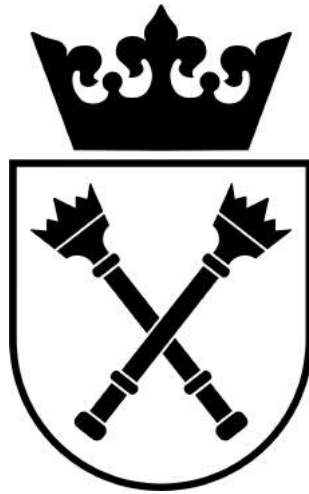




MORPHOLOGICAL STUDY OF TEV EMISSION FROM 1ES 0414+009
AND CENTAURUS A WITH H.E.S.S. DATA

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The H.E.S.S. data used for this research are not publicly available and the results obtained in this work have not been published yet. Therefore, one should not make any reference to the results presented in this thesis, but rather to the future respective official H.E.S.S. publications.

*To my family
and to everyone who helped me reach this point.*

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ABSTRACT

Analysis of unpublished High Energy Stereoscopic System (H.E.S.S.) data revealed that two AGN, namely a blazar 1ES 0414+009 located at redshift $z = 0.287$ and a Fanaroff-Riley type I (FR I) radio loud galaxy Centaurus A with redshift $z = 0.002$, possess an extended γ -ray morphology. All other AGN detected in the TeV range (~ 50 objects, [H.E.S.S. Collaboration et al., 2014b](#)) are marked to be point-like sources in the literature and in the TeVCat¹ catalogue. The significant extended morphology of both 1ES 0414+009 and Centaurus A in the H.E.S.S. data may result from physical processes outside the active nucleus, as well as from technical issues related to, among others, observational methods or data calibration, reduction, and analysis processes.

This thesis is dedicated to the detailed study of the extended VHE γ -ray emission of these two AGN. In case of the FR I radio galaxy, the extension in the VHE data was expected, however the blazar's extension was considered as an observational error or some kind of analysis systematics. The performed investigations are intended to verify the extended structures of both sources using improved reconstruction software and longer observations conducted with the H.E.S.S. telescopes compared to the previous analyses.

In order to verify the data analysis procedures for 1ES 0414+009 and Centaurus A, a reference sample of four additional blazars was selected, including 1ES 0347-121, 1ES 1101-232, 1ES 0229+200, and PKS 0548-322, which are claimed in the literature to be point-like VHE γ -ray emitters. Moreover, for the same reason, specially designed Monte Carlo (MC) simulations of the morphological models fitting were performed comparing the simulated and observed H.E.S.S. data.

All analysed blazars are classified as so-called extreme high frequency peaked BL Lacs (extreme HBLs). Thus, the conducted analyses will also shed light on the spectral and morphological properties of this kind of objects in the TeV γ -ray range.

The major results were cross-checked with two independent programs for data analysis commonly used in the H.E.S.S. Collaboration, i. e. *ImPACT* and *M++*, in order to verify the consistency of the output. The results are as follows:

- An extension in the VHE emission of 1ES 0414+009 is confirmed. The observational data limited by the cuts in the years of observations, the zenith angles, and the energy ranges do not show any significant changes in the extension parameters, i. e. width, semi-axes, and position angles. In this case, however, the measured position angle significantly deviates from the parsec scale Very Long Baseline Array (VLBA) and large scale Very Long Array (VLA) radio structures. It is noted that the eventual γ -ray extension could be generated by the

¹ <http://tevcat2.uchicago.edu/>

AGN activity on intermediate timescales between the VLBA and VLA structure formation, when the jet's orientation (pointing towards an observer) can significantly deviate from the current observations.

- An extension in the VHE γ -ray emission of Centaurus A is confirmed. Based on the analysis of a number of selected datasets limited by the same cuts as in the case of 1ES 0414+009, it appears that the angular extension and its position angle are independent on the data fluctuations. The derived position angles in all studied datasets are compatible with the Centaurus A parsec scale Very Long Baseline Interferometry (VLBI) and large scale VLA radio jet position angles.

The analyses of the selected extreme HBLs revealed interesting and unexpected systematic trends in the data:

- the measured extension in the VHE emission of all studied blazars seems to increase with redshift,
- the angular distance from the estimated best-fit VHE position to the position from different catalogues in lower frequencies decreases linearly with the redshift.

Since the analysed blazar sample includes only five objects, the significance of the observed trends is not high. Therefore, preliminary analyses of ten additional HBLs were performed to get better insight into this issue. A visual inspection of the resulting relation of semi-axes ratio to redshift of 15 blazars reveals a non-random distribution, however, a single clear systematic trend can not be pointed out due to two outliers at lower redshifts. This issue requires further study in the future.

This thesis is divided into three main parts. **Part I** contains three chapters constituting an introduction to the presented topic:

- [Chapter 1](#) consists of a brief description of radiative processes responsible for the emission of AGN, interactions of γ -rays with intergalactic ambient medium, production of particle cascades generated by γ -rays and cosmic rays in the Earth's atmosphere, as well as the Cherenkov radiation generated in such cascades.
- [Chapter 2](#) contains a description of the composition, emissivity regions, and phenomenological classification of AGN with particular emphasis on blazars.
- [Chapter 3](#) is dedicated to the imaging atmospheric Cherenkov observatories, in particular to data collection, calibration, reduction, and analysis methods employed within the H.E.S.S. Collaboration.

The next two parts are based on the author's original work, involving the new data analyses, modelling and discussion of the results. **Part II** describes the methodology and results of the accomplished investigations:

- motivation, framework, and methods of spectral and morphological analyses carried out during this study are described in [Chapter 4](#),

- results of spectral and morphological analyses, as well as a comparison between models used to study the morphology of objects in this work, are reported in details in [Chapter 5](#),
- a summary, outcome, and future perspectives are gathered in [Chapter 6](#). In this chapter, the results are also compared to additionally performed limited analysis of ten HBL blazars.

Part III contains two appendices:

- [Appendix A](#), containing a description of the MC simulations based on generated and observed TeV H.E.S.S. data,
- [Appendix B](#) presents the radio contour maps of examined AGN generated based on the VLBA, VLBI, and VLA observations and estimated position angles of the radio jets, which were later compared to the VHE extension position angles derived from the H.E.S.S. data.

STRESZCZENIE

Analiza niepublikowanych dotąd danych wysokoenergetycznych zebranych przez naziemne obserwatorium promieniowania Czerenkowa High Energy Stereoscopic System (H.E.S.S.) ujawniła, że blazar 1ES 0414+009 z przesunięciem ku czerwieni $z = 0.287$ oraz galaktyka radiowo głośna typu Fanaroff-Riley I (FR I) Centaurus A ulokowana na $z = 0.002$, posiadają rozciągłą strukturę wysokoenergetyczną w zakresie promieniowania γ . Pozostałe aktywne jądra galaktyk obserwowane w zakresie TeV (~ 50 źródeł, [H.E.S.S. Collaboration et al., 2014b](#)) są oznaczone w literaturze oraz katalogu TeVCat² jako źródła punktowe. Znacząca rozciągłość obu aktywnych jąder galaktyk w bazie danych H.E.S.S. może być wynikiem procesów fizycznych zachodzących poza aktywnym jądrem, jak również wynikiem problemów technicznych związanych z metodami obserwacyjnymi, kalibracją, redukcją, bądź analizą danych.

Niniejsza rozprawa doktorska jest poświęcona szczegółowemu zbadaniu rozciągłej wysokoenergetycznej emisji w zakresie γ obu aktywnych jąder galaktyk. Rozciągłość w danych wysokoenergetycznych jest spodziewana dla galaktyki radiowej, jednak w przypadku blazara była do tej pory uznawana za błąd wynikający z problemów na poziomie obserwacji lub analizy danych. Analizy przeprowadzone w ramach niniejszej rozprawy mają na celu zweryfikowanie, czy taka rozciągłość jest prawdziwa. Do tego celu zostały użyte dłuższe obserwacje uzyskane teleskopami H.E.S.S. oraz ulepszone oprogramowania do rekonstrukcji danych w porównaniu do wcześniejszych badań tych obiektów.

W celu sprawdzenia poprawności przeprowadzonej analizy danych dla 1ES 0414+009 i Centaurusa A, zanalizowane zostały również dane czterech dodatkowych blazarów rozważanych w literaturze jako obiekty punktowe, czyli 1ES 0347-121, 1ES 1101-232, 1ES 0229+200 i PKS 0548-322. Z tego samego powodu przeprowadzone zostały specjalnie zaprojektowane symulacje Monte Carlo dla procedury dopasowania modeli morfologicznych dla dwóch rodzajów danych: sztucznie wygenerowanych oraz bazujących na obserwacjach teleskopów H.E.S.S..

Wszystkie blazary badane w ramach niniejszej pracy zostały sklasyfikowane jako obiekty typu extreme high frequency peaked BL Lacs (extreme HBLs). Przeprowadzone analizy wybranych źródeł rzucą również światło na widmowe i morfologiczne własności tego typu obiektów w wysokoenergetycznym zakresie promieniowania γ .

Rezultaty uzyskane dwoma niezależnymi programami do analizy danych powszechnie używanymi przez grupę H.E.S.S., czyli *ImPACT* i *M++*, zostały skorelowane między sobą w celu potwierdzenia ich spójności. Głównymi wynikami zawartymi w niniejszej rozprawie są:

- Potwierdzona została rozciągłość wysokoenergetycznej emisji blazara 1ES 0414+009. Dane obserwacyjne ograniczone odcieczami w latach

² <http://tevcat2.uchicago.edu/>

obserwacji, kątach zenitalnych i zakresach energetycznych nie wykazały żadnych znaczących zmian w parametrach opisujących rozciągłość źródła, czyli szerokości, półosiach, czy kątach pozycyjnych. Jednakże zmierzone kąty pozycyjne rozciągłości wysokoenergetycznej znacząco odbiegają od kątów pozycyjnych obliczonych na podstawie danych radiowych w skali parseków z VLBA i wielkoskalowych z VLA. W dyskusji zaznaczono, że ewentualna wysokoenergetyczna rozciągłość może być generowana aktywnością jądra galaktyki w skalach czasowych między formowaniem się struktur widocznych w VLBA i VLA, kiedy orientacja dżetu (który w przypadku blazarów jest skierowany w stronę obserwatora) może się znacząco odchylić od aktualnych obserwacji.

- Potwierdzona została również rozciągłość w wysokoenergetycznej emisji Centaurusa A. Bazując na danych obserwacyjnych ograniczonych takimi samymi odcięciami jak w przypadku blazara 1ES 0414+009, okazuje się, że poszerzenie oraz kąt pozycyjny Centaurusa A są niezależne od fluktuacji w danych. Uzyskane kąty pozycyjne we wszystkich badanych zakresach są zgodne z kątami pozycyjnymi obu struktur radiowych widocznych w VLBI i VLA.

Analizy wybranych extreme HBLs ujawniły interesujące i niespodziewane trendy w danych:

- zmierzona rozciągłość wysokoenergetycznej emisji wszystkich badanych blazarów zdaje się wzrastać wraz z przesunięciem ku czerwieni,
- odległość kątowa między zmierzoną pozycją w danych wysokoenergetycznych i pozycją na niższych częstotliwościach z różnych katalogów zmniejsza się liniowo wraz z przesunięciem ku czerwieni.

Istotność obserwowanych trendów nie jest znacząca z powodu niewielkiej próbki przeanalizowanych blazarów zawierającej jedynie pięć obiektów. Z tego powodu wykonane zostały analizy dodatkowych dziesięciu blazarów typu HBL. Wizualna inspekcja uzyskanej relacji stosunku półosi do przesunięcia ku czerwieni dla 15 blazarów wykazała nielosowy rozkład. Jednak bezsprzeczny systematyczny trend nie może być wykazany z powodu dwóch blazarów z mniejszymi przesunięciami ku czerwieni, które wyraźnie odstają od trendu. Kwestia ta wymaga dalszych badań.

Niniejsza rozprawa doktorska podzielona jest na trzy główne części. **Część I**, składa się z trzech rozdziałów stanowiących wstęp do prezentowanych badań:

- **Rozdział 1** stanowi krótki opis procesów odpowiedzialnych za emisję aktywnych jąder galaktyk, oddziaływania promieniowania γ z międzygalaktycznym polem magnetycznym i materią, produkcji kaskad cząstek wtórnych generowanych przez promieniowanie γ oraz cząstki kosmiczne w ziemskiej atmosferze, a także promieniowania Czerenkowa produkowanego przez takie kaskady.

- **Rozdział 2** obejmuje opis aktywnych jąder galaktyk, w tym ich budowę, regiony promieniowania i ich klasyfikację fenomenologiczną, ze szczególnym uwzględnieniem blazarów.
- **Rozdział 3** jest poświęcony naziemnym obserwatoriom promieniowania Czerenkowa, szczególnie obserwacjom, kalibracji, redukcji i analizie danych praktykowanych wewnątrz grupy obserwatorium H.E.S.S.

Dwie kolejne części opisują pracę autora rozprawy, obejmującą nowe analizy danych, modelowanie oraz dyskusję. W **części II** opisane zostały metodologia i wyniki zrealizowanych analiz:

- **Rozdział 4** jest opisem motywacji i struktury przeprowadzonych badań w zakresie widmowym i morfologicznym,
- **Rozdział 5** zawiera wyniki widmowych i morfologicznych analiz wysokoenergetycznych danych badanych obiektów, jak również porównanie wyników dopasowania dwóch modeli morfologicznych użytych w ramach tej pracy,
- **Rozdział 6** stanowi podsumowanie wyników badań i wylicza przyszłe perspektywy wynikające z uzyskanych rezultatów. W tym rozdziale uzyskane wyniki zostały porównane z dodatkowo przeprowadzonymi analizami dla dziesięciu blazarów typu HBL.

Część III składa się z dwóch aneksów:

- **Aneks A** zawierający opis symulacji Monte Carlo wygenerowanych i obserwowanych danych H.E.S.S.,
- **Aneks B** prezentujący konturowe mapy radiowe badanych obiektów wygenerowane w oparciu o dane z trzech obserwatoriów: VLBA, VLBI i VLA, a także obliczone na ich podstawie kąty pozycyjne dżetów radiowych poszczególnych obiektów badanych w ramach niniejszej pracy, które zostały następnie porównane z kątami pozycyjnymi oszacowanymi dla wysokoenergetycznych rozciągniętych struktur na podstawie danych H.E.S.S.

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ACRONYMS AND ABBREVIATIONS

2MASS	Two Micron All Sky Survey
ADC	Analogue to Digital Converter
AGN	Active Galactic Nucleus/Nuclei
ATOM	Automatic Telescope for Optical Monitoring
BH	Black Hole
BL Lac	BL Lacertae
CMB	Cosmic Microwave Background
CR	Cosmic Ray
CT	Cherenkov Telescope
CTA	Cherenkov Telescope Array
DAQ	Data Acquisition System
EBL	Extragalactic Background Light
EC	External Compton
FOV	Field of View
FR I	Fanaroff-Riley I
FR II	Fanaroff-Riley II
FSRQ	Flat Spectrum Radio Quasar
HBL	High Frequency Peaked Blazar
HE	High Energy
HEGRA	High Energy Gamma Ray Astronomy
H.E.S.S.	High Energy Stereoscopic System
IACT	Imaging Atmospheric Cherenkov Telescope
IBL	Intermediate Frequency Peaked Blazar
IC	Inverse-Compton
IGMF	Intergalactic Magnetic Field
IR	Infrared
LBL	Low Frequency Peaked Blazar

LC Light Curve

MAGIC Major Atmospheric Gamma-ray Imaging Cherenkov telescope

MC Monte Carlo

NVSS National Radio Astronomy Observatory Very Large Array Sky Survey

PIC Proton-Induced Cascade

PMT Photo-Multiplier Tube

PSF Point Spread Function

RBL Radio selected Blazar

SED Spectral Energy Density

SSC Synchrotron Self-Compton

UV Ultraviolet

VERITAS Very Energetic Radiation Imaging Telescope Array System

VHE Very High Energy

VLBI Very Long Baseline Interferometry

XBL X-ray selected Blazar

NOTATIONS

Parameters	
Bulk Lorentz factor of emission region	Γ
Lorentz factor of an individual particle	γ
Relativistic Doppler factor	δ
Speed of light in the vacuum	c
Speed of light in a given medium	c_m

Part I

INTRODUCTION

This thesis begins with an introduction to the basic physical mechanisms and processes responsible for a nonthermal emission of the sources of interest. Special attention is put on the description of the interactions between γ -rays with ambient medium, the atmospheric showers of secondary particles generating the Cherenkov radiation observed by the ground-based imaging atmospheric Cherenkov telescopes as well as basic information on AGN, especially blazars, and the H.E.S.S. telescope array.

At the end of the 19th century, Paul Villard investigated the properties of β radiation in experiments based on measurements of refraction of β -rays in a glass capsule containing a mixture of radium and barium chloride. His experiments led to the discovery of a new type of highly penetrating γ radiation (Gerward, 1999), i.e. electromagnetic waves with photon energies from $\sim 5 \times 10^5$ eV up to $\gtrsim 10^{20}$ eV (Aharonian, 2004) for which the Earth's atmosphere is not transparent (see Section 1.3.1 on the atmospheric opacity). It was noticed at some point that γ -rays arriving from space interact with components of the atmosphere and the results of these interactions can be studied. At the beginning of the 20th century, the air ionization at various levels of the atmosphere was intensively investigated. In 1912, Victor Hess discovered a new ionizing radiation, later called cosmic rays (CRs), during his balloon flight experiments. He noticed an increase in radiation as the altitude increased, implying that the observed radiation comes from outside the Earth's atmosphere. The CRs are relativistic particles like ions, protons, electrons, and their anti-particles, and are produced in the Galaxy and beyond in a variety of astrophysical sources. Interactions of CRs with the ambient medium and photon fields can create radiation in a wide frequency range, including γ -rays. By studying these radiations one can learn about sources generating CRs and the particle propagation.

The observational γ -ray astronomy is a relatively young and fast-growing research domain which covers a wide range of the electromagnetic spectrum, and is divided mainly into six energy bands, i.e. low energy: $< 3 \times 10^7$ eV, high energy (HE): $3 \times 10^7 - 3 \times 10^{10}$ eV, very high energy (VHE): $3 \times 10^{10} - 3 \times 10^{13}$ eV, ultra high energy: $3 \times 10^{13} - 3 \times 10^{16}$ eV, and extremely high energy: $> 3 \times 10^{16}$ eV (Aharonian, 2004). Since γ -ray photons are blocked by the Earth's atmosphere, their direct measurement from the ground is not possible. For this very reason, γ radiation from astrophysical sources was unexplored until the first balloon and space-based experiments (e.g. Strong et al., 1974; Hirata et al., 1987; Matz et al., 1988; Buehler, 2015). Satellites (space telescopes) are able to detect low and high energy γ -rays and successfully measure the HE radiation in the Universe since the first instrument, Explorer 11, was launched in 1961 (Kraushaar & Clark, 1962). On the other hand, ground-based detectors are able to conduct indirect observations of VHE photons. Both types of observatories allow to investigate astrophysical sources and phenomena which emit γ -rays, such as the Galaxy plane, supernovae remnants, AGN, γ -ray bursts, pulsars and their wind nebulae, to study nonthermal processes generating these emissions, radiation processes in extreme environments, origin and composition of the CRs, and to look for dark matter.

1.1 RADIATION PROCESSES

Light is disturbed on its way to the observer through scattering and absorption resulting in an increase or decrease of energy of photons. Radiation processes are widely and precisely described in the literature (e. g. Rybicki & Lightman, 1979; Dermer & Menon, 2009; Boettcher et al., 2012; Ghisellini, 2013b), therefore only basic information about those studied in this thesis is briefly recapitulated below.

Since the sources of emission considered here are AGN (Chapter 2), in particular blazars, which mostly emit nonthermal radiation caused by relativistic particles, the difference between relativistic and non-relativistic terms has to be mentioned. If a particle is moving with a relativistic velocity, i. e. close to the speed of light in the vacuum, c , then its Lorentz factor $\gamma \gg 1$. The Lorentz factor of an individual particle is defined as $\gamma \equiv (1 - \beta^2)^{-1/2}$, where $\beta = v/c$ is the normalised velocity of the particle (otherwise, the particle is non-relativistic). Dimensionless energy of a photon is $\epsilon = \frac{h\nu}{m_e c^2}$ in units of the electron rest-mass energy $E_e = m_e c^2$.

The bulk Lorentz factor of a jet emission region is also distinguished and defined as

$$\Gamma \equiv (1 - \beta_\Gamma^2)^{-1/2}, \quad (1)$$

where β_Γ is the normalised velocity of the emission region. The Γ parameter is related to the Doppler factor, δ , via

$$\delta = \frac{1}{\Gamma(1 - \beta_\Gamma \cos \psi)}, \quad (2)$$

where ψ is the angle between the direction of jet propagation and the line of sight of an observer.

1.1.1 Compton scattering

One of the simplest interactions between charged particles and electromagnetic radiation (photons) is scattering, i. e. change of a particle's path caused by a collision with another particle. The Thomson scattering is considered in the rest frame of an electron e^- or a positron e^+ as a collision between the incoming photon with $\epsilon \ll 1$ and e^- (or e^+). The particle transfers part of its energy to a photon in an elastic process when the energy before interaction, ϵ , is equal to the energy after interaction, ϵ_s . The Compton and inverse-Compton (IC) mechanisms occur for more energetic incoming photons, with $\epsilon \gg 1$ (Klein-Nishina regime, referred to as K-N regime), when the energy transfer takes place in an inelastic process, i. e. $\epsilon \neq \epsilon_s$. Since the same scattering can take place with either e^- or e^+ , in the further discussion only the e^- case will be considered for simplicity.

The Compton scattering takes place in the e^- rest frame and can be interpreted as a collision between an incoming HE photon and a lower energy e^- . As a result of this interaction, the photon transfers some of its energy to the e^- . The energy and momentum conservation yield

$$\epsilon_s = \frac{\epsilon}{1 + \epsilon(1 - \cos \theta)}, \quad (3)$$

where θ is the angle between trajectories of the photon before and after scattering (referred to as the scattering angle). This expression can be also transferred to the wavelength form, where $\epsilon = \lambda_c/\lambda$ and $\epsilon_s = \lambda_c/\lambda_s$, as

$$\lambda_s - \lambda = \lambda_c(1 - \cos \theta), \quad (4)$$

where $\lambda_c \equiv h/m_e c$ is the Compton wavelength. Thus the wavelength changes by λ_c due to the scattering process.

The probability of scattering depends on its cross section, namely the differential K-N cross section

$$\frac{d^2\sigma}{d\Omega'_s d\epsilon'_s} = \frac{r_e^2}{2} \left(\frac{\epsilon'_s}{\epsilon'} \right)^2 \left(\frac{\epsilon'_s}{\epsilon'} + \frac{\epsilon'}{\epsilon'_s} - \sin^2 \theta' \right) \delta \left(\epsilon'_s - \frac{\epsilon'}{1 + \epsilon'(1 - \cos \theta')} \right), \quad (5)$$

where the primed quantities are in the e^- rest frame, $d\Omega'_s$ is the solid angle of the scattered photon direction, $r_e = \frac{e^2}{m_e c^2}$ is the classical e^- radius, ϵ'_s is the scattered photon energy, θ' is the scattering angle, and $\delta(\cdot)$ is the energy and momentum conservation function. The total K-N cross section is

$$\begin{aligned} d\sigma(\epsilon') &= \int_0^\infty d\epsilon'_s \oint d\Omega'_s \frac{d^2\sigma}{d\Omega'_s d\epsilon'_s} \\ &= \frac{\pi r_e^2}{\epsilon'^2} \left(4 + \frac{2\epsilon'^2(1 + \epsilon')}{(1 + 2\epsilon')^2} + \frac{\epsilon'^2 - 2\epsilon' - 2}{\epsilon'} \ln(1 + 2\epsilon') \right). \end{aligned} \quad (6)$$

For $\epsilon' \ll 1$, the cross section is

$$\sigma(\epsilon') \approx \sigma_T \left(1 - 2\epsilon' + \frac{26}{5}\epsilon'^2 + \dots \right), \quad (7)$$

where $\sigma_T = \frac{8}{3}\pi r_e^2$ is the Thomson cross section. For the other limit, $\epsilon' \gg 1$, i. e. in a deep K-N regime, the cross section yields

$$\sigma(\epsilon') = \sigma_{KN}(\epsilon') \approx \frac{3\sigma_T}{8\epsilon'} \left(\ln(2\epsilon') + \frac{1}{2} \right). \quad (8)$$

The IC scattering is a process opposite to the Compton scattering, in the sense that a moving relativistic e^- collides with a lower energy (soft) photon with energy ϵ in the e^- rest frame, transferring part of its energy to the photon. Shifting from the observer frame to the e^- rest frame, the photon energy will increase by a factor of $\sim \gamma$,

$$\epsilon' = \gamma\epsilon(1 - \beta \cos \phi), \quad (9)$$

where ϕ is the angle between e^- and photon directions before scattering. During the interaction, the Compton formula (Equation 3) is used in the e^- rest frame:

$$\epsilon'_s = \frac{\epsilon'}{1 + \epsilon'(1 - \cos \phi')}. \quad (10)$$

In the Thomson regime, the photon will be scattered in an elastic process, thus $\epsilon'_s = \epsilon'$. Moving back from the e^- rest frame to the observer's frame, the photon energy after scattering is

$$\epsilon_s = \gamma\epsilon'_s(1 - \beta \cos \phi'_s), \quad (11)$$

where ϕ_s is the angle between e^- and photon directions after scattering. As a result of the IC scattering and after angle averaging, the photon energy increases by the γ^2 factor, i. e. $\epsilon_s \simeq \epsilon\gamma^2$, due to the double Doppler boost.

The average energy of scattered photons is defined as the ratio of first to zeroth moments of the scattering cross section. The n th moment of σ in the $\epsilon' \ll 1$ limit is

$$\langle \epsilon_s^n \sigma \rangle_T \equiv \oint d\Omega_s \int_0^\infty \epsilon_s^n \left(\frac{d\sigma}{d\epsilon_s d\Omega_s} \right) d\epsilon_s, \quad (12)$$

hence the $n = 0$ and $n = 1$ moments are

$$\begin{aligned} \langle \epsilon_s^0 \sigma \rangle_T &= \sigma_T, \\ \langle \epsilon_s^1 \sigma \rangle_T &= \sigma_T \gamma \epsilon', \end{aligned} \quad (13)$$

and the mean energy of isotropically distributed photons is

$$\langle \epsilon_s \rangle_T = \frac{\langle \epsilon_s^1 \sigma \rangle_T}{\langle \epsilon_s^0 \sigma \rangle_T} = \gamma \epsilon'. \quad (14)$$

In case when an isotropic monochromatic distribution of photons is scattered in the IC process, the mean energy yields

$$\langle \epsilon_s \rangle_T = \frac{4}{3} \gamma^2 \epsilon. \quad (15)$$

The power of the IC scattered photons is

$$P_{IC} = -\frac{d\gamma}{dt} = c \oint d\Omega \int_0^\infty (1 - \beta \cos \phi) n_{ph}(\epsilon, \Omega) (\langle \epsilon_s^1 \sigma \rangle - \epsilon \langle \epsilon_s^0 \sigma \rangle) d\epsilon, \quad (16)$$

where n_{ph} is the photon distribution. Thus, in the Thomson regime, inserting Equation 12 into Equation 16, the scattered radiation power of the isotropic photon distribution in the Thomson regime is

$$P_{IC_T} = -\frac{d\gamma}{dt} = \frac{4}{3} c \sigma_T U_{ph} \beta^2 \gamma^2, \quad (17)$$

where U_{ph} is the photon field energy density.

