Angle reconstruction for Cosmic Rays at CONDOR Observatory

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I. Introduction

• The COmpact Network of Detectors with Orbital Range (CONDOR) Observatory is the highest cosmic ray detector array in the world. Designed to operate at an altitude of 5300 m a.s.l., CONDOR uniquely targets cosmic rays with energies starting at ∼100 GeV.

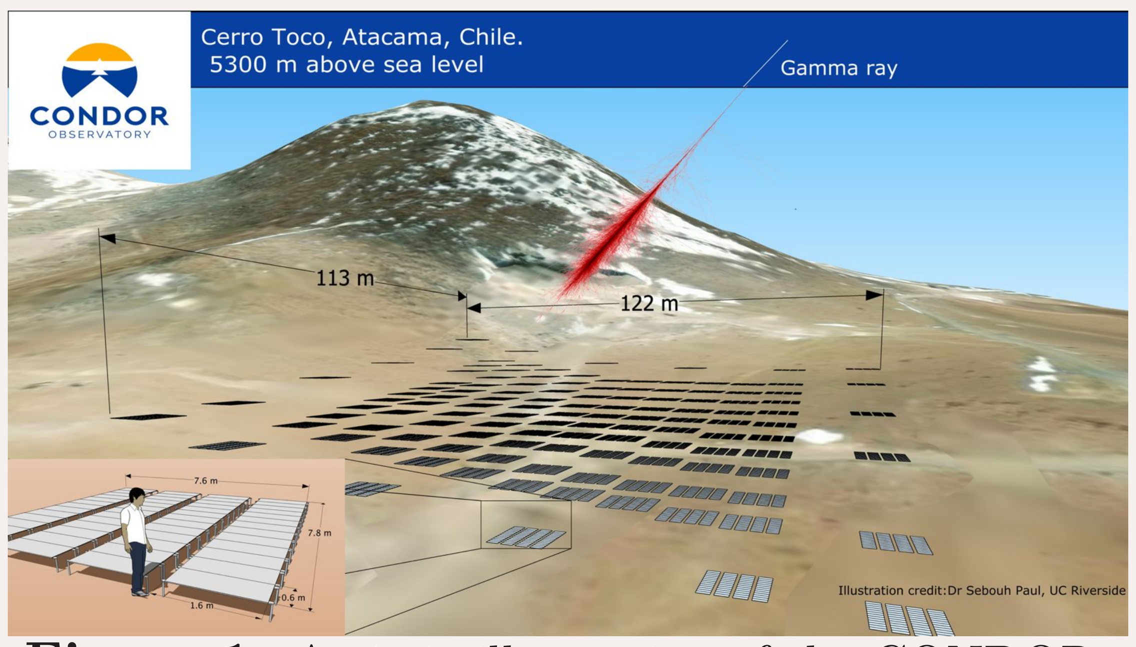


Figure 1: Artistic illustration of the CONDOR. Image source: [1].

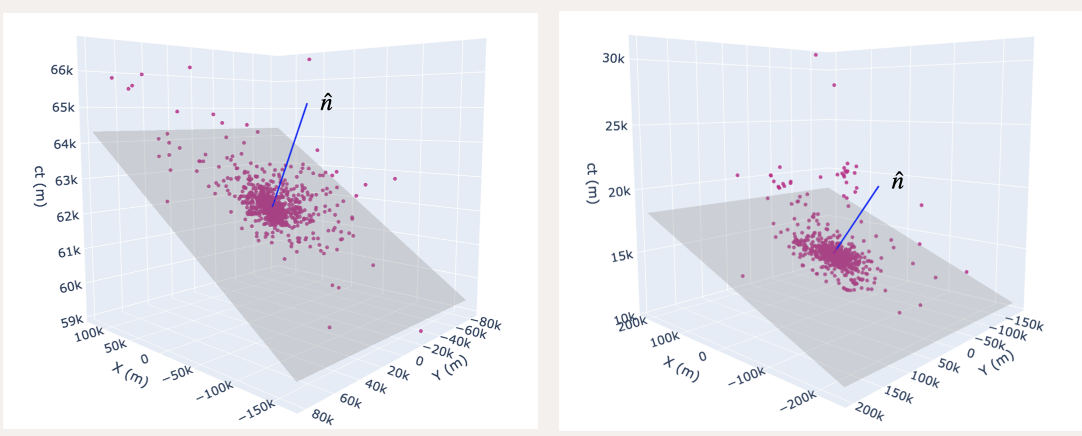
• This work presents simulation-based results on the reconstruction of cosmic ray angles using CORSIKA (COsmic Ray SImulations for KAscade) [2]. These findings demonstrate CONDOR's effectiveness in tracking particles at high altitudes and probing unexplored energy ranges.

