H.E.S.S. Data Analysis of the Galactic Center Region

Bachelorarbeit aus der Physik

Vorgelegt von

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Abstract

The conduction of a detailed H.E.S.S. data analysis of the Galactic center is the main purpose of this bachelor's thesis, in order to characterize different gamma-ray sources and separate them from diffuse emmisions and hadronic background emissions. With the open-source package gammapy, it is possible to fit the observed sources, the hadronic background and estimate diffuse emissions in the given area. In contrast to previous analyses it is possible to fit the morphology and the spectrum of the observed sources simultaneously. This way spectral index values can be fitted for the Galactic center, G0.9+0.1 and the source HESS J1745-303 by varying spectral parameters like the index and the amplitude until they match the data and at the same time fit the morphology by adjusting spatial parameters like width and length of the sources to the dataset. As a result, indices of 2.097 ± 0.0455 for the Galactic center, $2.475 + 0.0505$ for G0.9+0.1, 2.191 ± 0.221 for the source HESS J1745-303 and 2.390 ± 0.021 for diffuse emissions in the Galactic center area are obtained. These fitted index values accord with indices from prior publications. Also the morphology is in accordance with the detected counts from H.E.S.S. I data which can be assessed by regarding the difference in counts between modelled data and measured counts.

Contents

1 Introduction

H.E.S.S. (High Energy Stereoscopic System) is a system of Imaging Atmospheric Cherenkov Telescopes (IACTs), located near the Gamsberg mountain in Namibia. When a gamma-ray photon of high energy strikes the atmosphere, it initiates Extensive Air Showers (EAS). These are electromagnetic cascades of relativistic charged particles that then generate flashes of Cherenkov radiation which last between 5 and 20 ns. First, the gamma-ray undertakes pair-production, leading to a highly energetic electron-positron pair. Next, bremsstrahlung is produced by the high-energy pair which then leads to highly energetic photons, repeating the process of encountering pair-production and generating bremsstrahlung. This way a shower of charged particles emerges which generate Cherenkov radiation. The Cherenkov flashes can then be collected in a large mirror of the IACTs and measured by a pixeled camera.
Apart from H.E.S.S., also the system CANGAROO operates in the Southern hemisphere, while VERITAS and MAGIC are IACT systems that are used the Northern hemisphere. The H.E.S.S. I system, whose data has been used in the following Galactic center region analysis, consists of four IAC telescopes that have been collecting data since 2003. The aim is to analyze count data from the Galactic center region that has been taken during 424 H.E.S.S. observations in approximately 190 hours of observational time.
The area of interest ranges from 357.5° and 2.5° of Galactic longitude and $-2°$ and 2° of Galactic latitude. That means that the observed area is centered around the Galactic center and its active galactic nucleus Sagittarius A* (Sgr A*). Sgr A* is a bright astronomical radio source and most likely a supper-massive black hole. It is assumed to have a mass which is 4.1 million times higher than the mass of the sun and to be 26.500 light years away from planet earth (Issaoun et al., 2019).

At 0.9° of Galactic longitude and 0.1° of Galactic latitude, the source G0.9+0.1 can be at. It is a composite supernova remnant (SNR) which is recognized as such by analyzing its radio morphology. SNRs are structures that result from the explosion of a star in a supernova and consist of the ejected stellar material, but also include interstellar material. The shockwave which expands as a consequence of the supernova explosion bounds the stellar material and takes up interstellar material along its way away from the explosion. Composite supernovas remnants, like G0.9+0.1, comprise of a central pulsar wind nebula in their center and a shell around it. G0.9+0.1 has compact core of about $2'$ and a shell of $8'$ (Aharonian, F. et al., 2005).
The biggest challenge in the analysis of H.E.S.S. I data seems to be the separation of diffuse gamma-ray emissions, hadronic background emissions and gamma-ray photons of

the main sources themselves like the Galactic center and G0.9+0.1.
Sgr A* is a low-luminosity Galactic nucleus (LLAGN) and is therefore thought to accelerate high-energy cosmic ray protons in its accretion flows. Afterwards, the accelerated protons interact with photons or other protons which then results in the production and gamma-rays. Gamma-rays that can be observed as a consequence of this process are what is reffered to as diffuse gamma-ray emissions (Fujita, Kimura, and Murase, 2016). As the acceleration of protons happens in the accretion flows of Sgr A*, diffuse emissions are mostly emitted from the area right around the Galactic center and modelled between 357.75° and 1.25° of Galactic longitude and −0.6° and 0.6° of Galactic latitude throughout this analysis.
Background emissions are the result of hadronic and electromagnetic showers (Abramowski et al., 2014). Electromagnetic showers, as previously mentioned, are the result of high energy electrons and photons which interact with compact matter, undergo pair-production and lead to bremsstrahlung. The high energy photons that result from these interactions repeat the process. Hadronic showers are initiated by a high energy hadrons. Due to the fact that hadrons carry an electric charge, hadronic showers are partially electromagnetic but also interact with atomic nuclei through strong interactions, leading to the production of low-energy hadrons. Electromagnetic and hadronic showers (throughout this thesis mostly just referred to as hadronic background) result in gamma-ray photons that in conjunction are referred to as background emissions.
The main problem is that gamma-ray sources like the Galactic center and G0.9+0.1, diffuse emissions and background emissions can originate in the same area. As a consequence a step-by-step approach has to be taken in order to model and fit the main sources, diffuse emissions and hadronic background emissions separately.

The first aim is to model and fit background emissions in the Galactic center region. In order to accurately predict the hadronic background, H.E.S.S. observations are used where the pointing direction of the IACTs is targeted outside of the Galactic plane. Then, gamma-ray events can be detected and averaged throughout several of these background observations, while not taking into account gamma-ray events that originate in known gamma sources (Lars Mohrmann, 2019). This is necessary in order to model background emissions on their own, unaffected by the count values of gamma-ray sources.
Next, known gamma-ray sources like the Galactic center and G0.9+0.1 can be modelled by fitting width and length of their morphology to the count data with the use of a spatial model. Simultaneously, the spectrum of these sources can be fitted by using a spectral model which varies spectral index and amplitude of the sources to the spectral data in order to simulate their spectra. Now, background emissions and count values of the 424 H.E.S.S. observations can each be stacked one over the other. The stacked background data and the created source models can then be fitted to the overall measured stacked count data by again varying spatial and spectral parameters. At this point, the sources and the hadronic background are modelled in cohesion.
In the next step, diffuse gamma-ray emissions need to be taken into consideration as well.

As diffuse gamma-rays primarily originate in the area right around the Galactic center, a region between 357.75° and 1.25° of Galactic longitude and $-0.6°$ and 0.6° of Galactic latitude is used in the modeling procedure. The aim is to fit the morphology right to the shape of this template area. The problem is that diffuse gamma-rays also originate in the area of the Galactic center and G0.9+0.1. By masking these areas, diffuse emissions of 0 would be assumed in these areas which is inaccurate. The issue is solved by averaging over the amount of counts in close proximity to the sources and assuming that the area of the sources has the same count value as the averaged data of the pixels right around it. Afterwards spatial and spectral parameters of diffuse gamma-ray emissions are fitted to the count data.

In the last step, sources, background emissions and diffuse emissions can be fitted in cohesion. In order to assess the accuracy of the fitted morphologies, residual images can be produced which subtract the modelled data from the actual count data. By this means it is possible to realize the difference between model and reality and then compare it the amount of overall measured counts. Also, regions with higher differences in counts can be seen in residual maps which help to see if specific areas require separate modeling and how well individual sources have already been modelled. The quality of the spectral analysis can be asessed by comparing fitted index values to indices from prior publications and plotting the spectra of the Galactic center and G0.9+0.1. For the Galactic center an index of 2.14 ± 0.12 is expected (Abramowski et al., 2016), while G0.9+0.1 is thought to have an index of 2.40 ± 0.13 (Aharonian, F. et al., 2005). Additionally it is necessary to fit the source HESS J1745-303 where an index of 2.71 ± 0.13 is expected (Aharonian, F. et al., 2008). Diffuse emissions in the Galactic center region have the spectral index 2.32 ± 0.16 in prior publications (Abramowski et al., 2016).

2 Gammapy Setup

With the open-source Python package gammapy it is possible to import the needed H.E.S.S. I observations, generate maps of the observed gamma-ray counts and model the morphology and spectrum of the Galactic center by varying spatial and spectral parameters. In this chapter, it will be explained how gammapy is set up and how it structures and works with the needed data.

