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Muon Ring Fitting Algorithms For the Cherenkov Telescope Array

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Introduction

When Very High Energy gamma rays and charged particles interact with the atmosphere, they produce cascades of subatomic particles, known as **Extensive air showers (EAS)**. In air, very-high energy particles can travel faster than light, creating a cone of blue **Cherenkov light**. **Cherenkov Telescopes** capture the light events.

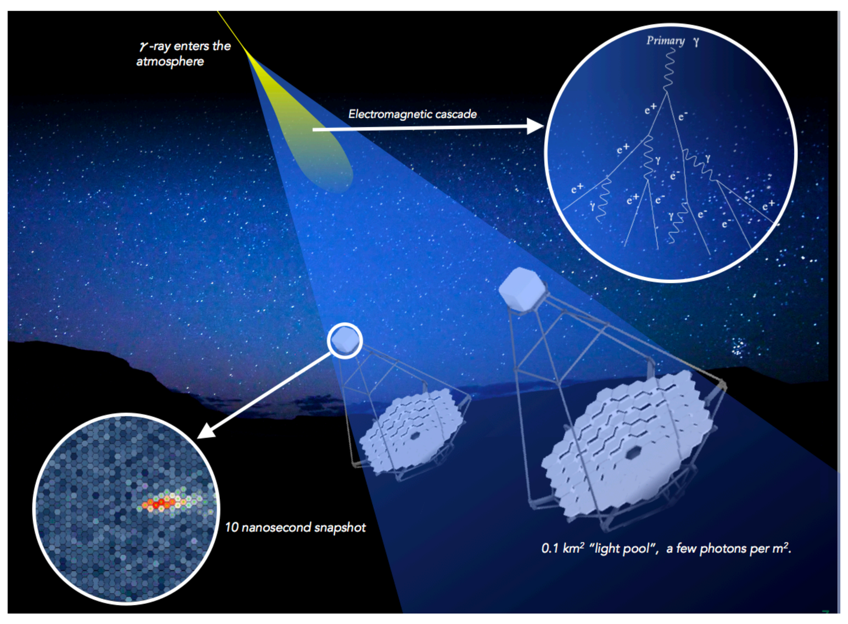
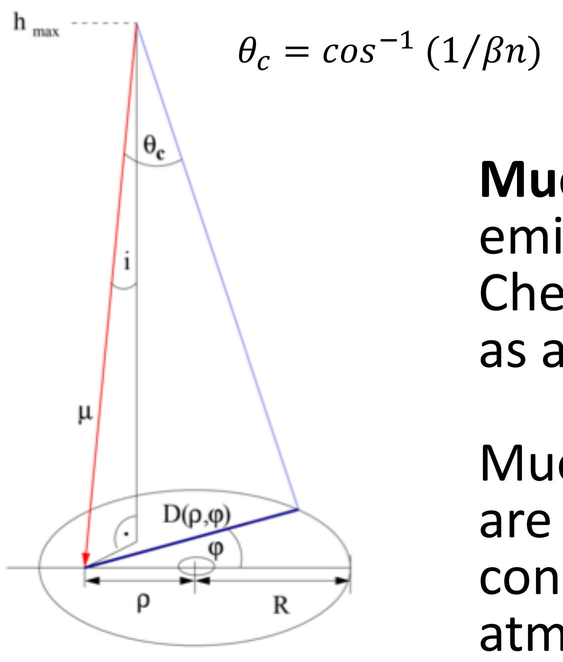


Fig.1 Cherenkov Telescope Array detects Cherenkov light with the mirror and camera



[1]

Muons are generated by the air showers. They emit a light in a cone with opening angle θ_c, the Cherenkov angle. As a result, the muons appear as a **ring image**.

Muons are suitable for calibration because they are easily identifiable, freely available, and constantly bright through the path in both atmosphere and the telescope optical system.

Fig.2 Geometry of muon falling inside the mirror with a radius R, showing a muon with a trajectory with inclination i, with Cherenkov angle θ_c. Impact parameter ρ shows the distance between the point of impact and the center of the mirror

Muon Ring Fitting Algorithms

Muon images on camera are identified with a ring fitting algorithm, which calculates the components of muon ring.

