PROCEEDINGS OF SCIENCE

Computing sky maps using the open-source package Gammapy and MAGIC data in a standardized format

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The open-source Python package Gammapy, developed for the high-level analysis of gamma-ray data, requires gamma-like event lists combined with the corresponding instrument response functions. For a morphological analysis, these data have to include a background acceptance model. Here we report an approach to generate such a model for the MAGIC telescope data, accounting for the azimuth and zenith dependencies of the MAGIC background acceptance. We validate this method using observations of the Crab Nebula with different offsets from the pointing position.

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1. Introduction

So far, the analysis of MAGIC data is traditionally performed with the proprietary software `MARS`[1]. For the future generation of very-high-energy gamma-ray instruments, the gamma-ray community is developing standardized data formats *Data Formats for Gamma-ray Astronomy* (GADF)[2], and Gammapy[3], an open-source tool, compatible with this data format.

In this contribution, we present an approach to create a background acceptance model for MAGIC data, which accounts for the zenith distance dependence of the MAGIC background. The background models created in this way are then used to create skymaps with Gammapy and MAGIC data for the first time. For validation, Crab Nebula datasets with different offsets to the pointing position are analyzed.

2. Characterisation of the MAGIC gamma-like acceptance

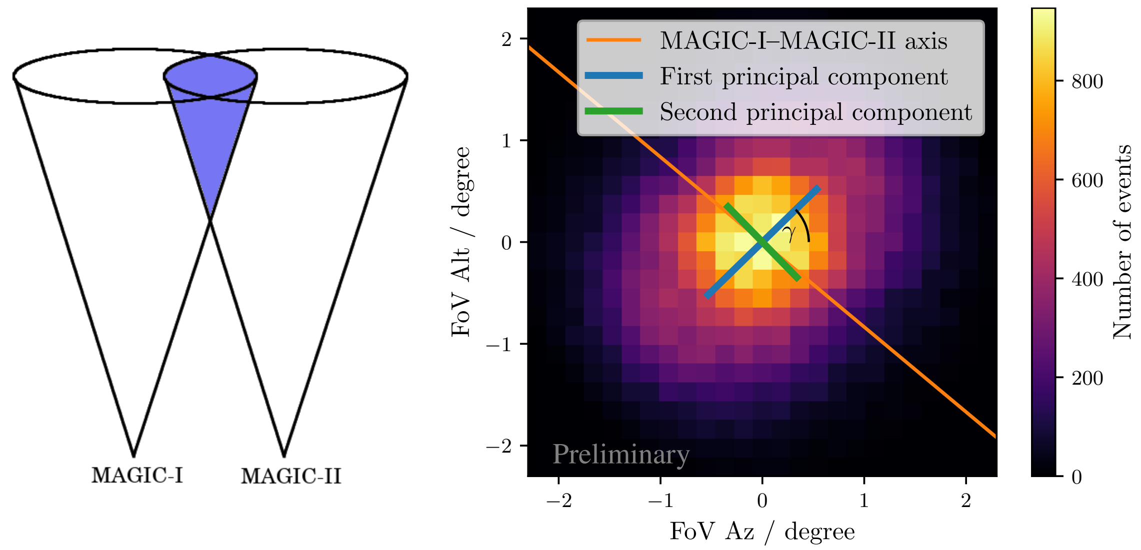

Figure 1: Left: Schematic illustration of the viewing cones of MAGIC-I and MAGIC-II. The overlapping part is coloured in blue. Right: The plot shows an exemplary azimuth bin from 69° to 99°. A principle component analysis is applied to the events in each azimuth bin. The angle between the horizontal and the first principal component (blue line) is called rotation angle γ.

In a previous study[4], it was found that the shape of the MAGIC acceptance is rotating dependent on the azimuth angle of the pointing position of the observation.

Here, we present an explanation for the azimuth-dependent rotation and compare this theory with the data. In the left part of Figure 1, the viewing cones of MAGIC-I and MAGIC-II are illustrated. An air shower has to pass both viewing cones to be triggered. As the non-symmetrical overlapping part of both viewing cones has its broadest part perpendicular to the connection line between both telescopes, it is predicted that events from that direction will be triggered preferentially. Projected into the sky, the overlapping part of the viewing cones is rotating dependent on the azimuth angle of the observation. In this analysis, the azimuth angle Az is counted from the Geographic

North ($Az = 0°$) to East ($Az = 90°$). The angle α between the North-South axis and the MAGIC-I–MAGIC-II axis is calculated as

$$\alpha = \arctan((\overrightarrow{M_1} - \overrightarrow{M_2})_y / (\overrightarrow{M_1} - \overrightarrow{M_2})_x) \approx 34.23° \tag{1}$$

with the positions $\overrightarrow{M_1}$ and $\overrightarrow{M_2}$ of the two telescopes:

$$\overrightarrow{M_1} = (41.054, -79.275)^\top \text{ m and } \overrightarrow{M_2} = (-29.456, -31.295)^\top \text{ m.} \tag{2}$$

