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Performance of the First G-APD Cherenkov Telescope evaluated using Crab Nebula Observations

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Abstract The First G-APD Cherenkov Telescope (FACT) is an Imaging Air Cherenkov Telescope (IACT) located on the Canary Island of La Palma.

FACT pursues two main goals: It is the first IACT to use Silicon Photo Multipliers (SIPMs) to detect the faint flashes of Cherenkov lights induced by extensive air showers in the atmosphere. Using this technology, FACT monitors the brightest extragalactic sources of gamma-ray emission in the TeV range.

Using extensive simulations and observations of the so-called standard candle in gamma-ray astronomy, the Crab Nebula, the sensitivity of the telescope and the newly developed analysis chain is evaluated. This analysis chain uses only free and open source software and deploys modern machine learning techniques to solve the reconstruction tasks in gamma-ray astronomy.

Keywords FACT · Gamma-Ray Astronomy · Imaging Air Cherenkov Telescope

1 Introduction

The First G-APD Cherenkov Telescope (FACT)[1] is an Imaging Air Cherenkov Telescope, located at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma. As the first of its kind, FACT uses Silicon Photomultipliers (SiPMs) to detect the Cherenkov Photons emitted by extensive air showers in the Atmosphere. Since first light in October 2011, the FACT Collaboration pursues the goals of continuously monitoring the brightest known sources of gamma-ray emission[2], showing the suitability of SiPMs for gamma-ray astronomy[3] and making FACT the first completely robotically operating IACT.

The performance of the telescope and the analysis chain is evaluated on crab nebula observations taken between October 2013 and April 2014 as well as extensive simulations.

In Section 2 a brief overview of the FACT telescope is given. Section 3 introduces the used datasets for the analysis in this paper, both simulations and observations. In Section 4 the analysis chain is presented. Section 5 discusses the performance of FACT in terms of angular resolution, effective area and detection sensitivity. Also the reconstructed spectral energy distribution of the Crab Nebula is shown. Section 6 concludes this paper.

2 The First G-APD Cherenkov Telescope

3 Datasets used in the analysis

To determine the performance characteristics of FACT, observations as well as simulations are used. Simulations are needed, because in gamma-ray astronomy, there are no test-beams available to calibrate the detector response. Instead, extensive simulations are performed to obtain datasets with known truth values for the properties of the primary particle inducing the extensive air shower. The most important properties are the energy, direction and particle type of the primary.

For this analysis, Crab nebula observations taken between October 2013 and April 2014 with a total observation time of 91.1 h are used. Only observations with a zenith distance smaller than 30° and during dark night were selected. In total, the dataset contains just over 8 million events.

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The simulations were performed using CORSIKA [4] to simulate the extensive air showers in the atmosphere and CERES [5] to simulate the detector.

Three types of simulations were performed:

1. Gamma rays from a point source observed in wobble mode.
2. Diffuse gamma rays, scattered over the field of view of FACT.
3. Diffuse protons, scattered over the field of view of FACT.

Gamma rays were simulated between 200 GeV and 50 TeV using a power law spectrum with a spectral index of -2.7. Protons were simulated between 100 GeV and 200 TeV using the same power law. In total, 12 million gamma-ray and 720 million proton showers were simulated using CORSIKA. Of those showers, approximately 2 million point-source, 550 000 diffuse gamma rays and 500 000 protons triggered the telescope.

4 The FACT-Tools Analysis chain

Several preprocessing steps have to be performed on the FACT data, to get from the raw timeseries in each pixel to eventwise parameters suitable for event reconstruction.

These steps are performed using the `FACT-Tools` [6], which was developed at TU Dortmund and ETH Zurich to perform these tasks. `FACT-Tools v1.0.0` [7] is used for the analysis presented in this paper.

In the following, each of the applied analysis steps is shortly introduced.

4.1 Preprocessing and Image Parameterization using FACT-Tools

DRS4 Calibration FACT is using the Domino Ring Sampler 4 [8] chip to sample the output signal of the SiPMs. The amplitude of the sampled data has to be calibrated using measurements that are taken in between observations several times a night. The time of the measurements can be calibrated using constant calibration constants, that only need to measured once for a given DRS4 chip.

Artifact Removal Data sampled using the DRS4 chips shows two artifacts, that have to be removed before further processing: so called spikes are large increases in the timeseries for one or two adjacent values, jumps are a suddenly occuring shift in the baseline. These artifact are removed after the amplitude and time calibration steps are performed.