In the K-N regime, the n th moment of σ is

$$\langle \epsilon_s^n \sigma \rangle_{KN} = \frac{\pi r_e^2 \gamma^n}{\epsilon'} \int_{\frac{1}{2\epsilon'}}^1 (1-y)^n \left(y + \frac{1}{y} \right) dy, \quad (18)$$

where $y \equiv 1 - \frac{\epsilon_s}{\gamma} = \frac{\epsilon'}{\epsilon}$. Hence the $n = 0$ and $n = 1$ moments in the limit of $\epsilon' \gg 1$ are

$$\begin{aligned} \langle \epsilon_s^0 \sigma \rangle_{KN} &\rightarrow \pi r_e^2 \frac{\ln(2\epsilon') + \frac{1}{2}}{\epsilon'}, \\ \langle \epsilon_s^1 \sigma \rangle_{KN} &\rightarrow \gamma \langle \epsilon_s^0 \sigma \rangle_{KN} - \frac{4\gamma \pi r_e^2}{3\epsilon'}. \end{aligned} \quad (19)$$

The mean energy of isotropically distributed photons in the limit of $\epsilon' \gg 1$ is

$$\langle \epsilon_s \rangle_{\text{KN}} = \frac{\langle \epsilon_s^1 \sigma \rangle_{\text{KN}}}{\langle \epsilon_s^0 \sigma \rangle_{\text{KN}}} \rightarrow \gamma \left(1 - \frac{4}{3 \ln(2\epsilon') + \frac{1}{2}} \right) \cong \gamma. \quad (20)$$

Inserting Equation 19 into Equation 16, the scattered radiation power of the isotropic photon distribution in the K-N regime is

$$P_{\text{ICKN}} = r_e^2 c \pi \int_{\frac{1}{\gamma}}^{\infty} \frac{n_{\text{ph}}(\epsilon)}{\epsilon} \left(\ln 4\gamma\epsilon - \frac{11}{6} \right) d\epsilon. \quad (21)$$

1.1.2 Synchrotron process

Synchrotron radiation is a result of the acceleration of a charged relativistic particle moving in a magnetic field. The non-relativistic case of this process is known as the cyclotron radiation.

Relativistic charged particles, e. g. e^- or protons p with mass m_e or m_p , respectively, velocity vector $\mathbf{v}$, and charge q are gyrating in a magnetic field $\mathbf{B}$ due to the Lorentz force

$$\mathbf{F}_L = \frac{q}{c} \mathbf{v} \times \mathbf{B}. \quad (22)$$

A particle with mass m moves in a spiral trajectory along the magnetic field with the gyration frequency

$$\omega_B = \frac{qB}{\gamma mc} \quad (23)$$

and a gyration radius

$$r_B = \frac{c}{\omega_B} \sin \theta \quad (24)$$

where θ is the *pitch angle*, i. e. an angle between velocity and the magnetic field. One particle emits energy with the synchrotron power

$$P_s = 2\sigma_T c \beta^2 \gamma^2 u_B \sin^2 \theta, \quad (25)$$

where $u_B = B^2/(8\pi)$ is the magnetic field energy density. If the distribution of the pitch angle θ is isotropic then the particle loses its energy at a rate

$$-\frac{d\gamma}{dt} = \frac{4}{3} c \sigma_T u_B Z^4 \left(\frac{m_e}{m} \right)^3 \beta^2 \gamma^2. \quad (26)$$

where $U_B = u_B/(m_e c^2)$ and Z is the charge of a particle in units of the electron's charge, e . It shows that the energy losses scale as $d\gamma/dt \propto -m^{-3}$. e^- and p , which are the main particle ingredients of the relativistic outflows, can emit synchrotron radiation efficiently, although e^- seem to be much more effective at a given γ . On the other hand, one can note that there is a difficulty to accelerate e^- to ultrarelativistic energies due to their fast energy loss in a strong magnetic field, while protons are more susceptible to acceleration.

Equation 26 can be also expressed in terms of the e^- Lorentz factor change rate as

$$-\frac{d\gamma}{dt} = \frac{4}{3}c\sigma_T U_B \beta^2 \gamma^2. \quad (27)$$

The synchrotron radiation is generated in every magnetized plasma system in the space.

Photons, produced during the synchrotron radiation process, are likely to interact with the primary synchrotron e^- in the IC scattering. This mechanism of emission, the synchrotron self-Compton (SSC) process, is crucial to produce high and very high energy photons in astrophysical sources. Recalling Equation 17 and Equation 27, a similarity between the rate of the synchrotron and IC energy loss can be noticed. The ratio of the synchrotron and IC energy loss rates is

$$\frac{P_s}{P_{IC}} = \frac{U_B}{U_{ph}}, \quad (28)$$

where interaction occurs in the Thomson regime. The relativistic e^- passing through any medium with both U_B and U_{ph} densities radiate by the synchrotron as well as IC processes. The emission of e^- in this case decreases with the increase of the radiation region.

1.1.3 Bremsstrahlung

The Bremsstrahlung radiation, also known as the free-free emission, is a mechanism for energy loss of a charged particle due to emission in the Coulomb field of another particle. In the non-relativistic Bremsstrahlung process the interactions between the electron–ion pairs are prominent, while interactions between e^+ and e^- dominate the relativistic Bremsstrahlung radiation. The effectiveness of this radiation in the non-relativistic case depends on how close one particle passes the other, on the number of the particles and their velocity, thus energy and temperature.

The power of the Bremsstrahlung radiation is

$$P = \frac{e^6}{m_e^2 c^3 b^4}, \quad (29)$$

where b is the impact parameter and the emissivity is

$$j = \frac{n_e n_p}{4\pi m_e^2 c^3} \frac{\sqrt{m_e kT}}{\hbar}, \quad (30)$$

where n_e and n_p are e^- and p number densities, respectively, k is the Boltzman constant, T is the temperature, and $\hbar = h/2\pi$ is the reduced Planck constant.

1.2 γ -RAY INTERACTIONS IN INTERGALACTIC AMBIENT MATTER

The TeV γ -ray photons produced by cosmic γ -ray sources, e. g. AGN, travel long distances in the Universe interacting with background radiation in infrared (IR)–optical–ultraviolet (UV) photon fields, i. e. the diffuse extragalactic background light (EBL) and the cosmic far-IR background (CIRB). As

a result of these interactions, γ -ray photons are absorbed and $e^\pm$ pairs are created. Subsequently, the $e^\pm$ pairs can upscatter the 2.7 K cosmic microwave background (CMB) photons via the IC effect, cooling down and initiating linear electromagnetic cascades. The trajectories of both e^- and e^+ can be deflected through the intergalactic magnetic field (IGMF) with adequate intensity, thus the electromagnetic cascades could be further observed as a γ -ray halo around the powerful source of primary emission (see e.g. Aharonian et al., 1994; Franceschini et al., 2008; Ando & Kusenko, 2010; Eungwanichayapant & Aharonian, 2009; Meyer et al., 2016, and references therein). Since no direct measurements of the IGMF were obtained up to date, the IGMF intensity is theoretically determined to be between 10^{-7} G and 10^{-12} G (Eungwanichayapant & Aharonian, 2009), 10^{-15} G (Ando & Kusenko, 2010), or even down to 10^{-18} G (Dermer et al., 2011) to effectively bend the $e^\pm$ pairs' trajectories. In weaker fields ($< 10^{-18}$ G), the γ -ray halo should not be formed, since e^- and e^+ are not bent and propagate linearly. In stronger magnetic fields ($> 10^{-7}$ G), the synchrotron cooling process of the produced $e^\pm$ pairs can not be neglected and it can suppress the formation of γ -ray radiation.

1.3 PARTICLE CASCADES IN THE EARTH'S ATMOSPHERE

1.3.1 Transparency of the atmosphere

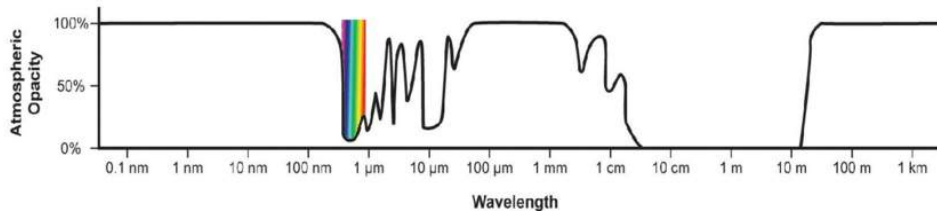


Figure 1: Opacity of Earth's atmosphere. A rainbow visualises the optical range of the electromagnetic spectrum. Source: NASA.

The Earth's atmosphere is a protective gaseous layer that prohibits dangerous radiations from reaching the surface of our planet, which, as a consequence, could jeopardize biological life on Earth. As shown in Figure 1, the atmosphere allows only limited ranges of the electromagnetic spectrum to pass through. That is why the ground-based observations of a part of radio and infrared (IR) radiation and whole visible light range are manageable. In the case of γ , X and UV bands, the atmosphere is opaque due to absorption in its upper layers. This makes difficult or even prevents the investigation of these energy regimes from the surface of the Earth, which, however, can be successfully observed by devices on board balloons and space telescopes.

In order to measure these rarely appearing particles, large collective areas are needed, otherwise the observations will be highly ineffective and time-consuming. It is impossible to launch instruments with large apertures into space, so another detection method was developed. If the atmosphere becomes a part of the detector, then indirect observations of the HE CRs are

possible from the Earth's surface due to secondary particles generating the Cherenkov radiation.

1.3.2 *Electromagnetic and hadronic air showers*

Upon entering the Earth's atmosphere, a HE/VHE primary particle, such as a γ -ray photon or CR nucleus, interacts with an atomic nucleus in the upper atmosphere at an altitude of ~ 25 km, and initiates a cascade of secondary particles, also known as a shower. The particle cascade reaches its maximum at the elevation of ~ 10 km above sea level, then diminishes. The showers can be detected through the generated Cherenkov radiation. The cascades initiated by more energetic primary particles (above hundreds of TeV) can even reach the sea level (Hillas, 1996).

In the case of an electromagnetic air shower, a γ -ray photon interacts with the Coulomb field of an atomic nucleus in the atmosphere resulting in the $e^\pm$ pair production. Both e^- and e^+ get the same amount of energy from the primary photon. If the generated particles have enough energy, they emit the Bremsstrahlung radiation in the same field producing new less-energetic γ -rays, which create another $e^\pm$ pairs. This development of secondary particles repeats keeping the same pattern, i.e. $\gamma\gamma \rightarrow e^\pm \rightarrow \gamma\gamma \rightarrow \dots$, and they are produced until their energy achieves a level where the processes will be suppressed by ionization losses (critical energy, $E_{c,e}$). The scheme of the electromagnetic air shower development initiated by a γ -ray photon is shown in Figure 2. The electromagnetic air shower expansion model was introduced by Heitler (1954) and then developed into more advanced schemes including γ -rays as well as protons/atomic nuclei as the primary particles (e.g. Matthews, 2005).

In addition to the scheme introduced above, the particle shower initiated by a hadron, usually proton, atomic nucleus, or α particle, consists of supplementary ingredients (Figure 2; bottom panel) such as fragments of atomic nuclei, neutral or charged pions and their decay products, i.e. $e^\pm$, $\mu^\pm$, and $\pi^\pm$. The generated π^0 decomposes into two γ -rays, which initiate additional sub-showers of $e^\pm$. If $\pi^\pm$ reach the critical energy, $E_{c,\pi}$, they start to decay into $\mu^\pm$ (e.g. $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$). The characteristic features of the electromagnetic and hadronic showers are summarized in Table 1.

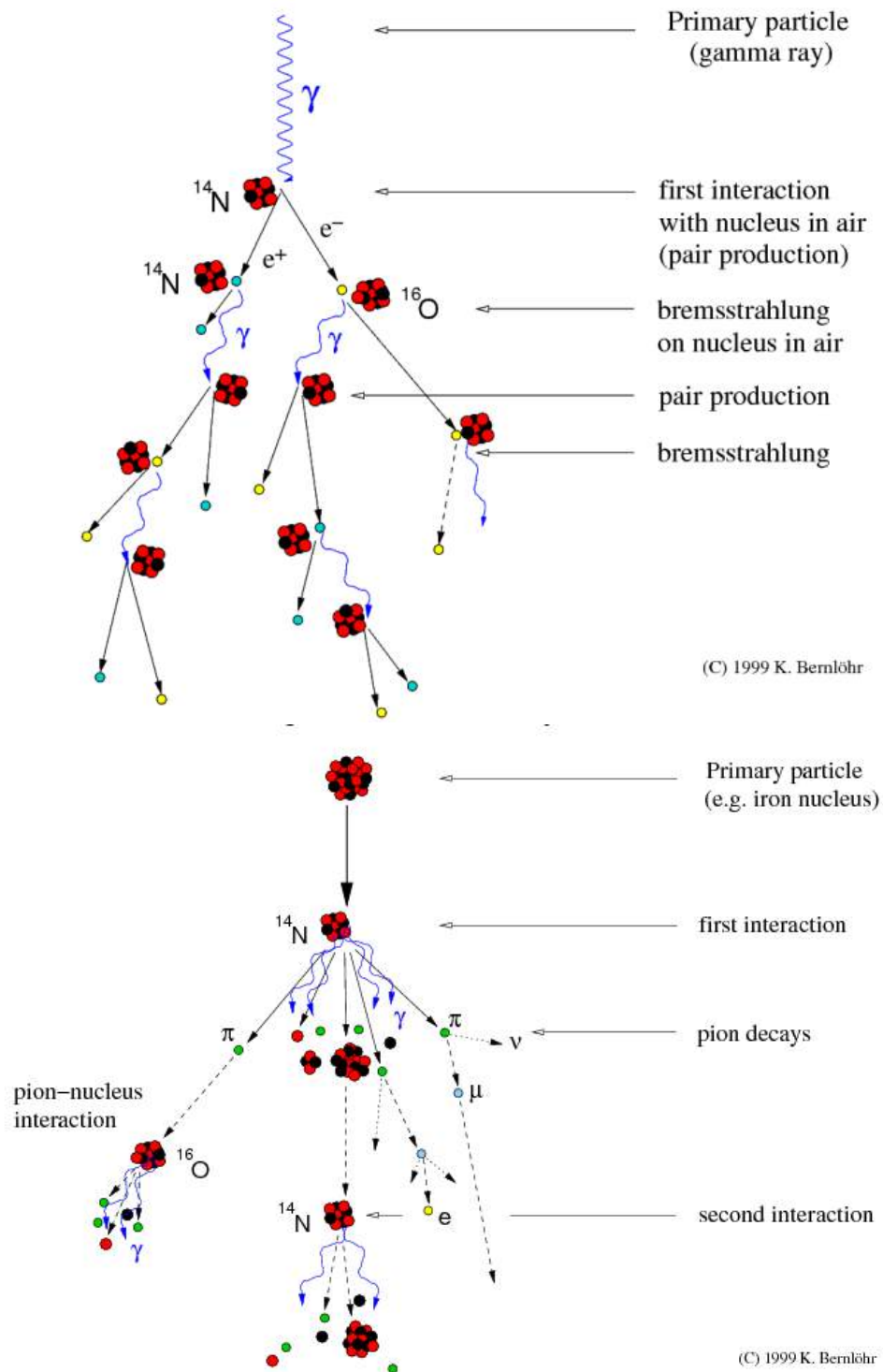


Figure 2: Development of air particle cascades initiated by a γ -ray photon (top panel) and CR iron nucleus (bottom panel) primary particles. Courtesy of Konrad Bernlöhner.

air shower properties		
	electromagnetic shower	hadronic shower
primary particle	γ -ray	proton or atomic nucleus
initial energy	$> 10^9$ eV	
first interaction altitude	~ 25 km above sea level	
maximum size altitude	~ 10 km above sea level	
elongation length Λ	~ 85 g cm $^{-2}$	~ 58 g cm $^{-2}$
E_c in air	85×10^6 eV	10×10^9 eV
shape	regular	irregular
components	$e^\pm$ and γ -rays	$\pi^{0,\pm}$, e^- , $\mu^\pm$, $\nu^\pm$ and ions
Cherenkov light properties		
duration	$3 - 4$ ns	
wavelength	$300 - 600$ nm	
light pool size	~ 120 m at ~ 2 km	
opening angle	$\sim 1^\circ$	

Table 1: Typical parameters and characteristic features of air showers and generated Cherenkov light. The E_c of exemplary primary proton with $E_0 = 10^{17}$ eV is taken from [Matthews \(2005\)](#).

1.3.3 Simulations of air showers

Based on the physical parameters describing individual particle cascades, such as shape and components, hadronic and electromagnetic showers can be effectively distinguished from each other. A more detailed description of the various air showers' developments can be found in, e. g., [Svensson \(1987\)](#) and [Völk & Bernlöhr \(2009\)](#). The simulations of the air showers initiated by different particles with various primary energy are shown in [Figure 3](#). As demonstrated, the cascades have distinctive shapes and sizes. The electromagnetic air showers are more regular and homogeneous, while other kinds are much wider, often divided into supplementary sub-cascades. The Monte Carlo (MC) simulations showed that the individual hadronic showers also differ from each other much more than in the case of electromagnetic cascades, which do not change much from one particle distribution to another ([Hillas, 1996](#)).

It is worth mentioning that the γ -ray showers are only a small fraction of the whole population of particle cascades. Most of them are initiated by hadrons, which are later considered as background events. Moreover, the secondary particle showers caused by hadrons generate much more muons than the electromagnetic cascades, thus they can be used as a distinguishing indicator between showers.

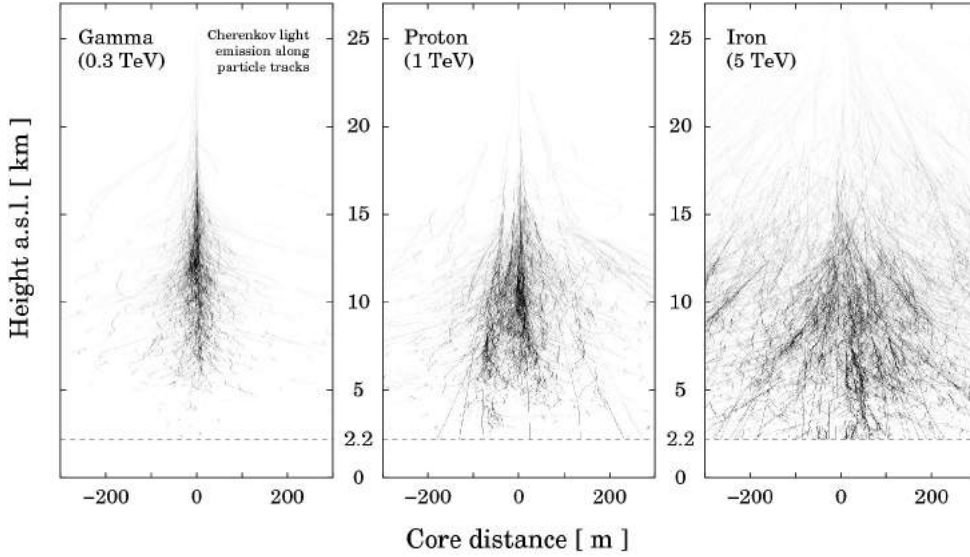


Figure 3: Simulations of air showers initiated by different primary particles with various initial energies: 0.3 TeV γ -ray (left panel), 1 TeV proton (middle panel), and 5 TeV iron nucleus (right panel). Scheme taken from (Bernlöhner, 2008).

The *extensive showers* model proposed by Matthews (2005) follows the main assumptions of the Heitler model (Heitler, 1954), adapting it to both (i) electromagnetic and (ii) hadronic showers.

- (i) The electromagnetic showers are characterized by a splitting length $d = \lambda_r \ln 2$, where λ_r is the radiation length, which depends on the type of atomic nuclei in the air and the primary energy of a γ -ray. The critical energy in the air is $E_c = 85$ MeV, i.e., the particle energy below which the pair production is stopped. Considering the electromagnetic cascade initiated by a γ -ray photon with primary energy $E_0 = E_c N_{\max}$, the maximum size of the shower is $N_{\max} = 2^{n_c}$, where n_c is a number of the splitting lengths d to reduce the energy per particle to E_c . The electromagnetic shower attains its $N_{\max}$ at the penetration depth $X_{\max} = n_c \lambda_r \ln 2$, while it allows to obtain the elongation rate $\Lambda = \frac{dX_{\max}}{d \log_{10} E_0}$. This allows for the reconstruction of the γ -ray E_0 . The elongation rate of the γ -ray shower is $\Lambda^\gamma = 85 \text{ g cm}^{-2}$ per decade.
- (ii) The hadronic showers are simulated analogously to the γ -ray showers. In this case, the interaction length is considered, i.e. $\lambda_I \sim 120 \text{ g cm}^{-2}$ for π interactions between 10 and 10^3 GeV in the air. The E_0 of a primary hadron is split into pions in the hadronic cascade and $e^\pm/\gamma$ -rays in the electromagnetic sub-cascade. The E_0 of the primary hadron can be reconstructed based on $E_0 \sim 8.5 \times 10^8 (N_e + 24N_\mu)$, where N_e is the number of e^- and N_μ is the number of muons. In this approach, E_0 does not depend on the primary particle type. The elongation rate of the hadronic shower is $\Lambda^p = 58 \text{ g cm}^{-2}$ per decade.

Modelling and simulations of the air showers support the techniques of the Cherenkov light observations hence enable reconstruction of the primary particle parameters, which ultimately allows the study of the radiation sources, the nonthermal processes, and the powerful phenomena in the Universe. Nevertheless, the air showers, although crucial, are only the intermediate carrier of information. What is really observed is the Cherenkov radiation emitted by the relativistic particles passing through the air.

1.3.4 Cherenkov radiation

The secondary electrons show their presence with faint short nanosecond flashes (typically lasting 3–4 ns) generated and emitted while moving in the atmosphere with a velocity higher than the speed of light in a given medium, c_m . These flashes were primarily detected in 1934 by Pavel Cherenkov ([Čerenkov, 1934](#)) and are known as the Vavilov-Cherenkov radiation, referred to as Cherenkov radiation for simplicity. Cherenkov studied radiation occurring in different liquids, caused by γ -rays from radium and eventually discovered that the emission is also present in various solvents, e. g. sulphuric acid. The Cherenkov radiation was later described by [Čerenkov \(1937\)](#), theoretically explained by [Frank & Tamm \(1937\)](#), and then widely studied by, e. g., [Allison & Wright \(1991\)](#); [Bolotovskii \(2009\)](#); [Watson \(2011\)](#).

The appearance of the Cherenkov radiation is closely related to the velocity of an interfering particle. The charged particle passing through a dispersive medium generates a dipole field and polarises other particles along its path. If a velocity of the charged particle is much smaller than c_m , the polarisation field in its direct vicinity is symmetric, the resultant field is equal to zero, and no light is emitted. However, if the charged particle exceeds c_m , then the polarisation field exhibits an asymmetry along the particle's trajectory, giving a non-zero resultant field and generating short flashes emitted by the particles in the medium.

The Cherenkov light initiated by a single charged particle is characterized by the opening angle θ of the radiation cone extending along the particle's path, known also as the Cherenkov angle,

$$\cos \theta = \frac{1}{\beta n(\omega)}, \quad (31)$$

where $n(\omega)$ is the refractive index of the medium depending on the frequency ω . The emission intensity

$$I(\omega)d\omega = v \frac{q^2}{c^2} \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) \omega d\omega \quad (32)$$

determines a velocity threshold, $\beta > 1/n$, establishing a limit when the radiation is emitted. In the extreme case, for an ultrarelativistic particle with $\beta \approx 1$, the radiation is emitted within the maximum angle of $\cos \theta = 1/n(\omega)$. The total energy loss of radiation per path length is

$$\frac{dE}{dx} = \frac{q^2}{c^2} \int_{\beta > 1/n} \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) \omega d\omega. \quad (33)$$

All of the above mentioned relations show that the radiated energy and its intensity increase with frequency. The Cherenkov light is visible for $n(\omega) > 1$ and is the brightest in the blue part of the optical range. It is also emitted and can be observed in other ranges, but much less efficiently.

Observations of the Cherenkov radiation generated in the air showers of a light pool of the size ~ 120 m require large optical detectors on the ground preferentially at altitude of ~ 2 km above sea level. Below this elevation the intensity of the Cherenkov light drops drastically, thus it may be difficult to detect (e. g. [Hillas, 1996](#); [Aharonian, 2004](#)). The observational characteristic features of the Cherenkov light are listed in [Table 1](#).

Active galactic nucleus (AGN) is a compact region located in the central part of its host galaxy, which can emit broadband, mostly nonthermal electromagnetic radiation from radio up to, in some cases, TeV γ -ray energies. The activity of the AGN is understood as gravitational processes producing significant amounts of energy, namely high rate of plasma accretion onto the black hole (BH), which dominate over the starlight at optical and IR frequencies (Rees, 1984; Blandford, 1989b; Krawczynski & Treister, 2013).

The AGN consists of a massive or supermassive BH, an accretion disk formed from ionized gas, a corona of hot plasma, emission line clouds, i. e. regions of narrow and broad lines, regions of absorbing dust (torus or warped disk), and occasionally occurring two-side jets, i. e. streams of ionized, relativistic and collimated plasma. Figure 4 illustrates the complexity of the AGN structure. The particular components are shortly described in Section 2.1.

2.1 EMISSION REGIONS AND STRUCTURE OF AGN

EMISSION REGIONS

AGN are very luminous objects with observed bolometric luminosities between $\sim 10^{44}$ and $\sim 10^{49}$ erg s $^{-1}$ (Dermer & Menon, 2009). Their activity processes are directly connected with the supermassive BH and accretion disk system. Observations of the central engine of AGN can give information about the basic BH parameters such as its mass and spin.

Large amounts of energy are produced in concentrated areas in different AGN regions, as presented in Figure 4. The moving plasma in the inner part of the accretion disk is heated up and generates thermal radiation observed in optical, UV, and soft X-ray bands (e.g. Czerny & Elvis, 1987). As discussed in e.g. Liang & Narayan (1997); Różańska et al. (1999), the accretion disk is surrounded by a corona composed of hot plasma which scatters emission from the disk and magnifies it up to X-ray energies. Radiation from the disk also interacts with the emission line clouds resulting in optical and UV emission from both broad and narrow line regions. Urry & Padovani (1995) pointed out that the active region is obscured by a thick dusty torus or a warped disk, which absorbs emission generated in the central parts of AGN and radiates it in IR band. The relativistic jet emits in the whole electromagnetic spectrum from radio to γ -rays as it is shown in Figure 4 and discussed below.

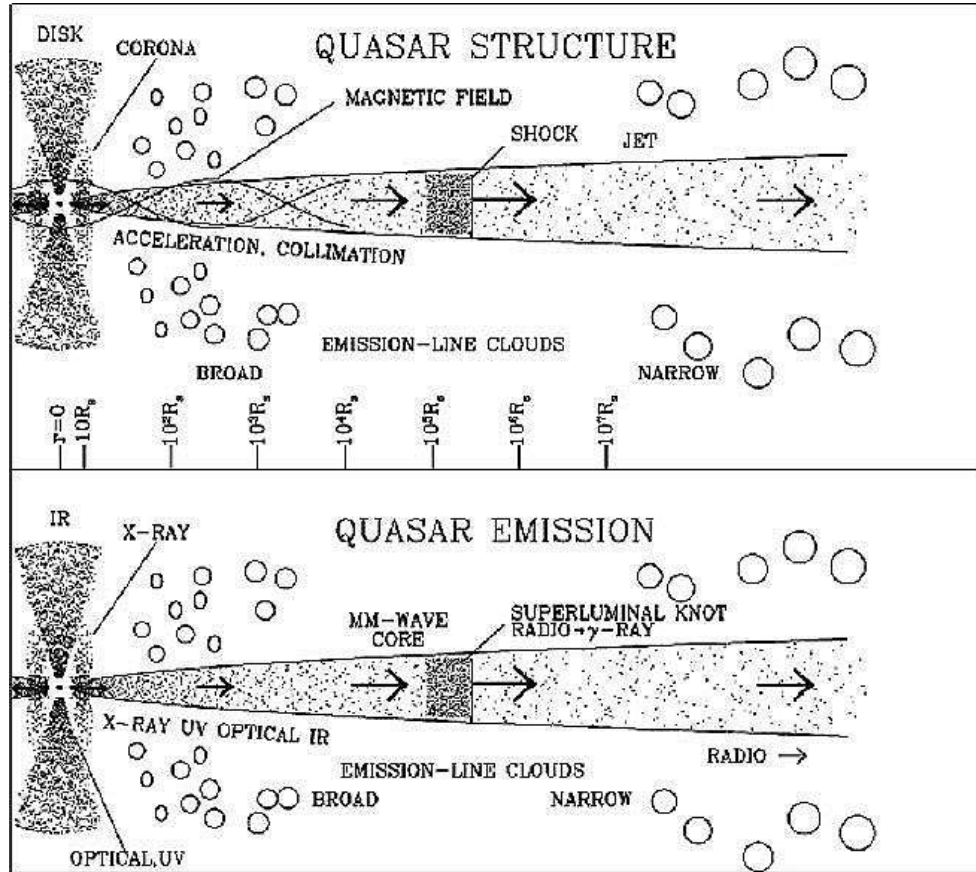


Figure 4: Scheme of AGN structure (top panel) and emission regions (bottom panel), taken from (Marscher, 2005). The AGN central engine consisting of a black hole, an accretion disk, and an ionized corona are placed between 0 and $10 R_{\odot}$. This region is relatively small and compact in comparison to the jet. The elongated jet structure possibly involves helical magnetic field and particle acceleration regions (shocks).