In this definition, the y-axis points towards North, the x-axis points towards East and the coordinate origin is the dish-area-weighted center of MAGIC-I, MAGIC-II and the LST-1. As the overlapping part of the two viewing cones has its broadest part orthogonal to the MAGIC-I–MAGIC-II axis, the theoretical expected function of the rotation angle is:

$$\gamma_{\text{theory}}(Az) = Az - \alpha \approx Az - 34.23°. \tag{3}$$

To compare this assumption with observations, a large DL3[1] dataset of off observations is analyzed in twelve azimuth bins. The estimated energy of those gamma-like events ranges from 0.05 TeV to 10 TeV. In each azimuth bin, a principal component analysis is performed on the events in field-of-view (FoV) coordinates. The first principal component is indicating the direction of the greatest variance in the data and is therefore expected to be perpendicular to the connection line of the two telescopes. In the right part of Figure 1, this procedure is visualized in an exemplary azimuth bin from 69° to 99°. In Figure 2, the comparison between the measured rotation angles from the data and the theory curve (3) shows a good agreement.

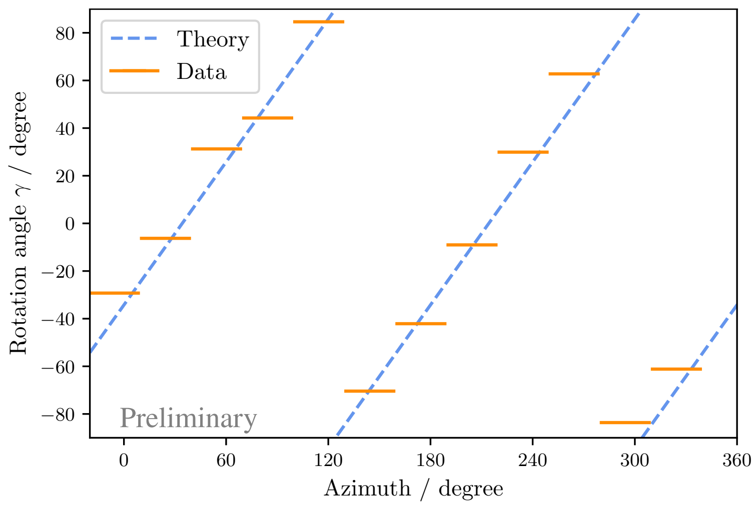

Figure 2: Rotation angle γ dependency on the azimuth angle of an observation.

To study the zenith dependency, the first-order influence of the azimuth can be removed by a correction. The FoV coordinates of the events are de-rotated by the theoretical rotation angle $\gamma_{\text{theory}}(Az_{\text{Pointing}})$ of the corresponding pointing position:

$$\begin{pmatrix} \text{lon}_{\text{rotated}} \\ \text{lat}_{\text{rotated}} \end{pmatrix} = \begin{pmatrix} \cos(\gamma_{\text{theory}}) & -\sin(\gamma_{\text{theory}}) \\ \sin(\gamma_{\text{theory}}) & \cos(\gamma_{\text{theory}}) \end{pmatrix} \cdot \begin{pmatrix} \text{lon} \\ \text{lat} \end{pmatrix} \tag{4}$$

[1] Data Level 3 (DL3) data format according to GADF: https://gamma-astro-data-formats.readthedocs.io/

On the de-rotated event coordinates, again a principal component analysis is performed in different zenith bins. With the resulting semi-major axis of the covariance ellipse a and the semi-minor axis of the covariance ellipse b the ellipticity

$$\epsilon = \frac{\sqrt{a} - \sqrt{b}}{\sqrt{a}} \tag{5}$$

can be calculated. As visible in the left part of Figure 3, the ellipticity is decreasing with higher zenith distances, which confirms the results of [4]. Furthermore, we investigated the ellipticity in different energy bins. At lower energies, the ellipticity of the acceptance is higher as shown in the right part of Figure 3. This indicates that the effect of a higher ellipticity at a lower zenith distance may not be an effect of the zenith distance, but of the energy of the events, because at higher zenith distances the data contains a higher percentage of high-energy events. In a certain energy bin – especially at low energies – the ellipticity is constant over a large zenith range. At higher energies, there is less statistics, but no clear trend is visible.