2.1 Maps and Geometries

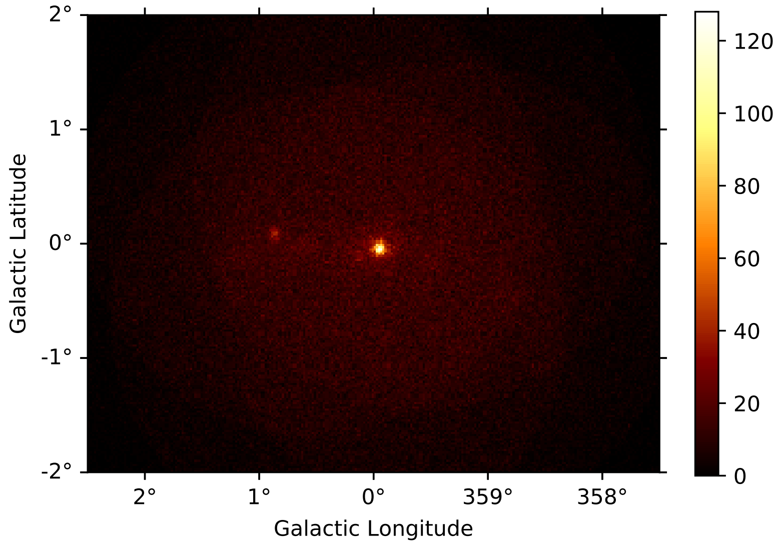

Figure 2.1: Plotted counts map of the H.E.S.S. I observation 77248. The two axes represent the Galactic longitude and latitude, whereas the colorbar indicates the amount of counts in any given area. The Galactic center at 0° of each Galactic longitude and latitude and G0.9+0.1 at 0.9° of Galactic longitude and 0.1° of Galactic latitude are clearly visible as yellow dots.

H.E.S.S. I data consists of morphology and spectral data. That means that every measured gamma-ray count has a known Galactic longitude, latitude and energy value. The morphology, which is described by the amount of counts per given Galactic longitude and latitude, can be visualized by maps. The properties of these maps can be adjusted by a geometry. A geometry basically is the plan upon which maps can be generated by setting the needed map parameters. It sets up the position of the map, its length, width, the coordinate system which it operates in and the size of the individual bins. For the following galactic center analysis Galactic coordinates are used and the map is centered at a Galactic longitude and latitude of each 0°. The maps are set up to have a width of 5° (ranging from 357.5° to 2.5° of Galactic longitude) and a length of 4° (ranging from −2° to 2° of Galactic latitude). The binsize is further set to 0.02, allowing for detailed count and model images.

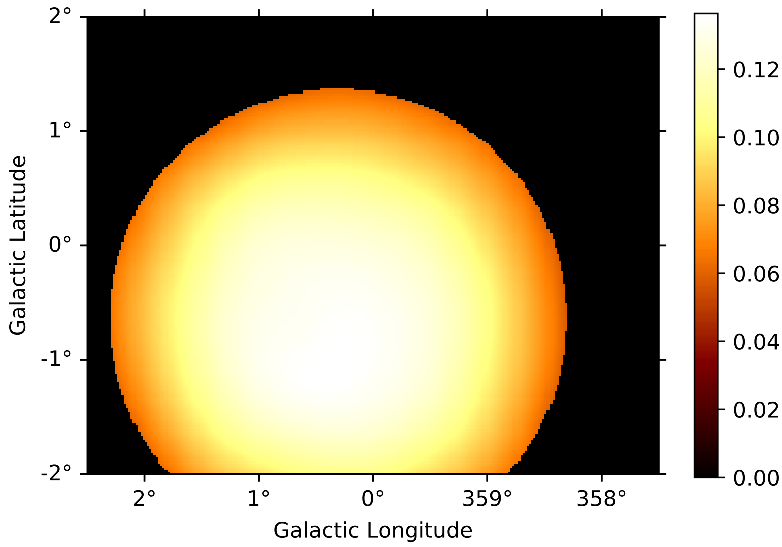

Figure 2.2: Plotted background map of the H.E.S.S. I observation 77248. The two axes represent the Galactic longitude and latitude, whereas the colorbar indicates the amount of counts in any given area.

Next, it is possible to plot a count map of a chosen H.E.S.S. observation that can be seen in Figure 2.1. In this example the morphology of the count data from the H.E.S.S. observation 77248 is visualized. Gamma-ray sources can be localized on the map with the use of the x- and y-axis, representing Galactic longitude and latitude. The amount of counts is indicated by the colorbar. Different colors are therefore indicative of different count ranges.

While the two main sources, the Galactic center and G0.9+0.1, are visible in the plot, one observation is not enough to fit the data properly. One reason for this is that atmospheric fluctuations cannot be taken into account by simply analyzing one observation. Also instrument conditions can influence the measured count values and

might vary (Abramowski et al., 2014).
As a result, all observations will be stacked one over the other in order to create a model for the Galactic center area which is discussed in chapter 4. The background image that is taken throughout the same observation can also be plotted separately, as seen in Figure 2.2. chapter 3 explains how these background images are generated and how the pointing direction of the telescope affects the measured background data. To obtain an accurate representation of the background it is again necessary to stack several background images one over the other and the pointing direction of the telescope needs to be varied throughout these observations.

2.2 Source Detection

In order to be able to model the given data later on, it is possible to select specific sky coordinates on the map. These coordinates can then for example be used to create sky regions of a circular or a Gaussian shape around the chosen coordinates on the map. Creating these regions might serve several purposes. One example is the creation of spatial models for gamma-ray sources which is explained in section 2.3. Another example might be that certain regions can be masked out of an observational dataset. That can be necessary in order to, for example, separate diffuse gamma-ray emission from source emissions as shown in chapter 5. Taking all these purposes into account, the following regions have been created:
For the galactic center at 0° of each Galactic longitude and latitude, a region with a

Table 2.1: Set circular regions, their Galactic coordinates and the set region radius. The regions which have been called HAP1-4 do not have any specific name and are just regions of higher gamma-ray emissions (Mohrmann, 2019) which can be masked in the fitting procedure of the background model.

Region	Galactic longitude[°]	Galactic latitude[°]	region radius[°]
Galactic center	0	0	0.15
G0.9+0.1	0.9	0.1	0.15
HAP 1	359.5	−0.15	0.35
HAP 2	0	−0.02	0.35
HAP 3	0.55	−0.05	0.35
HAP 4	1.1	0	0.35

0.15° radius is set. The same happened for G0.9+0.1 at 0.9° of Galactic longitude and 0.1° of Galactic latitude.
Throughout this analysis it is further necessary to create a sky region around HESS J1745-303 as it is a source of significant gamma-ray emissions which would negatively affect the created model if left unfitted. The morphology of HESS J1745-303 is approximated with the use of a Gaussian function as seen in chapter 3. Additionally, four

unnamed regions of higher gamma-ray emissions have been set as regions (Mohrmann, 2019) which are called HAP1-4 in this thesis. Those are later masked in the fitting procedure of the background model as they represent count data that the background fit can be falsely considering background emissions. That would then lead to an inaccurate representation of the background and estimating it higher than it actually is. All circular regions can be seen in Table 2.1.

In contrast to previous analyses, this analysis also consists of an energy dimension. This means that the energies of the given counts can be measured. As a consequence, energy thresholds can be set in order to only analyze counts above or below a certain energy value. For a proper source detection, an energy threshold can be set as a lower barrier. Then, counts with energies over the given energy threshold can be detected on the map, as seen in Figure 2.3.
Apart from the map, gammapy also shows a table, consisting of coordinates of all circled sources. The source detection tool is used in order to localize the source HESS J1745-303 and model it afterwards. Apparently, another source is placed right next to HESS J1745-303 which is relevant for further analysis as it affects the modeling procedure for the source. One can say that the additional source does not represent a new source and is a part of HESS J1745-303. This can be the case as HESS J1745-303 has a more complex spatial shape and cannot be described as a point source (see chapter 4).