Examples

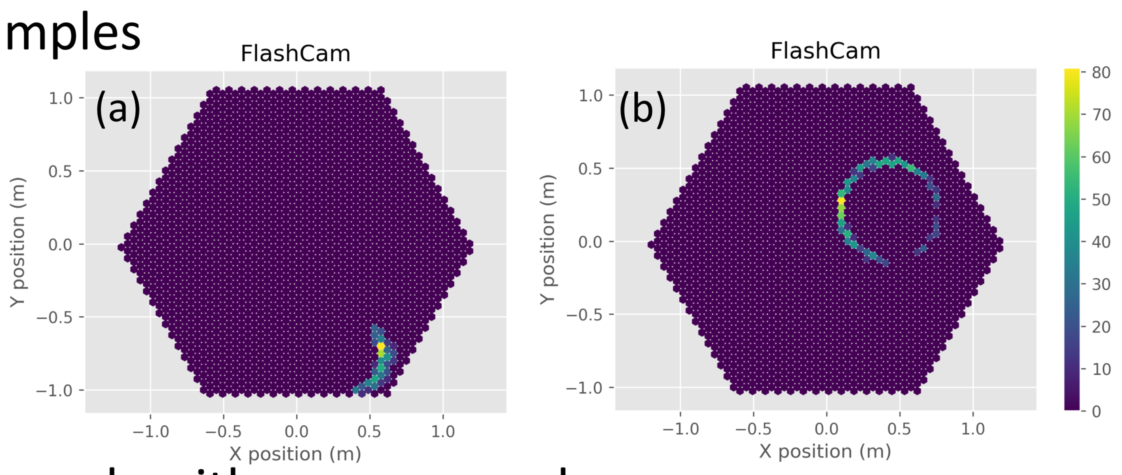


Fig.3 Simulated muon images on MST FlashCam with ring-like images (a) partial and (b) full ring

Three algorithms compared:

- **Chaudhuri Kundu Fit:** finds a solution to an analytical expression for a circle of the pixel charges and locations [2]
- **Taubin Fit:** minimizes the squared distances from all the points to the circle

$$\mathcal{F}_T = \frac{\sum_i^n [(x_i - a)^2 + (y_i - b)^2 - R^2]^2}{4n^{-1} \sum_i^n [(x_i - a)^2 + (y_i - b)^2]}$$ [3]

- **Hough Fit:** finds a circle with best contribution by looping over possible values for the circle in 3D parameter spaces [4]

Testing Performance

Three fits on Image

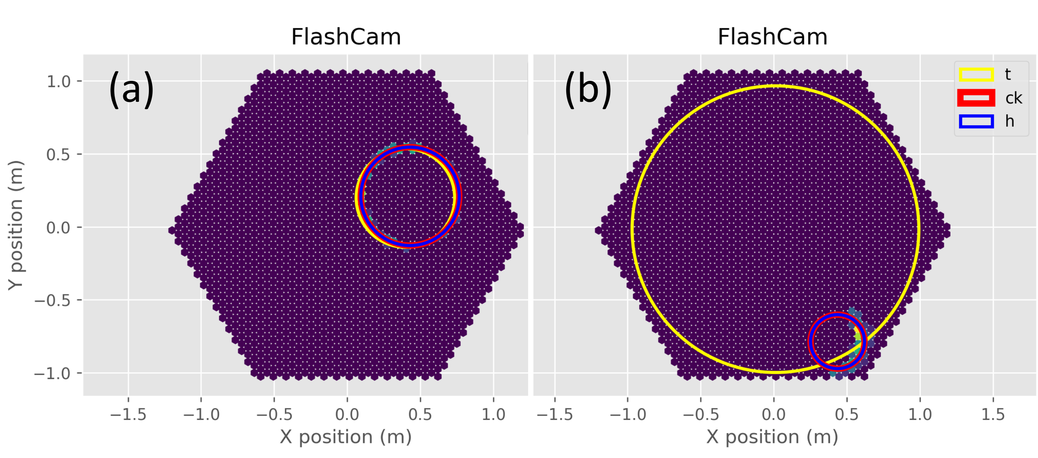


Fig.4 Three ring fits (Chaudhuri-Kundu = red, Taubin = yellow, Hough = blue) on FlashCam images in which (a) all three fit well similarly and (b)Taubin fit fails while the others have similar parameters

Comparing the three fits described above, **Taubin fit** does not perform as well, failing to find the ring when the images are at the edge of the camera with small partial ring as Figure 4 shows.