ACCRETION DISK - BLACK HOLE SYSTEM

Properties of BHs and interactions with their surroundings are widely discussed in many scientific articles and books, e. g. [Penrose \(1972\)](#); [Blandford \(1989a\)](#); [Meier \(2012\)](#). Direct observations of BHs are impossible, however these objects can be still investigated experimentally due to their gravitational interaction with the surrounding matter. It is commonly accepted that the majority of AGN and non-active galaxies, including the Milky Way, possess a BH in their central regions (e. g. [Rees, 1989](#); [Schödel et al., 2002](#); [van den Bosch et al., 2012](#)).

Since AGN are much more powerful than non-active galaxies, they require efficient processes responsible for their emitted power. The stellar processes turn out to be inefficient in producing extremely high thermal and nonthermal emissions observed in AGN. This suggests a relation between the origin of the AGN power and the gravitational processes generated by a central engine of any AGN, and more specifically by a supermassive BH with a mass between $10^6 M_\odot$ and $10^{10} M_\odot$ ([Krawczynski & Treister, 2013](#)) together with an optically thick and geometrically thin ([Shakura & Sunyaev, 1973](#)) or optically thin and geometrically thick ([Ichimaru, 1977](#)) accretion disk of magnetised ionized plasma. In such systems, matter accretes onto a BH causing a transformation of gravitational potential energy into thermal radiation directly in the disk.

The Eddington ratio is defined as ([Dermer & Menon, 2009](#))

$$l_{\text{Edd}} = \frac{\eta \dot{m} c^2}{L_{\text{Edd}}}, \quad (34)$$

where η is the conversion efficiency of gravitational energy of accreting gas or plasma into radiation, $\dot{m}$ is the accretion rate, and L_{Edd} is the Eddington luminosity. L_{Edd} determines the highest possible luminosity of an AGN which can be obtained through the accretion process and in case of plasma consisting of e^- and p is defined as:

$$L_{\text{Edd}} = \frac{4\pi G M (m_p + m_e) c}{\sigma_T}, \quad (35)$$

where M is the BH mass, m_p and m_e are the proton and electron masses and σ_T is the Thomson cross-section.

The system can also produce collimated outflows of relativistic plasma, jets, which generate nonthermal radiation through the synchrotron and IC processes.

JETS

M87, the galaxy catalogued by Charles Messier in the 18th century, also known as one of the AGN closest to the Solar System, possesses a jet visible across the entire electromagnetic spectrum. The jet of M87 was observed in the optical range in 1918 ([Curtis, 1918](#)) and despite misunderstanding its origin, it was noticed that the structure is brighter at the end and associated with the core. Subsequently, together with more advanced technology of

observations, more AGN were discovered not only in the optical domain, but throughout the whole electromagnetic spectrum.

A jet is a powerful, collimated relativistic outflow of magnetised plasma, produced by a BH–accretion disk system in e. g. the Blandford-Znajek mechanism (Blandford & Znajek, 1977), and ejected perpendicularly to the disk’s surface. Its composition is not fully understood, however the most widely accepted hypotheses are leptonic (electron-positron), hadronic (mostly protons), or lepto-hadronic outflows. The jet has a heterogeneous structure including magnetic fields with a helical component, blobs, knots, and bends. Magnetic field in the jet decreases with distance, possibly like $B \propto r^{-1}$, changing from $B \lesssim 10^4$ G at the base of the jet and reaches $B \sim \mu\text{G}$ at the outermost parts of the jet (in radio sources). Large scale jets can interact with the intergalactic medium creating lobes with hot spots, visible in the radio range. Jets can accelerate electrons and/or protons up to GeV/TeV energies or even higher, reaching high spatial scales of $\sim\text{kpc}$ and $\sim\text{Mpc}$ (for a more detailed description and observational examples see Sikora & Madejski, 2000; Begelman et al., 1984; Krawczynski & Treister, 2013; Marchenko et al., 2017).

EMISSION LINE CLOUDS

AGN possess characteristic emission features in their spectra, which are different than in case of non-active galaxies, such as permitted and forbidden emission spectral lines, the hydrogen Balmer lines (including H_α , H_β , and H_γ), and Lyman α line ($\text{Ly}\alpha$). The lines can be broad or narrow depending on the region they come from, i. e. the emission line clouds of the cold interstellar matter. The broad line region consists of plenty small clouds moving with high velocities reaching $\sim 300 \text{ km s}^{-1}$ and located in direct vicinity of a BH, i. e. $\ll 1 \text{ pc}$. The narrow line region is composed of slower clouds located further away from a BH at a distance of $\sim 100 \text{ pc}$ (see e. g. Ghisellini, 2013b). It is believed that lines are generated by the accretion disk’s radiation passing through the emission line clouds where the matter is heated up and photoionised, or/and by interactions between the jet’s components with the emission line regions. The lines are used to distinguish particular AGN types from each other, like in case of the Seyfert galaxies or blazar classes, to estimate distances to the objects based on the redshift measurements in the observed spectra, or to evaluate the accretion rate (e. g. Rawlings & Saunders, 1991; Celotti et al., 1997; Boettcher et al., 2012).

2.2 PHENOMENOLOGY OF AGN

According to the *Unification Scheme* summarized by Urry & Padovani (1995) and showed in Figure 5, AGN are primarily divided into two groups: *radio-quiet*, with comparable or lower radio to optical fluxes, and *radio-loud*, with much higher radio than optical emission. The ratio of radio flux at 5 GHz (6 cm) to the optical flux in the B band is defined as $R = \frac{F_{5\text{GHz}}}{F_B}$. Objects characterised by $R \geq 10$ are termed radio-loud, while sources with $R < 10$

are called radio-quiet (e.g. Kellermann et al., 1989; Ho, 2002). The majority of the AGN population is radio-quiet (see Antonucci, 1993, for a review on the radio-quiet AGN), while only $\sim 15 - 20\%$ of them are radio-loud (Urry & Padovani, 1995).

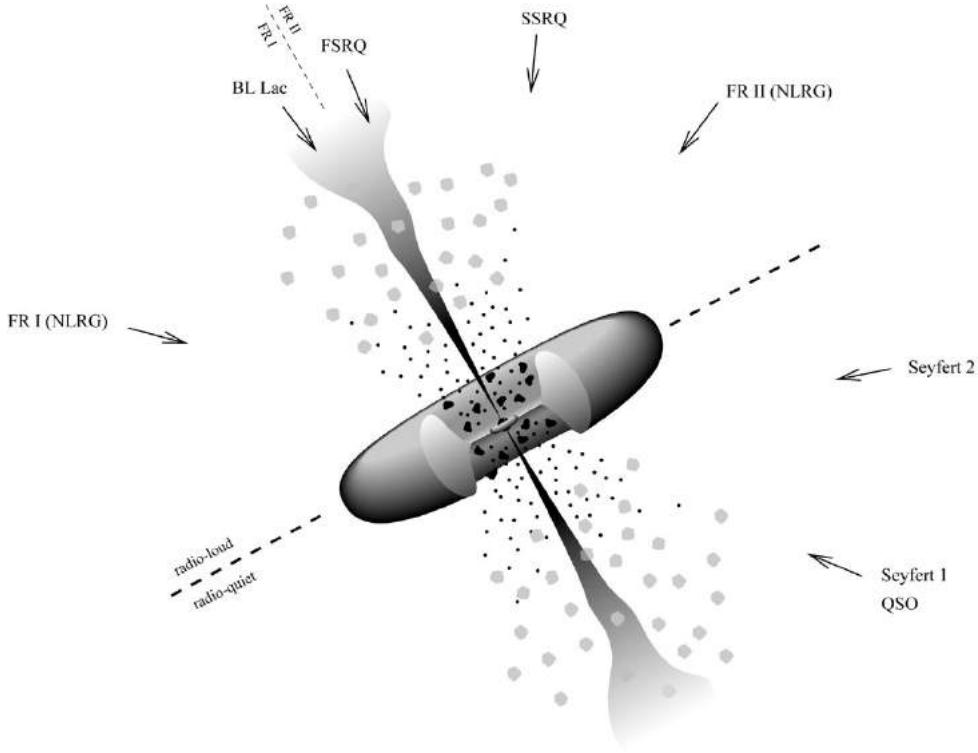


Figure 5: Unification Scheme of AGN. The sketch shows the geometry of an AGN, general division into radio-quiet and radio-loud types, and phenomenology of the AGN: quasars (QSO, SSRQ), blazars (FSRQ and BL Lac), Seyfert galaxies (type 1 and 2), and radio galaxies (FR I, FR II, and NLRG). Image reproduced from Urry & Padovani (1995) and taken from ned.ipac.caltech.edu.

Over the years, many alternative classifications of AGN have been proposed, including grouping established on individual energy ranges or properties resulting from the multiwavelength investigation. The division of AGN based on their observational properties at radio and optical frequencies is presented below (after Lawrence, 1987; Urry & Padovani, 1995):

- **Type 0**, including objects with smooth featureless or uncertain continua of their optical spectra; *radio-loud*: blazars, i.e. flat spectrum radio quasars (FSRQs) and BL Lacertae (BL Lac) type objects; *radio-quiet*: broad absorption lines quasars. This group contains objects with jets close to the line of sight.
- **Type 1**, including objects with bright continua and broad emission lines; *radio-loud*: steep spectrum radio quasars, FSRQ, and broad line radio galaxies; *radio-quiet*: quasars and Seyfert 1 galaxies.
- **Type 2**, including objects with weak continua and narrow emission lines; *radio-loud*: both types of Fanaroff–Riley galaxies, i.e. FR I and FR II; *radio-quiet*: narrow emission lines galaxies, IR-luminous quasars, and Seyfert 2 galaxies.

FANAROFF–RILEY RADIO GALAXIES

Advanced radio instruments, like the Very Large Array (VLA)¹, the Very Long Baseline Array (VLBA)², the Event Horizon Telescope³, or RadioAstron⁴, are able to resolve observed sources due to their high angular resolution reaching the level from arcseconds down to miliarcseconds or even microarcseconds, depending on the frequency. Based on such observations, sources can be investigated in more detail with separation of individual elements, such as the core, jets, lobes, and hot spots. AGN, which can be observed at radio frequencies and whose radio fluxes are significant compared to other bands, are the so-called *radio galaxies*. These powerful radio galaxies are objects with the apparent luminosity at 1.4 GHz of $L_{1.4\text{GHz}} > 5 \times 10^{25} \text{ W Hz}^{-1}$, while sources with $L_{1.4\text{GHz}} < 5 \times 10^{25} \text{ W Hz}^{-1}$ are usually classified as weak radio galaxies (Boettcher et al., 2012). The majority of radio galaxies are hosted by elliptical galaxies.

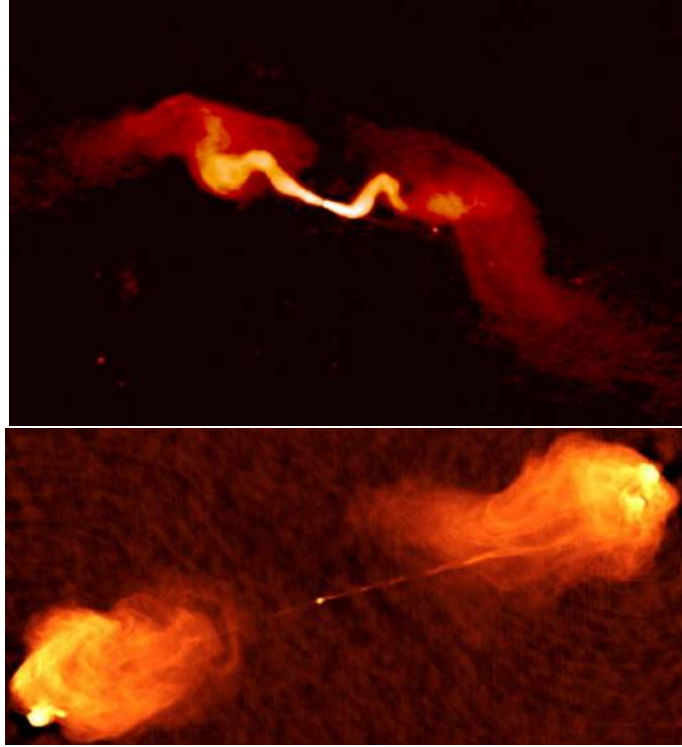


Figure 6: Example of FR I and FR II radio galaxies. Top panel: the 1.4 GHz VLA map of an FR I radio galaxy 3C 31. Bottom panel: VLA map of an FR II radio galaxy Cygnus A. Credit: NRAO/AUI.

Fanaroff & Riley (1974) divided the two-sided radio AGN into two groups: Fanaroff–Riley I (FR I) and Fanaroff–Riley II (FR II). The main principle of this separation is the ratio of the highest apparent brightness of components on both sides of the core to the absolute size of the galaxy. If this parameter is < 0.5 , i. e. the region of the highest brightness is situated in smaller dis-

¹ public.nrao.edu/telescopes/vla/; access date 15.07.2018

² public.nrao.edu/telescopes/vlba/; access date 15.07.2018

³ eventhorizontelescope.org; access date 15.07.2018

⁴ asc.rssi.ru/radioastron/; access date 15.07.2018

tance to the core than half of the galactic size, such sources are classified as FR I type. Otherwise, galaxies are labeled as FR II.

On the other hand, the FR I and the FR II type galaxies reveal significant morphological differences apparent at radio frequencies. This discrepancy is also illustrated in [Figure 6](#), where the top panel shows an example of FR I radio galaxy, namely 3C 31, and the bottom panel displays a typical FR II source, i. e. Cygnus A. Radio lobes of the FR II type galaxy, which are supported and maintained by symmetric jets, have clearly visible hot spots, while optional lobes of the FR I are entirely diffuse without any distinct features. Furthermore, jets of the FR I are symmetric and not collimated. Similarly, the jet is turbulent continuing from the core in case of the FR I type galaxy, while for the majority of FR IIs the observed jets are often one-sided and detached from the core.

Recently, a new class of the Fanaroff–Riley galaxies was proposed, namely FR 0 radio galaxies, characterised as compact core-dominated low luminosity radio sources appearing in the local Universe ([Baldi et al., 2016](#)). As stated in [Baldi et al. \(2016\)](#), classification of FR 0s is based on radio as well as optical (photometric and spectroscopic) observational properties. FR 0s are small galaxies without extended radio structures, which is most likely caused by small bulk Lorentz factors ($\Gamma \lesssim 1 - 2$) resulting in slow jets. FR 0s are similar to FR Is and the only feature distinguishing both classes is a complete lack of an extended structure in radio data in case of FR 0. Both populations seem to possess similar BH masses, colours, optical spectra properties, and radio-core to emission line luminosity ratios. It is also suggested that the FR 0 galaxies can constitute the largest population of radio galaxies in the local Universe.

SEYFERT GALAXIES

The first AGN were identified by Carl Seyfert, who carefully observed and analysed optical spectra of six spiral nebulae. Based on the characteristics of the emission lines (their strength and profiles) and optical properties (average absolute brightness and shape), he noticed that nebulae with nuclear emission can constitute a separate group of sources ([Seyfert, 1943](#)).

The local Universe is highly populated by the so-called Seyfert galaxies compared to the other AGN types. In the optical range, the host galaxy (usually spiral) is easily distinguished from the highly luminous point-like core, wherefore each of them can be precisely investigated. The broad ionized emission lines in their optical spectra, which were also noticed by C. Seyfert, originate from the unresolved active core, whereas the host galaxy has the regular galactic continuum with emission and absorption lines. Based on the properties of 71 optical spectra of some Seyfert galaxies, [Khachikian & Weedman \(1974\)](#) split them into two groups: Seyfert 1 and Seyfert 2 types. This classification depends on the appearance and width of the forbidden lines, such as [N II], [O III], or [Fe II] and hydrogen (Balmer), mostly H_α , H_β , and H_γ lines. In the spectra of the Seyfert 1 type AGN, the hydrogen lines are wider than forbidden lines, while both types of lines have comparable widths in the Seyfert 2 galaxies.

QUASARS

One of the first discovered quasi-stellar source (quasar) active in radio is 3C 273. The object was observed in 1960s and it was confused with a star due to its point-like appearance in the optical band. Schmidt (1963) analysed the optical and radio data of 3C 273 and noticed that in addition to the stellar object with brightness of 13 magnitudo, the $2''$ width jet is also visible. The most suprising fact was its redshift of $z = 0.158$, measured based on broad lines located in the blue part of the spectrum, suggesting an extragalactic or even cosmological origin of the source.

Quasars can be found in the very distant space, with the highest observed redshift of $z = 7.541$ (Bañados et al., 2018), thus allowing investigation of the early Universe. One of the most characteristic optical features of quasars, which distinguish them from the non-active galaxies, is the so-called *blue bump*. The blue bump originates from the accretion disk thermal emission and is visible in the blue or UV part of their spectra. Quasars are primarily separated into two groups: radio-quiet and radio-loud quasars, wherein only up to $\sim 20\%$ fall in the latter group. Subsequently, based on multi-wavelength observations, they were divided into several subgroups, such as extended lobe-dominated quasars and compact core-dominated quasars, steep and flat spectrum radio quasars, optically violent variable quasars, and highly polarised quasars.

BLAZARS

The term *blazar* was proposed for the very first time by Edward A. Spiegel and officially introduced by Angel & Stockman (1980). It was created for extragalactic objects highly polarised and rapidly variable in the optical range, which posses a nonthermal continuum along the entire electromagnetic spectrum and compact radio emission. Since the very beginning, the blazar group included optically violent variable quasars and BL Lac type objects.

Blazars form a small and extreme class of radio-loud quasars, pointing their relativistic jets along the line of sight to an observer. They are primarily divided into two groups: FSRQs and BL Lac objects. Both types share similar observational properties, such as variability, high linear optical polarisation degree $PD_o > 3\%$ (Impey & Tapia, 1990), high radio-loudness, flat radio and steep infrared spectra, and apparent superluminal motions. Blazars are highly variable among the whole electromagnetic spectrum from radio up to γ -rays at different time scales reaching minutes in the most extreme cases. The FSRQs exhibit prominent emission lines in their optical spectra due to ionized plasma contribution from the accretion disk, while the BL Lacs possess at most weak emission and absorption lines, or some of them can be also featureless, i.e. with a smooth continuum only (Giommi et al., 2012).

The broad-band spectral energy distribution (SED) of blazars, extending along the entire electromagnetic range, consists of two humps (see Figure 7): a low energy part assigned to the synchrotron emission from

relativistic electrons or protons (in hadronic models), and a high energy component identified with the IC scattering of photons. Considering the standard $\nu - \nu F_\nu$ plane, the synchrotron part stretches from radio up to UV/soft X-rays with its peak, ν_{peak}^S , appearing at different frequencies within this range. The IC part is located in the high energy regime from X-rays to γ -rays. Based on the ν_{peak}^S position, the BL Lac objects are usually divided into three subclasses: low- ($\nu_{\text{peak}}^S \lesssim 10^{14}$ Hz), intermediate- ($10^{14} \text{ Hz} \lesssim \nu_{\text{peak}}^S \lesssim 10^{15}$ Hz), and high- ($\nu_{\text{peak}}^S \gtrsim 10^{15}$ Hz) frequency peaked BL Lacs (Abdo et al., 2010); LBL, IBL, and HBL, respectively. An example of the multiwavelength SED of BL Lacertae classified as an LBL blazar is shown in Figure 7. In addition, a group of extreme HBLs with $\nu_{\text{peak}}^S \gtrsim 10^{17}$ Hz was suggested by Costamante et al. (2001). On the contrary, the ν_{peak}^S frequency of the FSRQ objects occurs between $10^{12.5}$ Hz and $10^{14.5}$ Hz. All classes form together the so-called *blazar sequence* introduced by Fossati et al. (1998). According to it, the FSRQ is the most powerful class of blazars with the observed bolometric luminosities of $10^{47} - 10^{48}$ erg s $^{-1}$ and the ν_{peak}^S located in the lower energy range due to high cooling process. Consistently, each subsequent class is less powerful and the ν_{peak}^S is moving to higher energies, reaching the soft X-ray range in the case of the extreme HBL group. The BL Lac objects are often considered as successors of the FR I radio-loud galaxies, while the FSRQ blazars are identified with the FR II ones (Ghisellini, 2013a). An alternative blazar classification is based on their observations in different frequency bands and extracts other blazar subclasses such as X-ray (XBL) or radio (RBL) selected BL Lacs (e.g. Padovani & Giommi, 1995), which are related to HBL and LBL, respectively.

The aforementioned class of the extreme HBLs is characterised by

- high radio flux, $F_r \geq 3.5$ mJy, and high ratio of X-ray to radio flux, $\frac{F_x}{F_r} \geq 3 \times 10^{-10}$ erg cm $^{-2}$ s $^{-1}$ Jy $^{-1}$ (Giommi et al., 1999),
- synchrotron emission dominated by X-rays with the peak reaching even $\nu_{\text{peak}}^S \gtrsim 10^{19}$ Hz in case of 1ES 1426+428 (Costamante et al., 2001),
- high spectral variability in the synchrotron part comparing to the lower ν_{peak}^S blazars (Costamante et al., 2001),
- hard TeV spectra with $F(\nu) \propto \nu^{-1}$ (Akiyama et al., 2016),
- no variability in the TeV range.

Due to their peculiar features, the extreme HBLs can be used to study the particle acceleration mechanisms, the IR-optical-UV intergalactic photon fields, and VHE γ -rays interactions with the ambient matter. However, only ~ 10 extreme HBLs are known up to date (Akiyama et al., 2016), thus no statistical study of this class of objects was carried out and the list of characteristics is not completed or confirmed yet. As Costamante et al. (2001) claim, some extreme HBLs can be hidden in the HBL class of blazars. In order to properly classify them and extend the list, repeated observations in the HE and VHE should be conducted.

The multiwavelength approach is a highly effective investigation method of the physical properties of blazars. Since blazars are extremely variable in the entire range of the electromagnetic spectrum, observations in each of the considered SED frequency ranges have to be conducted simultaneously. Otherwise, it is impossible to fit any physical model to the data in a trustworthy way.

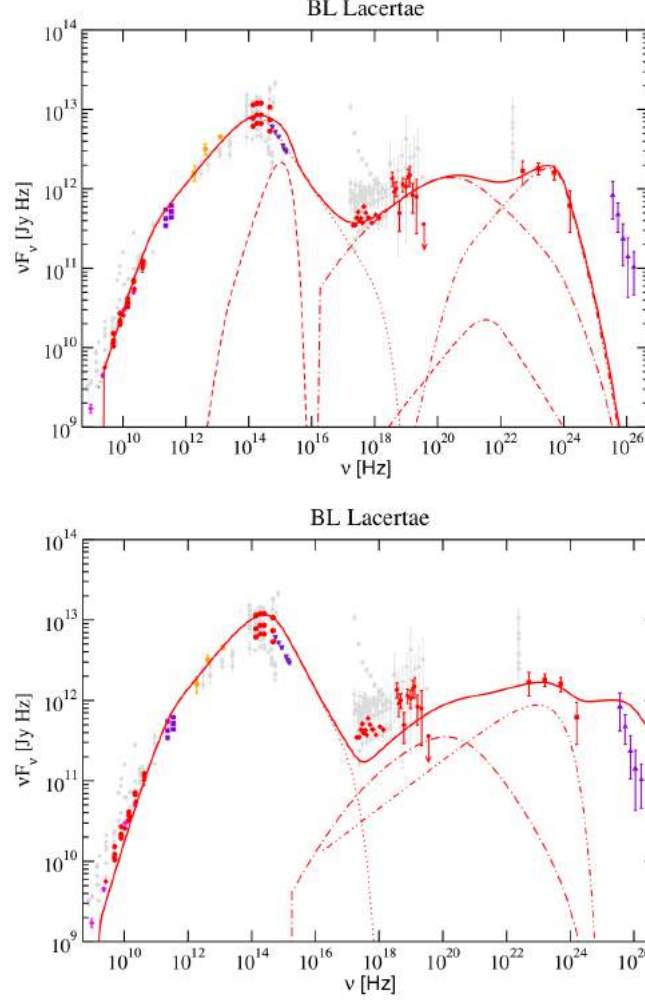


Figure 7: Multiwavelength spectral energy distribution of BL Lacertae. Plots taken from [Böttcher et al. \(2013\)](#). BL Lacertae is the precursor of the BL Lac objects and the example of the LBL blazar class. Points indicate observations taken at various frequencies. Red lines are leptonic (top panel) and hadronic (bottom panel) model fits to the particular emission components which the SED consists of, i.e. synchrotron is marked by dotted lines, emission from the accretion disk – dashed lines, synchrotron self-Compton – dot-dashed line, external Compton from the disk – dot-dot-dashed lines, and external Compton from broad line region – dot-dot-dashed lines.

The SED is characterised by two humps which can be parametrised via the *leptonic*, *hadronic*, or *lepto-hadronic* models. These models differ from each other merely in the description of the high energy emission. The low frequency peak is usually identified with leptonic/hadronic emission from the jet, while the contribution to emission in the high frequency peak is from the jet as well as the external components. The external ingredients of

the emission can come from the jet's vicinity, such as accretion disk, corona, and broad-line region, or more distant regions like the narrow-line region, the dusty torus, and the interstellar matter clouds. Nevertheless, a convincing interpretation of the second hump is still obscure. An exemplary fitting of the leptonic and hadronic models to the observational multifrequency data is presented in [Figure 7](#).

IMAGING ATMOSPHERIC CHERENKOV OBSERVATORIES

Since VHE γ -ray sources emit characteristic photon fluxes $\lesssim 10^{-12}$ erg cm $^{-2}$ s $^{-1}$, large collecting areas > 100 m ^{2} are required to detect them. Otherwise the observations are statistically insignificant (too low ratio of observed photons to exposure time). This makes it impossible to send an instrument into space, thus depriving us of the direct observations. The imaging atmospheric Cherenkov telescopes (IACTs) take advantage of the Cherenkov radiation which is visible in the optical range (300–600 nm), and give an opportunity to perform indirect ground-based observations of the VHE radiation. The technique relies on the detection of short Cherenkov light flashes lasting 3–4 ns, caused by air showers generated during collisions of ultrarelativistic γ -ray photons or hadrons with particle nuclei in the upper layer of the Earth’s atmosphere (for details see [Section 1.3](#)). The ground-based detectors register incomplete and degenerate information, leading to a precise identification of the primary particles, i. e. to measure their initial energy, establish direction of emission, and, finally, to determine the nature of the source of radiation.

3.1 BEGINNING OF IACTS

WHIPPLE 10 M TELESCOPE

The Crab Nebula is the first source discovered in the TeV energy range by a ground-based IACT ([Weekes et al., 1989](#)). The observations were conducted in 1988 by a single 10 m telescope located in the Whipple Observatory on Mount Hopkins in Arizona, USA, on an elevation of 2300 m above sea level. The Whipple telescope was built in 1968 and is a pioneering experimental detector of the Cherenkov radiation. The very first version of the instrument was composed of the Davies-Cotton design dish covered with 252 hexagonal mirrors of 61 cm in diagonal each and was operated on the altitude-azimuth mount. The prototype ([Fazio et al., 1968](#)) reached an energy threshold of 400 GeV with the flux sensitivity of 1.4×10^{-10} photons cm $^{-2}$ s $^{-1}$. Then the telescope and, in particular, its camera were consecutively upgraded. The current telescope consists of 248 mirrors giving a reflecting area of 75 m ^{2} with a 7.3 m focal length at which the camera is installed. The camera contains 379 photo-multiplier tubes (PMTs), giving a field of view (FOV) of 2 $^\circ$ 8, and reaching the energy threshold of 340 GeV (more details on the telescope and camera can be found in [Kildea et al., 2007](#)).

Besides the first detection of the VHE source in the sky, the microvariability (variability on short time scales down to hours and minutes) of blazars in the TeV range was also discovered ([Schubnell et al., 1993](#)).

HEGRA ARRAY

High Energy Gamma Ray Astronomy (HEGRA) observatory was an instrument consisting of six Cherenkov telescopes operating between 1992 and 2002, located on La Palma in the Canary Islands, at an altitude of 2200 m. In the very early stage of the experiment, since 1992, a single Cherenkov telescope (CT 1) was commissioned on the site. The spherical dish possessed a 5 m^2 reflective area composed of 18 spherical mirrors, 60 cm in diameter each (Mirzoyan et al., 1994). The second telescope (CT 2) was built in 1993, worked in a stand-alone mode, similarly to the CT 1, and constituted a preliminary model of the future array. The CT 2 was operated on an altitude-azimuth mount. Its dish was covered with 30 spherical mirrors giving an 8.5 m^2 reflective area (Aharonian et al., 1999). The telescope in the stand-alone mode gained definitely lower sensitivity than provided by the stereoscopic configuration, what was also predicted by the Monte Carlo (MC) simulations. In order to obtain better quality data, the HEGRA collaboration built a system of four new telescopes, i. e., CT 3-6, identical to the CT 2. After the CT 2 upgrade, the instrument worked as an array of five identical telescopes, achieving an energy threshold of 500 GeV. It was the first ground-based IACT observatory that worked in the stereoscopic mode.