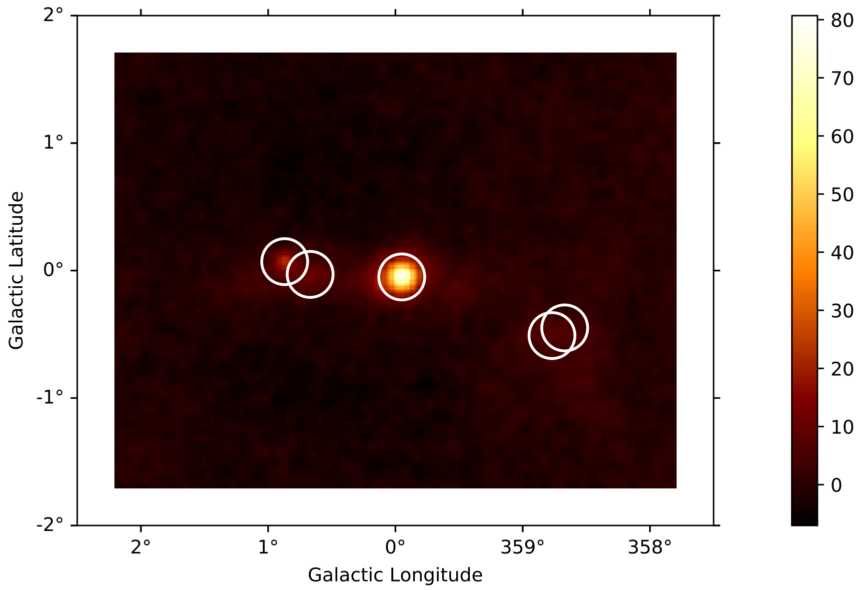

Figure 2.3: Source detection of the five highest energy sources which are marked by the white circles. The axes represent the Galactic longitude and latitude, while the colorbar is indicative for the amount of measured counts.

2.3 Fitting and Modeling Procedure

As a consequence of the energy dimension of the H.E.S.S. I data, the morphology and spectrum of gamma-ray sources can simultaneously be modelled in gammapy. In order to enable a proper spatial and spectral fitting, spatial and spectral models need to be created and afterwards fitted to the dataset by varying their specific parameters until they match the data. For generating a spatial model, first the expected shape of the source morphology has to be set. The Galactic center and G0.9+0.1 a point source is set in this analysis, whereas HESS J1745-303 is modelled by a Gaussian distribution. //

Fit function for point sources:

$$\phi(lon, lat) = \delta(lon - lon_0, lat - lat_0) \tag{2.1}$$

lon_0 and lat_0 indicate the expected longitude and latitude of a given coordinate system. The function can be fitted by adjusting lon and lat to the dataset.

Fit function for a Gaussian source:

$$\phi(lon, lat) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) \tag{2.2}$$

In this case θ is the angular separation between the center of the Gaussian function and the evaluation point.

The chosen shape indicates which parameters need to be set. For point sources only a longitude (lon_0), latitude (lat_0) and coordinate system needs to be set. A Gaussian function further requires to set a σ value, indicating the width of the region. The fitting procedure then starts by taking these parameter values and adjusting them until lon, lat and σ until the functions match the data as closely as possible.
In order to enable a spectral analysis, the function describing the spectrum has to be set first. For the Galactic center a power law function with an exponential cutoff is set, while G0.9+0.1 and HESS J1745-303 are modelled with power law functions which can be described the following way:

$$\phi(E) = \phi_0 \cdot (E/E_0)^{-\Gamma} \tag{2.3}$$

In order to fit a power law spectrum, parameters for the amplitude ϕ_0, the spectral index Γ and the reference energy E_0 need to be set. As in the spatial model, Γ and ϕ will then be varied, starting from set parameters values, until they fit the actual spectral data as closely as possible. A power law distribution with an exponential cutoff is modelled the following way:

$$\phi(E) = \phi_0 \cdot (E/E_0)^{-\Gamma} \cdot \exp(-\lambda E) \tag{2.4}$$

Apart from the previously mentioned parameters, a value for λ needs to be set which afterwards is also adjusted to the data.

3 Background Fit and Analysis

Air showers which are produced by hadrons and electrons can look like gamma-ray showers (Abramowski et al., 2014) and will therefore be detected and included in the H.E.S.S. I data. These emissions are referred to as background emissions and need to be fitted, modelled and afterwards subtracted from the rest of the data in order to enable a proper analysis of the sources and diffuse gamma-ray emissions.
The reason for this is that sources and background emissions overlap in terms of their galactic longitude and latitude, but still need to be modelled as separate entities. In order to create background images like Figure 2.2, H.E.S.S. I observations are used that have not been taken in the direction of the galactic plane. First, a field-of-view coordinate system is constructed around the pointing direction of the telescopes. Then, coordinates

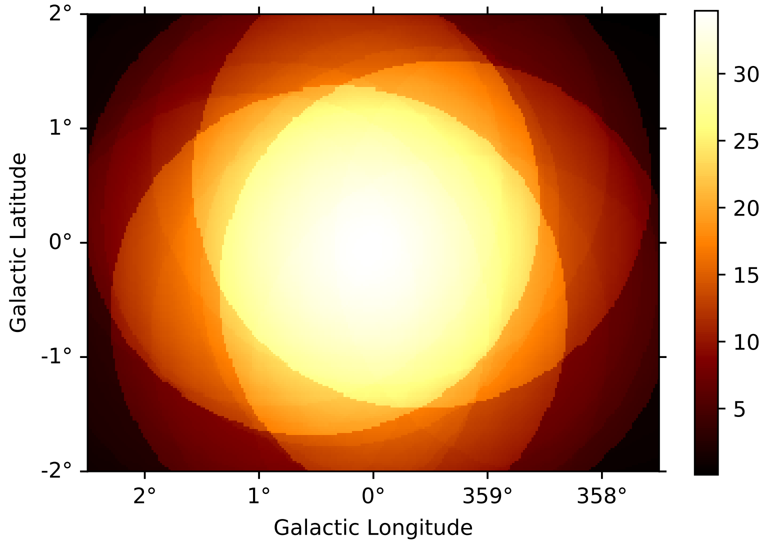

Figure 3.1: Model of the hadronic background that has been stacked over all observations. The colorbar represent the amount of counts that have been simulated as being part of detected background emissions, while the axes indicate the Galactic longitude and latitude.

of the measured events are transformed into this coordinate system and those events are averaged over multiple observations, in order to obtain a predicted rate for background emissions in every area. Events that originate in gamma-ray sources are taken out of

the data so that solely background emissions are used in the process of generating the hadronic background model (Lars Mohrmann, 2019).
As can be seen in Figure 2.2, the background image has the shape of a circle which is centered around the pointing direction of the telescope. To model the whole background, it is therefore necessary to stack background images of several observations. This way the pointing direction can be varied over all observations, in order to model the background of the whole area equally.
In our case 424 H.E.S.S. observations are taken into account.

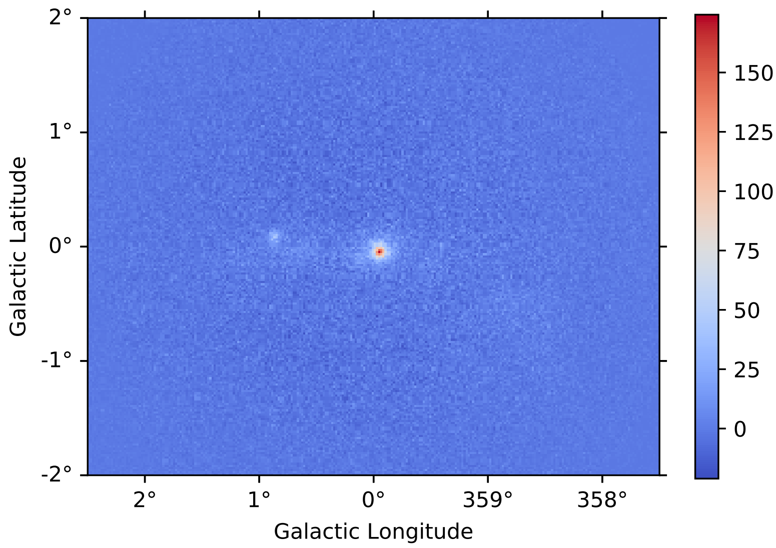

Figure 3.2: Stacked residual image. The modelled background has been subtracted from the stacked count values. The axes represent Galactic longitude and latitude, whereas the colobar indicates the number of counts.

Figure 3.1 shows a map that is generated by stacking all background maps one over the other. In the modeling procedure, the regions from Table 2.1 are masked out. That is necessary to ensure that the background model is solely fitted to background gamma-ray emissions. Otherwise, the background model would include actual gamma-ray sources and therefore be estimated as being a higher value. For every observation the smallest count value is used as an energy thresholds and the fitted models have been stacked afterwards (Mohrmann, 2019).
In a next step, it is possible to subtract the background model from the overall count data. This way, the differences between the model and the actual data is visible which is needed to model parts of the data that have been left unmodelled yet. The Galactic center and G0.9+0.1 can be noticed as red, respectively white dots on the residual map as they have not been modelled yet.
Diffuse emissions and the source HESS J1745-303 can further be noticed as light blue areas of about 25 counts. The count values therof are not as high as the counts of the

Galactic center and G0.9+0.1, but still require separate modeling. By masking areas

of higher gamma-ray emissions like the sources and the regions mentioned in Table 2.1, the accuracy of the background model can be better assessed. As seen in Figure 3.3, differences count values only range from -4 to 4, whereas the differences in Figure 3.2 reached up to more than 150 counts. The aim of further modeling is to reduce differences in counts between model and reality by simulating diffuse gamma-ray emissions and the emitted counts of the Galactic center, G0.9+0.1 and HESS J1745-303.