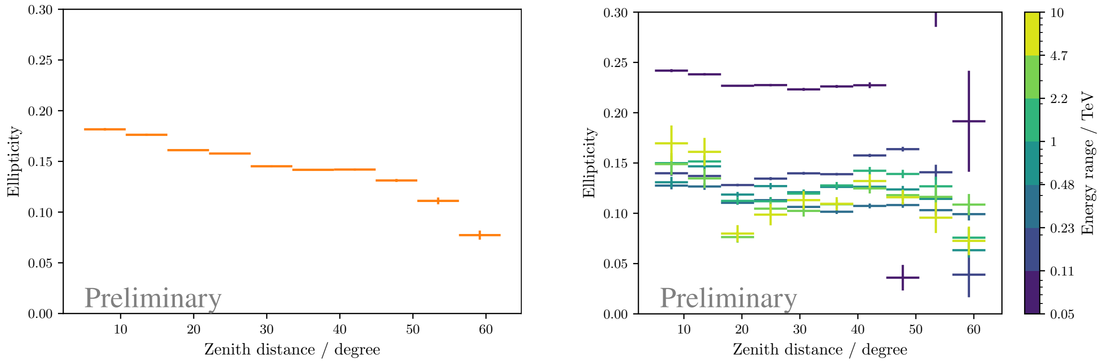

Figure 3: Ellipticity of the gamma-like acceptance as a function of the zenith distance in one energy bin (left) and splitted in seven energy bins (right) from 50 MeV to 10 TeV. The errorbars in these plots are calculated using a bootstrap approach.

3. Creation of skymaps with Gammapy

To perform a morphological analysis with Gammapy[3], the data has to contain an acceptance model. With the knowledge about the azimuth dependence, we create acceptance models from an off dataset with the following procedure:

1. De-rotate the position of all events from off observations around the predicted theory rotation angle (3) of the corresponding pointing position.
2. Rotate the position of all events around the theory rotation angle (3) of the pointing position from the observation for which the acceptance should be calculated.
3. Histogram events and calculate background rate in $\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}\,\mathrm{sr}^{-1}$.

The zenith dependency is implicitly taken into account by performing this procedure in different energy bins. Finally, the data is stored according to the GADF as `3DBackground` model. Gammapy offers the opportunity to normalize the background acceptance model to a single observation with the `FoVBackgroundMaker` (fit method and scale method) and the `RingBackgroundMaker`. Multiple observations can be stacked to a single `MapDataset`, from which the `ExcessMapEstimator` can produce skymaps. Here, we present the results of the `FoVBackgroundMaker` (fit method) applied to a Crab Nebula dataset. The data contains observations measured within a zenith range of 5° to 35° with a standard wobble offset of 0.4°. In Figure 4, the resulting counts map and the predicted background counts maps are shown. The significance map and the corresponding significance value histrogram are shown in Figure 5.

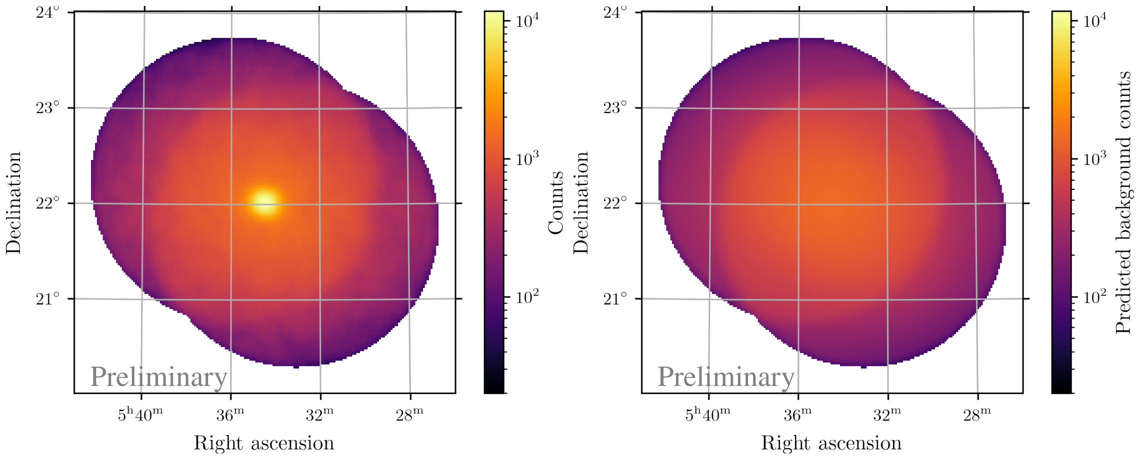

Figure 4: Counts map (left) and predicted background counts map (right) for a stacked Crab Nebula dataset.

