FACT - The First G-APD Cherenkov Telescope

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1 The First GAPD Cherenkov Telescope (FACT)

1.1 Facts about FACT

As gamma-rays cannot penetrate through the Earth‘s atmosphere down to the ground, **I**maging **A**ir **C**herenkov **T**elescopes (IACTs) use the Cherenkov effect, described in the previous chapter, for an indirect measurement. Examples of such IACTs are, e.g., MAGIC (Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes), HESS (High Energy Stereoscopic System), VERITAS (Very Energetic Radiation Imaging Telescope Array System) and FACT (First G-APD Cherenkov Telescope).

FACT is located on the Canary Island La Palma in Spain. It is next to the large MAGIC telescopes in the Observatorio del Roque de los Muchachos at 2200 meter above sea level. The mount and mirrors of FACT are the refurbished elements of the former HEGRA CT3 and HEGRA CT1 telescope, respectively. The mirrors were diamond-milled and newly coated (Anderhub et al. (2013)). In addition, a new drive system was installed.

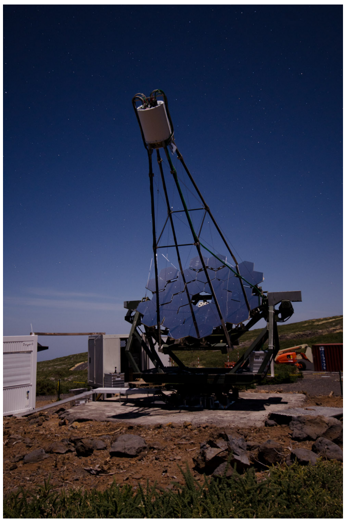


Abbildung 1.1: FACT at full moon. (Credit: T. Krähenbühl)

FACT was designed to detect cosmic gamma-rays with an energy ranging from several hundreds GeV up to approximately 10 TeV. It is the first Cherenkov telescope utilizing Geiger-mode avalanche photodiodes (G-APDs) instead of photomultiplier tubes (PMTs) for photon detection in regular observation. G-APDs promise a more stable gain, and a higher photon detection efficiency. Adapting their high voltage allows for a more precise operation even under strong moonlight conditions (Bretz et al. (2013)).

FACT can be operated fully remotely, aiming for robotic operation in the future. The data taking started in October 2011 and is continuously ongoing since then. The experience of the usage of G-APDs and the robotic operation of FACT is vital for the upcoming Cherenkov Telescope Array (CTA).

Besides proving the usage of G-APDs in the Cherenkov astronomy, FACT is monitoring bright TeV blazars on relatively long time-scales. FACT is ideally suited for this task, as long term is most effectively carried out with small telescopes of inexpensive operation. Ideally, such telescopes should be positioned around the world to enable 24/7 monitoring. The observation time of huge projects like the IACTs mentioned above is too expensive for such a monitoring of single sources. They have many scientific fields and many different astronomical objects to handle and in addition the searching for new sources. But studying blazars with their different flux-variations-time-scales from years down to minutes needs constant monitoring. Only this can provide a whole image of these highly interesting objects.

1.2 Components of FACT

Cherenkov telescopes in general consist of the same basic components. The principles of IACTs and their data analysis are introduced in the following using the example of FACT.

The Cherenkov light cone, coming from the air shower, is reflected by the mirrors of the telescope into the plane of the camera, producing an image of the shower, as illustrated in Fig. 1.2. This image is then analysed further on.

The mirrors of FACT are hexagonally shaped and sphere-like arranged in the so-called Davis Cotton arrangement. The total mirror area of the FACT telescope is 9.5 m^2.

The camera comprises 1440 pixels with 0.11 degree field-of-view (FOV) each, giving a total FOV of 4.5 degree of the whole camera. Each pixel comprises 3600 G-APD cells and has a solid light concentrator, a so-called Winston Cone, glued on top of it. The light concentrator is hexagonal shaped on the one end, and cubic shaped on the other end that is glued to the also quadratic G-APD cell. This enables maximum area compression for photons reflected by the mirrors, as the spaces between the G-APD cells, caused by their frames, can now be also used for the photon detection. In addition, it reduces the light loss due to Fresnel reflection on the compound of the light concentrator and the G-APD cell, and it shields the G-APD cells from photons, not arriving from the mirrors. The Winston cones are mounted behind a plexi glass to avoid dust entering the sensor compartment. The camera is further protected by a shutter.