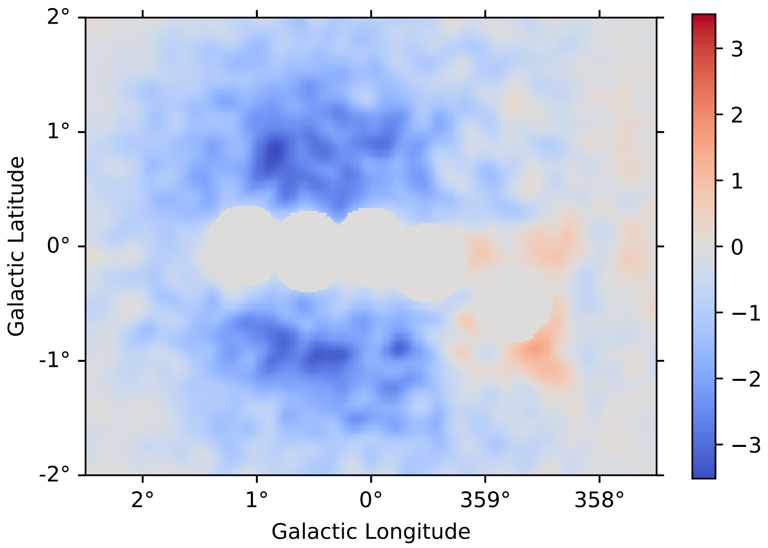

Figure 3.3: Stacked residual image with masked sources and regions of higher gamma-ray emissions (see Table 2.1. The axes are indicative Galactic longitude and latitude, whereas the colobar represents the number of counts.

4 Stacked Fit and Analysis

In this step, the Galactic center, G0.9+0.1 and HESS J1745-303 are modelled as sources and added to the overall model which then comprises the background model and these sources. The model of every one of these sources consists of a spatial model and a spectral model that then in their combined form are called a source model.
As seen in section 2.3 the spatial model requires to first set a function which describes the morphology of the source. The Galactic center and G0.9+0.1 are described as point sources in this analysis, while the morphology of HESS J1745-303 is approximated by a Gaussian distribution. Then the coordinate system and lon_0 and lat_0 are set for each source. Additionally the Gaussian function of HESS J1745-303 requires a σ value that is set as well. During the fitting procedure, lon, lat and σ are then adjusted in such a way that the morphology function fit the dataset as closely as possible.

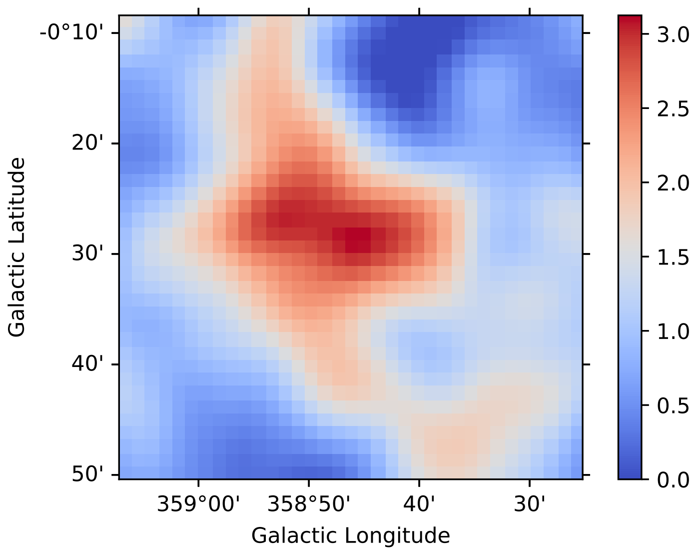

Figure 4.1: Plot of the source HESS J1745-303 that is then fitted as a Gaussian source. The axes represent the Galactic longitude and latitude, whereas the colobar indicates the amount of measured counts.

For a proper spectral model, the function describing the spectrum has to be set first. For the Galactic center a power law distribution with an exponential cutoff is set (see Abramowski et al., 2016), while normal power law functions are used for G0.9+0.1 and

HESS J1745-303. Then, starting parameters for the spectral index, the amplitude and, in case of the Galactic center, the λ value are chosen which are finally varied in order for the spectral functions to match the dataset accurately.
As can be seen in Figure 4.1 the shape of HESS J1745-303 is not exactly a spatial Gaussian distribution.
In chapter 2 is shown that two sources of gamma-ray emissions are detected in the area around HESS J1745-303. That can be the result of the more complex shape of HESS J1745-303 or there is in fact another source which has not been taken into consideration that requires separate modeling.
It is further to note that a σ value of 1° has to be used for the Gaussian distribution of the spatial dimensions of HESS J1745-303. By looking at Figure 4.1 a σ value of 0.5 would have been more suitable for the spatial dimensions of the source. However, due to errors in the fitting procedure only a σ value of 1 can be used which results in further inaccuracies. As a result, the model will only be an estimation of the actual source which leads to visible differences between the values of observed and modelled counts in that area.
Afterwards, all three source models are combined into a single source model, fitted to the H.E.S.S. I count data of the Galactic center region and plotted as seen in Figure 4.2.
Again, a residual image (see Figure 4.3) can be generated which subtracts the model

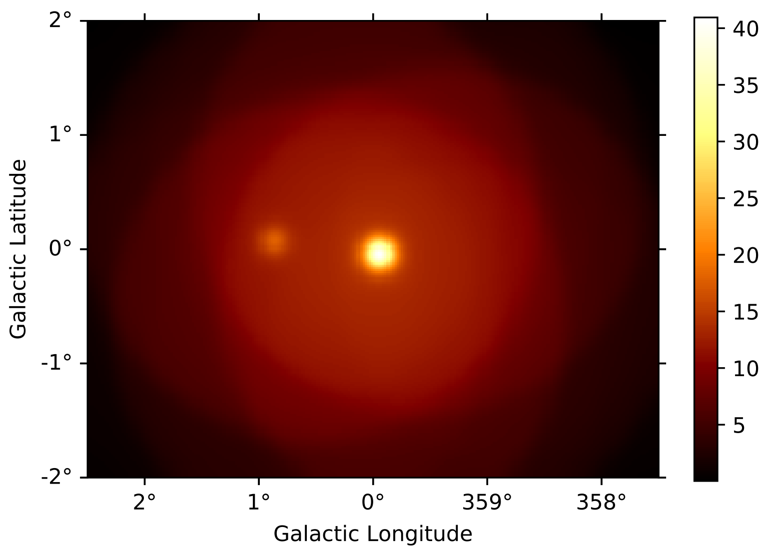

Figure 4.2: Model which comprises the source model of the Galactic center, G0.9+0.1 and HESS J1745-303. The axes show the Galactic longitude and latitude. The colorbar makes the count values visible.

values from the measured count values. By fitting the Galactic center, G0.9+0.1 and HESS J1745-303, pronounced differences in counts in the areas of these sources have been minimized which is the aim of the source models. The red dot next to the Galactic center is the radio arc (H.E.S.S. Collaboration et al., 2018) that is not separately modelled in this analysis. Other gamma-ray emissions in the central area (between 359° and 1° of Galactic longitude and −0.5° and 0.5° of Galactic latitude) with count values of about 2 are a consequence of diffuse emissions and are fitted and modelled in the chapter 5. The fitted spectral index value for the Galactic center is 2.106, while a value