The array was not only the first highly advanced γ -ray observatory, but also a pioneer in the reconstruction methods of air shower parameters. Data collected by HEGRA telescopes were used to check the sensitivity and efficiency of various algorithms. The experience acquired in the experiment was used by the next generation Cherenkov observatories such as the High Energy Stereoscopic System (H.E.S.S.; described in details in Section 3.2), the Major Atmospheric Imaging Cherenkov (MAGIC; Tridon et al., 2010), the Very Energetic Radiation Imaging Telescope Array System (VERITAS; Park & VERITAS Collaboration, 2015), or the Cangaroo (Kubo et al., 2004).

3.2 HIGH ENERGY STEREOSCOPIC SYSTEM EXPERIMENT



Figure 8: The H.E.S.S. observatory at its phase II. Photography taken from the Astronomy Center of Heidelberg University webpage¹.

¹ www.lsw.uni-heidelberg.de/projects/hess/HES/

The H.E.S.S. experiment is an IACT observatory located in the southern hemisphere in Khomas Highlands in Namibia, about 100 km south-west from the capital, Windhoek. The site was carefully selected to perform the high quality observations. Proximity of the Tropic of Capricorn allows to observe the inner parts of the Galaxy at low zenith angles. The Cherenkov light emitted by the air showers close to the zenith is less absorbed by the atmosphere, which leads to a better sensitivity of observations in this sky region. The Khomas Highlands is a sparsely-populated area with excellent weather conditions, i. e. low humidity, cloudless nights, and low light/air pollution. The observatory is situated at the altitude of 1800 m above sea level. The site is equipped with meteorological devices to monitor atmospheric conditions, like temperature or humidity, to ensure a better quality selection of observations. The Automatic Telescope for Optical Monitoring (ATOM) installed at the H.E.S.S. site is a 70 cm class optical telescope used to monitor sources in visible range giving a possibility for simultaneous γ -ray-optical study.

3.2.1 *System of the H.E.S.S. telescopes*

The first phase of the experiment (H.E.S.S.-I) started in June 2002 with the installation of the first H.E.S.S. Cherenkov telescope (CT 1) on the site. In the end of 2003, an array of four telescopes was completed and fully operational in the stereoscopic mode. The second phase (H.E.S.S.-II) started in September 2012 when the large fifth telescope was added at the centre of the former array (Figure 8). The complete array of telescopes is therefore composed of five instruments which observe in the energy range from ~ 30 GeV up to 100 TeV (Giavitto et al., 2015).

The H.E.S.S.-I stage consisted of four identical 13 m telescopes, CT 1-4, which form a square with a 120 m side. This type of arrangement allows sensitivity optimization of the system at a level of ~ 100 GeV and stereoscopic view of the atmospheric showers by two or more telescopes at the same time (Funk et al., 2004). The dish of the small telescope is built in a Davies-Cotton design (Figure 9, left panel). It consists of 382 round-shape mirrors, 60 cm in diameter each, giving a reflective area of $\sim 100 \text{ m}^2$. Atmospheric showers and the background radiation are registered by the camera, which is placed at the focal length of 15 m in each CT 1-4 telescopes. The camera is built of 960 PMTs equipped with light concentrators, the Winston cones, to reduce light losses between tubes and eliminate noise mostly noticeable at low elevations. All the PMTs are located in 60 drawers connected to the rest of the electronic facility. The drawers can be easily removed and replaced if needed.

All telescopes, including CT 1-4 and CT 5, operate on altitude-azimuth mounts, which provide a precise source pointing and tracking. The massive steel construction, installed on circular rails, ensures stability of the dish and camera as well as effective movement in both azimuth and elevation.

The parabolic dish of the CT 5 (Figure 9, right panel) is composed of 875 hexagonal glass mirrors, 90 cm in size each. The reflective area of this huge, $33 \cdot 24 \text{ m}$ ($\sim 28 \text{ m}$ circular shape), telescope is 614 m^2 . The camera,

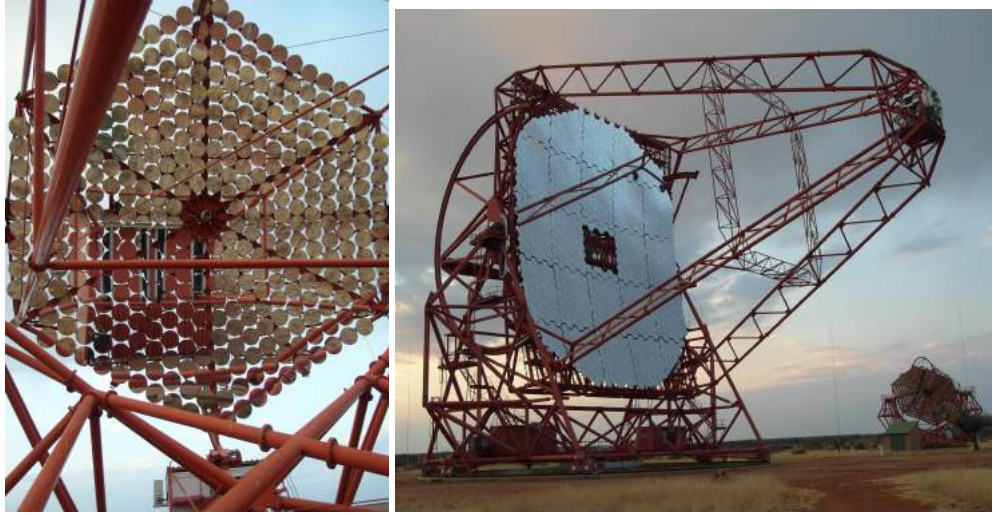


Figure 9: Telescopes of the H.E.S.S.-I and H.E.S.S.-II phase. Left panel: mirror configuration of the 13 m H.E.S.S.-I Telescope. Right panel: 28 m CT 5. Source: the author.

analogous to the H.E.S.S.-I telescopes, is located at the focal length of 36 m and consists of 2048 PMTs, which are fixed in 128 drawers. The H.E.S.S.-II phase, by adding the CT 5 telescope, increased the sensitivity and expanded the energy coverage of the H.E.S.S. instrument. The main motivation behind this upgrade was to fill the gap between the energy threshold of space-based detectors and to observe the VHE sources up to the greatest possible distances. The technical details about the telescopes, mirrors, and cameras are summarized in [Table 2](#).

3.2.2 *Data gathering and analysis*

3.2.2.1 *Observation strategy*

Observations of γ -ray showers require perfect weather conditions, such as moonless nights and clear air. Continuous monitoring of the atmospheric quality at the H.E.S.S. site is performed by three instruments, including a weather station to control temperature, humidity, and wind speed, the infrared radiometers to measure sky temperature, and the ceilometer to monitor air pollution. These measurements are used to decide whether or not to start and continue observations.

Observations conducted by the H.E.S.S. telescopes are split up to 28 minute-long runs and are taken by at least two telescopes simultaneously (stereo mode), except for the CT 5 which can also observe in the stand-alone (mono) mode. The camera is triggered to register the Cherenkov light event at the PMT level of > 5 photo-electrons (p.e.) in 3 to 5 adjacent pixels. The observations conducted by only one of the CT 1-4 telescopes are suspended after a few seconds. The telescopes track a source or a position in the sky close to the source, usually in an offset mode. The offset is a small distance (mostly $0^{\circ}.5$ and $0^{\circ}.7$ in right ascension and/or declination, respectively) between the target position and the place where the telescope is actually directed. The offset mode supports a background extraction from

	CT 1-4	CT 5
Construction details		
Dish design	Davies-Cotton	Parabolic
Dish size	$\varnothing$ 13 m	$\varnothing$ 28 m (32.6 m $\times$ 24.3 m)
Mount	altitude-azimuth	altitude-azimuth
Height of elevation	10 m	24 m
Total weight	60 tons	580 tons
Mirror structure		
Mirror shape	spherical	hexagonal
Number of mirror segments	382	875
Size of single segment	$\varnothing$ 60 cm	$\varnothing$ 90 cm
Reflective area	107 m ²	614 m ²
Focal length	15 m	36 m
Camera framework		
Pixel size	$0^\circ.16 \times 0^\circ.16$	$0^\circ.067 \times 0^\circ.067$
PMTs	960	2048
Drawers	60	128
FOV	$5^\circ.0 \times 5^\circ.0$	$3^\circ.2 \times 3^\circ.2$
Weight	0.9 tons	3 tons

Table 2: Design and parameters of the CT 1-4 (Bernlöhr et al., 2003; Aharonian et al., 2006b) and CT 5 (Krayzel et al., 2013) H.E.S.S. telescopes.

the registered signal from an observed object. The runs are collected and controlled through a real-time analysis performed by the data acquisition system (DAQ) directly on the site. Investigation of the observed source is based on many runs collected over a long time, often over many months or even years, in order to achieve the required level of the signal significance. The event reconstruction strategy is a two-step approach, including parametrization of measured signal to reproduce the primary particle properties. This implies required variables used further for discrimination of the air showers, and simulations of the air shower parameters, in order to compare them with the parameters derived from the detected events.

3.2.2.2 Signal calibration

The signal, collected by the telescopes and acquired through the PMTs in the cameras, is a mixture of source emission and a sky background contamination mostly by the hadronic cascades. The observations have to be electronically processed to distinguish both types of events from each other. First, the recorded signal is amplified, then sent to an analogue memory and to a trigger system. The trigger system recognizes an event pattern in the image, compares it between structures of both shower types, and minimizes the input rate of the background by rejecting events initiated by hadrons. Subsequently, the signal is redirected from the analogue memory

to the analogue-to-digital converter (ADC) and finally transferred to the storage memory device.

The signal calibration process is performed to convert the ADC counts to physical units and initially prepare data for further analysis. The calibration method involves a chain of procedures, including:

- signal gain calibration,
- electronic pedestal estimation,
- LED flat-fielding,
- p.e. to the Cherenkov light conversion,
- damaged (bad/dead) pixel rejection.

3.2.2.3 Run quality selection

In order to avoid additional undesirable effects, such as the weather conditions or electronic issues, resulting from the poor data quality overlapping with the good quality data used in further analysis, special restrictions are imposed on the runs enabling proper selection of observations. The standard run quality selection is based on a number of factors, including amount of bad or dead pixels, mean trigger rate, mean number of the inactive PMTs, and tracking errors, resulting in an adequate number of runs ready for further analysis.

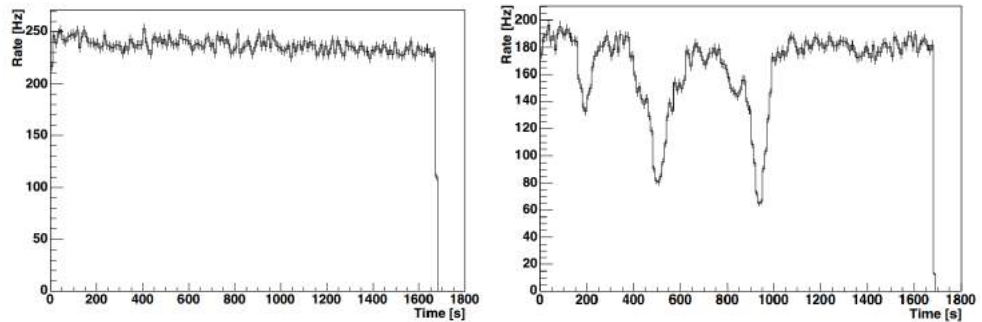


Figure 10: Trigger rate vs. run duration of two runs. Left panel shows a good quality run, while right panel presents a bad quality run with visible fluctuations in trigger efficiency caused by the moving clouds or polluted air. Plots are taken from [Aharonian et al. \(2006b\)](#).

An example of a real time run quality verification directly on the site, a system trigger rate (detailed description by [Funk et al., 2004](#)), is shown in [Figure 10](#). The good quality run (left panel) and bad quality run (right panel) are immediately recognized by an observer and the DAQ system. Passing clouds, dust in the air, or other undesired events cause trigger fluctuations resulting in additional systematic errors in the measured Cherenkov light parameters. The trigger rate depends also on the number of simultaneously observing telescopes and the zenith angle. The uncertainties in the reconstruction of the source position can be minimized through monitoring of the tracking system of the array. In general, strict limiting values of the run quality factors are fixed, i.e. runs with $< 70\%$ of the mean trigger

rate, $> 10\%$ bad/dead pixels, $> 10\%$ of the inactive PMTs, or exposure time < 5 minutes are suspended during the run selection process and not used in the data analysis.

3.2.2.4 Signal parametrization and air shower reconstruction

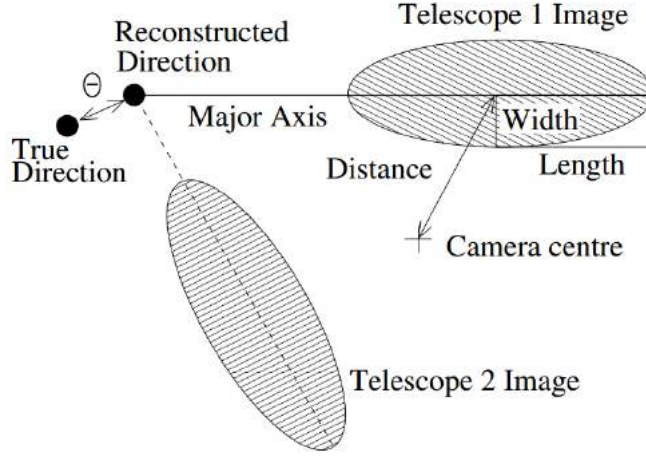


Figure 11: Scheme of a shower reconstruction using the Hillas parameters. The θ is an angular distance between the reconstructed and true directions of the registered event. Sketch taken from: [Aharonian et al. \(2006b\)](#).

According to [Hillas \(1985\)](#), the recorded Cherenkov light can be approximated to be an ellipse-shaped image on the detector and described with adequate parameters, hereinafter referred to as the *Hillas parameters*; their definitions are shown in [Figure 11](#). Based on the parametrization of the ellipse and its geometrical system, in particular

- width w ,
- length l ,
- angular size,
- distance from the camera centre,
- major axis of the image in the detector,
- centre of the Cherenkov light pool,
- intensity distribution of signal in the detector,

the characteristic features of the detected air shower, the primary particle, and the source of emission can be derived. For example, direction to the observed source is correlated with the major axis of the image. If the target is observed in the stereoscopic mode, the major axis of the image collected by one telescope intersects with the major axes of other images, providing a geometrical reconstruction method of the air shower direction (direction to the source; e.g. [Hofmann et al., 1999](#)). The real direction to the source can be then estimated based on the θ angle, which is an offset between the reconstructed and the true directions. Moreover, knowing the intensity

amplitude of the image on each detector and the impact parameter from observations as well as the mean energy and the impact parameter derived from the MC simulations of a γ -ray event, the energy of the primary γ -ray can be reconstructed. The MC simulations are performed for different zenith angles and based on these calculations, the energy is first linearly interpolated and then averaged over a number of telescopes observing an event.

Another important application of the approximation of the air shower elliptical shape introduced by Hillas (1985) is the discrimination of air shower types. In Figure 12, images of two different events collected by the CT 5 detector are shown. The event illustrated in the left panel is most probably caused by a γ -ray, whereas the structure visible in the right panel may have a hadronic origin. The Cherenkov light emitted during the γ -ray event has a narrow elongated elliptical shape, while the hadronic emission creates a wide irregular pattern, often containing ring- or arc-shaped structures that can be a result of a muon event detection. However, it should be borne in mind that it is impossible to distinguish an air shower initiated by the VHE γ -ray photon from the hadronic secondary particle cascade by eye, so an appropriate analytical method must be used for this purpose.

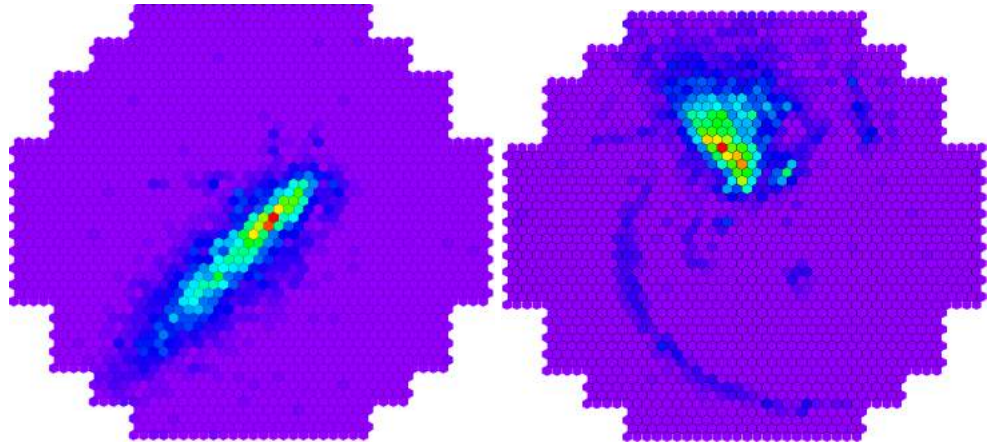


Figure 12: Images of events taken by the CT 5. Left panel shows an event initiated by a γ -ray, while a hadronic shower candidate is illustrated in right panel. Shower started by the γ -ray can not be distinguished from the hadronic cascade by eye only based on the images collected by the IACTs. However, narrow arcs or ring-shaped structures in the image suggest muon detection, which are produced in the hadronic showers. Source: Max Planck Institute for Nuclear Physics².

The most common concept, also used in the H.E.S.S. data analysis, is to compare the Hillas parameters derived from the observed images with the MC simulations of the same parameters. The simplest and also the most effective procedure is to rely on computations of the w and l ellipse parameters. The simulated parameters are then averaged using the mean scaled framework

$$sw = \frac{w - \langle w \rangle}{\sigma_w}, \quad sl = \frac{l - \langle l \rangle}{\sigma_l}, \quad (36)$$

² www.mpi-hd.mpg.de

where sw and sl are the scaled w and l of the ellipse and σ_w and σ_l are the variances of w and l parameters (the scatter), respectively. The mean parameters as well as the scatter vary differ with the zenith angle, impact parameter, and amplitude of the image. In case of the stereoscopic observations, the mean scaled width msw and length msl are used

$$msw = \frac{\sum_{tel} sw}{\sqrt{N_{tel}}}, \quad msl = \frac{\sum_{tel} sl}{\sqrt{N_{tel}}}. \quad (37)$$

These computed parameters are eventually compared with parameters of detected events to derive photon energy and direction of an event.

The modelled ellipse parameters of the γ -ray and the background events are optimized in order to achieve the highest possible level of significance of source excess counts for the given data set. The significance is estimated using a statistical likelihood method described in [Li & Ma \(1983\)](#) as

$$S = \sqrt{-2 \ln \lambda}$$

$$= \sqrt{2N_{On} \ln \left[\frac{1 + \alpha}{\alpha} \left(\frac{N_{On}}{N_{On} + N_{Off}} \right) \right] + 2N_{Off} \ln \left[(1 + \alpha) \left(\frac{N_{Off}}{N_{On} + N_{Off}} \right) \right]} \quad (38)$$

where λ is the maximum likelihood ratio and N_{On} and N_{Off} are the numbers of events coming from the source and background regions, respectively. The normalisation parameter α is usually defined as a time ratio of N_{On} to N_{Off} , i.e. $\alpha = t_{On}/t_{Off}$.

The configuration cuts used in the standard H.E.S.S. analysis, based on [Aharonian et al. \(2006b\)](#), are:

1. **standard** (std), optimized for $\theta^2 = 0.0125 \text{ deg}^2$, image intensity of 80 p.e., $-2 < msw < 0.9$, $-2 < msl < 2$, 10% of Crab flux and $\Gamma = 2$,
2. **loose**, optimized for $\theta^2 = 0.04 \text{ deg}^2$, image intensity of 40 p.e., $2 < msw < 1.2$, $-2 < msl < 2$, 100% of Crab flux and $\Gamma = 3 - 4$, used for strong sources,
3. **hard**, optimized for $\theta^2 = 0.01 \text{ deg}^2$, image intensity of 200 p.e., $-2 < msw < 0.7$, $-2 < msl < 2$, 1% of Crab flux and $\Gamma = 2$, used for both weak and hard spectrum sources,
4. **extended**, optimized for $\theta^2 = 0.16 \text{ deg}^2$, image intensity of 80 p.e., $-2 < msw < 0.9$, $-2 < msl < 2$, used for extended sources.

First three configuration cuts are defined with an assumption that the analysed emission comes from a point-like source. The distribution of the θ^2 parameter of the air shower reconstructed directions is described by the point spread function (PSF). In this approach, the θ^2 value is smaller than the point-like source size in order to reduce the background contribution to the studied source emission.

Up to date, two software packages have been implemented to analyse the H.E.S.S. data, i. e. *Model Analysis* (de Naurois & Rolland, 2009) and *HD-hap* (the method based on the Hillas parametrization described above). Furthermore, as a part of the *HD-hap* package, Image Pixel-wise fit for Atmospheric Cherenkov Telescopes (*ImPACT*; Parsons & Hinton, 2014) was released as an improvement of the former.

The *Model Analysis*, hereinafter referred to as an *M++*, is a technique to reconstruct the γ -ray events based on the comparison within a semi-analytical model of unprocessed images of the Cherenkov light distribution collected by the IACT detectors with the images of air showers generated with the MC simulations. The air shower parameters are modelled from the Cherenkov light distribution with respect, among others, to the atmospheric absorption, the first interaction depth, the angular and lateral distributions of particles, the production rate of the Cherenkov photons, and the quantum efficiency of the detector. As a result of the simulation and interpolation procedure, the air shower images in the four-dimensional (4D) space are obtained, which form a model ready to be compared with the observed images. The Hillas parametrization approach is used to estimate initial parameters, i. e. length and width of the ellipse.

The comparison between parameters of generated and observed images is performed based on the log likelihood statistics (after de Naurois & Rolland, 2009)

$$P(s \mid \mu \gg 0, \sigma_p, \sigma_\gamma) \approx [2\pi\sigma_p^2 + 2\pi\mu(1 + \sigma_\gamma^2)]^{-\frac{1}{2}} \times \exp \left[-\frac{(s - \mu)^2}{2\sigma_p^2 + 2\mu(1 + \sigma_\gamma^2)} \right], \quad (39)$$

where μ is the expected signal in each pixel, σ_p is the width of the distribution of the background signal and electronic noise (so-called pedestal) and σ_γ is the width of the single p. e. peak. The configuration cuts used in the standard H.E.S.S. data analysis based on the *M++* technique correspond to those used in Aharonian et al. (2006b).

ImPACT is an algorithm to reconstruct the air shower events collected by the IACT detectors by finding the best-fit parameters of a maximum likelihood fitting of an image template to an observed image. The image template is generated using the MC modeling of the air shower parameters that takes into account simulations of the raytracing and electronics of the telescope. Since the image template is prepared, a comparison between it and an observed image is made using the maximum log likelihood fitting based on the same log likelihood statistics as in the case of the *M++* (Equation 39) to find the best parameters reflecting the observed data.

The disadvantages of the *ImPACT* approach are greater computing power and longer simulation time required in comparison to other semi-analytical models. On the other hand, the advantage is better angular resolution at high energies and the improved PSF which leads to higher sensitivity than the previously implemented methods. The improvement in the angular resolution is extremely useful for studying morphology of various sources.

3.2.2.5 Background estimation

The H.E.S.S. telescopes observe targets in the offset mode giving an opportunity to measure background events along with the source, thus each run contains both the night sky background emission and the excess counts, i. e. a number of events from the observed source. Notwithstanding, to evaluate the background emission level, all of the aforementioned procedures for the registered events should be accomplished, i. e. the signal calibration, the run selection, and the signal parametrization. Moreover, known sources in the FOV of the analysed region have to be excluded (blinded) in order to prevent additional contamination of the foreground or background sources. The scheme of the background emission level estimation used in the H.E.S.S. data analysis, which is crucial to calculate the primary γ -ray flux, is shown in Figure 13. The left panel displays the *ring background* model, whereas the *reflected-region background* model is illustrated in the right panel. The *On Region*, i. e. the position of the target in the sky, is marked by the dashed white ring, the solid red rings are regions of background level estimation (*Off Regions*), and solid yellow rings are positions where the telescopes really looked at. The number of excess counts is defined as

$$N_{\text{excess}} = N_{\text{On}} - \alpha N_{\text{Off}}. \quad (40)$$

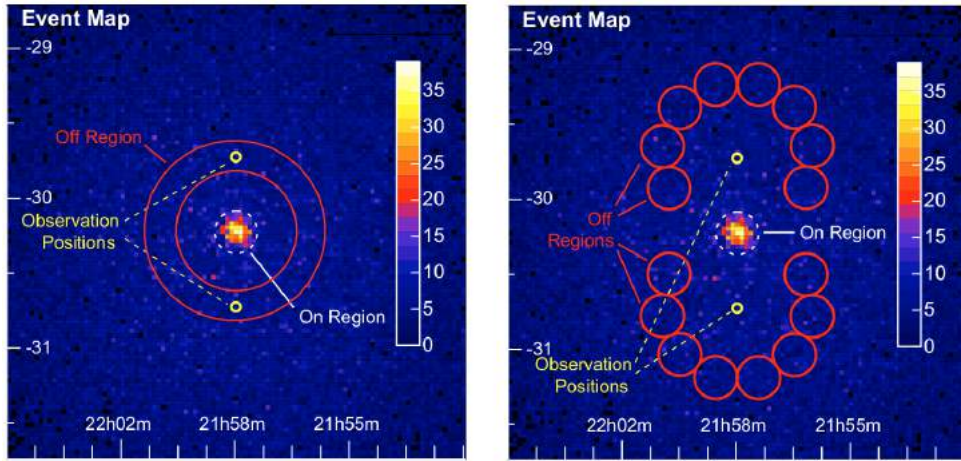


Figure 13: Scheme of background models (Berge et al., 2007) imposed on a γ -ray event count map (*excess map*) of the PKS 2155-304 blazar. The ring background model is illustrated in left panel, while the reflected-region background model is shown in right panel.

1. In the ring background model, the background events are estimated for an accumulated set of runs within a ring surrounding the test position of the source at some distance. The ring is bounded on two sides, with the inner limit setting a safe background separation from the source to prevent the background flux contamination by the source emission. The outer limit defines the size of the Off region. The offsets within the ring are distributed differently with respect to the observation position, so the background events need to be normalised. However, the heterogeneous offset distribution adds additional systematic

errors, which makes it a highly disfavoured model for an energy spectrum derivation. The ring background model is mostly used in basic analysis of excess and significance maps, in the investigation of extended objects or in very crowded fields, and to confirm the detection of a source.

2. In the reflected-region background model, multiple Off regions for determining the background level are distributed equidistantly from the observation positions in a way to avoid overlapping between the individual Off regions. The On and Off regions are alike, having the same ring-shape and size. The background events are measured in each Off ring and then accumulated. Since the offsets between the Off regions and the observation positions are identical, the normalisation of the background events is not needed. The offsets do not introduce supplementary systematic errors, thus this approach is commonly used in the energy spectrum estimation, light curve study, and the morphological investigation of a source. Unfortunately, due to high sensitivity of the Off regions for an additional signal from sources in the FOV and a distribution limitation of the Off regions, the model can not be applied to the investigation of dense fields or to study extended sources.

The next stages of the H.E.S.S. data analysis prepared in accordance with the procedure described above, depending on the intended purpose of the investigation, are:

- Evaluation of the energy spectrum or γ -ray emission distribution to study the particle acceleration mechanisms. It involves, similarly as for the background subtraction, a comparison of the number of events between the On and several Off regions. The reflected-region background model is used in this case to reduce the systematic errors together with a *forward-folding method* (see [Section 4.3](#)) enabling adjustment of the appropriate spectrum shape to the data.
- Investigation of the luminosity evolution based on the derived LCs from the data. The LCs are simulated on different time scales to study the physical mechanisms responsible for their variability.
- Examination of the source morphology to study the radiation mechanisms and the interaction processes. The source shape and the flux distribution are determined based on statistical methods together with the forward-folding method.

The more detailed description of the energy spectrum and morphology analyses is given in [Chapter 4](#) with an explanation of adjusting the relevant parameters to the examined data.