Signal Extraction From the calibrated timeseries in each pixel, two numbers are extracted: the number of photons and their mean arrival time. To estimate the number of photons, the timeseries is integrated for thirty values after the half-height of the maximum value. The rising edge of the pulse is fitted with a third order polynomial and the point of inflection is used as the mean arrival time.

Image Cleaning As a last step before the parameterisation of the images, pixels which are not likely to contain Cherekov photons are discarded using the following algorithm:

1. step 1

Image Parameterization Hillas, statistics, bla

4.2 Event Reconstruction using Machine Learning

To solve the three main reconstruction tasks in gamma-ray astronomy – particle class, energy and direction, an open source software package called `aict_tools` has been developed [9], that makes use of machine learning algorithms of the Python package `scikit-learn`.

For this analysis, a random forest regressor is trained on simulated point-source gamma-rays to estimate the energy of each particle.

For the particle type classification, a random forest classifier trained to distinguish between showers induced by gamma rays and protons is used.

The reconstruction of the particle origin is performed using the so called *Disp-Method* [**?**].

The disp method simplifies the reconstruction task from a two-dimensional regression, e. g. x- and y-coordinate of the source position in the camera plane, to a one-dimensional regression and a binary classification. Based on the assumption, that the true source position lies somewhere on the main shower axis, a regressor is trained to estimate the distance between the center of gravity of the light distribution and the source position. This results in two possible solutions, one in either direction on the main shower axis. A random forest classifier is used to pick the correct solution.