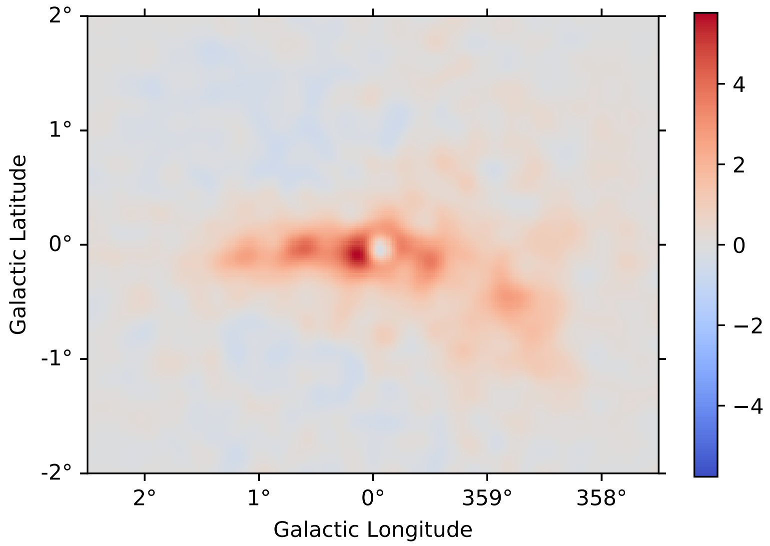

Figure 4.3: Model which comprises of the source model of the Galactic center, G0.9+0.1 and HESS J1745-303. The axes show the Galactic longitude and latitude. The colorbar makes the count values visible.

of $2.14 \pm 0.02_{stat} \pm 0.1_{syst}$ is expected in theory (Abramowski et al., 2016). Taking the error range into consideration, the fitted value is in accordance with the expectations. For G0.9+0.1 that has an expected spectral index of $2.4 \pm 0.11_{stat} \pm 0.2_{syst}$ (Aharonian, F. et al., 2005), 2.508 is fitted as the index value which also places itself in the expected range.

Table 4.1: For every source fitted index values and their error range are compared to expected index values.

Source	fitted index	error range	expected index
Galactic center	2.106	±0.0347	2.14 ± 0.12
G0.9+0.1	2.508	±0.0487	2.40 ± 0.13
HESS J1745-303	3.178	±0.174	2.71 ± 0.13

For HESS J1745-303 an index of 3.178 is fitted, while the expected index value is $2.71 \pm 0.11_{stat} \pm 0.2_{syst}$(Aharonian, F. et al., 2008). As seen in Table 4.1, the Galactic center and G0.9+0.1 have a suitable index, taking the error ranges of the expected value and the fitted value into account. Only the index of HESS J1745-303 lies outside both error ranges by 0.16. This is again the result of the spatial dimensions of HESS J1745-303 which is discussed beforehand.

5 Analysis of the Estimated Diffuse Emissions

At this point, background emissions and source emissions are included in the model which means that diffuse emissions are left to require separate modeling. By adding a model for diffuse gamma-ray emissions to the model, differences between modelled and observed count data can be minimized and spectral indices can be compared to prior publications.

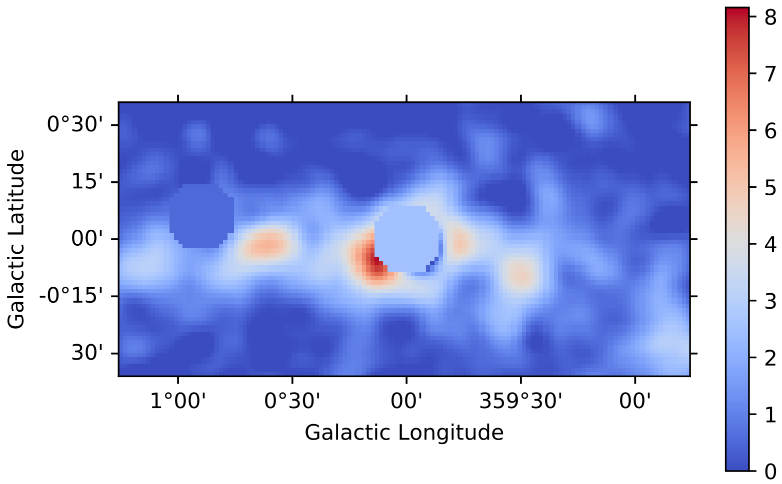

Figure 5.1: Estimated diffuse emissions in an area between 385.75° and 1.25° of Galactic Longitude and between −0.6° and 0.6° of Galactic latitude. The Galactic center is placed at 0° of longitude and 0° of latitude and is given an estimated count value of 2.578 by averaging over pixels in close proximity. For G0.9+0.1 (0.9° of longitude and 0.1° of latitude) is estimated with a count value of 0.551 by following the same procedure.

Sagittarius A* is known to be a low-luminosity galactic nucleus (LLAGN) and therefore thought to be generating accelerated high-energy cosmic-ray (CR) protons as LLAGNs have been indicated to accelerate CR protons in their accretion flows. In a following, the cosmic-ray protons interact with photons or other protons, resulting in the production of gamma-rays and neutrinos which can later be observed. Sagittarius A* is surrounded by the central molecular zone which is the dense molecular gas in the given area. A part of the previously accelerated protons enter the central molecular zone and result in gamma-rays and neutrinos by the mentioned interactions with protons and photons. (Fujita, Kimura, and Murase, 2016)

For this thesis, gamma-ray emissions which are generated in this process are analyzed as they are what is referred to as diffuse emissions. As the emissions of the point sources overlap with these diffuse emissions, it is important to mask the source regions out in the fitting procedure. Otherwise, the fitting parameters would be adjusted to the count values of the sources as well and would therefore not reflect diffuse emission counts on their own.
At the same time, the masked source areas still generate diffuse gamma-ray emissions which is the reason as to why the regions cannot be set to zero either. In the following, it is important to estimate diffuse emissions in the given areas in order to enable an accurate diffuse fit. The estimation is done by averaging over the pixels right next to the mentioned source areas.
These areas predominantly emit diffuse gamma-ray photons and are therefore indicative

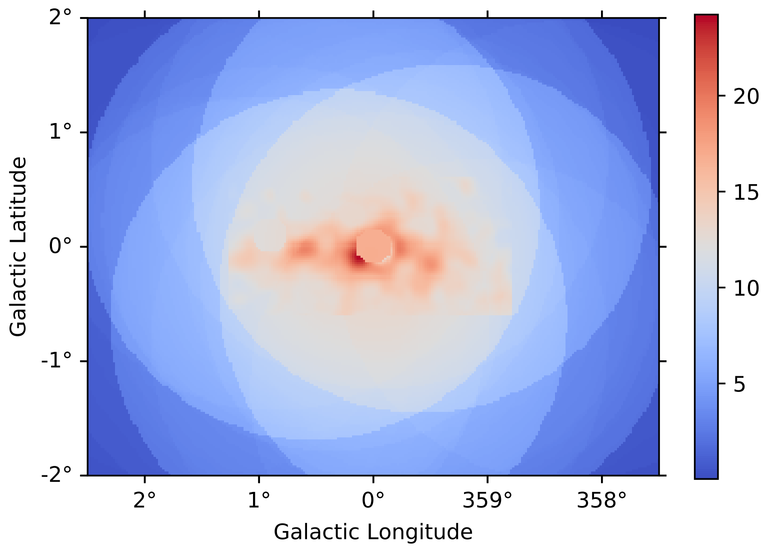

Figure 5.2: Model of diffuse emissions and the stacked background fit. The axes make it possible to localize different areas in terms of their Galactic longitude and latitude, while the colorbar indicate the amount of modelled counts.

of diffuse emissions in the source area due to their close proximity thereof. In Figure 5.1 the area and data can be seen which is then used to fit diffuse emissions. It is important to note that the area only ranges from 385.75° and 1.25° of Galactic Longitude and $-0.6°$ and 0.6° of Galactic latitude. That means that diffuse emissions are only modelled and

fitted arount the Galactic center.
Just as in the stacked fit, a source model for the area needs to be created which comprises a spatial model and a spectral model. The difference is that the previously utilized map from Figure 5.1 is used as spatial model.

The expected index for diffuse emissions near the Galactic center is $2.32 \pm 0.05_{stat} \pm 0.11_{syst}$ Abramowski et al., 2016, while the fit resulted in an index of 2.361 ± 0.0161. Therefore the fitted index value lies in the expected value range. Next it is possible to plot the diffuse model, consisting of the stacked background map from Figure 3.1 and the fit which solely takes into consideration the estimated diffuse emissions.