Comparing three fits

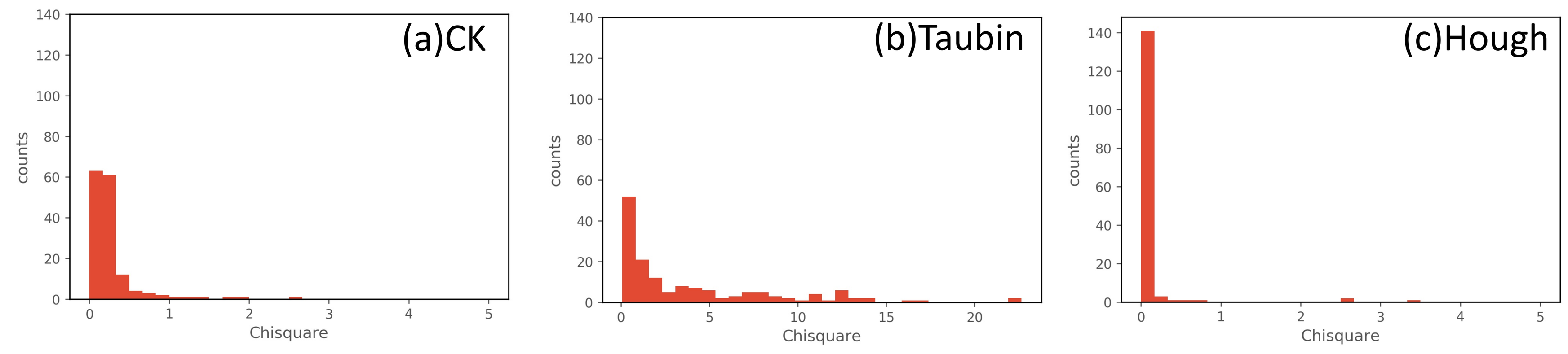


Fig.5 Histograms of Chi-squares in each fitting algorithms

Taubin fit's chi-squares are significantly larger and spread. The greater chi-squares come from the failed circle fit produced with large radius.

Pixel number: total number of pixels after cleaning with a mask
Pixel charge: sum of charge after cleaning with a mask
Average distance: distance of pixels from the camera center after cleaning

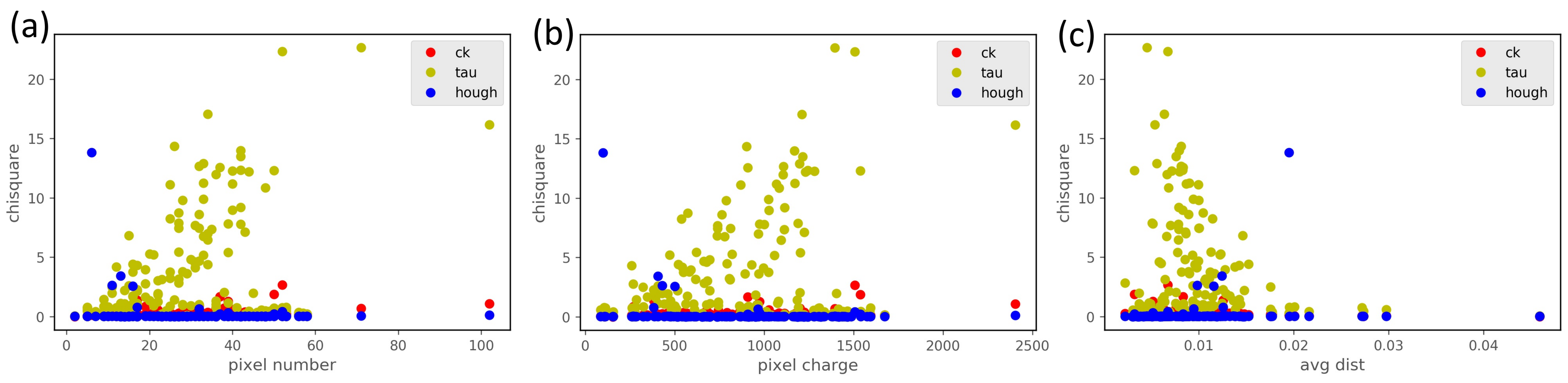


Fig.6 Comparisons of chi-squares among the three fitting algorithms in terms of (a) pixel number, (b) pixel charges, and (c) average distance

Hough fit and Chaudhuri Kundu fit

Larger chi-squares from Hough fit are due to small pixel number and charge. Larger chi-squares from Chaudhuri Kundu fit are more spread in these plots that does not show any pattern. Overall, Chaudhuri-Kundu fit have larger and more spread chi-squares than Hough fit.

