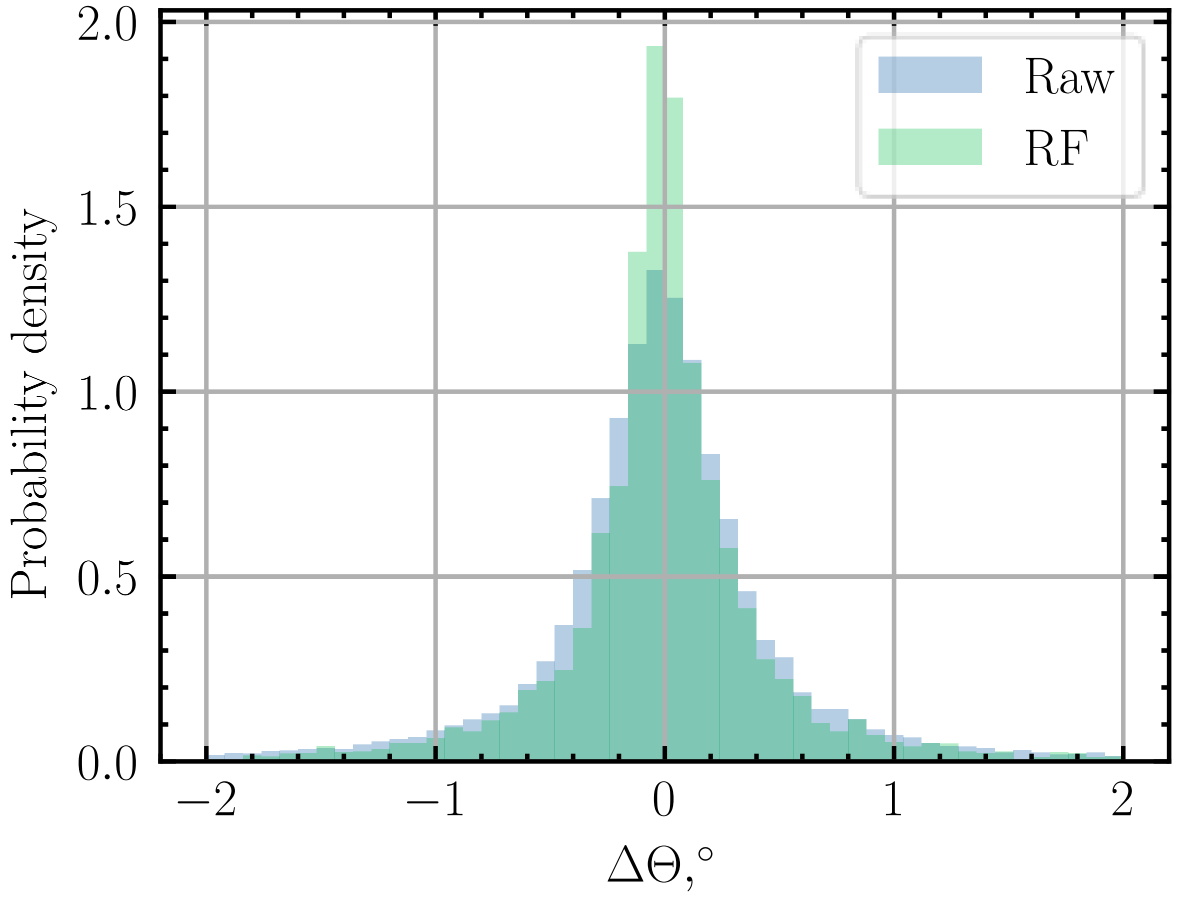


Fig. 8. Distribution of the n_{SDP} zenith angle error, $\Delta\theta$. Comparison of the reconstruction accuracy before (Raw) and after (RF) applying the Random Forest method.

