Das Energiespektrum des Krebsnebels, gemessen mit FACT

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1 Theorie

1.1 FACT

The *First G-APD Cherenkov Telescope* (FACT), depicted in figure 1, is a ground based imaging cherenkov telescope. It was built in 2011 at the Observatorio del Roque los Muchachos, is operated remotely since 2012 and operates robotically since 2017. The observed objects are the Crab-Nebula and mainly blazars.

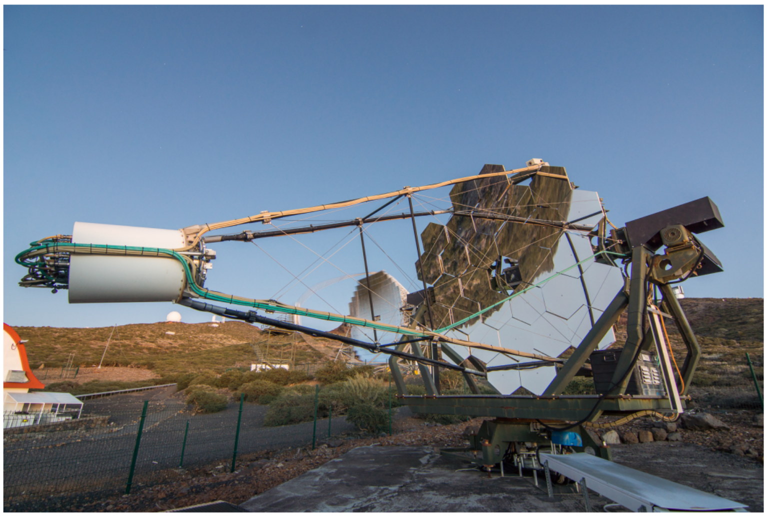

Abbildung 1: The telescope FACT at the Observatorio del Roque los Muchachos on La Palma, Spain. [3]

The telescope is operated in the wobble mode which enables it to observe sources of γ-radiation in the sky while also getting an estimate for the background radiation. In the mode it is aimed 0.6° next to the observed source. The estimated region where the source is located is called the on-region while five geometrically equivalent points are selected, which are called off-regions, are selected to estimate the background as depicted in figure 2.

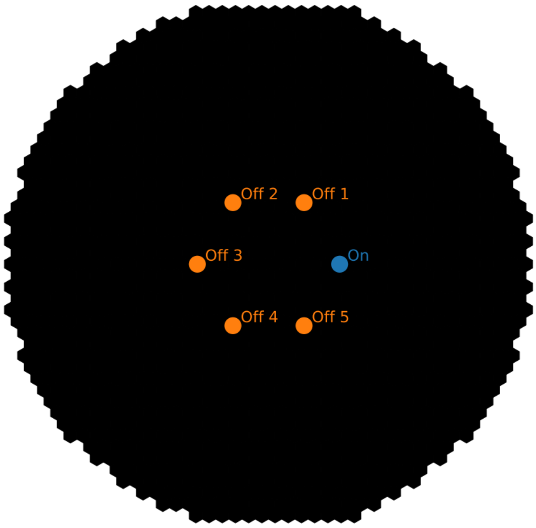

Abbildung 2: The field of view of FACT with the on- and the off-positions marked. [3]

To calculate the significance of the measurement is calculated with the Likelihood-Ratio-Test

$$S = \sqrt{2} \cdot \sqrt{N_{\text{on}} \ln\left(\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}}\right)\right) + N_{\text{off}} \ln\left((1+\alpha)\frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}}\right)} \tag{1}$$

where N_{on} and N_{off} are the numbers of reconstructed events in the on- and off-region respectively and α is the ratio of the number of on- and off-regions, therefore here $\alpha = \frac{1}{5}$.

1.2 Deconvolution

In experiment the physical quantities of interest are usually not measured directly but have to be extracted from the distribution of the signals produced by a detector $g(y)$ depending on an ensemble of observables y. This inverse problem can be written as the integral-equation

$$g(y) = \int A(y, x) f(x)\, dx + b(y) \tag{2}$$

where $A(y, x)$ is the detector response function that describes how a physical quantites x are converted into observables y by the detector, $f(x)$ is the measured distribution of physical quantities to be extracted from the data and $b(y)$ is the background for the measurement.
One way to solve such a problem is to discretize the data to receiva an equation of the form

$$\vec{g} = \mathbf{A} \cdot \vec{f} + \vec{b} \tag{3}$$

where $\vec{g}$ and $\vec{b}$ are the N-dimensional vectors containing the histograms of the observable and the background, $\mathbf{A}$ is the $M \times N$ migrationmatrix and $\vec{f}$ the M-dimensional vector containing the histogram of physical quantity of interest.