The G-APDs are read out by electronics that are directly integrated in the camera box. The following analysis uses the data taken directly from the G-APD read-out.

1.3 Data-taking with FACT

The intensity of the light that is reflected onto the camera has to be above a certain value in order to trigger the read out electronics, avoiding background noise triggering, saving storage space as well as keeping the size of the data output on a manageable level. Trigger thresholds are set for a sum of nine pixels, a so-called patch, individually. Thus no single disturbance, like a star, which would shine only to a small part of the camera, can increase the trigger threshold for the whole camera. The setting of the threshold is always a

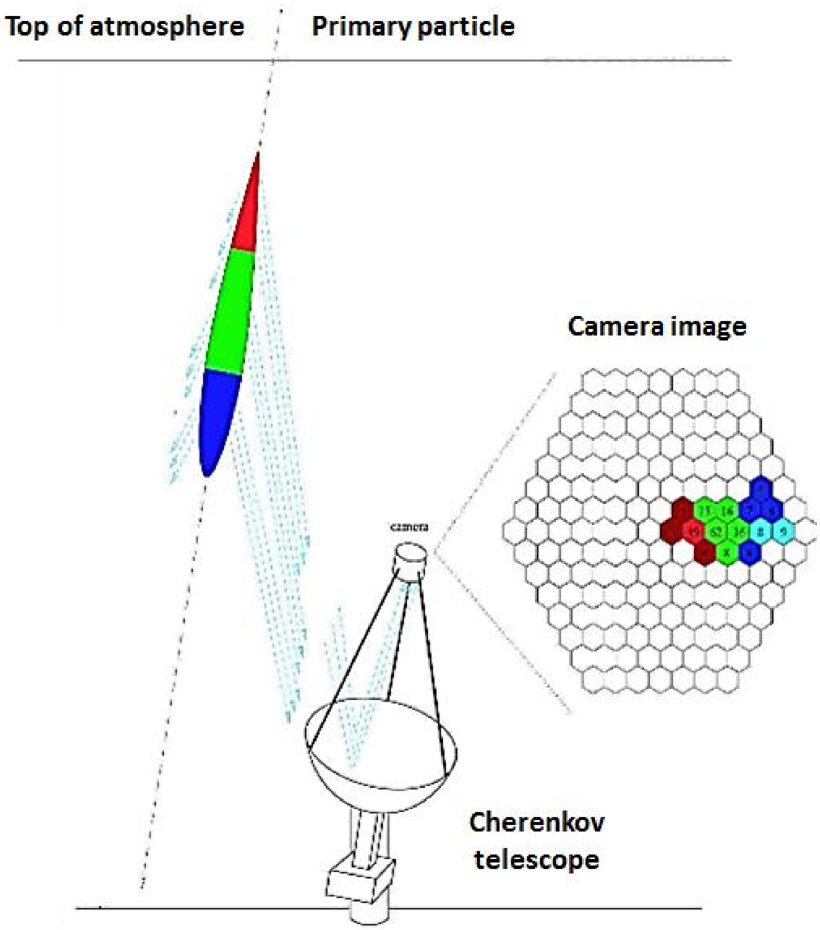


Abbildung 1.2: The working principle of an IACT. The Cherenkov light, emitted by the extended air shower of a primary particle, hitting the atmosphere of the Earth, is reflected by the mirrors of the telescope into the plane of the camera, producing an image of the particle shower that can be analysed. Adapted from: Backes (2011).

weighting between an effective background suppression of the night sky background (NSB) and the wish to detect also the fainter Cherenkov events.

The recorded data consist of raw data from the light reflected to the camera and of auxiliary data files, containing additional information to enable interpreting the raw data.

Examples of auxiliary data are e.g. the tracking position and the zenith distance of the source from the drive system, allowing for the reconstruction of the origin of the light source. In addition, there are data from the weather station or the effective on-time from the trigger control program, which is needed to calculate event rates from the measured events. The trigger rates during operation provide hints to possible non-physical events, disturbing the data taking. These can be car flashes or laser shots from neighbouring telescopes. These laser shots are used from the telescopes to measure the current atmospheric conditions. During dark nights with no clouds the trigger rate of FACT is around 80Hz. With larger zenith distances or higher trigger threshold the rate decreases.