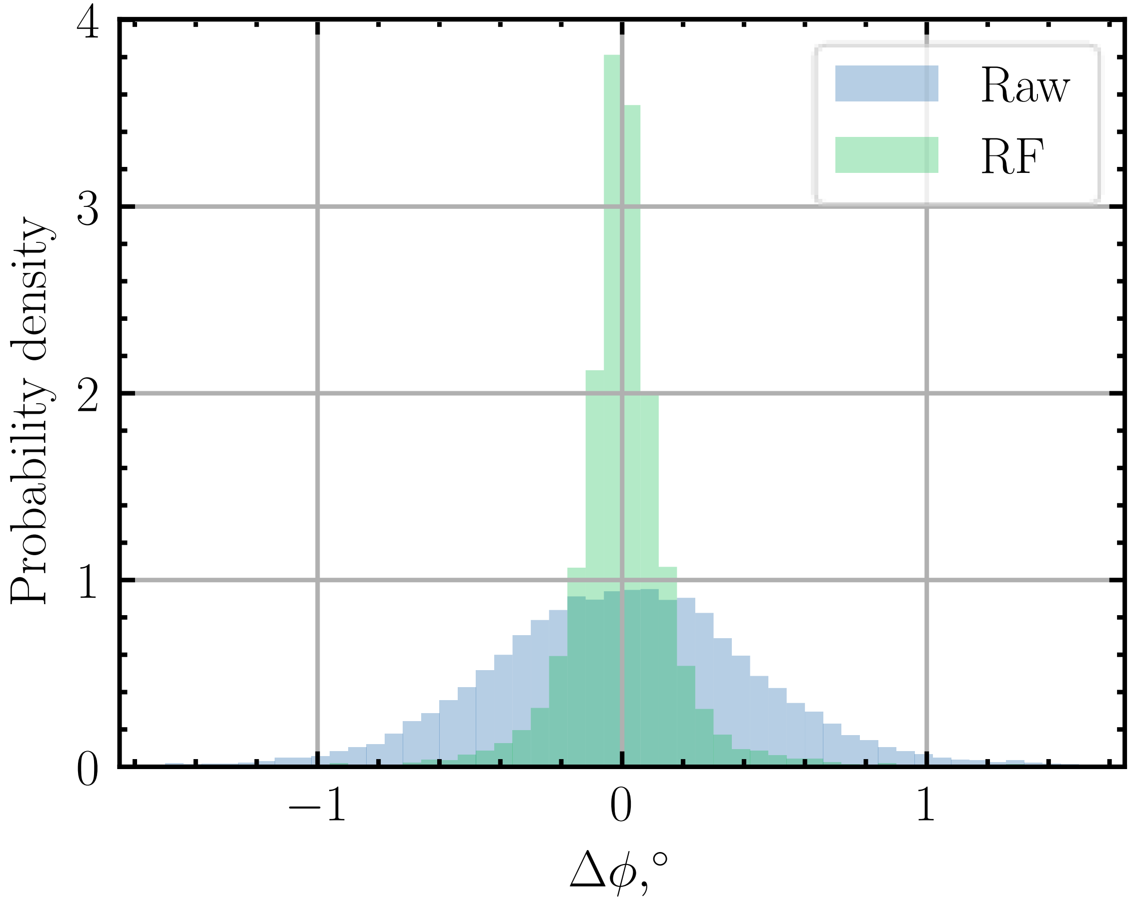


Fig. 9. Distribution of the n_{SDP} azimuthal angle error, $\Delta\phi$. Comparison of the reconstruction accuracy before (Raw) and after (RF) applying the Random Forest method.

Further Steps and Motivation

- To extend this approach to stereo-mode observations to enable a more accurate analysis of the anisotropy of cosmic rays.
- To achieve the HiRes experiment’s 0.6° angular resolution in stereo mode, enabling more precise studies of the anisotropy of cosmic rays.
- To test correlations between cosmic ray arrival directions and BL Lacertae objects using this improved directional accuracy with FDs in addition to the studies with surface detectors.

Thank you for your attention!

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