Since the end of 2003, when the complete array of CT 1-4 began to carry out observations, the H.E.S.S. telescopes collected huge amounts of data, allowing detection and investigation of many various types of galactic and extragalactic sources of the VHE γ -ray emission, including

- centre of the Galaxy (Sgr A*, [Aharonian et al., 2004](#); [Acero et al., 2010](#)) and the Galactic plane ([Donath et al., 2017](#); [H.E.S.S. Collaboration et al., 2018b](#)),
- pulsars and pulsar wind nebulae, e.g. N 157B ([H.E.S.S. Collaboration et al., 2012a](#)) and HESS J1303–631 ([H.E.S.S. Collaboration et al., 2012c](#)),
- γ -ray binaries, e.g. 1FGL J1018.6–5856 ([H.E.S.S. Collaboration et al., 2015a](#)) and LMC P3 ([H.E.S.S. Collaboration et al., 2018a](#)),
- binary neutron star merger (not detected, [Abdalla et al., 2017](#)),
- stellar clusters, e.g. Westerlund 2 ([H.E.S.S. Collaboration et al., 2011a](#)) and Terzan 5 ([H.E.S.S. Collaboration et al., 2011b](#)),
- supernovae remnants, e.g. HESS J1640–465 ([Abramowski et al., 2014](#)), Vela Junior ([H.E.S.S. Collaboration et al., 2016a](#)), and RCW 86 ([H.E.S.S. Collaboration et al., 2016b](#))
- nearby galaxies, e.g. Large Magellanic Cloud ([H.E.S.S. Collaboration et al., 2015b](#)),
- starburst galaxies, e.g. NGC 253 ([Abramowski et al., 2012a](#)),
- active galaxies ([H.E.S.S. Collaboration et al., 2014a](#)), e.g. M 87 ([Abramowski et al., 2012b](#)), and more examples can be found in [Chapter 5](#),
- γ -ray bursts, e.g. GRB 100621A (only upper limits, [H.E.S.S. Collaboration et al., 2014c](#)),
- dark matter search (only upper limits, [Aharonian et al., 2006a](#)).

3.3 FUTURE OF IACTS

Cherenkov telescope array (CTA; [Cherenkov Telescope Array Consortium et al., 2017](#)) is a forthcoming ground-based IACT observatory situated both in the southern (99 telescopes) and northern (19 telescopes) hemispheres in order to provide a whole sky coverage. The system will consist of three telescope types: small (4 m with $\sim 10^\circ \times 10^\circ$ FOV), medium (12 m with $\sim 8^\circ \times 8^\circ$ FOV), and large (23 m with $\sim 4.5^\circ \times 4.5^\circ$ FOV)³. The southern site array will consist of 70 small, 25 medium, and 4 large size telescopes, which will allow to cover the energy range between 0.2 and 300 TeV. In the northern hemisphere, 15 medium and 4 large size telescopes will be installed, yielding the energy range between 0.2 and 50 TeV. A high flux sensitivity (comparison with currently operating γ -ray detectors is presented in [Figure 14](#)) will be ensured by small (at high energies) and large (at

³ www.cta-observatory.org/project/technology/; access date: 15.07.2018

low energies) telescopes. The expected angular resolution of $\sim 1'$ is the highest specification since the X-ray observatories. It is expected that the CTA observatory will be able to resolve extended sources and to observe fainter γ -ray astrophysical targets.

In the case of special observational tasks and sudden events, such as γ -ray bursts or multiwavelength multi-messenger incidents, dedicated subarrays will be in operation.

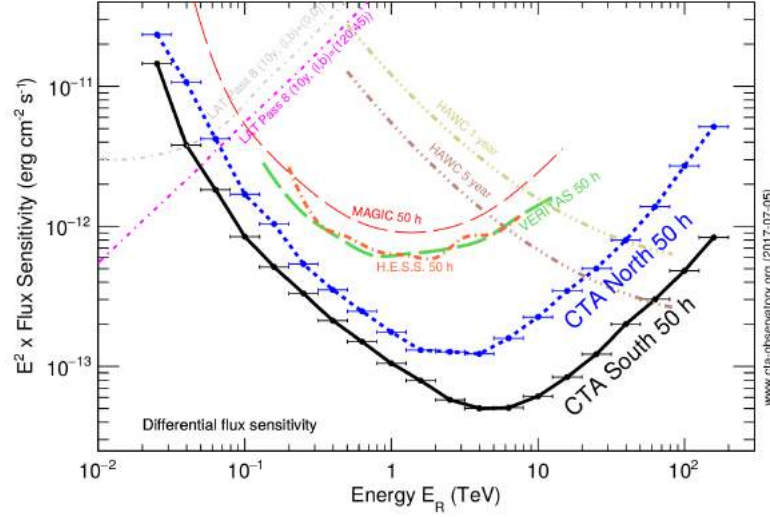


Figure 14: HE and VHE flux sensitivity comparison between the South and North CTA sites and currently operating γ -ray detectors evaluated at 50 h of integration time (Cherenkov Telescope Array Consortium et al., 2017).

The CTA observatory key science projects are:

- investigation of astrophysical targets which can accelerate CR particles to HE and VHE,
- deep observations of the nearest dwarf galaxy — Large Magellanic Cloud,
- research on dark matter, especially concerning detection of weakly interacting massive particles,
- study of the Galaxy centre and the survey of the Galaxy plane,
- search for galactic pevatrons,
- study of the AGN, the starburst galaxies, and the galaxy clusters,
- sky monitoring for transients.

Part II

MORPHOLOGY STUDY AGN

The second part of the thesis describes original work on VHE emission of 1ES 0414+009, Centaurus A (both found to be extended sources), and four additionally selected extreme HBL blazars.

METHODOLOGY OF AGN MORPHOLOGY STUDY

The following chapter contains a description of the analysis procedure undertaken in order to study TeV γ -ray data of six sources, including the FR I radio galaxy Centaurus A and five blazars, i.e. 1ES 0414+009, 1ES 0347-121, 1ES 1101-232, 1ES 0229+200, and PKS 0548-322. All selected blazars are classified as HBLs and allegedly belong to a small group of extreme HBLs (~ 10 known blazars of this type known, [Akiyama et al., 2016](#)). The objects of interest were observed by the small H.E.S.S.-I CT 1-4 telescopes. Due to the poor angular resolution of the H.E.S.S.-I telescope array, reaching $\sim 0.1^\circ$, these objects are expected to possess a point-like morphology.

4.1 MOTIVATION

The main reason for the performed studies is to check whether any of the selected objects have an extended intrinsic morphology in the TeV energy range. If such morphology is confirmed for any of the studied sources, this AGN could be employed to investigate a potential γ -ray halo around it and characteristics of the intergalactic magnetic field. Since almost all selected objects are classified as extreme HBLs, thus spectral and morphological analyses will also allow to study the properties in the TeV energy range of this peculiar group of blazars.

Moreover, the preliminary standard morphological analysis of two selected objects, namely Centaurus A and 1ES 0414+009, revealed an extension in the excess distribution of their TeV data. Each result must be confirmed by an analogous analysis of the same dataset, i.e. a cross-check, with another analysis technique. In case of Centaurus A, both the analysis and its cross-check with the *M++* and *ImPACT* techniques gave similar results revealing the extension in the object data. On the other hand, the preliminary morphological study of 1ES 0414+009 was not conclusive. In the former approach the event distribution seems to be extended, while in the latter it exhibits a point-like morphology. The difference between the results obtained with both methods must be verified in order to determine whether this object is actually point-like or extended.

4.2 STRATEGY OF ANALYSIS

The TeV data of all selected objects were collected by the CT 1-4 telescopes. The observations were first calibrated and then prepared for further study using techniques shortly described in [Section 3.2.2.4](#), i.e. the *HD-hap*, the *ImPACT*, and the *M++* analysis methods commonly used in the H.E.S.S. Collaboration. Briefly speaking, the *HD-hap* procedure is based on the Hillas parametrisation of the ellipse-shaped image of Cherenkov light on the detector. The *ImPACT* algorithm, which is also an extended version of the

basic *HD-hap*, relies on a maximum-likelihood fitting of the image template to the collected data. The *M++*, like the previous method, relies on the comparison of the images from the detector to the simulated data. Since all three methods are based on different calibration and reconstruction procedures, they were all used to cross-check the compatibility of data reduction and analysis results. The applied approaches usually give comparable outputs, however in many cases the latter two methods provide a higher level of significance through better separation of γ -ray events, and higher sensitivity than the first one. Especially in analyses where it was necessary to split the run list into several smaller parts, i.e. in the investigation of 1ES 0414+009 and Centaurus A based on the division of data sets into the zenith angle value ranges, the years of observations, or the different energy ranges, it turned out that the *HD-hap* method is not sensitive enough. Due to the low sensitivity, this method, after initial analysis, was not used in the further spectral and morphological studies. All results presented in this work are based on two methods, i.e. the *ImPACT* with the *hap-15-12_HESSI* environment and the *M++* with the improved *o-8-24* software, i.e. *Prod26_NewPointing*. In addition to the standard analysis with the H.E.S.S. software, the morphological analysis was performed using the *Mathematica 10.4* computing system.

The quality selection criteria, which were imposed on the data to identify the best runs for the spectral and morphological analyses of the selected objects, include:

- spatial and spectral modes to generate maps and estimate spectral parameters, respectively,
- an array configuration of at least 3 small H.E.S.S. telescopes,
- exposure time ≥ 5 minutes,
- mean trigger rate $> 70\%$,
- bad pixels $< 10\%$,
- inactive PMTs $< 10\%$.

The purpose of imposing such quality criteria for the run selection is to extract only the highest quality data while maintaining as much runs as possible.

The framework of the spectral and morphological study performed in this work consists of:

- generation of the γ -ray On and Off maps as well as excess and significance distributions of events using the ring background model to test a source detection with at least a 5σ level of significance,
- estimation of the θ^2 distribution with respect to an averaged background level,
- data analysis using the spectral mode to derive spectra with the reflected-region background model to prevent estimated parameters from additional systematic errors in the energy domain,

- spectral analysis based on fitting different models in order to find the most optimal one, allowing to estimate the appropriate differential photon spectral index and the integral flux,
- deriving the PSF and the angular resolution parameters for each data set,
- fitting the point-like, circular Gaussian, and elliptical Gaussian models to the TeV data.

Since AGN are visible as point-like objects in the TeV data collected by IACTs with their current angular resolution, the initial analysis is carried out with the three configuration cuts predefined for the point-like sources, including the std, loose, and hard cuts (see [Section 3.2.2.4](#)), to check which optimisation gives the best statistics and allows the highest possible quality spectral and morphological data analysis. The loose cuts results in higher γ -ray photon statistics due to lower energy threshold comparing to the std and hard cuts, allowing more events to pass the criterion but also giving deficient background subtraction. On the other hand, the hard cuts often restrict too many events to pass the imposed limit parameters. Since the objects studied here are relatively weak, the results obtained in the std cuts were used in the detailed analysis of the selected sources.

As mentioned in [Section 3.2.2.5](#), the commonly used approach to estimate and then subtract the background emission contamination to the analysed data involves the ring background and reflected-region background models. Both of them are used in this study. The former model is applied in the spatial (detection and morphological) analysis, i. e. to detect the object and generate particular sky maps. The latter model is employed in the spectral analysis, namely to estimate the differential photon index Γ of the emission, which is necessary for proper determination of the PSF parameters, and the fit of the morphological models to the sky maps prepared earlier. The results of this study are presented in [Chapter 5](#).

In addition to the morphological analysis of all considered objects, a detailed investigation of two sources, namely 1ES 0414+009 and Centaurus A, was conducted as well. The study is based on the division of the run lists into the years of observations, the zenith angle values, and the energy ranges in order to check possible influence of these factors on the shape of the source in the maps. In this analysis, the entire list of available H.E.S.S. observations was split according to the following criteria:

- **The year of observations** and weather condition check. Both the year and individual seasons of observations can have an impact on the data, i. e. a haze caused by burning grass in the summer, lightnings in the rainy season, or very low temperatures in winter. Due to the advanced techniques of data selection taking into account various weather conditions using the weather condition monitoring or the trigger rate system to track frequency changes ([Section 3.2.2.1](#) and [Section 3.2.2.3](#), respectively), the majority of poor quality runs are rejected at the level of their selection.

- **The zenith angle.** Response of the instrument varies depending on the zenith angle at which the object is observed, i.e. when the zenith angle increases, the pool of Cherenkov light also increases and the PSF widens. Through dividing the list of observations into individual zenith angle ranges, it is possible to check how the atmosphere thickness affects the detection of TeV emission and eventually the shape of the source.
- **The energy range.** Investigation of the H.E.S.S. data with various TeV energy cuts will show if the extension of the event distribution is related to the total energy or rather depends on particular energy ranges.

All of the above criteria can be only applied to data with sufficiently high level of significance, i.e. for data with statistical significance reaching at least 5σ , also after splitting the run lists into smaller sublists. The significance of each data set is calculated from Equation 38 introduced in Li & Ma (1983), while the number of excess events is estimated based on Equation 40.

4.3 SPECTRAL ANALYSIS

A good qualitative spectral analysis is necessary to determine the PSF of the instrument and to be able to study the morphology of sources' emission. The differential energy spectra of the sources are fitted with the H.E.S.S. *Fit-Spectrum* tool using the *forward-folding method* (Piron et al., 2001) based on the likelihood statistics. In this method, the fit to the data relies on an earlier assumption of a spectrum shape of the source motivated by the particle acceleration processes. The shape of the spectrum taken into account is related to the type and nature of the examined source. The selected objects were examined by fitting different models to their VHE data, such as a power law with exponential cut-off or a broken power law. However, it turned out that only the power law and the log parabola fit the data properly with relatively small errors and good results of statistical tests.

The power law function is defined as

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma}, \quad (41)$$

where N_0 is the differential photon flux normalisation factor at the reference energy E_0 , and Γ is the photon index.

The log parabola model, also known as the curved power law, is given by

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma - \beta \log(E/E_0)}, \quad (42)$$

where β is the curvature parameter.

On top of that, the intrinsic spectral index was estimated for all studied blazars by fitting the power law with the EBL absorption correction model to the spectrum, according to the Franceschini et al. (2008) model. This was

done to check how the photon index Γ changes with the redshift z under the influence of the EBL emission. Furthermore, hard intrinsic spectra are expected in most of the selected sources (see [Section 2.2](#)) due to their classification as extreme HBLs, which can be easily verified using this model. The power law with the EBL correction model is defined as

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma} \times \exp[-N_{\text{opt}}\tau(E, z)], \quad (43)$$

where N_{opt} is the normalisation of the optical depth $\tau(E, z)$ at a given redshift z .

In addition to the spectral index estimation, which is a substantial parameter in the PSF modeling and morphological analysis, an integral flux at an adequate energy $E > E_0$ was calculated for individual datasets based on the shape of the spectrum. The integral flux is defined as

$$\Phi = \int_{E_0}^{\infty} \frac{dN}{dE} dE. \quad (44)$$

POINT SPREAD FUNCTION

High quality reconstruction of γ -ray events is required for precise estimation of the source coordinates (α_{fit} , δ_{fit}) in the VHE regime and allows investigation of the shape and emission features of resolved sources. The angular resolution of the H.E.S.S. array has limitations resulting in a spread in the detector's response to a point source, i. e., point spread function (PSF), meaning that the γ -ray emission of any point source is not well-fitted by the Dirac delta. The PSF is approximated by the triple Gaussian function as

$$\text{PSF}(\theta^2) = S \left[\exp\left(-\frac{\theta^2}{2\sigma_1^2}\right) + A_2 \exp\left(-\frac{\theta^2}{2\sigma_2^2}\right) + A_3 \exp\left(-\frac{\theta^2}{2\sigma_3^2}\right) \right], \quad (45)$$

where S is the scaling factor, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, whereas A_2 and A_3 are the amplitudes of the second and third Gaussian functions relative to the first one. The broadening of the PSF is not constant and depends on several factors related to conditions during the observations and the chosen method of data analysis, including the values of zenith and azimuth angles, number of telescopes observing the target, offset parameter, and configuration cuts used.

The distribution of excess events is characterised by a containment radius, $R_{68\%}$, i. e. a radius that defines a circle containing 68% of the excess events, which is also referred to as the angular resolution of the telescope and depends on the energy range.

The PSF parameters and its containment radius of each source were determined using the *ExtractPSF* simulation model under the assumption of the spectral index Γ value resulting from the power law function fitting. Since all of the studied sources are variable, a weight-by-excess option was used which weighs the runs by the excess events in contrary to a default live time option. The PSF strongly depends on the zenith angle and the offset, therefore their non-averaged values for each run were used to determine the PSF parameters.

4.4 MORPHOLOGICAL ANALYSIS

The VHE excess event distribution of the sources is studied with the same technique as in case of the spectral analysis, i. e. the forward-folding method. Thus the event parameters are first reconstructed and then compared with simulated (with the MC methods) parameters convolved with the PSF of the particular datasets.

The morphological analysis of all selected objects were performed using three models, including the point-like model as well as the circular and elliptical Gaussian models. The point-like model is used in order to estimate the best-fit position of the γ -ray emission and then to compare the distance between the derived and the catalogued positions. Both types of Gaussian models are employed to estimate a putative extension in the VHE emission of the objects.

The point-like model is defined as

$$f(x, y) = N_0 \sqrt{(x - x_m)^2 + (y - y_m)^2}, \quad (46)$$

where N_0 is the normalisation factor and (x_m, y_m) is the estimated position of the source, which corresponds to the Right Ascension, α_{fit} and declination, δ_{fit} . Afterwards, the potential extension of the sources was checked by fitting the circular and elliptical Gaussian functions. The circular Gaussian model is defined as

$$f(x, y) = \frac{N_0}{2\pi\sigma^2} \exp \left[- \left(\frac{(x - x_m)^2 + (y - y_m)^2}{2\sigma^2} \right) \right], \quad (47)$$

where N_0 is the normalisation factor and σ is the width of the examined source. This model has four free parameters, including the estimated position of a source (x_m, y_m) , the normalisation N_0 , and the width σ . The elliptical Gaussian model is defined as

$$f(x, y) = \frac{N_0}{2\pi\sigma_a\sigma_b} \exp \left\{ - \frac{[-(x - x_m) \sin \varphi + (y - y_m) \cos \varphi]^2}{2\sigma_a^2} \right\} \times \exp \left\{ - \frac{[(x - x_m) \cos \varphi + (y - y_m) \sin \varphi]^2}{2\sigma_b^2} \right\}, \quad (48)$$

where N_0 is the normalisation factor, σ_a and σ_b are the major and minor semi-axes of the ellipse, and φ is the position angle of the ellipse. This model contains six free parameters, including the (x_m, y_m) , the normalisation N_0 , the semi-axes σ_a , σ_b , and the angle φ . In this study, the angle φ is counted counterclockwise from the northern direction.

The morphological models were fitted to the model maps prepared according to the following scheme:

$$\text{Model map} = \text{PSF} * (\text{exposure} \times \text{source}) + \text{background}. \quad (49)$$

The statistics were calculated using the log likelihood method, mentioned in [Section 3.2.2.4](#). The parameters resulting from the fitting procedure of the point-like source and both types of the Gaussian models to the objects of interest are presented for all studied AGN in [Chapter 5](#).

RESULTS OF SPECTRAL AND MORPHOLOGICAL ANALYSES

In the following chapter, results of the performed spectral and morphological analyses of the six objects of interest are presented. Since all AGN were analysed in the same way, certain common elements repeated for each object are described below.

1. Spatial and spectral analyses of all objects were performed using *ImPACT* and *M++* techniques with std, loose, and hard configuration cuts in order to verify which configuration cuts are the best for individual datasets, to check the statistical level of detection and spectral significance of data in each cut, and to cross-check the obtained results with independent methods. Since results achieved by the analysis with the std configuration cuts were taken into account in further considerations, only those are displayed in this chapter, with an exception of the significance maps, which are shown for all three configuration cuts.
2. The excess maps are calculated with the std configuration cuts and shown together with the PSF distribution (in the inset added in each map) to compare the PSF to the excess events distribution of the source. These maps have a size of 0.5×0.5 and are smoothed with a Gaussian function with a width of 0.08 . The PSF distribution was generated using the power law index Γ calculated individually for each source for all accumulated runs weighted by excess events. This approach allows to stabilise the modelling of variable objects such as blazars.
3. The significance 0.4×0.4 maps are shown with the superimposed radio and X-ray contours. The radio contours of blazars were calculated based on the National Radio Astronomy Observatory Very Large Array Sky Survey (NVSS), while in case of Centaurus A, the Australia Telescope Compact Array (ATCA) at 1.4 GHz map was used. The X-ray contours were generated from the archival data provided by the ROSAT X-Ray all-sky survey in 0.1 – 2.4 keV energy band images. The source position is taken from the adequate catalogue given in the text on the individual objects.
4. The θ^2 histogram with the PSF profile was plotted for each source to illustrate distribution of the reconstructed directions of the registered air showers.
5. The significance histograms, generated for each studied source, demonstrate a quality of the background subtraction from the On source region. The shaded spaces denote the significance distribution from the source region and from the entire FOV, while the red dotted line

shows a Gaussian fit to the On region, giving *Mean* and *Width* parameters. In analysis with the H.E.S.S.-I array the background is subtracted correctly if *Mean* is close to 0 and *Width* ~ 1 .

6. Furthermore, the Very Long Baseline Array (VLBA) 8.4 GHz contour maps of the studied blazars were generated and the Very Long Baseline Interferometry (VLBI)¹ contour map of Centaurus A was taken from Müller et al. (2014) to compare the parsec scale radio emission with the large scale VHE morphology of the H.E.S.S. data of all objects of interest. Similarly, based on the available archival Very Large Array (VLA) radio data, the large scale structures in both energy ranges were studied (see Appendix B).

The spectral and morphological analyses of VHE data begin with blazar 1ES 0414+009 and FR I radio galaxy Centaurus A. The obtained results are then compared with four other blazars, which are expected to be visible as point-like sources in observations performed with the H.E.S.S. telescopes.

5.1 VHE STUDY OF THE BLAZAR 1ES 0414+009

1ES 0414+009 ($\alpha = 04^{\text{h}}16^{\text{m}}52^{\text{s}}.50$, $\delta = +01^{\circ}05'23''.98$; Cutri et al., 2003), located at $z = 0.287$ (Halpern et al., 1991), is one of the most distant blazars detected in the TeV range by the H.E.S.S. observatory. The source was discovered by the HEAO 1 X-ray satellite (Gursky et al., 1978) in the energy range between 0.2 keV and 10 MeV and was identified, based on the multi-wavelength observations taken in the X-ray, optical, and radio ranges, as a BL Lac candidate (Ulmer et al., 1983). Subsequently, Impey & Tapia (1988) confirmed its blazar origin using optical polarimetric measurements, thus the object is classified now as an HBL. 1ES 0414+009 consists of a supermassive BH with a mass of $M_{\text{BH}} = 2 \times 10^9 M_{\odot}$ and constitutes the centre of an elliptical galaxy with an absolute magnitude of $M_{\text{R}} = -23.5$ in the R filter (Falomo et al., 2003).

McHardy et al. (1992) studied the 1.5 GHz VLA map (A configuration), which revealed an unresolved core and a one-sided jet-like structure, extending to the east. Laurent-Muehleisen et al. (1993) confirmed the one-sided morphology visible in the low resolution 1.5 GHz VLA map. Furthermore, the high resolution 1.5 GHz VLA map revealed the one-sided jet which breaks up at ~ 20 kpc and extends up to ~ 70 kpc towards the east. On top of that, an intrinsic one-sided radio structure elongated to the west is visible in the 8.4 GHz VLBA map (Piner & Edwards, 2018). The radio polarimetric observations show that 1ES 0414+009 is highly variable with the average radio polarization of $\sim 3\%$ from the core and $\sim 8\%$ from the jet. In case of HBLs, the complex radio morphology is unusual and can be caused by an association with a galaxy cluster and interactions between galaxies as well as the intergalactic ambient medium. Indeed, 1ES 0414+009 is the brightest member of a poor galaxy cluster (McHardy et al., 1992).

¹ <http://www2.whittier.edu/facultypages/gpiner/research/archive/archive.html>; date of access: 12.06.2018

PREVIOUS H.E.S.S. ANALYSIS

Five years of H.E.S.S. observations of 1ES 0414+009, between 2005 and 2009, were conducted mainly to study the EBL parameters with this distant object. Results of a preliminary analysis of the source emission are included in [H.E.S.S. Collaboration et al. \(2012b\)](#). The blazar was observed within the zenith angle range of $22^\circ - 41^\circ$ and it was detected within a live time of 74 hours. The significance level of the source detection reaches 7.8σ in the std configuration cuts. The TeV data analysis has not proven the source to be variable on any of the studied timescales for the flux at > 0.2 TeV energy, indicating a possible physical extension of the source. 1ES 0414+009 is one of the weakest extragalactic sources detected in the TeV range, with an integral flux at > 0.2 TeV of $\Phi = 1.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, which corresponds to $\sim 0.6\%$ of the Crab Nebula flux above the same energy threshold. The observed spectrum of this blazar is well described by a power law model with the photon index $\Gamma = 3.5$. No extension in the H.E.S.S. data of 1ES 0414+009 was reported in the literature nor in the TeVCat². However, the preliminary standard morphological analyses of this object performed with both the *ImPACT* and *M++* techniques were not conclusive on a point-like or extended event distribution of the source. In the first approach the extension in the TeV data was absent, while in the second it was visible.

DESCRIPTION OF CURRENT DATA ANALYSIS

Observations of 1ES 0414+009, which were used in the following analysis, were collected between 1st October, 2005 and 17th October, 2010. The entire data set consists of 245 and 182 runs lasting 110 and 83 hours of accumulated exposure time, available for the spatial and spectral analysis, respectively. The selection quality criteria were imposed on this data to extract runs with the optimal quality. The datasets, which were eventually used in the spectral and morphological studies, are characterised by

- 239 runs in the spatial analysis,
- 180 runs in the spectral analysis,
- 0.5° offset,
- the averaged zenith angle $\sim 26^\circ$,
- the averaged azimuth angle $\sim 11^\circ$.

The 1042 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0.01 \text{ deg}^2$ and centred at $\alpha = 64^\circ 221$, $\delta = 1^\circ 089$ J2000.0 epoch coordinates taken from the near-IR Two Micron All Sky Survey (2MASS) catalogue ([Cutri et al., 2003](#)). The detection significance yields $S_{\text{det}} = 10.3 \sigma$ within the live time of 101 hours, while in case of spectral analysis the significance reaches $S_{\text{spec}} = 8.6 \sigma$ and is derived from 76 hours of observations. The results acquired with *M++* as well as with *ImPACT* are consistent

² <http://tevcat2.uchicago.edu/>; access date: 20.07.2018

with each other and are sufficient to calculate the spectrum parameters of the object, to derive the PSF parameters, and to eventually fit the appropriate morphological models. All statistics of the initial spatial and spectral analyses obtained in the std configuration cuts with both *ImPACT* and *M++* are included in Table 3.

Spatial analysis with <i>ImPACT</i>	
Number of On events	1042
Number of Off events	33836
Live time [h]	101
Excess events	301
S_{det}	10.3σ
Rate of γ -ray flux [min^{-1}]	0.05 ± 0.01
Spectral analysis with <i>ImPACT</i>	
Number of On events	892
Number of Off events	12391
Live time [h]	76
Excess events	240
S_{spec}	8.6σ
Rate of γ -ray flux [min^{-1}]	0.05 ± 0.01
Spatial analysis with <i>M++</i>	
Number of On events	1593
Number of Off events	14904
Live time [h]	101
Excess events	351
S_{det}	9.1σ
γ -rays rate [min^{-1}]	0.07 ± 0.01

Table 3: Results of the 1ES 0414+009 spatial and spectral analyses using *ImPACT* and *M++*.

The TeV excess map is shown in Figure 15 together with the PSF distribution generated based on all accumulated runs using the power law index $\Gamma = 3.7$ derived in this work. Figure 16 shows the significance maps calculated in the std, loose, and hard configuration cuts with the 1.4 GHz NVSS radio and 0.1 – 2.4 keV ROSAT X-ray contours superimposed. The source position, taken from the 2MASS catalogue, is marked with the $\times$ symbol in order to visually verify its correlation with the VHE emission.

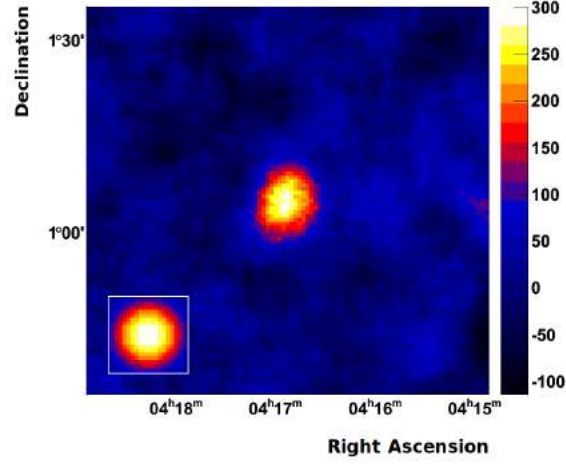


Figure 15: 1ES 0414+009 excess map derived with *ImPACT* and smoothed with the Gaussian function with $0^{\circ}08$ width. The PSF distribution is shown in the inset.