The data of FACT are measured in certain time intervals, called runs. The normal data runs last five minutes at maximum. Runs for calibration and background measurements have different durations. The runs are summarized to sequences comprising a pedestal run, to measure the background, a calibration run, to calibrate the response of each pixel and four following data runs. For the pedestal runs, the camera is triggered with a fixed rate in order to randomly measure the NSB. The calibration of the pixels is a relative one, meaning that each pixel response is adjusted individually to get a homogeneous signal over the camera, when all camera pixels are illuminated equally.

In certain time intervals an additional Domino Ring Sampler chip calibration is performed, and attributed to the following sequences. This DRS calibration measures the behaviour of the DRS that is used in the read out electronics. In this ring buffer, all measured data are stored temporally. Whenever a signal is above the threshold value, the Ring Buffer is read out and the events are saved to disk in 300 slices of 0.5 nanoseconds each. Depending at which position the Ring Sampler is read out, the data can be affected from the previous signal. This effect has to be corrected for by the calibration

The following chapter describes the individual analysis steps and the used programmes in detail.

1.4 Data Analysis with FACT

All analysis programmes are done in the framework of the software package Mars CheObs (**M**odular **A**nalysis and **R**econstruction **S**oftware) that is based on the object-oriented ROOT framework, which is in turn written with C++. ROOT was developed by CERN, to analyse the huge amount of data, particle physics experiments provide (http://root.cern.ch/drupal/)

1.4.1 Calibration with the Program CALLISTO

The program CALLISTO (**Cal**ibrate **li**ght **s**ignals and **t**ime **o**ffsets) calculates calibration constants with informations, that are gathered from pedestal, calibration and DRS calibration runs. These constants are then applied to the extrated signal of the raw data.

A sequence of data consists of a single pedestal run, followed by one calibration run and four data runs. The calculated callibration constants of the pedestal and the calibration run are applied to the following four data runs of one sequence. The DRS calibration run is done in certain times steps and its information is used for all following data sequences afterwards.

From the randomly triggered events of the pedestal run, the background, containing the NSB and the electronic noise, is calculated. The calibration of the camera pixels is a relative callibration. Therefore the response of the pixels is equalised. This is done with the calibration run, which illuminates the whole camera homogeneously. With DRS calibration runs the effects of the Domino Ring Sampler can be excluded.

CALLISTO also treats so-called bad pixels that are e.g. damaged. The value of the neighbouring pixels are used to interpolate the value of the bad pixel. The bad pixel treatment can also be used for software or analysis problems.

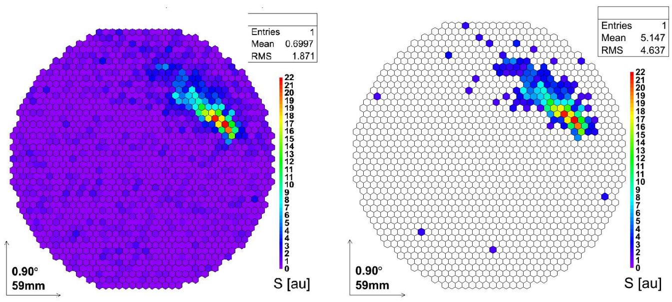
After the usage of CALLISTO a calibrated image of the camera is available.

1.4.2 Image Cleaning with the Program STAR

The next step is the so-called Image Cleaning, done by the program STAR. First connected pixels that are above a certain value, the level 1 value, are classified as the core pixels of a shower image. Pixels, that are above a lower value, the level 2 value, are classified as used pixels. Only used pixels surrounding the core pixels survive the image cleaning.

The core and used pixels have to be neighbours, building an island of pixels, the image of the shower. Pixels that are lying outside of these islands are cut away, even if there are some scattered pixels that are above the threshold values. Then the time evolution of the shower image is taken into account. Two neighbouring pixels can only have a time difference of 1.75 ns each.

A pure shower image remains which is described by parameters that are calculated now based on the light content of the shower image and its orientation in the camera. Generally gamma events have elliptically shaped shower images in contrast to muons that have a ring structure and hadron images that are mostly irregular shaped, with some sub-islands from electromagnetic sub-showers.