The goal here is to find an estimator $\hat{\vec{f}}(\mathbf{A}, \vec{g}, \vec{b})$ with which the distribution of the pyhsical quantity of interest can be determined if $\mathbf{A}$, $\vec{g}$ and $\vec{b}$ are known.

1.2.1 Naive SVD-Deconvolution

A method to solve the discretized inverse problem is to calculate the Moore-Penrose inverse of the migrationmatrix $\mathbf{A}^{+}$ and to rearrange equation (3) to

$$\hat{\vec{f}} = \mathbf{A}^{+}(\vec{g} - \vec{b}). \tag{4}$$

1.2.2 Poisson-Likelihood-Deconvolution

If one assumes the measured values $\vec{g}$ to be poisson distributed with

$$P(g_i) = \mathcal{P}(g_i, \lambda_i) \tag{5}$$

being the probability for measuring g_i where

$$\lambda_i = (\mathbf{A} \cdot \vec{f} + \vec{b})_i \tag{6}$$

one can find an estimate for the values of $\vec{f}$ by maximizing the likelihood

$$\mathcal{L} = \sum_{i=1}^{M} \mathcal{P}(g_i, \lambda_i). \tag{7}$$

For numerical reasons it makes sense to consider minima of the negative log-likelihood

$$-\ln \mathcal{L} = \sum_{i=1}^{M} \Big(\ln g_i! - g_i \cdot \ln \lambda_i + \lambda_i \Big). \tag{8}$$

If $\mathbf{A}$, $\vec{g}$ and $\vec{b}$ are known this leads to the estimator

$$\hat{\vec{f}} = \operatorname{argmin}(-\ln \mathcal{L}(f|\mathbf{A}, \vec{g}, \vec{b})). \tag{9}$$

1.3 Acceptance correction

Since the detector has only a limited acceptance a correction for this has to be taken into account. For this we define $p(E)$ as the probability of detecting an event of true energy E, A as the area covered by the experiment and finally

$$A_{\text{eff}} = p(E) \cdot A \tag{10}$$

as the effective area of the detector. If the events are sorted into energy bins the effective area has to be calculated for every bin i individually as

$$A_{\text{eff}, i} = \frac{N_{\text{selected}, i}}{N_{\text{simulated}, i}} \cdot A \tag{11}$$

The γ-events are simulated in a radius of 200 m which determines the detector radius. Utilizing this and the deconvoluted event numbers $\hat{f}_i$, the width of the individual energy bin ΔE_i and the observation time one can determine the flux for each bin i

$$\Phi_i = \frac{\hat{f}_i}{A_{\mathrm{eff},\, i} \cdot \Delta E_i \cdot t_{\mathrm{obs}}}. \tag{12}$$

2 Datasets

For the analysis three different datasets available at https://factdata.app.tu-dortmund.de/fp2/ are being used:

- `open_crab_sample_d13.hdf5`: reconstructed measurements from 17.7 h of observation of the crab nebula with FACT
- `gamma_test_d13.hdf5`: reconstructed simulated γ-events
- `gamma_corsica_headers.hdf5`: information about the simulated gamma air showers .

These datasets, except for the last one, are the result of the reconstruction of the type of particle, energy of the particle and direction of origin with the software `FACT-Tools` version 1.1.2 from either simulated or measured data [1].
For the simulated data the airshowers and cherenkov production have been simulated with `CORSIKA`[2] while the detector response has been simulated with `CERES`. The resulting data has the same format as the data directly from the telescope except that the initial events are known. Three different datasets have been simulated using this method:

1. γ-rays originating froim a point like source observed in the wobble-mode
2. diffuse γ-rays originating from random directions in the field of view of the telescope
3. diffuse protons originating from random directions in the field of view of the telescope.

The dataset of simulated events `gamma_test_d13.hdf5` contains 70 % of the simulated events. A Random Forest Regressor is trained on the dataset as an energy estimater and a Random Forest Classifier is trained to distinguish between diffuse γ-rais and protons.

3 Strategy

For the analysis only events that are classified by the Random Forest Classifier as γ-radiation with a confidence ≥ 0.8 are chosen.
After this a θ^2-plot is created with the measured values that have a distance from the on- or off-positions $\theta^2 \leq 0.025^{\circ 2}$
Next the energy migrationmatrix of the Random Forest Regressor with logarithmically

equidistant bins between 500 GeV and 15 TeV is determined. Utilizing the energy migrationmatrix and the background estimate from the wobble-mode a Naive SVD-deconvolution and a Poisson-Likelihood deconvolution is performed.
For the determined values an acceptance correction is performed, where it is important that only 70% of the simulated events are used, and the flux is calculated.
Finally the result are compared to the publicised results of the MAGIC- and HERA-collaboration.