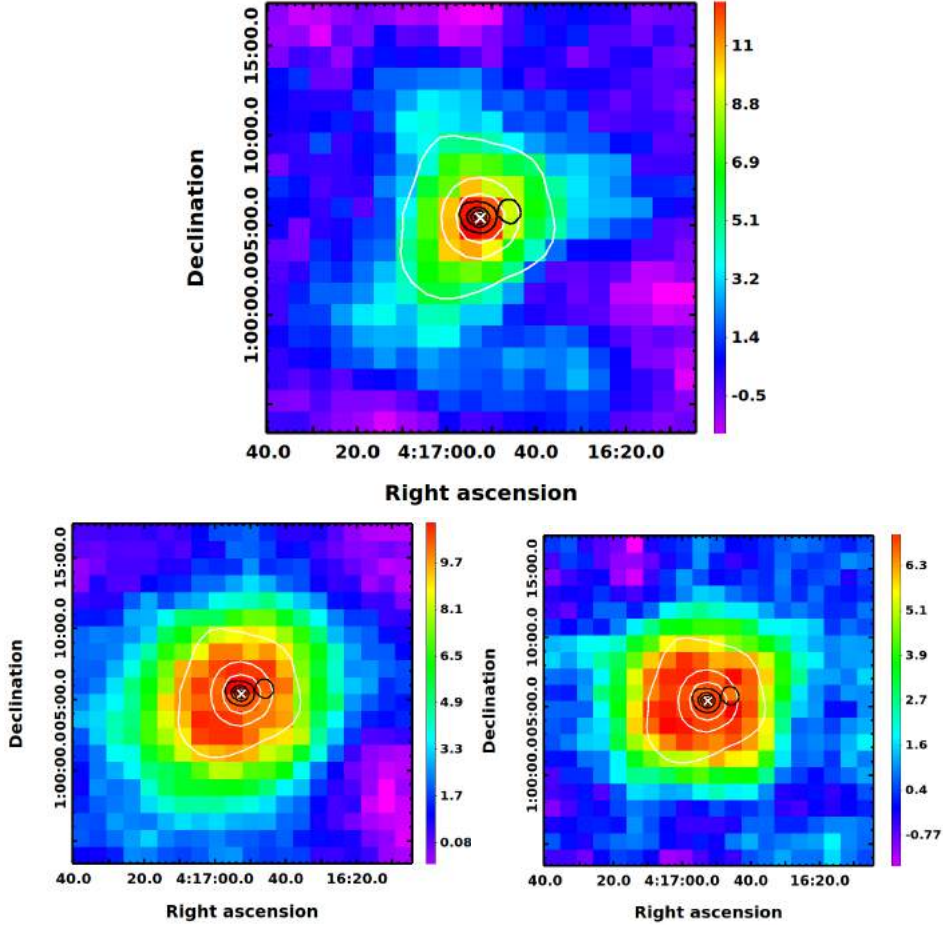


Figure 16: Significance maps of 1ES 0414+009 calculated in the std, loose, and hard configuration cuts with *M++* and smoothed with the $0^{\circ}1$ correlation circle. White X symbol indicates the source position from the 2MASS catalogue. Contours were generated with the 1.4 GHz NVSS map (black contours) and the 0.1 – 2.4 keV ROSAT image (white contours).

TeV γ -ray emission of 1ES 0414+009 shown in Figure 16 is consistent with 1.4 GHz radio frequency (the second radio maximum on the right is the foreground/background projected radio source) and 0.1 – 2.4 keV X-ray emission of the blazar. The NVSS radio contours suggest that a point-like event distribution of the source should be expected rather than an elliptical morphology in the H.E.S.S. data. However, as Laurent-Muehleisen et al. (1993) showed, the low and high resolution 1.5 GHz VLA maps reveal a one-sided radio jet, which additionally encourages to search for an extension in the VHE data. The maximum of significance, calculated in the std cuts, matches well with the near-IR source position. In case of the loose and hard cuts, the region around this maximum is wider and its comparison to the catalogue position is ambiguous. In the std cuts, the event distribution is more compact with a clearly marked centre (with the significance of $> 11 \sigma$) corresponding to the near-IR position. It is surrounded by a slightly elongated and less significant structure between 5.1σ and 8.8σ . In the loose cuts, the significance of the VHE emission is slightly elongated towards the north-east direction, while in the hard cuts the structure is evidently point-like without any spread or extension.

The θ^2 histogram of 1ES 0414+009 with the PSF profile plotted for comparison to the data is shown together with the significance distribution in Figure 17. The derived parameters from the Gaussian fit to the On region are $Mean = 0.03$ and $Width = 1.04$, which confirm the high quality background subtraction.

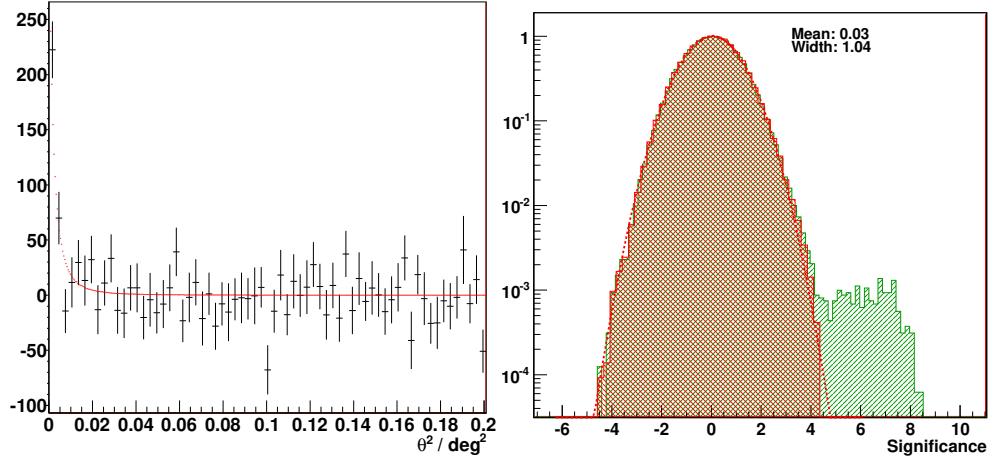


Figure 17: θ^2 and significance distributions of 1ES 0414+009. Left panel: the θ^2 histogram compared to the PSF distribution where black crosses indicate data points with their errors and red dashed line is for the PSF model. Right panel: the significance distribution of the map, where the red shaded space indicates the significance from the source region, red dotted line shows a Gaussian fit to the On region, and the green shaded area is for the entire significance map.

In comparison to the previously published study of the dataset consisting of observations taken between 2005 and 2009 with the detection significance $S_{\text{det}} = 7.8 \sigma$ in the std configuration cuts (H.E.S.S. Collaboration et al., 2012b), the detection significance derived here, i.e. $S_{\text{det}} = 10.3 \sigma$, is considerably higher. This discrepancy is caused by a longer run list used in the current work, which covers five years of observations as well as the

improved analysis procedures. Higher detection significance allows a more reliable morphological study of the event distribution of the source.

SPECTRAL AND MORPHOLOGICAL ANALYSIS

The spectral analysis of 1ES 0414+009 was performed within the energy range [0.2, 61.9] TeV using the *ImPACT* and *M++* techniques. In the first approach, the TeV differential energy spectrum is well described by both the power law (with $\chi^2/\text{ndf} = 2/5$) and the log parabola (with $\chi^2/\text{ndf} = 2/4$) models, resulting in the photon index of $\Gamma = 3.7$ and $\Gamma = 3.6$, and the integral flux $\Phi = 2.4 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and $\Phi = 2.3 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ normalized at > 0.2 TeV energy, respectively. The best-fit parameters obtained with both models are summarised in Table 4. The derived photon spectra with the fitted models are shown in Figure 18.

Power law model with <i>ImPACT</i>	
Γ	3.7 ± 0.2
N_0	$(3.4 \pm 0.4) \times 10^{-12}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(2.4 \pm 0.3) \times 10^{-12}$
χ^2/ndf	2/5
Log parabola model with <i>ImPACT</i>	
Γ	3.6 ± 0.3
β	0.3 ± 0.4
N_0	$(1.4 \pm 0.2) \times 10^{-12}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(2.3 \pm 0.3) \times 10^{-12}$
χ^2/ndf	2/4
Power law model with <i>M++</i>	
Γ	3.6 ± 0.3
N_0	$(2.8 \pm 0.3) \times 10^{-8}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(2.6 \pm 0.5) \times 10^{-12}$
χ^2/ndf	61/75
Power law with EBL correction model with <i>M++</i>	
Γ_{int}	1.7 ± 0.4
N_0	$(1.1 \pm 0.1) \times 10^{-7}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(3.2 \pm 0.4) \times 10^{-12}$
χ^2/ndf	59/70

Table 4: Spectral analysis of 1ES0414+009 using *ImPACT* and *M++*.

In the analysis using *M++*, the power law and power law with the EBL correction models fit well to the data with $\chi^2/\text{ndf} = 61/75$ and $\chi^2/\text{ndf} = 59/70$, respectively. The power law index $\Gamma = 3.6$ and the integral flux $\Phi = 2.6 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ calculated at the energy > 0.2 TeV are consistent within the errors with the power law index $\Gamma = 3.7$ and the integral flux $\Phi = 2.4 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ derived using *ImPACT*. The power law with the EBL correction model gives the intrinsic spectral index $\Gamma_{\text{int}} = 1.7$ and the integral flux at > 0.2 TeV as $\Phi_{\text{int}} = 3.2 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$.

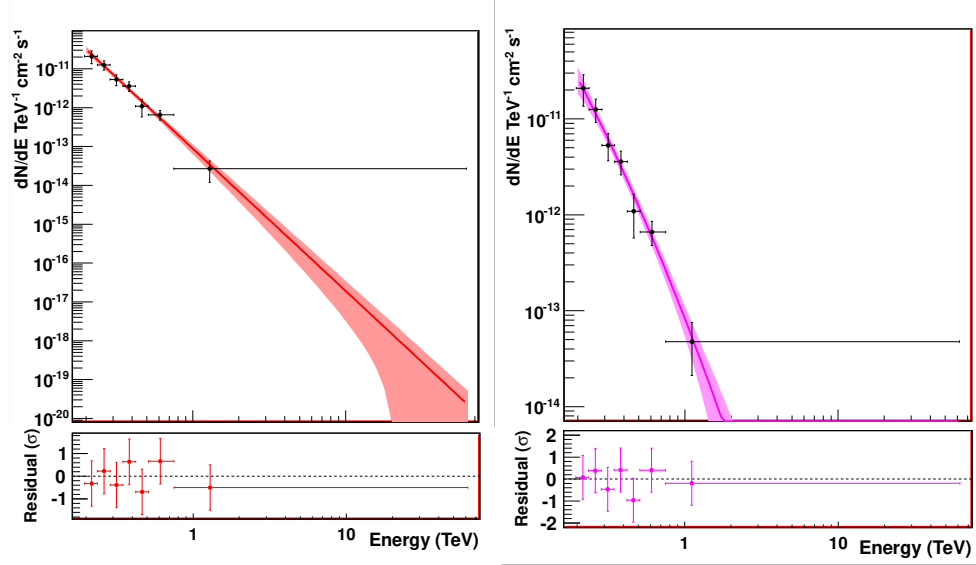


Figure 18: H.E.S.S. spectra of 1ES 0414+009. Left panel: power law and right panel: log parabola fits to the data. In the upper panel of each plot, the red and pink lines are the best fits of the power law and the log parabola models, respectively, the shaded areas illustrate the match range, and the black points are the differential flux points. In the bottom panels, the residuals of the fitted models are shown.

Comparing the corrected power law spectral index Γ_{int} with the uncorrected one Γ , it turns out that at the distance of $z = 0.287$, the EBL emission strongly softens the TeV spectrum. The observed intrinsic spectrum of the source is hard, confirming a possible classification of 1ES 0414+009 as an extreme HBL. In comparison to the previous spectral study of this object (i.e. $\Gamma = 3.5$ and $\Phi = 1.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, [H.E.S.S. Collaboration et al., 2012b](#)), the power law index $\Gamma = 3.7$ is slightly softer and the flux estimated at the same energy threshold $\Phi = 2.4 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ is larger, however, both values are consistent with previous estimates within the errors. Differences in the values of the calculated parameters result from inclusion of data observed in 2010 in the current analysis allowing to achieve a higher statistical significance level.

PSF model	
S	$(1.90 \pm 0.08) \times 10^{+2}$
σ_1	$(2.59 \pm 0.05) \times 10^{-2}$
A_2	$(7.10 \pm 0.98) \times 10^{-2}$
σ_2	$(8.49 \pm 0.15) \times 10^{-2}$
A_3	$(7.08 \pm 0.72) \times 10^{-1}$
σ_3	$(4.49 \pm 0.09) \times 10^{-2}$
$R_{68\%}$	0.07
χ^2/ndf	$48/94$

Table 5: Parameters of 1ES0414+009 PSF model according to [Equation 45](#). S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius of the PSF function.

The power law index $\Gamma = 3.7$ derived in this work was used to calculate the PSF parameters (with $\chi^2/\text{ndf} = 48/94$) and to estimate the angular resolution for the given data set. The resolution of the H.E.S.S. maps of this particular data set is $R_{68\%} = 0''.07$. The obtained factors of the PSF are listed in Table 5.

The position of 1ES 0414+009 was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution, with a test position of $\alpha = 64^\circ.219$, $\delta = 1^\circ.090$ in the J2000 epoch taken from the 2MASS catalogue. The fitted position is $\alpha_{\text{fit}} = 64^\circ.221$, $\delta_{\text{fit}} = 1^\circ.093$ and the angular distance from the 2MASS to the estimated best-fit VHE position attains $0''.004$.

The extension in the blazar emission was examined with the circular and elliptical Gaussian models. The former model gives the width parameter $\sigma = 0''.0113$. In the elliptical model fit, the major and minor semi-axes and the position angle of the ellipse fitted to the data are $\sigma_a = 0''.0385$, $\sigma_b = 0''.0163$, and $\varphi_{\text{H.E.S.S.}} = 174^\circ.4$, respectively. This suggests the extension of the source along the major semi-axis; all parameters calculated with *ImPACT* are summarised in Table 6.

Point-like source model	
α_{fit}	$64^\circ.221 \pm 0''.005$
δ_{fit}	$1^\circ.093 \pm 0''.006$
N_0	4.04 ± 0.45
D	$0''.004$
Circular Gaussian model	
N_0	4.00 ± 0.49
σ	$0''.0113 \pm 0''.0063$
Elliptical Gaussian model	
N_0	3.85 ± 0.38
σ_a	$0''.0385 \pm 0''.0064$
σ_b	$0''.0163 \pm 0''.0072$
$\varphi_{\text{H.E.S.S.}}$	$174^\circ.4 \pm 6^\circ.2$

Table 6: Morphological parameters calculated by fitting the point-like, circular, and elliptical Gaussian models to 1ES 0414+009 with *ImPACT*. α_{fit} , δ_{fit} is the best-fit source position, N_0 is the normalization parameter, D is the angular distance between test and best-fit source positions, σ is the source width estimated from the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The same Gaussian models were also used to investigate the blazar emission applying the *M++* technique. The circular Gaussian gives $\sigma = 0''.0187$. In case of the elliptical Gaussian model, the fitted parameters are $\sigma_a = 0''.0343$, $\sigma_b = 0''.0124$, and $\varphi_{\text{H.E.S.S.}} = 146^\circ.8$. Parameters derived by fitting both morphological models with *M++* are listed in Table 7.

Circular Gaussian model	
N_0	$1.6 \pm 0.2 \cdot 10^{-3}$
σ	$0''.0187 \pm 0''.0057$
Elliptical Gaussian model	
N_0	$1.8 \pm 0.3 \cdot 10^{-3}$
σ_a	$0''.0343 \pm 0''.0074$
σ_b	$0''.0124 \pm 0''.0068$
$\varphi_{\text{H.E.S.S.}}$	$146^\circ.8 \pm 10^\circ.5$

Table 7: Morphological parameters of 1ES 0414+009 calculated using the circular and elliptical Gaussian models with $M++$. σ is the source width estimated based on the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The parameters derived with the elliptical Gaussian model with both methods suggest an extension in the VHE data. The position angles, indicating orientation of the VHE emission, are not comparable with the position angle of the 1ES 0414+009 radio jet (i. e., $\varphi_{\text{VLA}} \sim 60^\circ$, [Laurent-Muehleisen et al., 1993](#)).

In order to investigate the intrinsic structure as well as the large scale morphology of 1ES 0414+009, the 8.4 GHz VLBA and 1.4 GHz VLA radio data were studied. The estimated parsec scale jet position angle is $\varphi_{\text{VLBA}} = 92^\circ.7$ and the large scale structure position angle is $\varphi_{\text{VLA}} = 62^\circ.8$. Comparing them to the VHE position angle $\varphi_{\text{H.E.S.S.}} = 174^\circ.4$, it turns out that both radio jets have different orientations than the extension visible in the VHE data.

5.1.1 Detailed analysis of 1ES 0414+009 with additional cuts imposed on the run list

In order to study the H.E.S.S. emission of 1ES 0414+009, the run list was divided into following sublists:

- run lists including observations in two zenith angle ranges, i. e. $[20^\circ, 25^\circ]$ and $[25^\circ, 30^\circ]$,
- six run lists containing data collected in the subsequent years of observations or their combinations, i. e. 2005, 2006, 2006/2007, 2008, 2009, and 2009/2010,
- run lists restricted to four selected energy ranges, i. e. $[0.1, 0.3]$, $[0.1, 0.5]$, $[0.3, 1]$, and $[0.5, 1]$ TeV.

[Figure 19](#) and [Figure 20](#) show the significance maps (colour scale) generated for the selected datasets. In order to compare the variations in the significance distribution, the radio and X-ray contours were superimposed on all maps. The significance distribution strongly fluctuates in all maps, which can be caused by the background radiation input in the analysed data characterised by low statistics.

The significance parameters S_{det} and S_{spec} , power law spectral index Γ , and parameters obtained during morphological modelling in all introduced cuts are listed in Table 8. This list also includes a few datasets which are not relevant enough for morphological analysis, i.e. run lists limited by the years of observations cut. In this case, the significance of each dataset is very low, reaching $[3.7\sigma, 5.6\sigma]$ and $[3.3\sigma, 5.0\sigma]$ for the spatial and spectral analyses, respectively.

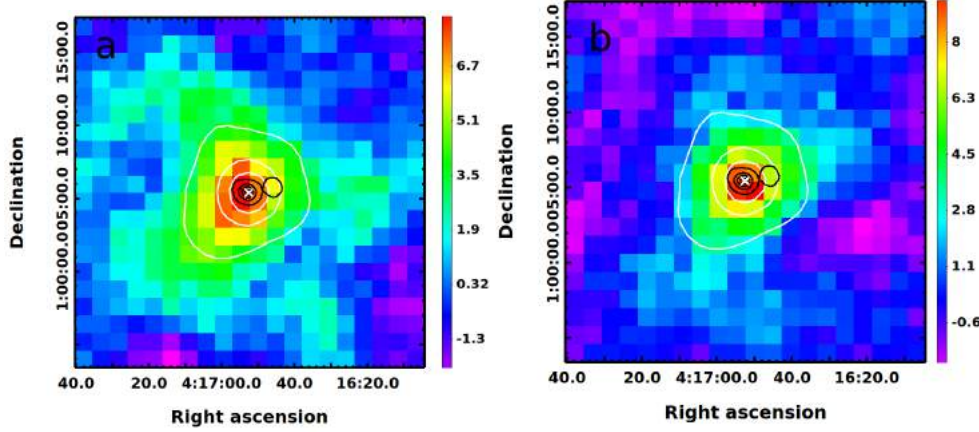


Figure 19: Significance maps of 1ES 0414+009 generated for observations with different zenith angles: panel a — $[20^\circ, 25^\circ]$ and panel b — $[25^\circ, 30^\circ]$. White $\times$ symbol indicates the source position from the 2MASS catalogue. Black contours were created with the 1.4 GHz NVSS map and white contours with the 0.1 – 2.4 keV ROSAT image.

As can be seen in Table 8, the fits of both Gaussian models are variable, as one could expect due to the low statistics obtained as a result of low data significance in smaller datasets compared to the case of the full live time analysis. However, the same pattern is repeated between the separate datasets, in particular the VHE position angle $\varphi_{\text{H.E.S.S.}}$ is well concentrated near the value calculated based on the full live time dataset. Any good match, in case of a too low value of significance, should be considered as very approximate or just accidental.

The run list division into the two zenith angle ranges results in sufficient significance levels for spectral and morphological study, i.e. 6.7σ and 6.5σ for spatial and in both cases 5.5σ for spectral analysis for the zenith angle ranges of $[20^\circ, 25^\circ]$ and $[25^\circ, 30^\circ]$, respectively. The parameters obtained during fitting the elliptical Gaussian model to the first dataset indicate an extension, giving $\sigma_a = 0^\circ 0480$, $\sigma_b = 0^\circ 0205$, and $\varphi_{\text{H.E.S.S.}} = 153^\circ 1$. Similarly, for the second dataset these parameters are: $\sigma_a = 0^\circ 0308$, $\sigma_b = 0^\circ 0210$, and $\varphi_{\text{H.E.S.S.}} = 145^\circ 8$. In both cases the position angles $\varphi_{\text{H.E.S.S.}}$ are compatible within the errors.

The data analysis based on the energy range cuts results in acceptable detection and spectral significance level, which is between 5.2σ and 9.7σ for the detection analysis and between 4.9σ and 8.6σ for the spectral analysis. The circular Gaussian model gives the highest width parameter $\sigma = 0^\circ 0346$ in the lowest energy range of $[0.1, 0.3]$ TeV. Similarly, the parameters obtained through the fitting of the elliptical Gaussian model to the VHE data clearly suggest an extension along the major semi-axis.

Zenith angle [°]							
	S_{det}	S_{spec}	Γ	σ	σ_a	σ_b	$\Phi_{\text{H.E.S.}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[20, 25]	6.7	5.5	3.4 ± 0.5	$0^\circ 0359 \pm 0^\circ 0076$	$0^\circ 0480 \pm 0^\circ 0113$	$0^\circ 0205 \pm 0^\circ 0114$	$153^\circ 1 \pm 5^\circ 2$
[25, 30]	6.5	5.5	4.0 ± 0.6	$0^\circ 0297 \pm 0^\circ 0118$	$0^\circ 0308 \pm 0^\circ 0110$	$0^\circ 0210 \pm 0^\circ 0124$	$145^\circ 8 \pm 11^\circ 3$
Year of observations							
2005	4.6	3.5	3.5 ± 0.7	$0^\circ 0465 \pm 0^\circ 0125$	$0^\circ 0274 \pm 0^\circ 0185$	$0^\circ 0237 \pm 0^\circ 0164$	$174^\circ 0 \pm 6^\circ 8$
2006	3.7	3.3	3.2 ± 0.8	—	—	—	—
2006/2007	4.8	3.8	3.1 ± 0.7	$0^\circ 0446 \pm 0^\circ 0372$	$0^\circ 0387 \pm 0^\circ 0151$	$0^\circ 0210 \pm 0^\circ 0105$	$147^\circ 2 \pm 9^\circ 2$
2008	5.4	4.7	3.7 ± 0.5	$0^\circ 0350 \pm 0^\circ 0059$	$0^\circ 0460 \pm 0^\circ 0371$	$0^\circ 0259 \pm 0^\circ 0128$	$144^\circ 5 \pm 11^\circ 3$
2009	4.9	4.5	4.2 ± 0.8	$0^\circ 0421 \pm 0^\circ 0154$	$0^\circ 0471 \pm 0^\circ 0233$	$0^\circ 0378 \pm 0^\circ 0201$	$130^\circ 9 \pm 7^\circ 9$
2009/2010	5.6	5.0	4.5 ± 0.8	$0^\circ 0436 \pm 0^\circ 0135$	$0^\circ 0459 \pm 0^\circ 0209$	$0^\circ 0343 \pm 0^\circ 0197$	$128^\circ 16 \pm 5^\circ 1$
Energy range [TeV]							
[0.1, 0.3]	6.8	5.6	5.4 ± 1.1	$0^\circ 0346 \pm 0^\circ 0066$	$0^\circ 0464 \pm 0^\circ 0150$	$0^\circ 0285 \pm 0^\circ 0078$	$175^\circ 9 \pm 9^\circ 1$
[0.1, 0.5]	9.7	8.6	3.7 ± 0.2	$0^\circ 0232 \pm 0^\circ 0081$	$0^\circ 0369 \pm 0^\circ 0171$	$0^\circ 0213 \pm 0^\circ 0051$	$167^\circ 2 \pm 7^\circ 2$
[0.3, 1.0]	8.7	7.3	3.0 ± 0.4	$0^\circ 0227 \pm 0^\circ 0083$	$0^\circ 0412 \pm 0^\circ 0274$	$0^\circ 0211 \pm 0^\circ 0049$	$176^\circ 9 \pm 8^\circ 6$
[0.5, 1.0]	5.2	4.9	1.6 ± 0.9	$0^\circ 0121 \pm 0^\circ 0031$	$0^\circ 0369 \pm 0^\circ 0254$	$0^\circ 0253 \pm 0^\circ 0065$	$173^\circ 2 \pm 5^\circ 2$
Full live time analysis							
101 h	10.3	8.6	3.7 ± 0.2	$0^\circ 0326 \pm 0^\circ 0083$	$0^\circ 0435 \pm 0^\circ 0064$	$0^\circ 0163 \pm 0^\circ 0072$	$174^\circ 4 \pm 6^\circ 2$

Table 8: Morphological analysis of $\text{IES } 0414+009$ for datasets divided by zenith angle, year of observation, and energy range cuts. Columns: (1) cut parameter, (2) detection significance, (3) spectral significance, (4) power law photon index, (5) the circular Gaussian model width parameter, (6)-(7) the elliptical Gaussian model width parameters, and (8) position angle. In the bottom row, the full livetime analysis is summarized for comparison.

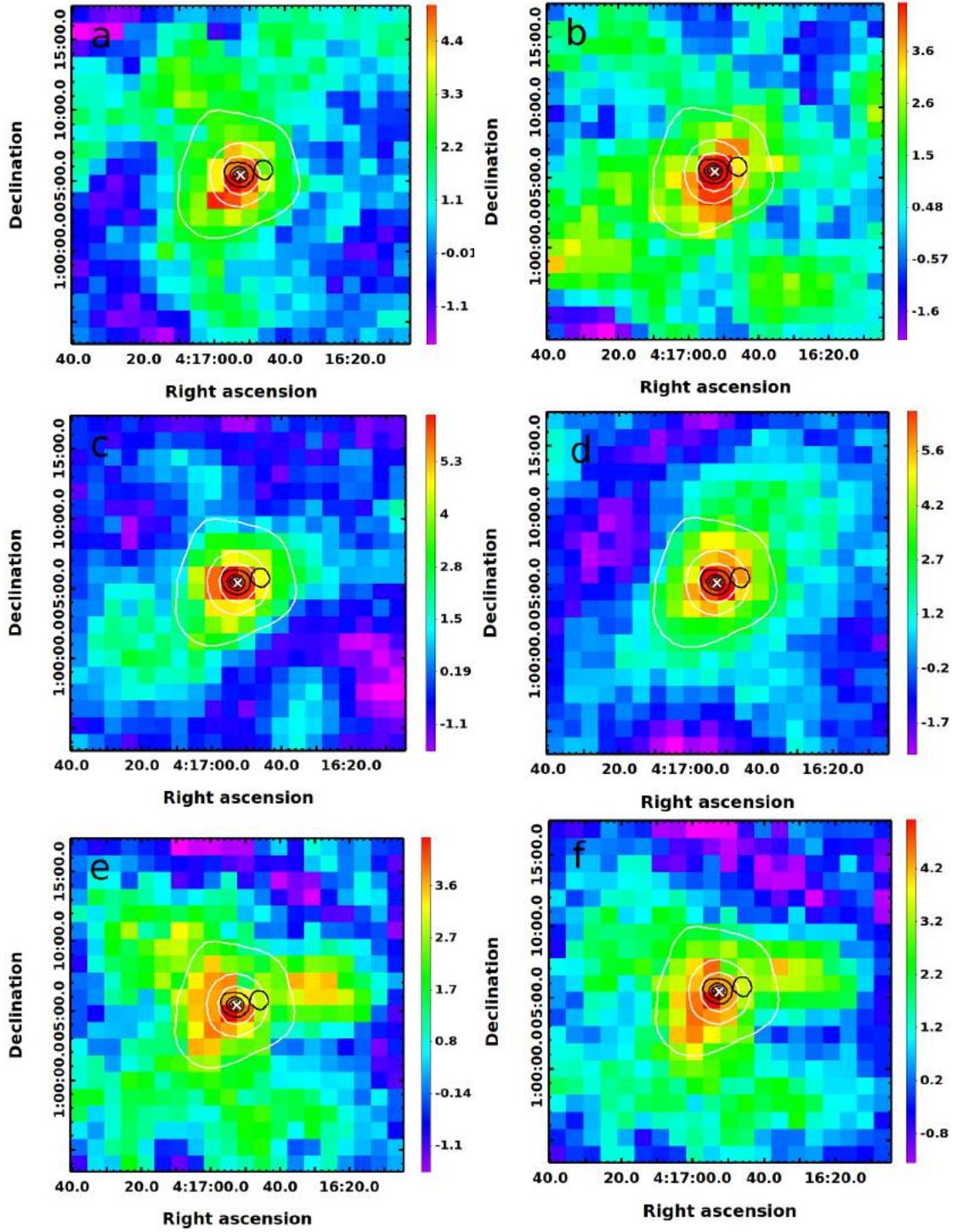


Figure 20: Mosaic of significance maps of 1ES 0414+009 made during the year-by-year analysis: panel a — 2005, panel b — 2006, panel c — 2006/2007, panel d — 2008, panel e — 2009, and panel f — 2009/2010. White X symbol indicates the source position from the 2MASS catalogue. Black contours were created with the 1.4 GHz NVSS map and white contours with the 0.1 – 2.4 keV ROSAT image.