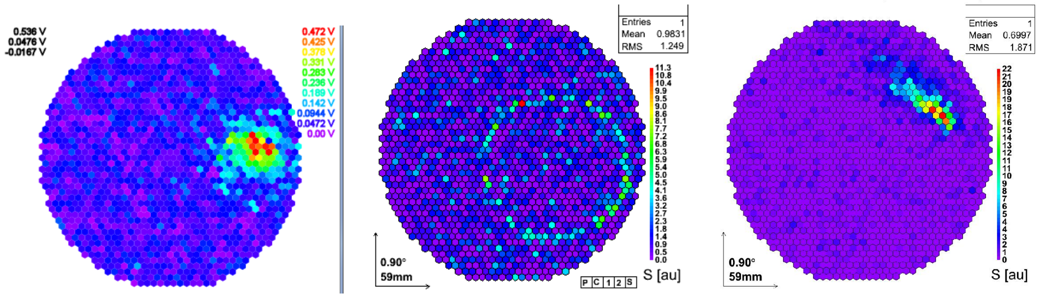


(a) gamma1 (b) gamma2

Abbildung 1.3: Process of Image Cleaning. Left side: before cleaning, right side: after cleaning.

The following parameters are based on signal data of the pixels and the geometry of the shower image:

- **Size**: This parameter describes the sum of all shower pixel signals.



(a) hadron (b) myon (c) gamma

Abbildung 1.4: Shower images from different types of events in the plane of the camera.

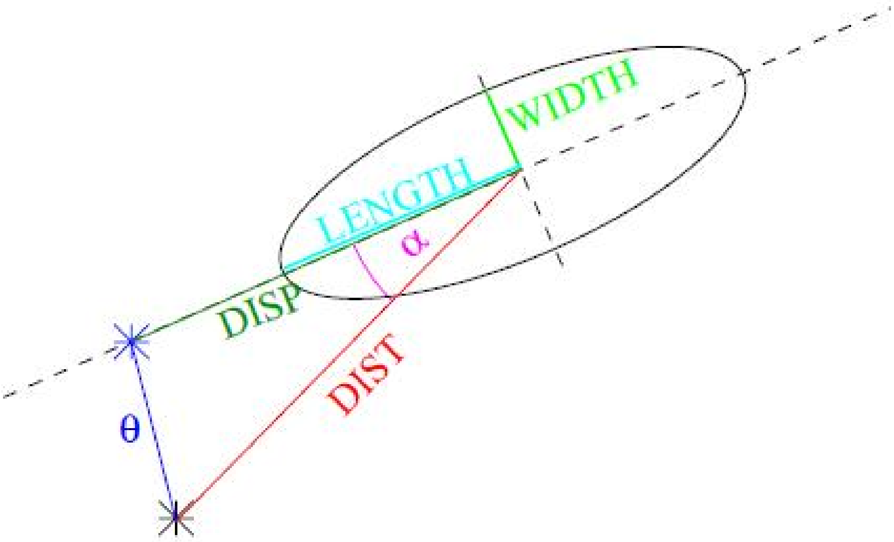


Abbildung 1.5: Definition of the image parameters. Image Credit: Sitarek (2011).

- **Width**: This parameter describes the standard deviation of the light distribution of the shower image in the direction of the small half-axis of the shower ellipse.
- **Length**: The standard deviation in the direction of the large half-axis of the ellipse.
- **Area**: Calculated by the equation: width $\times$ length $\times\pi$

Additional information is gained by the orientation of the shower image in the camera plane:

- **DIST**: The distance of the center of gravity of the shower image to the assumed source position.
- **DISP**: The distance of the center of gravity of the shower image to the reconstructed source position.
- **Theta**: The angular distance between the DISP and the DIST and thus the angular distance between the reconstructed and the assumed source position.

One the basis of these calculated parameters and with the aid of plotted distributions of differently combined parameters, muons, hadrons and gamma events not coming from the observed source can be sorted out of the data (for example see Fig. 1.6). This is done in the last step of the analysis chain (see 1.4.4). The auxiliary data are added to the data.

1.4.3 Adding of Auxiliary Data with the Program MERPP

The program MERPP merges data files and the auxiliary data that consist of informations from different subsystems of the telescope. As already introduced in the Section 1.3, examples of such auxiliary data are e.g. informations of the drive system, weather data, or the trigger rate.

The drive system delivers information of the tracking position of the observed source.