That means that the Galactic center, G0.9+0.1 and HESS J1745-303 are not modelled in the map. As shown by Figure 5.2, the modelled area around the Galactic center (between 385.75° and 1.25° of Galactic Longitude and between $-0.6°$ and $0.6°$ of Galactic latitude.) has higher count values as the counts of the background and the counts of diffuse emissions have been added in the given region, while the rest of the map only consists of background emission counts. With the modelled map a residual image can be

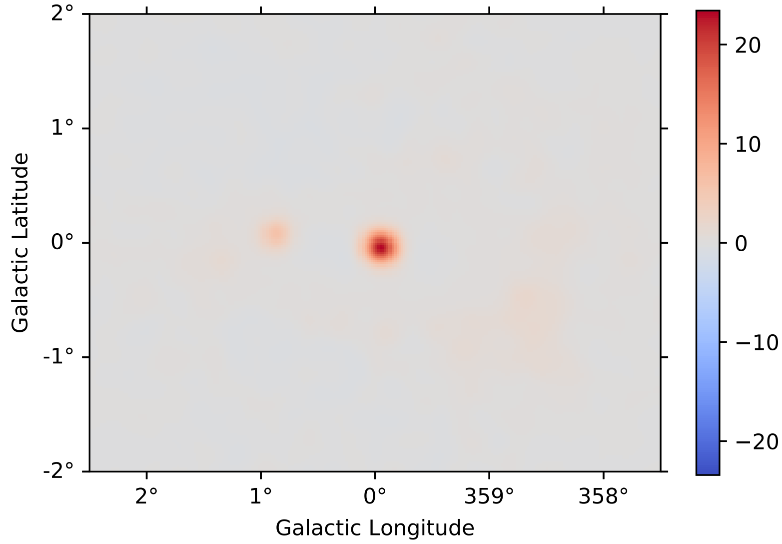

Figure 5.3: Diffuse residual image. The diffuse model, consisting of the modelled diffuse emissions and stacked background emissions is subtracted from stacked count values. The two axes represent Galactic longitude and latitude, while the colorbar is indicative of the difference in counts.

generated that can be seen in Figure 5.3. As expected, the regions of Galactic center and G0.9+0.1 have the highest count values due to the fact that the sources have not been modelled in Figure 5.2.

6 Combined Fit of the Background, Diffuse Emissions and Source Models

After background emissions, diffuse emissions and the gamma-ray emissions of the observed sources are fitted independently, all these models can be fitted in cohesion, as seen in Figure 6.1. Source models of the Galactic center, G0.9+0.1, HESS J1745-303 and diffuse gamma-ray emissions are therefore combined in one list. Afterwards, the individual models are fitted to the data by adjusting spatial and spectral parameters simultaneously to the data and the modelled counts of each model are added and plotted together, as seen in Figure 6.1. In order to make the differences to this counts map visible, again a residual image is generated which subtracts the modelled count values from the observation count map. Figure 6.2 shows that the model and the counts map differ only

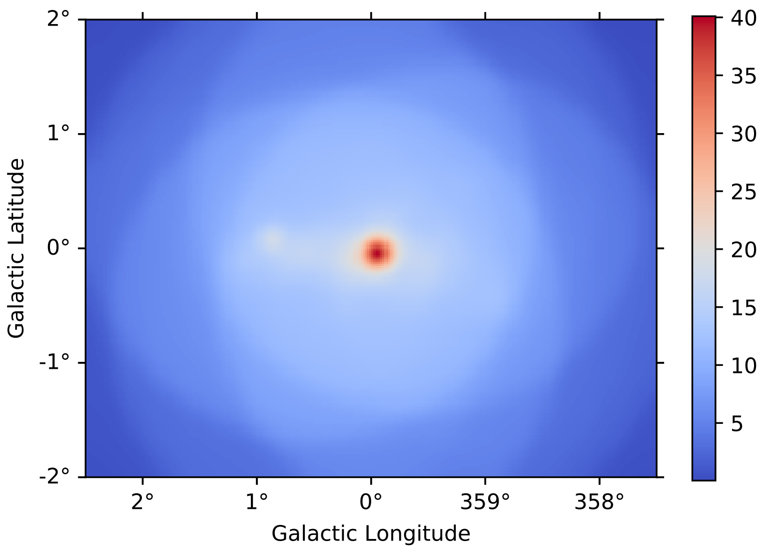

Figure 6.1: Model of the galactic center region which contains source models of the center, G0.9+0.1 and the Gaussian source HESS J1745-303 at 358.77° of Galactic longitude and −0.49° of latitude. These three sources have then been combined with the modelled diffuse emissions and plotted in conjuncture.

up to 2 counts, while the modelled regions' count scale, that can be seen in Figure 6.1, ranges up to 40 counts. Also previous residual images have a higher difference in counts. The subtraction of only the stacked background model from all counts produced a count difference up to more than 150 counts (see Figure 3.2), the residual of the diffuse model which comprised of diffuse emissions and the stacked background emissions reached up to more than 20 counts (see Figure 5.3).
Previously, the most accurate model and therefore lowest difference in counts is seen in a stacked model comprising the Galactic center, G0.9+0.1 and HESS J1745-303 which reached only up to about 6 counts (see Figure 4.3).

The difference in counts between models and measured count values is an indicator of

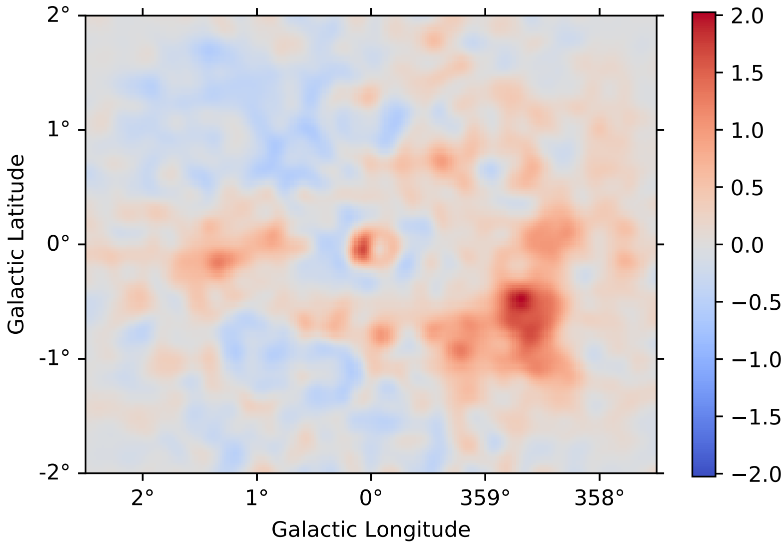

Figure 6.2: Residual image of the modelled combined data by subtraction of the model from the overall counts map. HESS J1745-303 seems not to be modelled quite as good as the further regions due to the fact that diffuse emissions are only fitted between 385.75° and 1.25° of Galactic Longitude and between −0.6° and 0.6° of Galactic latitude.

the accuracy of a model as it is used to depict observed counts as closely as possible. It is further noticeable that discrepancies between the modelled data and the actual counts seem to happen mainly near the source HESS J1745-303. The reason for this discrepancy seems to be the fact that diffuse emission are only estimated in a smaller area near the center between 385.75° and 1.25° of Galactic longitude and between −0.6° and 0.6° of Galactic latitude.
By estimating the diffuse emissions near HESS J1745-303, it is expented for these differences to become significantly smaller which means that the modelled data would be an even better representation of the actual observed count values in the Galactic center region. Also the shape of HESS J1745-303 seems not to be a Gaussian distribution (as

mentioned in chapter 4) which further affects the results.
The red circle around the center represents the galactic center radio arc (H.E.S.S. Collaboration et al., 2018). Modelling the radio arc separately as well would further improve the quality of the model and lead to lower differences in counts between observed counts and the model. While diffuse emissions in this area have been fitted, the radio arc source itself has not been included as a separate source in the fitting procedure. Afterwards a significance map has been produced that can be seen in Figure 6.3. As

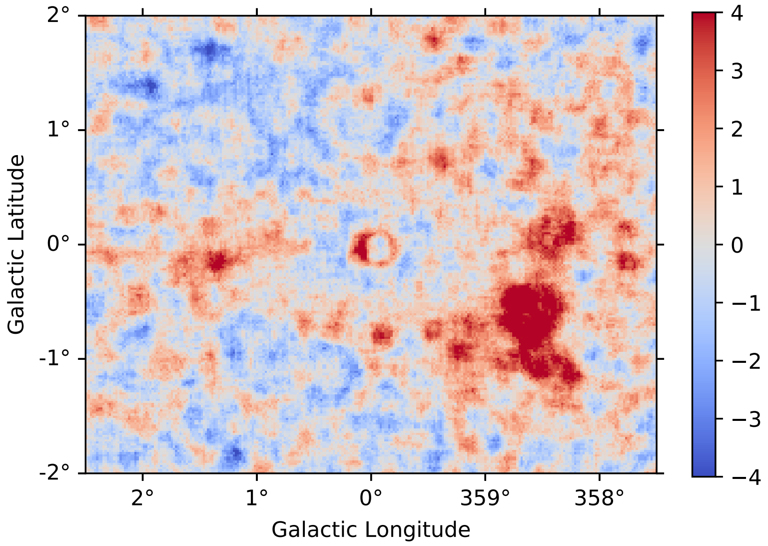

Figure 6.3: Significance of the previously generated residual image. The mentioned disparity in residual counts between HESS J1745-303 in Figure 6.1 is made visible even more.