II. Cosmic Ray (CR) Simulation

• Reconstructing CR angles helps trace their atmospheric trajectories, revealing origins like active galactic nuclei or supernovae.

• CORSIKA simulations used EPOS for high-energy and GEISHA for low-energy models, focusing on photons and protons with energies from 20–800 GeV and zenith angles from 0° to 60°.

• The Panama library [3] processed CORSIKA outputs, with axes representing spatial positions x, y (m) and particle arrival times t scaled by c (m/ns), is used as shown in Figure 2:



a) b)

Figure 2: Shower distribution in the coordinate system used for the simulation. a) Photon as CR, b) Proton as CR. Both with 150 GeV with Zenith angle equal to 45°. A planar fit (in grey) to the shower plane and its normal vector in blue line are shown.

VI. References

[1] Cóndor Observatory. Official website of the cóndor observatory. https://condorobservatory.ucr.edu/.

[2] CORSIKA Collaboration. Corsika: A monte carlo code to simulate extensive air showers. *Computer Physics Communications*, 100(3):271–282, 1998.

[3] Ludwig Neste. Panama 1.0.2 documentation. https://panama.readthedocs.io/en/latest/index.html, 2023, 2024.

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III. CR Zenith Angle Reconstruction

To determine the zenith angle of the simulated shower, a plane fit was applied to the particles arriving at the detector. The vector normal to the fitted plane was calculated starting from the centroid of the particle distribution, representing the central ray of the hadronic cascade. The zenith angle corresponds to the angle formed between the normal of the shower and the z-axis, calculated using the following formula:

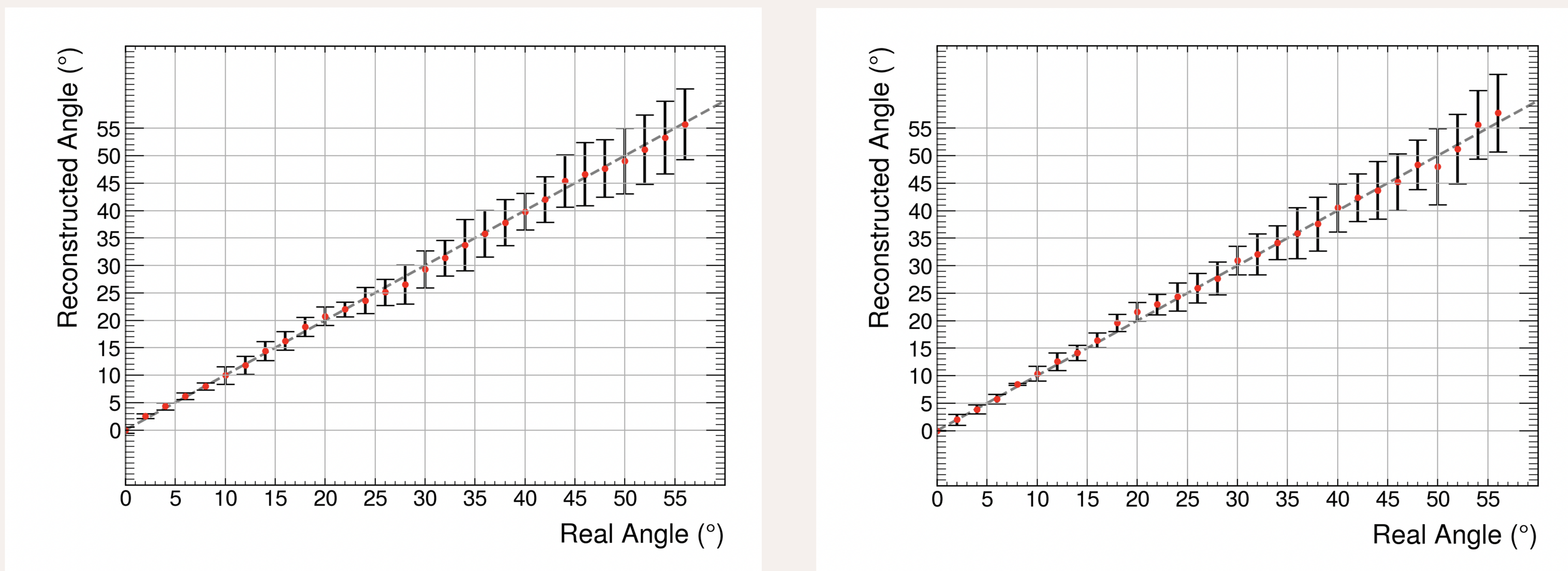
$$\theta = \arccos\left(\frac{\vec{n}\cdot\hat{z}}{|\vec{n}||\hat{z}|}\right)$$

where $\vec{n}$ is the normal vector to the fitted plane and $\hat{z}$ is the unit vector in the z-direction. This calculation allows us to determine the angle between the vertical axis and the central ray of the cascade.
The zenith angle values were obtained for three different regions of the detector:

1. Using the full detector.
2. Using only the central detector.
3. Defining regions around the central detector.

Finally, the definitive zenith angle is selected as the one with the lowest χ^2 value, ensuring the best fit for the direction of the central ray relative to the detector as shown in Figure 2.

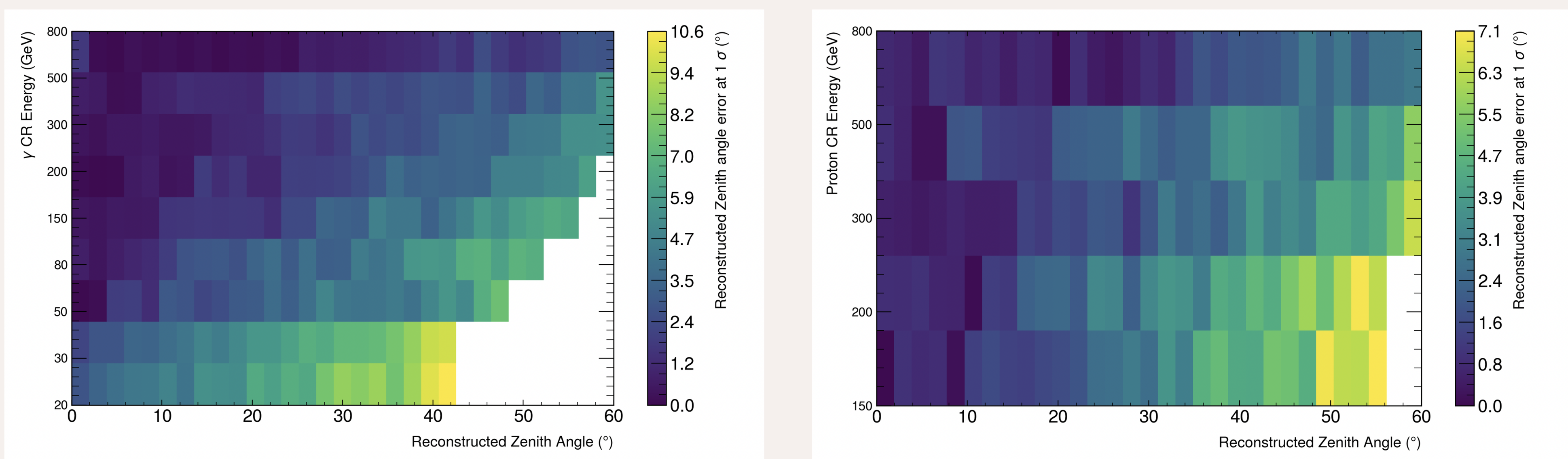
IV. Predictions and Results



a) b)

Figure 3: Comparison between reconstructed angles and true angles: (a) Photon as CR at 150 GeV (b) Proton as CR at 150 GeV.

As shown in Figure 3, the reconstructed angles for Photons and proton as CR induced showers exhibit an approximately linear correlation with the true angle. However, error bars increase with zenith angle, as CRs traversing larger atmospheric path lengths experience greater attenuation. This leads to fewer detected particles at higher inclinations, making precise reconstruction more challenging.



a) b)

Figure 4: Heat map of angular reconstruction errors as a function of true zenith angle and primary particle energy: (a) Photon as CR (B) Proton as CR.

Applying this method across a broad energy range (20 to 800 GeV for both gamma and proton CRs), we observe that reconstruction errors increase at lower energies. This is due to lower-energy cosmic rays producing fewer secondary particles, which affects the statistical precision of the planar fit and ultimately increases angular uncertainty, as shown in Figure 4.
These results demonstrate the robustness of the multiple planar fit approach for zenith angle reconstruction and underscore the dependence of reconstruction accuracy on both energy and CR primary type.

V. Conclusions and Future Work

• Reconstruction errors in the zenith angle increase at lower cosmic ray energies due to fewer detected particles.

• Higher incidence angles amplify attenuation and reconstruction errors as cosmic rays traverse more atmosphere.

• Future work includes improving low-energy CR reconstruction, enhancing atmospheric modeling, and utilizing machine learning for better detection accuracy.