5 Performance Evaluation

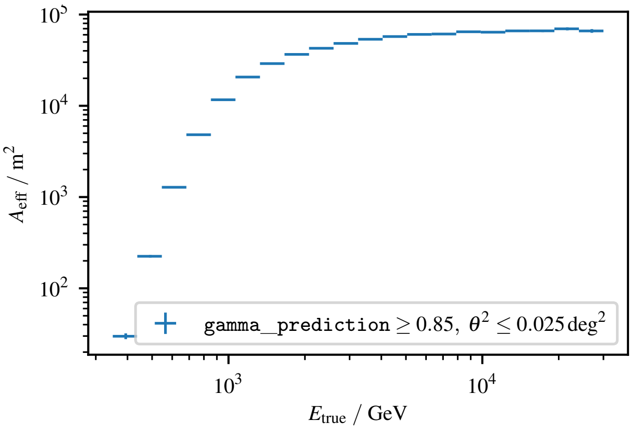

Fig. 1 Effective Area

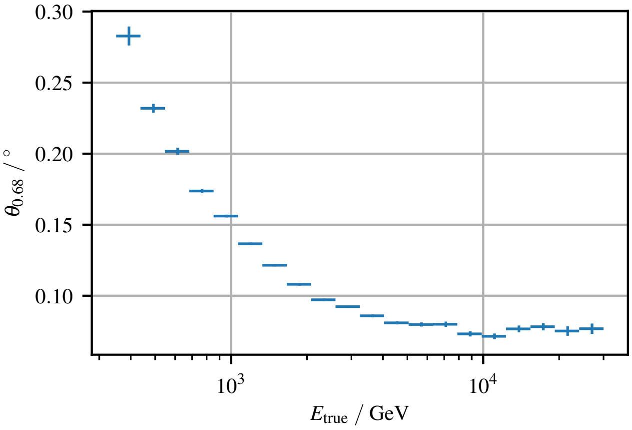

Fig. 2 Angular Resolution

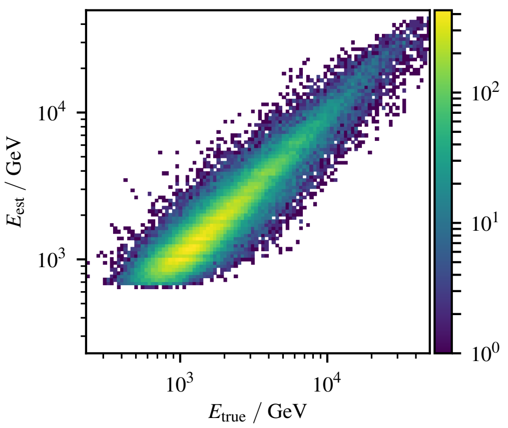

Fig. 3 Energy migration

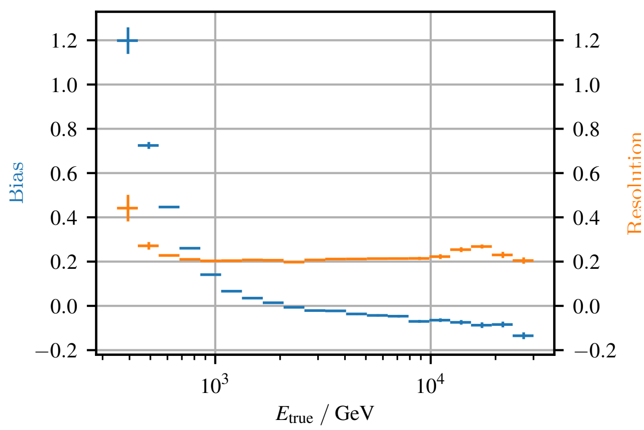

Fig. 4 Energy bias and resolution

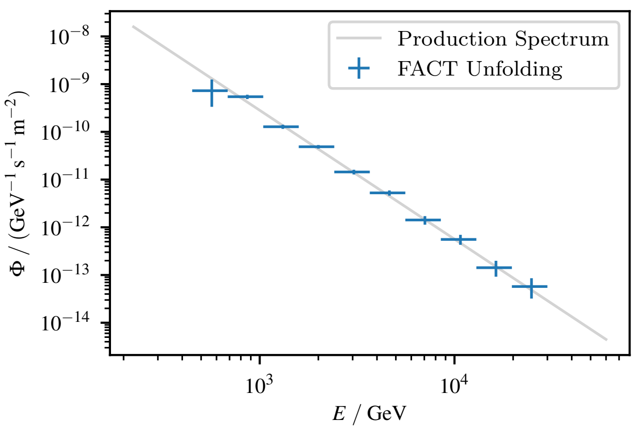

Fig. 5 Unfolding on simulated gamma-ray events.

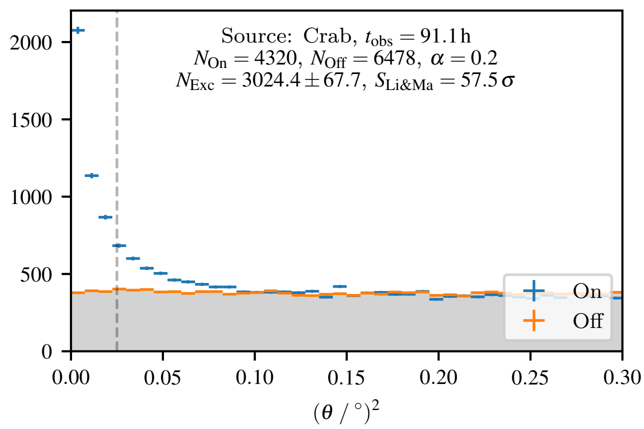

Fig. 6 Crab Nebular Theta Squared Plot

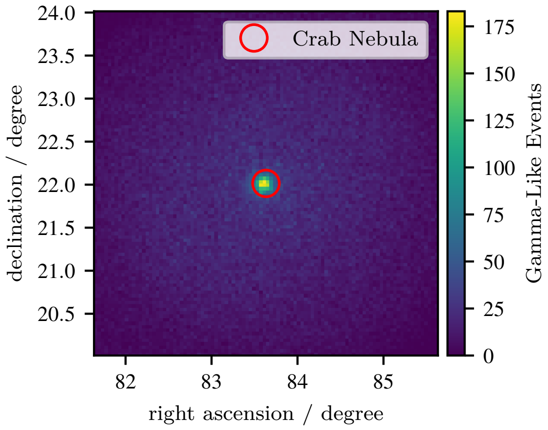

Fig. 7 Sky Map

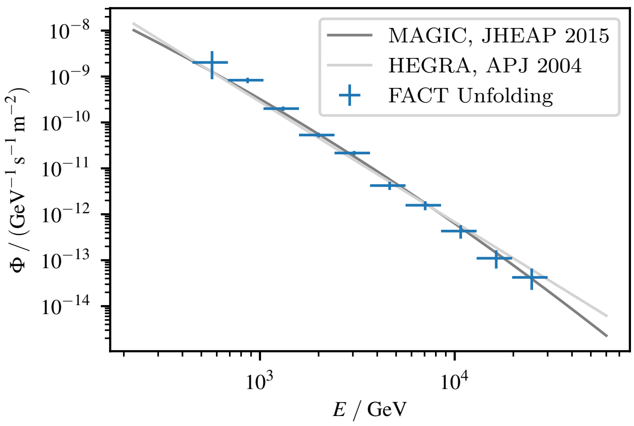

Fig. 8 Crab Nebular Energy Spectrum

6 Conclusions

FACT IS AWESOME!

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