5.2 ANALYSIS OF THE FR I RADIO GALAXY CENTAURUS A

Centaurus A ($\alpha = 13^{\text{h}}25^{\text{m}}27^{\text{s}}.62$, $\delta = -43^{\circ}01'08''.81$; Fey et al., 2004) is a counterpart of the NGC 5128 giant elliptical galaxy (the absolute magnitude is $M_{\text{B}} = -21.2$, Dufour et al., 1979) and is considered the nearest AGN, located at a distance of ~ 3.42 Mpc (Ferrarese et al., 2007), which corresponds to the redshift of $z \sim 0.002$. In the centre of the Centaurus A galaxy there is a supermassive BH with a mass $M_{\text{BH}} = 5.5 \times 10^7 M_{\odot}$ (Cappellari et al., 2009). This AGN is classified as a radio-loud galaxy with the FR I type of activity (Urry & Padovani, 1995).

Centaurus A reveals a clearly extended and complex multifrequency morphology. The source was repeatedly studied at different radio frequencies, as e. g. Burns et al. (1983) detected a north-east kiloparsec scale jet and two north-east/south-west lobes based on the 1.4 and 4.9 GHz VLA observations. Clarke et al. (1992) investigated the 1.4, 1.6, 4.9, and 15 GHz VLA maps finding the north-east oriented jet and two compact knots in the counterjet. The parsec scale radio structure was studied with the 8.4 GHz VLBI data revealing a linear jet towards the north-east and a weaker counterjet as well as changes in the internal jet structure, i. e., evolution of the knots (for a review on Centaurus A see Israel, 1998). The large scale jet is also visible in the $24 \mu\text{m}$ Spitzer data (taken with the MIPS instrument), where the IR jet perfectly coincides with the radio jet (Hardcastle et al., 2006). The X-ray data collected by the Chandra observatory also revealed a complex north-east jet consisting of a diffuse component and 31 discrete compact knots (Kraft et al., 2002). Since Centaurus A is the closest AGN to the Galaxy, it can be an excellent laboratory to perform detailed studies of the AGN's engine, central parts, and jets (e. g. Burns et al., 1983; Clarke et al., 1992; Kataoka et al., 2006; Espada et al., 2017, and many others) as well as the jet interactions with the environment nearest to the AGN (e. g. Oosterloo & Morganti, 2005; Santoro et al., 2015).

PREVIOUS H.E.S.S. ANALYSIS

Centaurus A was detected in the TeV γ -ray energy range by the H.E.S.S.-I observatory involving small CT 1-4 telescopes (Aharonian et al., 2009). This FR I radio galaxy was observed between 2004 and 2008 within the zenith angle range of $[20^{\circ}, 60^{\circ}]$. Centaurus A was detected with the live time of 115 hours, giving the detection significance level of 5.0σ in the std configuration cuts. The integral flux above an energy threshold of 0.25 TeV is $\Phi = 1.56 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and corresponds to $\sim 0.8\%$ of the Crab flux above the same energy threshold. γ -ray spectrum of the source is well described by a power law model with the differential photon index of $\Gamma = 2.7$. Centaurus A does not show variability in the TeV data on any of the analysed timescales. The obtained low level of significance prevented the morphological investigation of the galaxy allowing merely an upper limit of a 0.2° source extension with 95% confidence level based on a Gaussian surface brightness profile.

DESCRIPTION OF CURRENT DATA ANALYSIS

The current spectral and morphological analyses are based on observations of Centaurus A collected between 15th April, 2004 and 13th, July 2010. The dataset contains 572 and 507 runs lasting 260 and 232 hours of accumulated exposure time in the spatial and spectral analysis, respectively. The selection quality criteria were imposed on this data to extract the optimal quality runs. The datasets, which were eventually used in the following studies, are characterised by

- 558 runs for the spatial analysis,
- 505 runs for the spectral analysis,
- offset in the range $[0^\circ.5, 0^\circ.8]$ with the averaged offset of $0^\circ.6$,
- the averaged zenith angle of $\sim 23^\circ.5$,
- the averaged azimuth angle of $\sim 183^\circ.1$.

Spatial analysis with <i>ImPACT</i>	
Number of On events	2298
Number of Off events	80684
Live time [h]	235
Excess events	515
S_{det}	11.5σ
Rate of γ -rays [min^{-1}]	0.037 ± 0.003
Spectral analysis with <i>ImPACT</i>	
Number of On events	2149
Number of Off events	39560
Live time [h]	214
Excess events	443
S_{spec}	10σ
Rate of γ -rays [min^{-1}]	0.034 ± 0.003
Spectral analysis with <i>M++</i>	
Number of On events	3865
Number of Off events	46749
Live time [h]	235
Excess events	814
S_{det}	13.7σ
γ -rays rate [min^{-1}]	0.060 ± 0.004

Table 9: Results of the Centaurus A spatial and spectral analyses with *ImPACT* and *M++*.

The 2298 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0.01 \text{ deg}^2$ around the position $\alpha = 201^\circ 36'$, $\delta = -43^\circ 01'$ in the J2000.0 epoch coordinates taken from the radio catalogue (Fey et al., 2004). The detection significance of the source achieves $S_{\text{det}} = 11.5 \sigma$ within the live time of 235 hours, while in case of spectral analysis the significance reaches $S_{\text{spec}} = 10 \sigma$ within 214 hours of the live time. The results acquired with *ImPACT* and *M++* are consistent with each other and are sufficient to perform reliable spectral and morphological analyses, i. e. to calculate the spectral parameters, to derive the PSF, and to fit the morphological models. The statistical parameters calculated during the initial analysis are included in Table 9.

The excess map is shown together with the PSF distribution in Figure 21. The PSF was calculated using the power law spectral index $\Gamma = 2.6$ derived in this work for all accumulated runs weighted by the excess events.

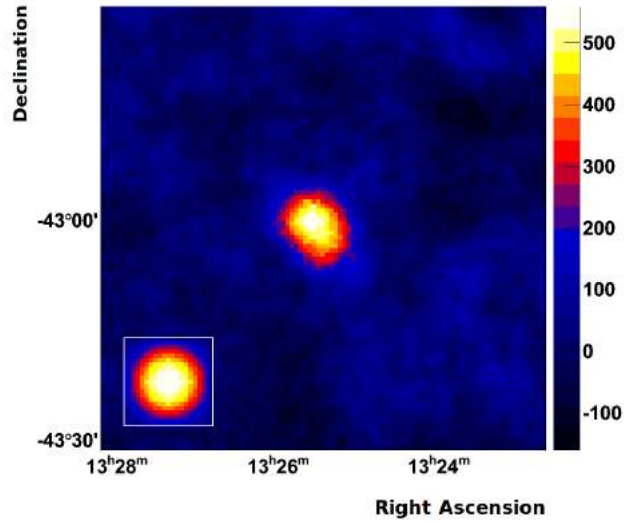


Figure 21: Excess map of Centaurus A. The map was calculated with *ImPACT* and smoothed with Gaussian function of $0''.08$ width. The PSF distribution estimated for the analysed dataset is shown in the inset.

Figure 22 shows the significance maps calculated in the std, loose, and hard configuration cuts with *M++*. The ATCA radio and ROSAT X-ray contours are superimposed on the H.E.S.S. significance maps with black and white lines, respectively, and the source position, taken from the radio catalogue, is marked with the $\times$ symbol.

This multiwavelength test shows that the VHE emission of Centaurus A is consistent with 1.4 GHz radio frequency and 0.1 – 2.4 keV X-ray emission. The jet structure visible at the radio frequency suggests to search for a related elongated event distribution in the H.E.S.S. data. The maximum significance regions calculated in all configuration cuts are wide and their comparison to the catalogue position of Centaurus A is ambiguous. These γ -ray maxima regions are clearly extended and surrounded by a slightly elongated structure with lower significance. In the std cuts, the region around the significance maximum is the widest, reaching $\sim 14 \sigma$ and the elongated structure is visible for $[\sim 5 \sigma, \sim 12 \sigma]$. The TeV emission with high signi-

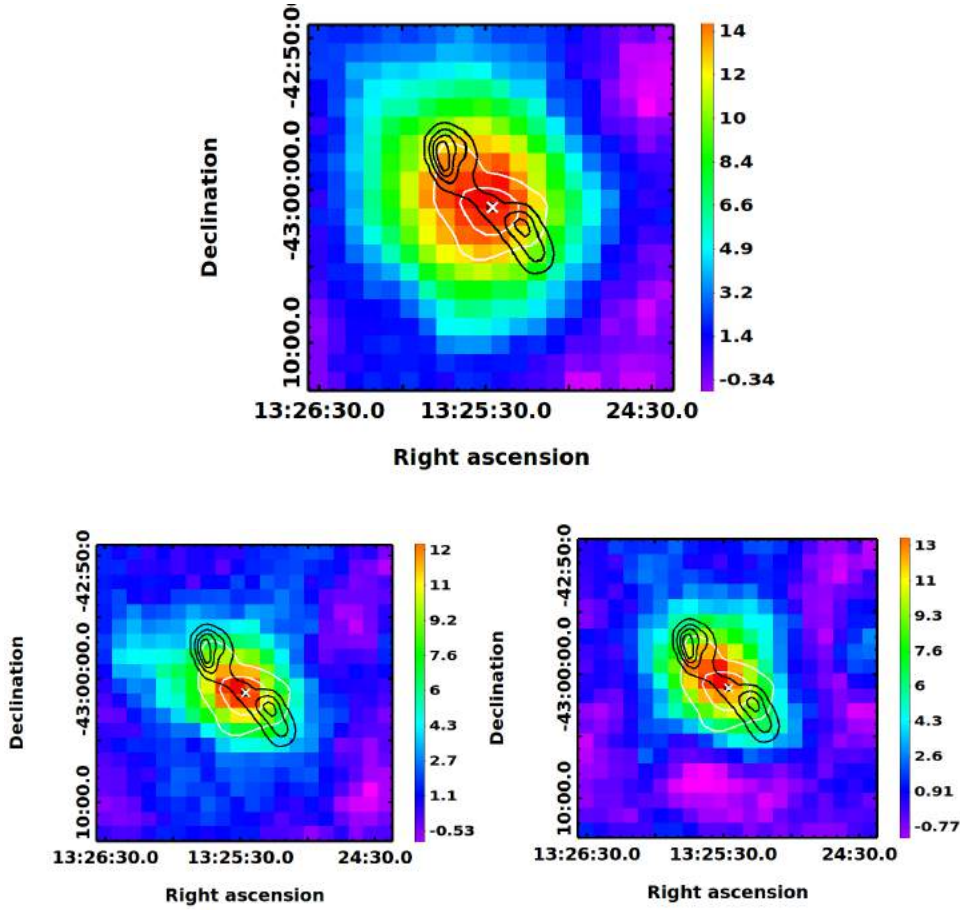


Figure 22: Significance maps of Centaurus A calculated with std, loose, and hard configuration cuts using *M++*. White X symbol indicates the source position from the radio catalogue, while contours were created with the 1.4 GHz ATCA data (black contours) and the 0.1 – 2.4 keV ROSAT image (white contours).

ficance coincides with the X-ray and radio emission from the central parts of Centaurus A, while the radio lobes are outside the maximum of VHE significance. In the loose and hard cuts, the significance maximum regions are more compact reaching $\sim 12\sigma$ and $\sim 13\sigma$, respectively, while the less significant envelope is in the range of $[\sim 5\sigma, \sim 11\sigma]$ in both cases.

In Figure 23, the θ^2 histogram with the PSF profile is shown together with the significance distribution. The derived parameters from the Gaussian fit are $Mean = 0.03$ and $Width = 1.04$, which indicate the high quality background subtraction.

In comparison to the previous study of Centaurus A VHE emission with the detection significance at the level of 5σ (H.E.S.S. Collaboration et al., 2012b), the statistical significance calculated in this work, i.e. $S_{\text{det}} = 11.5\sigma$, is much higher. In this case, the high level of the detection significance makes the morphological analysis possible.

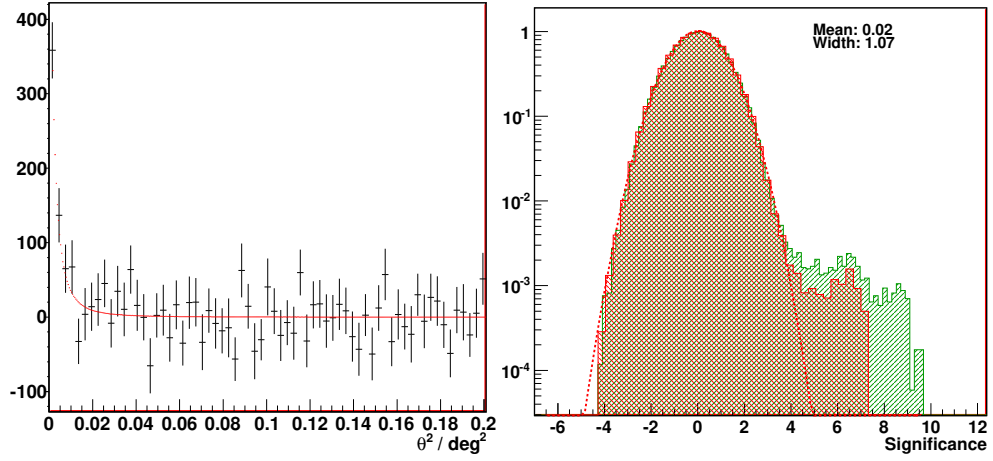


Figure 23: Significance and θ^2 distribution of Centaurus A. Left panel: the θ^2 diagram with the superimposed PSF profile, where black crosses indicate data points and red dashed line is for the PSF model. Right panel: the distribution of the significance map, wherein red shaded space indicates the significance from the source region, red dotted line shows a Gaussian fit, and green shaded space is for the entire significance map.

SPECTRAL AND MORPHOLOGICAL ANALYSIS

The spectral analysis of Centaurus A was performed within the energy range of [0.20, 90.85] TeV using the *ImPACT* and *M++* techniques. The parameters estimated during the fitting process are summarised in Table 10. In the first approach, the TeV differential energy spectrum is well described either by the power law (with $\chi^2/\text{ndf} = 8/13$) and log parabola models ($\chi^2/\text{ndf} = 9/12$). Both models match well to the data, giving the same spectral parameters, i.e. the photon index $\Gamma = 2.6$ and the integral flux $\Phi = 1.2 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.2 TeV energy. The obtained photon spectra with the fitted models are shown in Figure 24.

Applying the *M++* method, the power law model fits well to the data with $\chi^2/\text{ndf} = 69/79$, resulting in the spectral index $\Gamma = 2.6$ and the integral flux $\Phi = 1.2 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.2 TeV energy. The results are consistent within the calculated errors with the power law spectral index and the integral flux derived using the *ImPACT* method.

In the current study with *ImPACT*, it turned out that the power law and log parabola models fit better to the data using the energy > 0.2 TeV than at > 0.25 TeV. The fitting in the latter energy threshold is statistically good, with $\chi^2/\text{ndf} = 7/13$ and $\chi^2/\text{ndf} = 6/12$ for the respective models, however giving significant errors in the the integral flux calculations (the other parameters have small errors), i.e. $\Phi = (8.0 \pm 1.06) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and $\Phi = (7.4 \pm 1.2) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, for power law and log parabola models, respectively. The values of the spectral index remained the same as in case of fitting at > 0.2 TeV energy, i.e. $\Gamma = 2.6$.

In comparison to the previous study of Centaurus A ($\Gamma = 2.7$ and $\Phi = (1.6 \pm 0.7) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.25 TeV with $\chi^2/\text{ndf} = 3/4$, Aharonian et al., 2009), the spectral analysis at lower energy threshold gives improved results.

Power law model with <i>ImPACT</i>	
Γ	2.6 ± 0.1
N_0	$(2.7 \pm 0.3) \times 10^{-13}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.2 \pm 0.2) \times 10^{-12}$
χ^2/ndf	8/13
Log parabola model with <i>ImPACT</i>	
Γ	2.6 ± 0.2
β	0.8 ± 0.2
N_0	$(5.8 \pm 0.6) \times 10^{-13}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.2 \pm 0.2) \times 10^{-12}$
χ^2/ndf	9/12
Power law model with <i>M++</i>	
Γ	2.6 ± 0.1
N_0	$(7.2 \pm 0.6) \times 10^{-9}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.2 \pm 0.3) \times 10^{-12}$
χ^2/ndf	69/79

Table 10: Parameters of Centaurus A spectral analysis with *ImPACT* and *M++* using std configuration cuts.

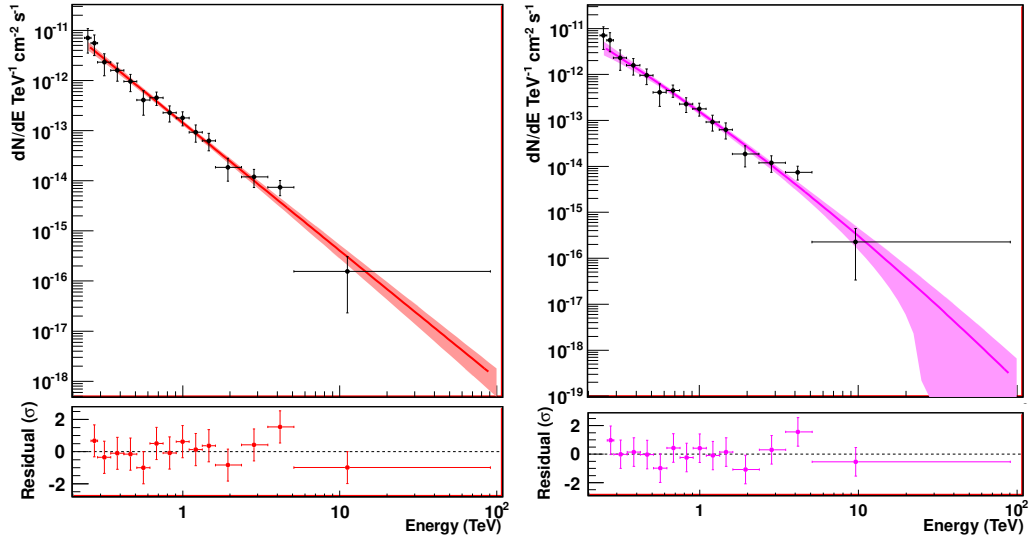


Figure 24: H.E.S.S. spectra of Centaurus A with the power law model (left panel) and the log parabola model (right panel). In the upper panel of each plot, the red and pink lines are the best fits of the power law and the log parabola models, respectively, the shaded areas illustrate the match range, and the black points are the differential flux points. In the bottom panels, the residuals of the fitted models are shown.

The power law index $\Gamma = 2.6$ was used to derive the PSF parameters (with $\chi^2/\text{ndf} = 72/94$) and to estimate the angular resolution of the detector for the given dataset. The obtained factors of the PSF are listed in [Table 11](#). The resolution of the H.E.S.S. maps of this particular dataset is $R_{68\%} = 0''.06$.

PSF model	
S	$(2.89 \pm 0.03) \times 10^{+2}$
σ_1	$(2.21 \pm 0.02) \times 10^{-2}$
A_2	$(4.81 \pm 0.02) \times 10^{-2}$
σ_2	$(8.46 \pm 0.07) \times 10^{-2}$
A_3	$(4.94 \pm 0.17) \times 10^{-1}$
σ_3	$(4.22 \pm 0.04) \times 10^{-2}$
$R_{68\%}$	$0''.06$
χ^2/ndf	$72/94$

Table 11: Parameters of Centaurus A PSF model according to [Equation 45](#). S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius.

The position of Centaurus A was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution. Giving the test position from the radio catalogue, namely $\alpha = 201^\circ 365$, $\delta = -43^\circ 019$ in the J2000 epoch coordinate system, the fitted VHE position is $\alpha_{\text{fit}} = 201^\circ 383$, $\delta_{\text{fit}} = -43^\circ 012$ and the angular distance from the test to the estimated best-fit position reaches $0''.0169$.

The extension of VHE emission of Centaurus A was examined with the circular and elliptical Gaussian models. The former model gives $\sigma = 0''.0145$, while in case of the latter model, fitted parameters are $\sigma_a = 0''.0427$, $\sigma_b = 0''.0137$, and $\varphi_{\text{H.E.S.S.}} = 38^\circ 4$. The parameters calculated using the *ImpACT* technique are summarised in [Table 12](#).

The same Gaussian models were also used to investigate this FR I radio galaxy emission applying the *M++* technique. In case of the circular Gaussian model, the width parameter yields $\sigma = 0''.0348$, while fitting the elliptical Gaussian model, the parameters are $\sigma_a = 0''.0487$, $\sigma_b = 0''.0198$, and $\varphi_{\text{H.E.S.S.}} = 146^\circ 8$; the morphological parameters derived using *M++* are listed in [Table 13](#).

The morphological parameters calculated with the elliptical Gaussian model using both techniques suggest the extension of the Centaurus A VHE emission along the major semi-axis. The VHE extension is expected to occur along the jet directions, where the γ -ray beam should propagate. In order to check that, a comparison between the derived VHE position angle $\varphi_{\text{H.E.S.S.}}$ with the jet position angles φ_{VLBI} and φ_{VLA} was performed. The derived position angle, $\varphi_{\text{H.E.S.S.}} = 38^\circ 4$, coincides with the angle $\varphi_{\text{VLBI}} = 45^\circ 2$ and the angle $\varphi_{\text{VLA}} = 46^\circ 4$, suggesting that the VHE emission of Centaurus A is extended in a direction similar to the parsec and large scale radio jets. The VLBI and VLA maps as well as the estimated position angles are included in [Appendix B](#).

Point-like source model	
α_{fit}	$201^{\circ}383 \pm 0^{\circ}005$
δ_{fit}	$-43^{\circ}012 \pm 0^{\circ}005$
N_0	9.15 ± 0.85
D	$0^{\circ}0169$
Circular Gaussian model	
N_0	7.66 ± 1.29
σ	$0^{\circ}0145 \pm 0^{\circ}0064$
Elliptical Gaussian model	
N_0	6.15 ± 0.79
σ_a	$0^{\circ}0427 \pm 0^{\circ}0098$
σ_b	$0^{\circ}0137 \pm 0^{\circ}0026$
$\varphi_{\text{H.E.S.S.}}$	$38^{\circ}4 \pm 7^{\circ}1$

Table 12: Morphological parameters calculated by fitting the point-like, circular, and elliptical Gaussian models to Centaurus A VHE emission using *ImPACT*. α_{fit} , δ_{fit} is the fitted position, D is the angular distance between the test and estimated best-fit position, σ is the source width from the circular Gaussian model, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model, and φ is the position angle.

Circular Gaussian model	
N_0	$1.1 \pm 0.1 \cdot 10^{-3}$
σ	$0^{\circ}0348 \pm 0^{\circ}0040$
Elliptical Gaussian model	
N_0	$1.1 \pm 0.1 \cdot 10^{-3}$
σ_a	$0^{\circ}0487 \pm 0^{\circ}0061$
σ_b	$0^{\circ}0198 \pm 0^{\circ}0060$
$\varphi_{\text{H.E.S.S.}}$	$38^{\circ}6 \pm 8^{\circ}0$

Table 13: Morphological parameters of Centaurus A calculated by fitting the circular and elliptical Gaussian models using *M++*. σ is the source width estimated based on the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

Figure 25 displays the complex and elongated structure of Centaurus A visible in both 1.4 GHz ATCA radio (dashed black contours) and 0.1 – 2.4 keV X-ray Chandra (black solid contours) data, which additionally suggests searching for a possible extension in the TeV emission. A visual inspection revealed that the orientation of the radio and X-ray jet is comparable to the TeV emission, which seems to be elongated in the same direction. The radio and X-ray large structure position angles of the source were calculated based on the radio and X-ray FITS maps, yielding $\varphi_{\text{ATCA}} = 46^{\circ}4$ and $\varphi_{\text{Chandra}} = 47^{\circ}2$, respectively. This shows that the large structure jet direction of Centaurus A is consistent with the H.E.S.S. data, i. e. $\varphi_{\text{H.E.S.S.}} = 38^{\circ}6$, thus the TeV elongation is along the jet.

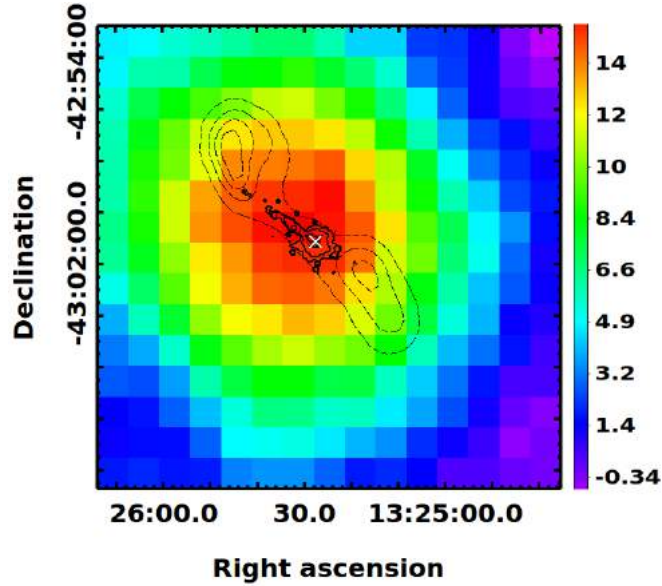


Figure 25: Significance map of Centaurus A with 0.1 – 2.4 keV Chandra X-ray jet (black solid line) and 1.4 GHz ATCA (black dashed line) contours superimposed. White X symbol indicates the position of the source estimated based on the radio data.

5.2.1 Detailed analysis of Centaurus A with additional cuts imposed on the run list

In order to study the TeV γ -ray emission of Centaurus A, the run list consisting of all archived data was splitted into the following sublists:

- three run lists limited with cuts in zenith angles: $[15^\circ, 20^\circ]$, $[20^\circ, 25^\circ]$, and $[25^\circ, 30^\circ]$,
- five run lists containing data collected over individual years: 2006, 2007, 2008, 2009, and 2010,
- five run lists with various energy ranges, i. e. $[0.1, 0.5]$, $[0.1, 1.0]$, $[0.5, 1.0]$, $[1.0, 10.0]$, and $[1.0, 125.0]$ TeV.

Figure 26 and Figure 27 show the significance maps (grey scale) generated with the zenith angle and the energy cuts, respectively. In order to compare the variations in the significance distribution, the radio and X-ray contours were superimposed on both sets of maps. As it is clearly seen, the distribution strongly fluctuates on maps with lower values of significance.

The significance values, power law spectral indices Γ , and parameters obtained during morphological modelling in all introduced cuts are listed in Table 14. This list also includes a few datasets which are not relevant enough for morphological analysis, i. e. the majority of run lists divided according to the year of observations cut, except for the run lists of 2008 and 2010, which reached the significance level $> 5\sigma$ in both the spatial and spectral analyses. In this case, the significance of each dataset is very low, reaching $[4.3\sigma, 5.8\sigma]$ and $[3.9\sigma, 4.1\sigma]$ for spatial and spectral, respectively. Based on analysis of 2008 and 2010 data, Centaurus A seems to be elongated

in both datasets, reaching $\sigma_a = 0^\circ 0496$, $\sigma_b = 0^\circ 0139$ and $\sigma_a = 0^\circ 0339$, $\sigma_b = 0^\circ 0125$ for the elliptical Gaussian model.