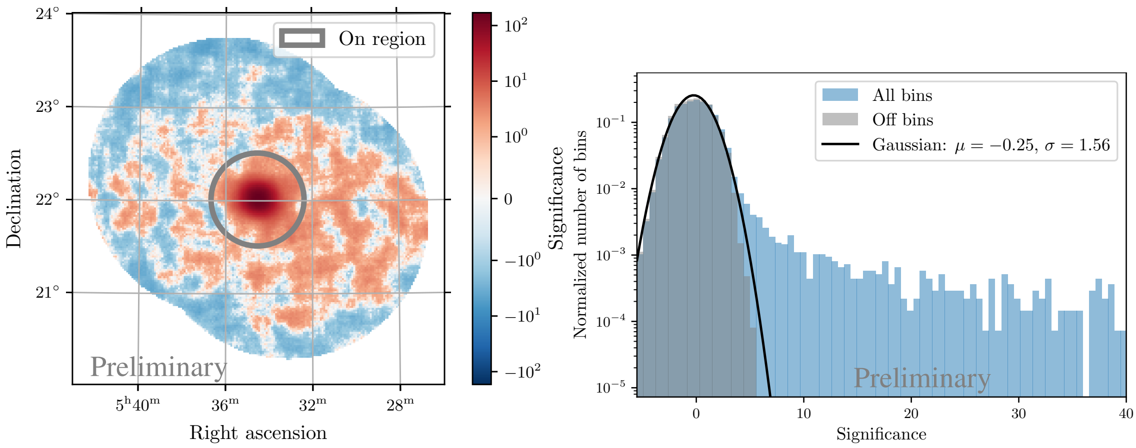

Figure 5: Excess significance map (left) for a stacked Crab Nebula dataset and corresponding significance value histogram (right).

4. Validation of the spectrum estimation using multiple Crab Nebula datasets

Based on the analysis in section 3, we estimated a Crab Nebula spectrum assuming a log-parabola model

$$\phi(E) = \phi_0 \left(\frac{E}{1\,\text{TeV}}\right)^{-\alpha-\beta\log(E/1\,\text{TeV})} \tag{6}$$

with the forward-folding likelihood analysis implemented in Gammapy. To validate the methods in the complete field of view, we analyzed multiple Crab Nebula datasets [5] with different offsets to the pointing position. The data is taken under a zenith angle from 5° to 35° and the wobble offset of the observations varies from 0.2° to 1.4°. As represented in Figure 6, the resulting log-parabola parameters show good agreement with the MAGIC reference curve [5].

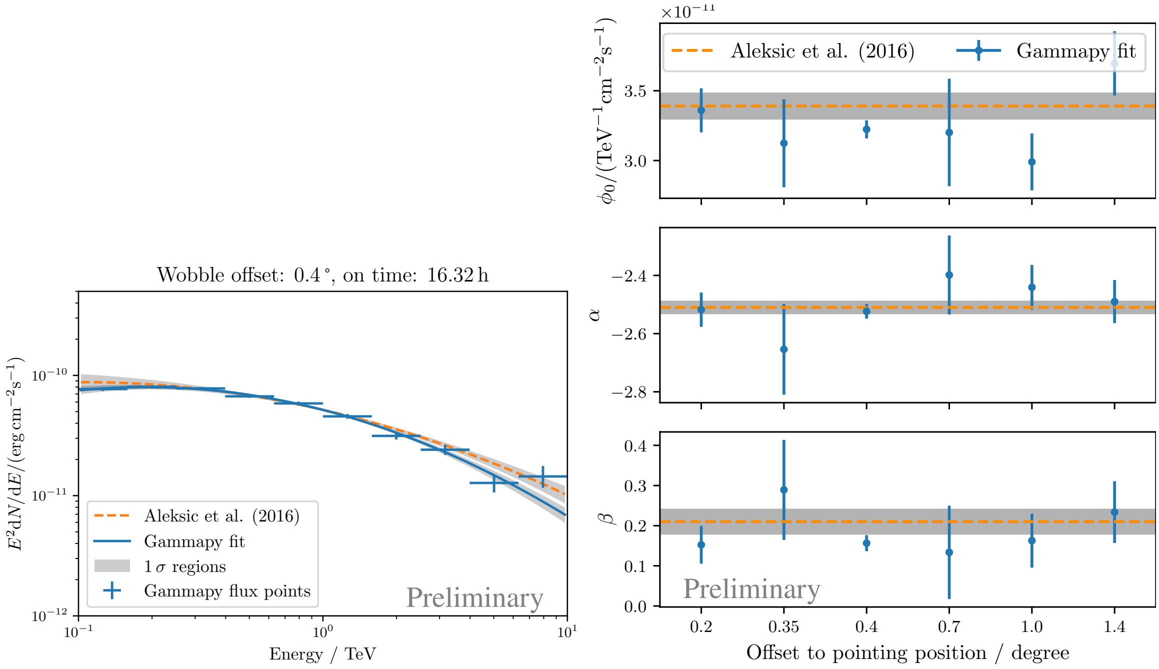

Figure 6: Left: Spectral energy distribution from a Crab Nebula observation with an offset of 0.4°. Right: Estimated parameters of the log-parabola model (6) for different wobble offsets.

Ackknowledgements

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