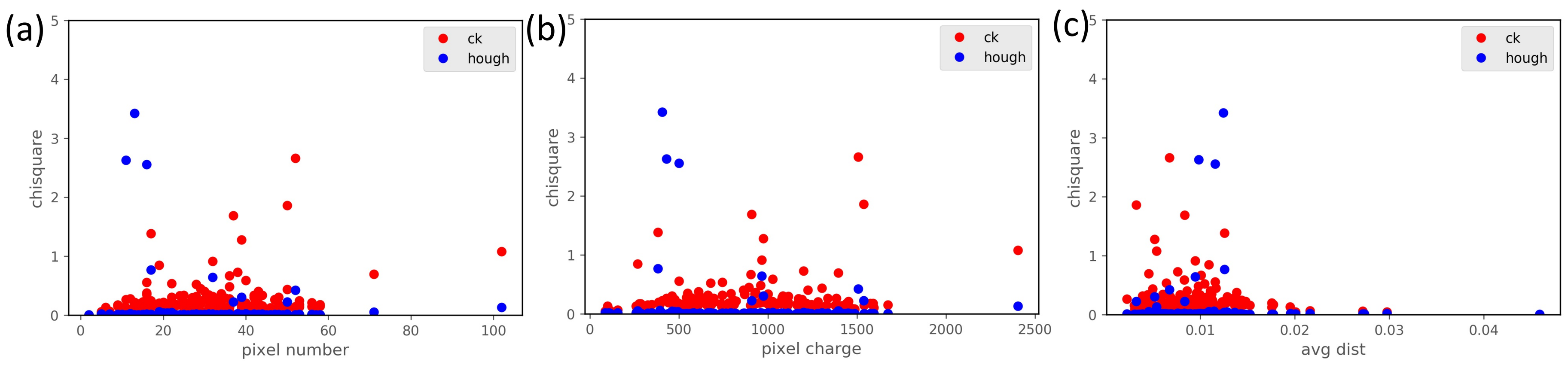


Fig.7 Comparisons of chi-squares between Hough and Chaudhuri Kundu fit in terms of (a) pixel number, (b) pixel charges, and (c) average distance in FlashCam simulation data file

Cut Optimization

Taubin Fit

Multiple parameters were combined to find a best optimization cuts in the right top of plots. Some combinations show that they can remove the bad ones well although the good ones are also not remaining.

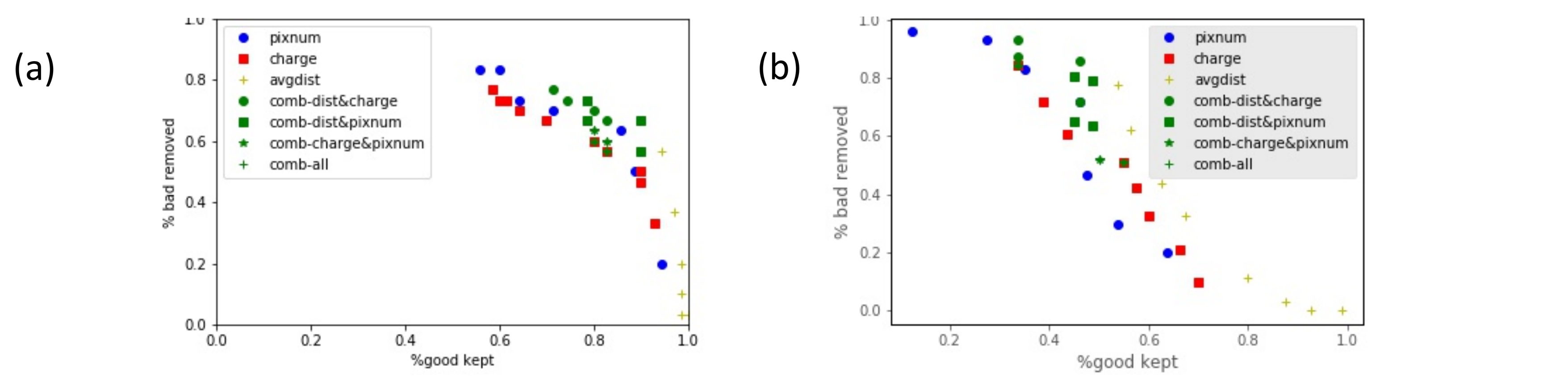


Fig.8 Cut optimization for Taubin fit with pixel numbers, pixel charges, average distance, and different combinations of the three in (a) FlashCam fake muon images and (b) FlashCam file data

Further Study

Next step for the performance test will be on **time optimization** of the algorithm. **More simulation data** files will be analyzed to test the ring fitting performance for different kinds of cameras from CTA.

Reference

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[2] Chaudhuri, B.B. and Kundu, P. “Optimum circular fit to weighted data in multidimensional space”, 14(1):1-6, 1993
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[4] L. Tani, “Circlehough.” https://github.com/Laurits7/circlehough.
CTA website: www.cta-observatory.org