in the residual image, the galactic arc and diffuse emissions around the source HESS J1745-303 are clearly visible, meaning that differences between model and reality are the most significant in this area by also taking into account the amount of overall measured counts. Index values and error ranges have again been fitted for the Galactic center, G0.9+0.1, HESS J1745-303 and diffuse emissions in the Galactic center area in cohesion. Taking into account the error ranges of the fitted indices and the error of expected index values, the Galactic center, G0.9+0.1 and diffuse emissions lie in the expected value range and are therefore an accurate representation of the measured data. HESS J1745-303 lies outside the expected range by an index value of 0.2. Again, this discrepancy can be explained by the fact that no diffuse emissions are fitted in the area of the source and the shape of HESS J1745-303 has been modelled as a Gaussian distribution.
Also a σ value of 1° has to be used in the Gaussian fit due to errors for smaller σ value which leads to in further inaccuracies.
The analysis of the modelled morphology can be intensified by analysing count values of background emissions, diffuse emissions and source emissions relatively to their Galactic

Table 6.1: Fitted index values and their error range for the Galactic center, G0.9+0.1, HESS J1745-303 and diffuse emissions in the Galactic center area are compared to expected index values.

Source	fitted index	error range	expected index
Galactic center	2.097	±0.0455	2.14 ± 0.12
G0.9+0.1	2.475	±0.0505	2.40 ± 0.13
HESS J1745-303	2.191	±0.221	2.71 ± 0.13
diffuse emissions	2.390	±0.021	2.32 ± 0.16

longitude and latitude. First, only count data in a range from −0.1° to 0.1° of Galactic latitude are extracted from the original dataset of the combined model. Then, count values can be integrated over the latitude range, resulting in set of count data per given Galactic longitude which can be plotted, as seen in Figure 6.4. The same procedure can be repeated in to plot count data over the Galactic latitude in a longitude range from 385.75° and 1.25°. In both plots, only counts with energies between 1 and 84 TeV are used as an example.

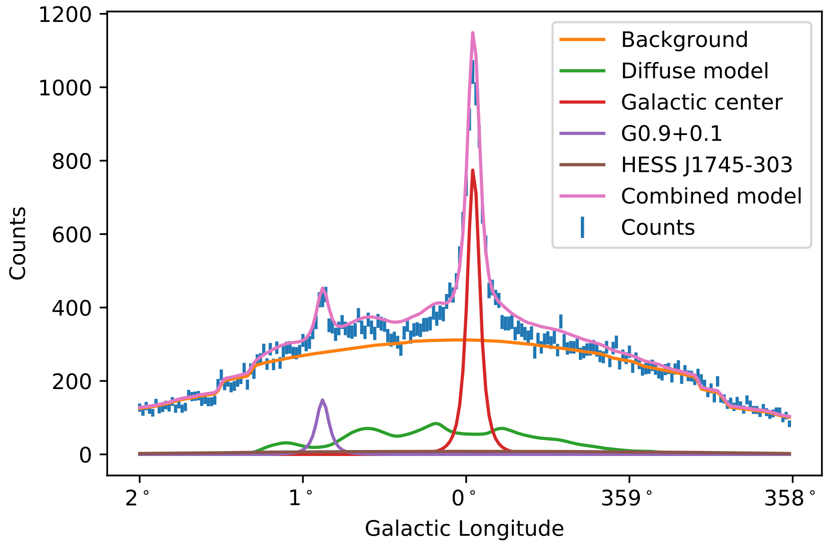

Figure 6.4: Counts of the combined dataset, source models of the Galactic center, the Gaussian source HESS J1745-303, background and diffuse emissions alongside observed count values plotted over their Galactic longitude in a latitude range of −0.1° to 0.1°.

Diffuse gamma-ray emissions, hadronic background emissions and source counts are plotted by differently colored curves. The overall model curve is the sum of these different datasets for a given value of Galactic longitude or latitude. By plotting count values

over the Galactic longitude it is visible that diffuse emissions have only been fitted in a range from 385.75° and 1.25° of longitude. The peak at 0° of longitude is indicative of the Galactic center, while emissions from G0.9+0.1 manifest themselves as a smaller peak at 0.9°.
By combining source, diffuse and background models measured gamma-ray emissions can be modelled as a whole which is shown by the pink curve. The blue lines represent the observed count data with an errorbar of the squarerooted count value. By comparing the overall count data from H.E.S.S. I observations to the modelled values, the model seems to mostly accord with reality.

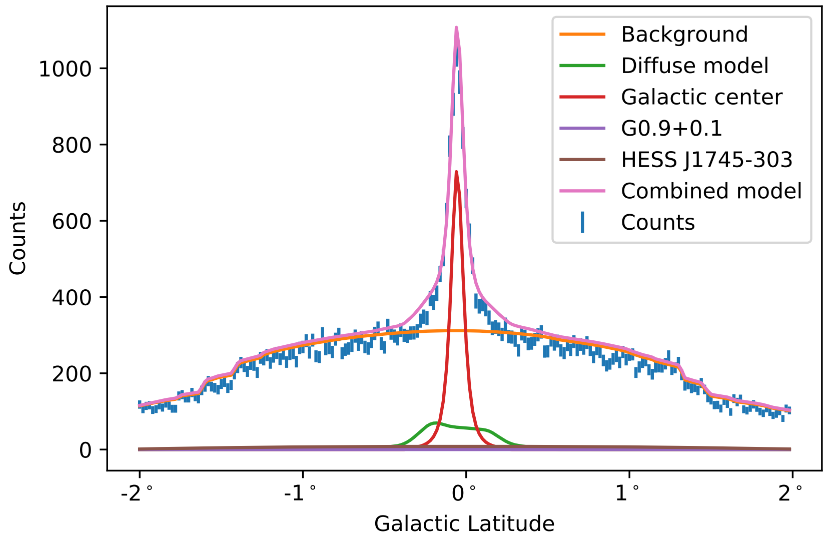

Figure 6.5: Counts of the combined dataset, source models of the Galactic center , the Gaussian source HESS J1745-303, background and diffuse emissions alonside observed count values plotted over their Galactic latitude in a range of 359.9° to 0.1° of Galactic longitude.

By plotting the counts over the Galactic latitude, only Galactic center count values are plotted due to the used range of longitude that excludes G0.9+0.1 from the data. It is further visible that diffuse emissions are modelled between $-0.6°$ and 0.6° of latitude. Again, measured count values seem to be in accordcance with the modelled count data.

7 Flux Point Analysis

As spectral properties of the Galactic center and G0.9+0.1 are fitted alongside the morphology of the sources, it is possible to afterwards plot the spectra of the Galactic center and G0.9+0.1. In order to estimate flux points, it is first necessary to select the dataset of a spectral model and choose the source for which flux points are to be computed. Also, a list of energy values is needed that determines the energy edges of the flux point bins. For the estimation of a given flux point, the amplitude of the selected spectral model is fitted within the energy range that has been set by the energy list. This is done for each energy group independently. The amplitude is altered by using the "norm" parameter, which specifies the deviation of the flux from the spectral model in the given energy range (*FluxPointEstimator*).