The weather can have a large impact on the measured data, as well. An example are clouds, reflecting ambient light, such as moonlight and thus brightening the night sky. They also can absorb a huge amount of the Cherenkov light and therefore increase the energy threshold. Another example is wind. Strong wind can move the camera out of its pointing position. Wind gusts decrease the accuracy of the camera tracking, leading to a constant need of correction from the drive system. Rain can build a water film on the mirrors that can absorb and deflect the light, as well as snow. Fog also has the effect of light absorption. Extreme temperatures, high and low, can have an impact on the electronics. Hence, all information on the current weather conditions are needed to interpret the data correctly.

Trigger rates can give hints on interfering artificial events, such as the laser shots from neighbouring telescopes measuring the atmospheric conditions. A peak in the trigger rate that lasts a certain time, can reveal these laser shots. The effective on-time during a run, needed to calculate rates of the measured events, is recorded in the trigger rate files.

All data that are available about the system and the surrounding conditions during data taking can be useful to exclude all unwanted data.

1.4.4 Calculation of Excess with the Program GANYMED

The last step in the analysis chain is the program GANYMED. There cuts are applied on the data to identify the events that are most likely gamma-rays from the observed source.

First, so-called quality cuts are applied to seperate events that can not be treated proberly because of technical influences. There is a cut on the number of pixels the shower image has after image cleaning (see 1.4.2). All events with a pixel number below 5 pixels are thrown out, because for events which have a smaller number of pixels, the shower origin can not be reconstructed well enough anymore.

Showers that are not completely in the camera plain are also cut away for the same reason. This so-called leakage cut has a limit of 0.3, meaning that the percentage of the shower in the outer ring of the camera must not be above 30 percent of the whole shower image. Otherwise the reconstruction of the shower image would be again too insecure.

After that, the background suppression cuts are applied. The background comprises mainly, protons, but also electrons, helium, iron and heavier nuclei. From the hadronic showers a lot of myons originate. In addition there is also a diffuse gamma-ray background. These cuts are based on plotted distributions of shower parameters. First, a cut on the basis of the Area versus Size distribution plot is used. Fig. 1.6 shows such a plot. Muon rings have a large Area with small Sizes, as their shower images have a ring structure. Gamma events show a typical distribution with limited Area values but a wide range of Size values. Hadrons instead have almost all combinations of Area and Size values. Therefore a cut can be applied to exclude many myon and hadron data, as seen in Fig. 1.6.

There is also a cut on the time evolution of the shower image. The slope parameters describe the time evolution along the two shower main axis. Hadron events with their sub-showers have different slopes than gamma events.

Finally, events not coming from the source are sorted out. This is done with the theta parameter. As mentioned before, theta is the angular distance between the assumed source position and the reconstructed origin of an event. If the event is coming from the direction of the source theta should be zero ideally. As the reconstruction of events is not always exact, the theta cut is set at 0.11 degree.

In between and after these main cuts, different parameters are plotted against each other, e.g. Width or Length versus Area, as control plots. These distributions are shown in the graphical output of GANYMED.

The program GANYMED calculates the final excess on data that is assumed to be gamma-rays coming from the observed source.

1.4.5 Sensitivity

Depending on whether the analysis is done to get maximum significance or a maximum possible amount of events and therefore a low energy threshold, the cuts can be adapted accordingly.

The Area versus Size cut can be chosen differently for example. The cut can be chosen to throw away preferably all data that might not be gamma events from the source, so that the gamma efficiency is large, or it can be loosened a bit to include more data, but with the disadvantage that now the hadron suppression efficiency is lower.

The same with the theta cut. If the cutting limit is set at higher values more events are available, but a tighter cut will lead to higher significance.