4 Auswertung

Für die Auswertung der Messergebnisse wird im Folgenden der Mittelwert immer als

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{13}$$

berechnet und die Standardabweichung mit

$$\Delta\bar{x} = \frac{\sigma}{\sqrt{N}} = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N}(x_i - \bar{x})^2}. \tag{14}$$

Weiterhin wird die Gaußsche Fehlerfortpflanzung

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x}\Delta x\right)^2 + \left(\frac{\partial f}{\partial y}\Delta y\right)^2 + \dots} \tag{15}$$

verwendet. Für Plots und Regression wird Python genutzt.

Tabelle 1: Beschreibung

f / kHz	U_C / V
50	4,08
52	3,76

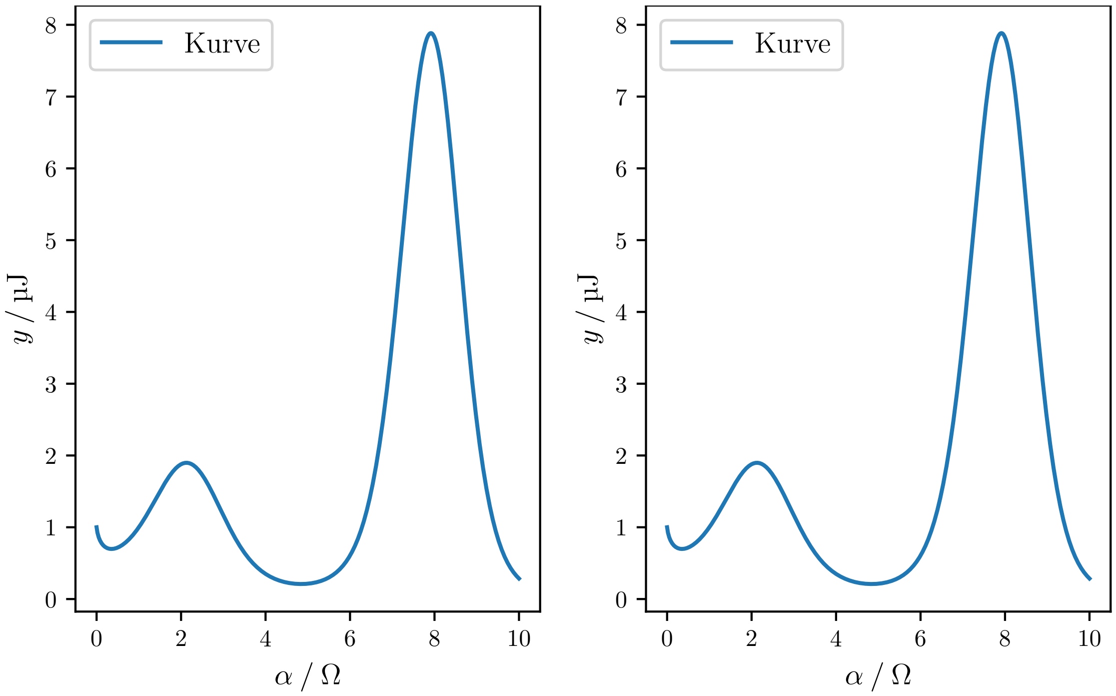

Abbildung 3: Plot.

5 Diskussion

Die relative Abweichung der Ergebnisse ergibt sich über

$$\Delta x = \frac{x_{\text{Messung}} - x_{\text{Theorie}}}{x_{\text{Theorie}}}. \tag{16}$$

Literatur

[1] Kai Brügge u. a. *fact-project/fact-tools: v1.1.2*. Version v1.1.2. Dez. 2018. DOI: 10.5281/zenodo.2386762. URL: https://doi.org/10.5281/zenodo.2386762.

[2] Ralph Engel u. a. „Towards A Next Generation of CORSIKA: A Framework for the Simulation of Particle Cascades in Astroparticle Physics“. In: *Computing and Software for Big Science* 3.1 (Dez. 2018). DOI: 10.1007/s41781-018-0013-0. URL: https://doi.org/10.1007%2Fs41781-018-0013-0.

[3] Astroparticle physics department TU Dortmund. *FP2 Teilchenphysik - Das Energiespektrum des Krebsnebens, gemessen mit FACT*. 2022.