By fitting suitable curves to the computed flux data, it is possible to analyze the

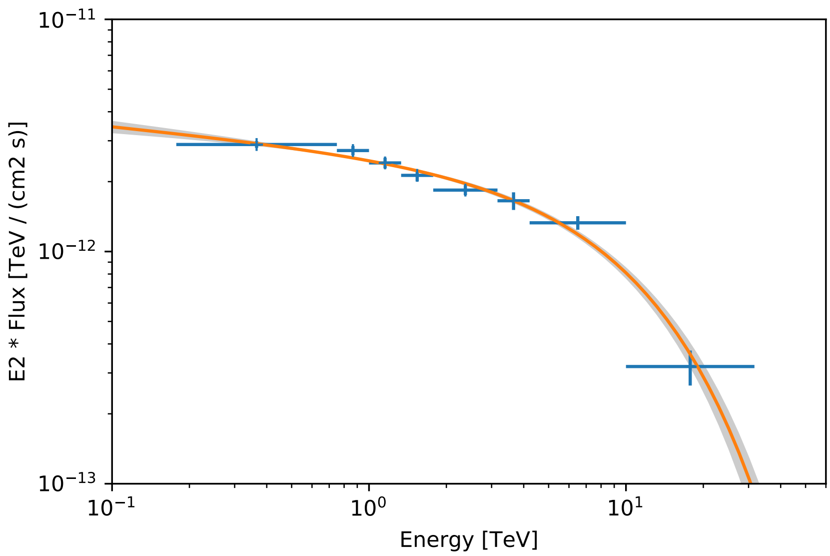

Figure 7.1: Flux points of the galactic center, fitted by a power law with an exponential cut-off. The fluxes have been multiplied with the value E^2, while E is the energy of the x-axis in units of TeV $cm^{-2}s^{-1}$. The grey areas represent confidence bands of the spectral fit, while the errorbars of each computed flux point is shown by the blue line.

gamma-ray flux for different energies. In Figure 7.1 the flux of the Galactic center is multiplied by E^2 with the energy value E and plotted over its energy. As expected the gamma-ray flux can be modelled by a power law distribution with an exponential cut-off. The previously fitted spectral index of 2.097 is used as a starting fitting parameter for the curve and varied in the fitting procedure. Also, the previously fitted spectral amplitude of $2.744 \cdot 10^{-12} cm^{-2} s^{-1} TeV^{-1}$ and the reference energy of 1 TeV are used as parameters which can then adjusted to the computed flux points.

The spectrum of G0.9+0.1 is fitted by a power law as previously assumed (see Figure 7.2). Again, the fitted index of 2.475 is used alongside an amplitude of $6.790 \cdot 10^{-13} cm^{-2} s^{-1} TeV^{-1}$ and a reference energy of 1 TeV in order to approximate the distribution of computed flux points by the power law function. The flux was plotted over the energy without multiplying it with E^2 as it was the only way to compare it with other publications. The plotted distribution of gamma-ray flux matches the expected distribution from Aharonian, F. et al., 2005.

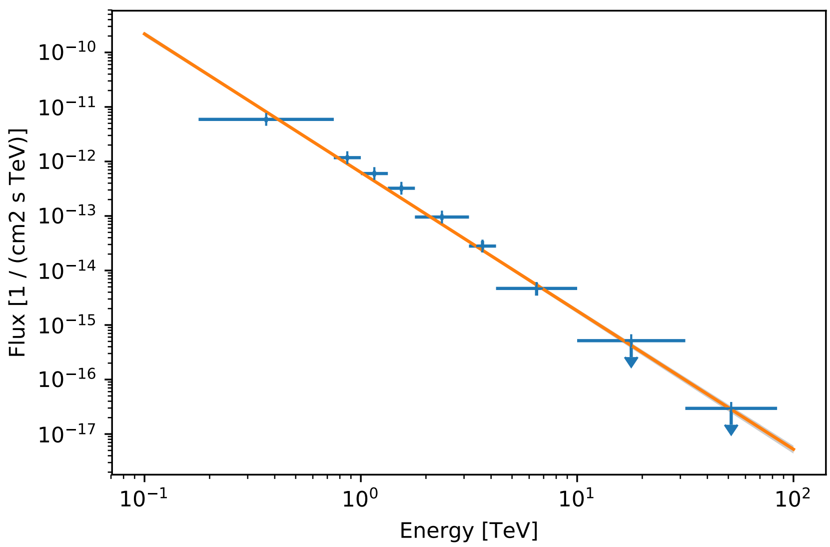

Figure 7.2: Flux points of G0.9+0.1, fitted by a power law distribution. The gamma-ray flux has been plotted over the energy axis. The grey areas represent confidence bands of the spectral fit, while the errorbars of each computed flux point is shown by the blue line.

8 Conclusions

The aim of the conducted H.E.S.S. data analysis is to generate a 3D model of the Galactic center region which consists of both the morphology and the spectrum of gamma-ray sources, background emissions and diffuse emissions.

The analysis is conducted in four steps. First, hadronic background emission are modelled by averaging gamma-ray emissions of several background observations and ignoring emissions from known gamma-sources in the process (see chapter 3). In a next step, the count and hadronic background data of all 424 observations is stacked, and the morphology and spectrum of the Galactic center, G0.9+0.1 and the source HESS J1745-303 is modelled by fitting spatial and spectral parameters to the dataset. This second model of the data then consists of these source models and the stacked background counts (see chapter 4). In a third step, diffuse emissions are additionally modelled in an area between 385.75° and 1.25° of Galactic Longitude and between $-0.6°$ and 0.6° of Galactic latitude and fitted to the observation data (see chapter 5). The final step is then taken in combining the models of the Galactic center, G0.9+0.1, HESS J1745-303, diffuse emissions and background emissions. Again, spatial and spectral parameters are fitted and comparisons between the model and reality can be made (see chapter 6).

By comparing the created model to the measured count values from 424 H.E.S.S. observations and comparing the fitted spectral indices to prior publications, it can be concluded that the modeling procedure is succesful and mostly led to the desired results. In the following, spatial and spectral properties are compared to the measured count data and publication indices:

The fitted model of the Galactic center is accurate regarding its morphology but also its spectral index. The modelled count data for the Galactic center can be compared to the measured morphology by assessing the plotted residual image of the model (see Figure 6.2). This residual image subtracts the modelled counts from the actually observed counts and therefore visualizes the differences between model and reality. As seen in Figure 6.2, the differences in counts in the area of the Galactic center (0° of Galactic longitude and latitude) are minimal. Regarding its spectral properties, an index of 2.14 ± 0.12 appeared in the work of Abramowski et al., 2016. The fitting procedure that is done in this analysis resulted in an index of 2.097 ± 0.0455 which fits the expectations by taking into account the error ranges of the expected value and the fitted value. G0.9+0.1 is also accurately modelled in term of its morphology which can also be seen in Figure 6.2. The fitted spectral index of $2.475 + 0.0505$ also fits to the expected index value of 2.40 ± 0.13 from Aharonian, F. et al., 2005. Diffuse emissions in the Galactic center area also are modelled well, resulting in an estimated index of 2.390 ± 0.021 which lies in the error range of the expected index of 2.32 ± 0.16 (Abramowski et al., 2016). The modelled morphology also is in alignment with measured count values in the area between 385.75° and 1.25° of Galactic Longitude and between $-0.6°$ and 0.6° of Galactic latitude where diffuse emissions are actually modelled.

The only slight discrepancy between model and reality occured in the modeling procedure of HESS J1745-303. One of the reasons for this is that the source had to be approximated by a spatial Gaussian distribution which does not properly reflect the spatial dimensions of the source. Also a potential second source, that can be seen in Figure 2.3, in the area around HESS J1745-303 can affect the fitted parameters and maps. Secondly, the σ value of the Gaussian distribution has to be set to a value of 1° which is too high. This happened due to errors in the fitting procedure for lower σ. The third reason as to why HESS J1745-303 cannot be modelled as accurately as the Galactic center and G0.9+0.1, is that diffuse emissions in the area of HESS J1745-303 are not estimated.

Taking all these factors into account, the fitted index of 2.191 ± 0.221 seems plausible in comparison to the expected value of 2.71 ± 0.13.

It is however important to note that the modeling of HESS J1745-303 is not the priority of this analysis. The focus is set on properly modeling spatial and spectral properties of the Galactic center, G0.9+0.1 and modeling background and diffuse emissions accurately in the area right around the Galactic center (between 385.75° and 1.25° of Galactic Longitude and between $-0.6°$ and 0.6° of Galactic latitude). Future gammapy analyses of the Galactic center can be improved by taking into account several aspects. First, diffuse emissions in the whole observed area need to be modelled in order to create a model which is as accurate as possible. Secondly, sources with more complex spatial shapes like HESS J1745-303 can be approximated by using two different source models in order to model the more complex source.

By placing two smaller sources one next to the other, the shape of HESS J1745-303 can be modelled more precisely. Thirdly, the analysis can be improved by taking into account more sources like the radio arc. Source models for these can be created and added to the combined source model. Afterwards all sources can be fitted and the observed count data can be approximated even better.

It can be overall concluded that the analysis of the Galactic center region is successful and resulted in accurate models of the prioritized area around the Galactic center. The modelled morphologies of the Galactic center, G0.9+0.1, diffuse emissions and hadronic background emissions matched the H.E.S.S. dataset and the fitted spectral indices accord to values from prior publications.

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Erklärung

Hiermit bestätige ich, dass ich diese Arbeit selbstständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt habe.

Erlangen, den 30.07.2019

Matei Ruta

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