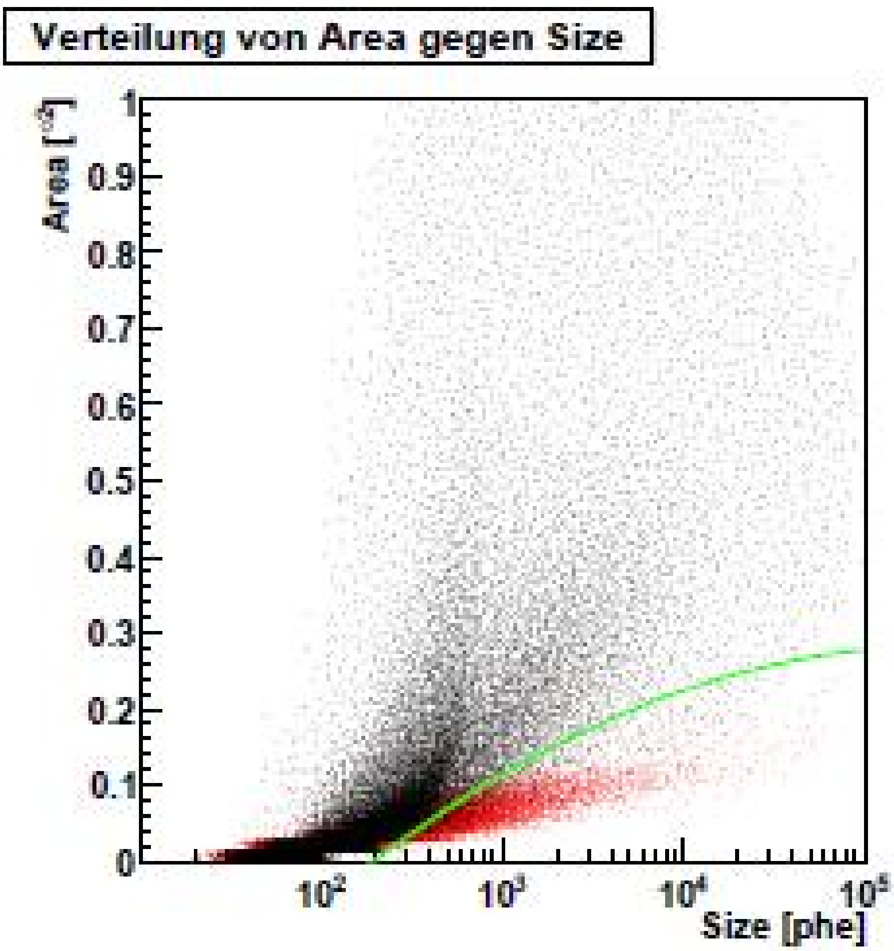


Abbildung 1.6: Example of a cut that is applied on the distribution of the image parameter Area versus Size. The red data points are Monte Carlo simulated gamma events, the black ponits Monte Carlo simulated hadron events. The green line shows the chosen cut. Image credit: Riegel (2005).

The Area versus Size cut has a direct impact on the theta square plots. With loosened cuts, there will be more events, gamma and background, and the background level will get higher.

For a maximum sensitivity, preferably pure gamma data and lowest possible background is needed to get a high significance. Hence the cuts are chosen tight.

To get a spectrum on the other hand, the highest possible amount of events is wanted now, to include also low energy events. Therefore the cuts will be widened accordingly, as the area cut includes an intrinsic size cut and a loosened area cut leads to an inclusion of events with lower size.

1.4.6 Lightcurves

A Lightcurve is a plot of the measured flux of a source against time. To get the energy flux of a source, Monte Carlo Simulations are needed in the Cherenkov astronomy, simulating the behaviour of the detector. For a calibration of the detector, measurements of events with defined energies would be needed. As there is no such source of well defined particles, that can be measured with the telescope, simulations are needed. In Monte Carlo simulations events and their reconstruction are simulated many times, to have high statistics and get probable conclusions on the behaviour of the detector. The energy of a gamma event is thus determined by comparing it to Monte Carlo events with certain energies that look similar.

The work on Monte Carlo Simulations for the FACT telescope are still ongoing. For the meantime, only excess rates are available, representing pseudo-lightcurves. The excess events are calculated from the output of GANYMED and filled into the database of the FACT project on run basis. Excess rate curves with different time binning can be made by reading the excess events and the ontime information of each single run from the database.

1.4.7 Skymaps

A skymap is a two dimensional theta-square plot of an observed part of the sky. This is especially important for extended sources such as e.g. Supernova Remnants (SNRs).

FACT only observes point-like sources in the moment, hence skymaps have lower priority and are therefore not yet produced.

1.4.8 Spectrum

A spectrum of a source shows its flux in dependence of the energy. For this, again Monte Carlo Simulations are needed, so no final spectra are available for FACT data so far.

Literaturverzeichnis

Anderhub H. et al., 2013, Journal of Instrumentation, 8, 6008P

Backes M., 2011, PhD Thesis, Technische Universität Dortmund

Bretz T. et al., 2013, arXiv:1308.1516

Riegel B., 2005, Diploma thesis, Universität Würzburg

Sitarek J., 2011, PhD Thesis, University of Lodz