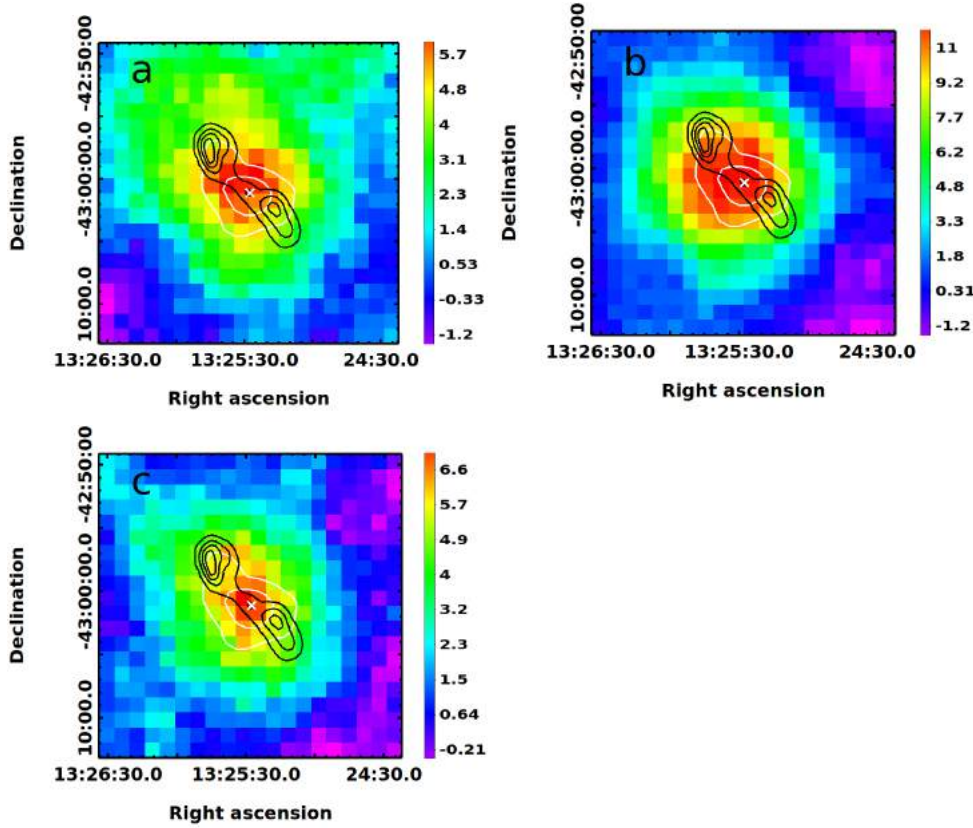


Figure 26: Significance maps of Centaurus A generated for different zenith angles: panel a — $[15^\circ, 20^\circ]$, panel b — $[20^\circ, 25^\circ]$, and panel c — $[25^\circ, 30^\circ]$. White X symbol indicates the source position from the radio catalogue (Fey et al., 2004). Black contours were created with the 1.4 GHz NVSS map and white contours with the 0.1 – 2.4 keV ROSAT image.

Based on derived parameters listed in Table 14, the fits of both Gaussian models are very variable, most likely due to the poor statistics obtained as a result of low significance. Any good match, in case of too low value of significance, should be considered as very approximate if at all.

The run list division into three zenith angle ranges results in high enough significance level for spectral and morphological studies only in case of the $[20^\circ, 25^\circ]$ range, giving 10.5σ for detection and 8.2σ for spectral analyses. Data generated based on the remaining ranges, i. e. $[15^\circ, 20^\circ]$ and $[25^\circ, 30^\circ]$, did not reach the minimum significance level which allows to perform a reasonable morphological analysis. The parameters obtained during fitting the circular and elliptical Gaussian models to the dataset give $\sigma = 0^\circ 0334$ for the circular Gaussian model and $\sigma_a = 0^\circ 0423$, $\sigma_b = 0^\circ 0207$ for the elliptical one.

The data analysis based on energy ranges cuts results in relatively high detection and spectral significance level, i. e. $[6.2 \sigma, 9.4 \sigma]$ range for the spatial analysis and $[5.6 \sigma, 8.2 \sigma]$ range for the spectral analysis. The parameters obtained through the elliptical Gaussian fitting to the H.E.S.S. data clearly suggest an elongation along the major semi-axis.

Zenith angle [°]							
	S _{det}	S _{spec}	Γ	σ	σ _a	σ _b	φ _{H.E.S.S.}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[15, 20]	5.8	4.8	2.7 ± 0.2	0°0469 ± 0°0111	0°0725 ± 0°0233	0°0487 ± 0°0349	30°8 ± 7°2
[20, 25]	10.5	8.2	2.5 ± 0.1	0°0334 ± 0°0049	0°0423 ± 0°0073	0°0207 ± 0°0071	33°9 ± 5°6
[25, 30]	6.7	4.2	2.8 ± 0.3	0°0387 ± 0°0099	0°0661 ± 0°0166	0°0268 ± 0°0142	37°0 ± 7°6
Year of observations							
2006	5.3	4.1	2.8 ± 0.3	0°0388 ± 0°0108	0°0461 ± 0°0156	0°0218 ± 0°0155	35°8 ± 5°8
2007	4.3	3.8	2.0 ± 0.3	0°0401 ± 0°0121	0°0509 ± 0°0194	0°0346 ± 0°0168	29°6 ± 7°8
2008	7.2	5.9	2.6 ± 0.2	0°0423 ± 0°0082	0°0496 ± 0°0132	0°0139 ± 0°0016	42°5 ± 3°6
2009	5.8	3.9	2.3 ± 0.2	0°0469 ± 0°0101	0°0688 ± 0°0164	0°0257 ± 0°0168	10°6 ± 5°1
2010	8.0	7.9	2.9 ± 0.2	0°0246 ± 0°0070	0°0450 ± 0°0043	0°0211 ± 0°0001	40°2 ± 3°1
Energy range [TeV]							
[0.1, 0.5]	7.2	6.1	4.0 ± 0.6	0°0335 ± 0°0056	0°0462 ± 0°0023	0°0200 ± 0°0032	37°2 ± 4°7
[0.5, 1]	6.2	5.6	1.8 ± 0.7	0°0299 ± 0°0077	0°0504 ± 0°0057	0°0216 ± 0°0075	42°8 ± 5°9
[0.1, 1]	9.4	8.2	2.9 ± 0.3	0°0436 ± 0°0091	0°0536 ± 0°0031	0°0100 ± 0°0030	40°4 ± 6°8
[1, 10]	7.5	6.9	2.6 ± 0.3	0°0241 ± 0°0057	0°0421 ± 0°0086	0°0121 ± 0°0032	31°2 ± 3°2
[1, 125]	7.4	6.7	2.8 ± 0.3	0°0232 ± 0°0061	0°0339 ± 0°0031	0°0125 ± 0°0043	22°2 ± 5°7
Full live time analysis							
235 h	11.5	10.0	2.6 ± 0.1	0°0145 ± 0°0064	0°0427 ± 0°0098	0°0137 ± 0°0026	38°4 ± 7°1

Table 14: Morphological parameters of Centaurus A with zenith and year of observation cuts. Columns: (1) cut parameter, (2) detection significance, (3) spectral significance, (4) power law photon index, (5) the circular Gaussian model width parameter, (6)-(7) the elliptical Gaussian model width parameters, and (8) position angle φ . In the bottom row, the full livetime analysis is summarized for comparison.

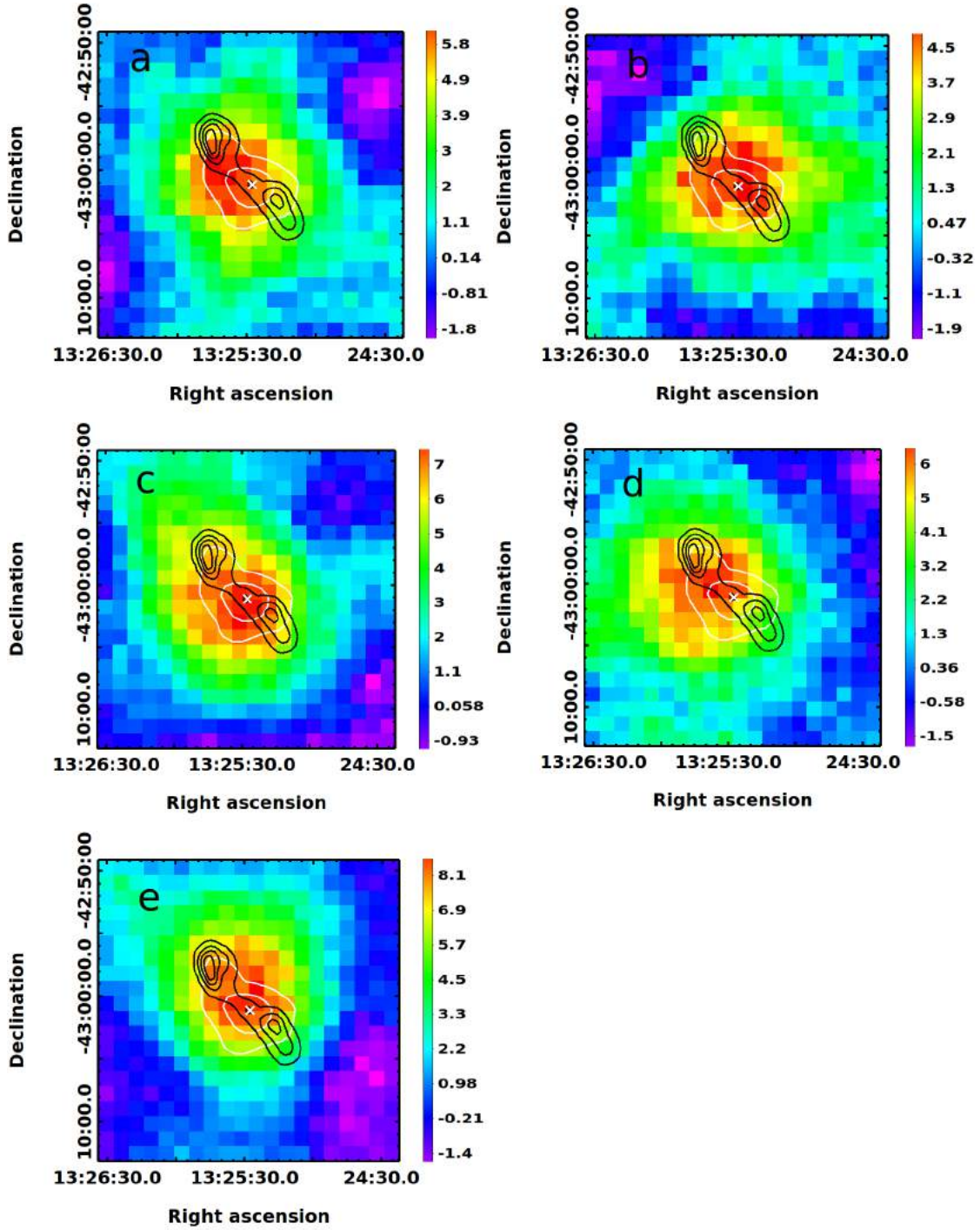


Figure 27: Mosaic of significance maps of Centaurus A generated during the year-by-year analysis: panel a — 2006, panel b — 2007, panel c — 2008, panel d — 2009, and panel e — 2010. White X symbol indicates the source position from the radio catalogue (Fey et al., 2004). Black contours were created with the 1.4 GHz NVSS map and white contours with the 0.1 – 2.4 keV ROSAT image.

5.3 THE STUDY OF THE REFERENCE BLAZAR 1ES 0347-121

The 1ES 0347-121 blazar ($\alpha = 03^{\text{h}}49^{\text{m}}23^{\text{s}}.19$, $\delta = -11^{\circ}59'27''.09$) is a distant object located at $z = 0.188$ (Woo et al., 2005). The source was discovered by the Einstein IPC Slew Survey (Elvis et al., 1992). Shortly after the discovery it was classified as a BL Lac based on its broadband spectral characteristics in the optical range, radio-loudness parameter, and the X-ray–radio–optical colours (Schachter et al., 1993). An estimated central black hole mass is $M_{\text{BH}} = 10^8 M_{\odot}$ and an absolute magnitude of its host elliptical galaxy is $M_{\text{R}} = -22.42$ (Woo et al., 2005).

Giroletti et al. (2004) studied the 1ES 0347-121 radio emission with the A+C combined configuration of the VLA telescopes and found a one-sided lobe-like component elongated to the north-west, suggesting that the structure is relativistic. Piner & Edwards (2014) found a one-sided extension directed to the south-east in the 8.4 GHz VLBA map.

PREVIOUS H.E.S.S. ANALYSIS

The initial study of the BL Lac 1ES 0347-121 was based on observations collected by the CT 1-4 H.E.S.S. telescopes between August and December 2006. The results of this investigation are presented in Aharonian et al. (2007b). The object was detected within a live time of 25.4 hours and the zenith angle range of $[12^{\circ}, 40^{\circ}]$, giving a detection significance level of 10.1σ in the std configuration cuts. The differential photon spectrum is well fitted by a power law model with the photon index of $\Gamma = 3.1$. The integral flux of the source at energy of > 0.25 TeV yields $\Phi = 3.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and corresponds to $\sim 2\%$ of the Crab flux above the same energy threshold. No TeV γ -ray variability was found in the analysed H.E.S.S. data on any studied timescale at > 0.25 TeV.

DESCRIPTION OF CURRENT DATA ANALYSIS

Observations of 1ES 0347-121, which were used in the following analysis, were collected between 20th November, 2005 and 14th December, 2009. The entire dataset consists of 136 and 112 runs lasting 61 and 51 hours of accumulated exposure time in the spatial and spectral analysis, respectively. The selection quality criteria were used to extract the optimal quality runs. The datasets, which were eventually used in the spectral and morphological studies, are characterised by

- 136 runs for the spatial analysis,
- 110 runs for the spectral analysis,
- offset of $0^{\circ}.5$,
- the averaged zenith angle of $\sim 17^{\circ}.5$,
- the averaged azimuth angle of $\sim 34^{\circ}.9$.

The 908 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0.01$ and centred at $\alpha = 57^\circ 35$, $\delta = -11^\circ 99$ coordinates in the J2000.0 epoch taken from the 2MASS catalogue (Cutri et al., 2003). The detection significance achieves $S_{\text{det}} = 17.5 \sigma$ within the live time of 57 hours, while in case of spectral analysis the significance reaches $S_{\text{spec}} = 16.5 \sigma$ in 46 hours. The results acquired in *M++* as well as *ImPACT* are consistent with each other and are sufficient to perform the spectral and morphological analyses. All statistics of the initial analysis are included in Table 15.

Spatial analysis with <i>ImPACT</i>	
Number of On events	908
Number of Off events	21393
Live time [h]	57
Excess events	434
S_{det}	17.5σ
Rate of γ -rays [min^{-1}]	0.13 ± 0.01
Spectral analysis with <i>ImPACT</i>	
Number of On events	828
Number of Off events	8160
Live time [h]	46
Excess events	399
S_{spec}	16.5σ
Rate of γ -rays [min^{-1}]	0.14 ± 0.01
Spatial analysis with <i>M++</i>	
Number of On events	1400
Number of Off events	9765
Live time [h]	57
Excess events	586
S_{det}	17.7σ
Rate of γ -rays [min^{-1}]	0.19 ± 0.01

Table 15: Results of the 1ES 0347-121 spatial and spectral analyses using *ImPACT* and *M++*.

The VHE excess map is shown in Figure 28 together with the PSF distribution generated applying the power law differential photon index $\Gamma = 3.2$ calculated in this work for all accumulated runs.

Figure 29 shows the significance maps calculated in the std, loose, and hard configuration cuts. The parameters achieved with *M++*, on the basis of which the maps were calculated, are summarised in Table 15. The NVSS radio and ROSAT X-ray contours are superimposed on the H.E.S.S. maps and the source position, taken from the 2MASS catalogue, is marked with the $\times$ symbol.

This multiwavelength test shows that the VHE emission of 1ES 0347-121 is consistent with both 1.4 GHz radio frequency and 0.1 – 2.4 keV X-ray energy band emission of the blazar. The NVSS radio data suggests that a compact point-like event distribution of the source should be expected

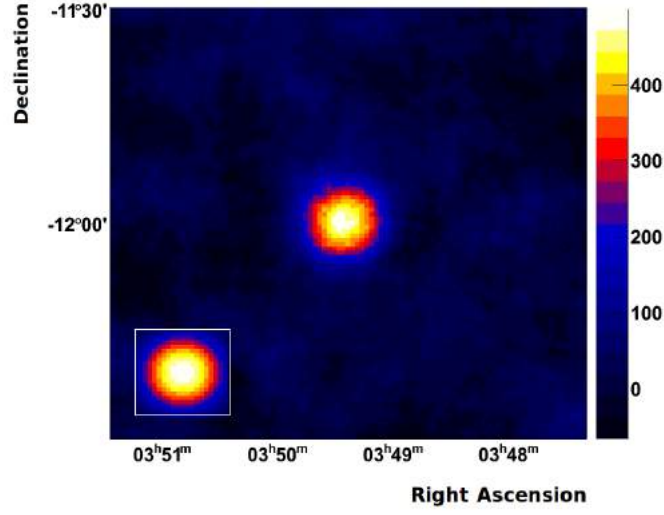


Figure 28: Excess map of 1ES 0347-121. The map was generated in *ImPACT* and smoothed with a Gaussian function of $0''.08$ width. The PSF distribution estimated for the analysed dataset and weighted by the excess is shown in the inset.

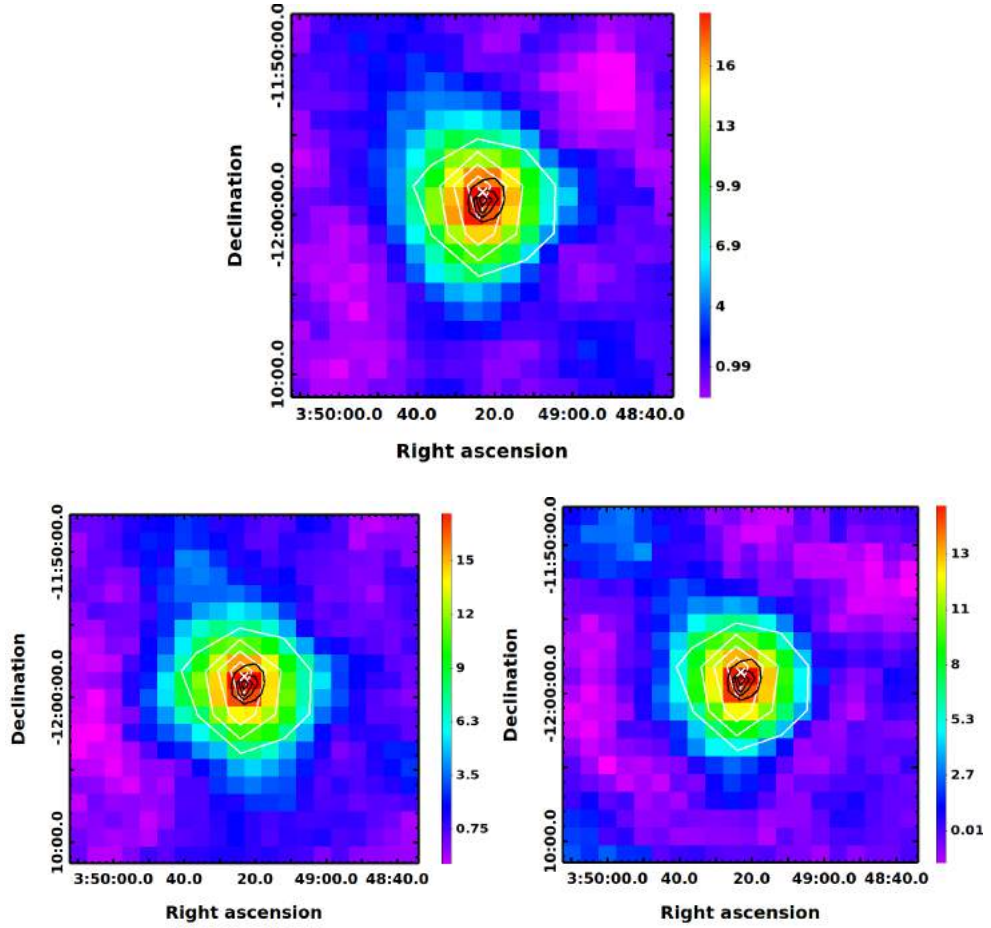


Figure 29: Significance maps of 1ES 0347-121 generated in std, loose, and hard cuts with *M++*. White X symbol indicates the source position from the 2MASS catalogue. Black contours were created with the 1.4 GHz NVSS map and white contours with the 0.1 – 2.4 keV ROSAT image.

rather than an elliptical morphology in the H.E.S.S. data. However, the one-sided radio jet found by [Giroletti et al. \(2004\)](#) in the VLA data encourages searching for an elongation in the VHE data. The maximum significance calculated in all cuts matches well with the near-IR position. In all cuts, the source is point-like with a clearly marked centre, which is surrounded by a circular and less significant envelope. The maximum significance reaches a level exceeding 16σ , 15σ , and 13σ , while the envelope significance is $[6.9\sigma, 13\sigma]$, $[6.3\sigma, 12\sigma]$, and $[5.3\sigma, 11\sigma]$ in the std, loose, and hard cuts, respectively.

[Figure 30](#) shows the θ^2 histogram with the PSF profile and the significance distribution histogram. The former plot illustrates the distribution of the air shower reconstructed directions, while the latter presents the quality of the background subtraction from the On source region, with $Mean = 0.02$ and $Width = 1.07$, indicating high quality background subtraction.

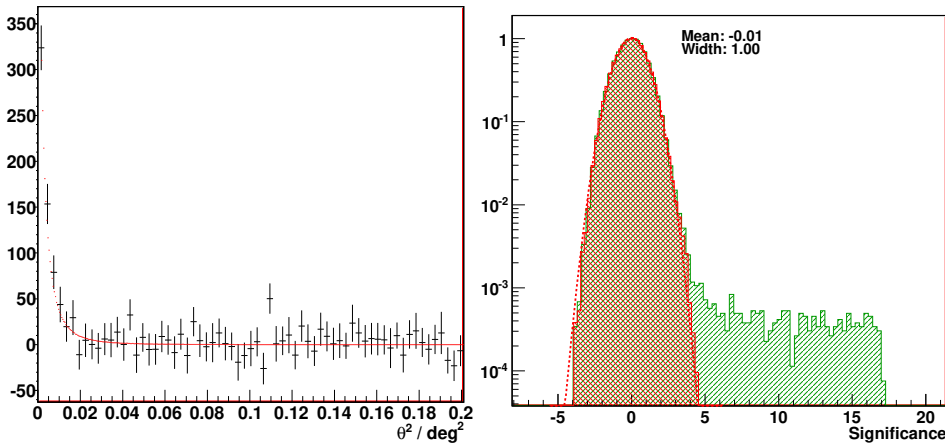


Figure 30: θ^2 (left panel) and significance (right panel) distributions of 1ES 0347-121. The θ^2 diagram is plotted with the PSF profile for a comparison to the data where black crosses indicate the data points and red dashed line is for the PSF model. The significance distribution histogram includes the significance from the source region (red shaded space), a Gaussian fit (red dotted line), and the entire map significance (green shaded space).

SPECTRAL AND MORPHOLOGICAL ANALYSIS

Spectral analysis of the blazar 1ES 0347-121 was performed within the energy range $[0.2, 51.1]$ TeV using the *ImPACT* and *M++* techniques. In the former method, the TeV differential energy spectrum is well described by both the power law (with $\chi^2/\text{ndf} = 11/13$) and log parabola (with $\chi^2/\text{ndf} = 10/11$) models, resulting in the photon index $\Gamma = 3.4$ and the integral flux at > 0.25 TeV of $\Phi = 3.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. The best-fit parameters obtained by both models are summarised in [Table 16](#), while the obtained photon spectra with the fitted models are shown in [Figure 31](#).

In the *M++* technique, the power law model and the power law with the EBL correction model were fitted to the data. The best-fit parameters derived based on the modelling are listed in [Table 16](#). Both models fit well to the data with $\chi^2/\text{ndf} = 51/67$ and $\chi^2/\text{ndf} = 49/67$ for the power law without and with the EBL correction models, respectively. The power law

Power law model with <i>ImPACT</i>	
Γ	3.4 ± 0.2
N_0	$(3.1 \pm 0.3) \times 10^{-12}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(3.0 \pm 0.3) \times 10^{-12}$
χ^2/ndf	11/13
Log parabola model with <i>ImPACT</i>	
Γ	3.4 ± 0.2
β	0.3 ± 0.2
N_0	$(1.7 \pm 0.2) \times 10^{-12}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(3.0 \pm 0.3) \times 10^{-12}$
χ^2/ndf	10/11
Power law model with <i>M++</i>	
Γ	3.4 ± 0.2
N_0	$(8.2 \pm 0.6) \times 10^{-8}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.7 \pm 0.2) \times 10^{-12}$
χ^2/ndf	51/67
Power law with EBL correction model with <i>M++</i>	
Γ_{int}	2.3 ± 0.2
N_0	$(1.7 \pm 0.1) \times 10^{-9}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.6 \pm 0.1) \times 10^{-12}$
χ^2/ndf	49/67

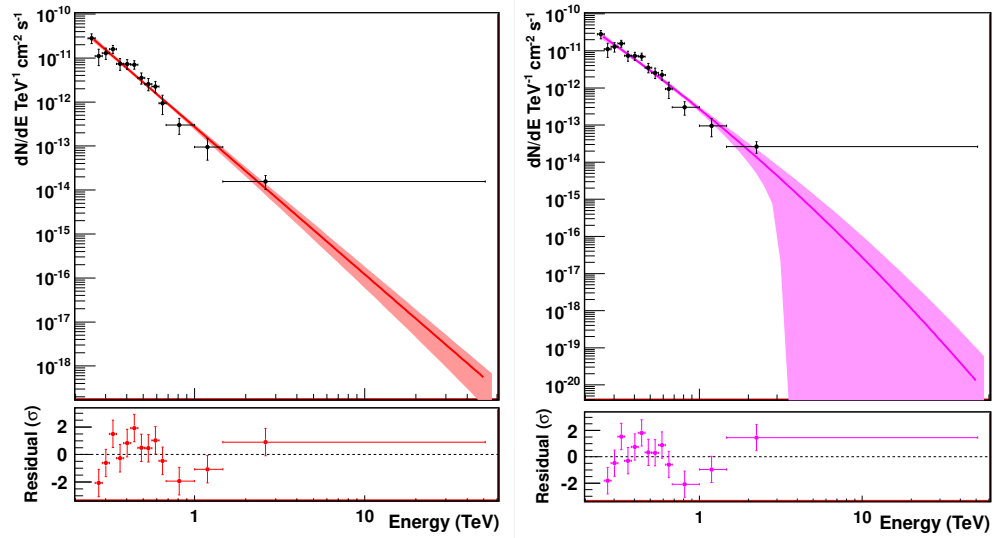
Table 16: Parameters of spectral analysis of 1ES 0347-121 using *ImPACT* and *M++*.

Figure 31: H.E.S.S. spectra of 1ES 0347-121. Left panel: power law model and right panel: log parabola model. In the upper panel of each plot, the red and pink lines are the best-fits of the power law and the log parabola, respectively, the shaded areas illustrate the match range, and the black points are the differential flux points. In the bottom panels, the residuals of fitted models are shown.

index $\Gamma = 3.4$ and the integral flux $\Phi = 1.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at $> 0.25 \text{ TeV}$ are slightly lower than the parameters derived using the *ImPACT* technique. The power law with the EBL correction model gives the spectral index $\Gamma_{\text{int}} = 2.3$ and the integral flux $\Phi = 1.6 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at the same energy threshold.

In comparison to the previous spectral study included in [Aharonian et al. \(2007b\)](#), i.e. $\Gamma = 3.1$ and $\Phi = 3.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, the power law index $\Gamma = 3.4$ derived in the current work is slightly softer and the integral flux $\Phi = 3.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ is lower at the energy $> 0.25 \text{ TeV}$.

Comparing the corrected power law spectral index $\Gamma_{\text{int}} = 2.3$ with the uncorrected one, it turns out that at the distance of $z = 0.188$ the EBL emission softens the TeV spectrum and the intrinsic spectrum of 1ES 0347-121 is hard.

The power law index $\Gamma = 3.4$ derived in this work was used to calculate the PSF parameters (with $\chi^2/\text{ndf} = 75/94$) and to estimate the angular resolution for the given dataset, which is $R_{68\%} = 0''.07$. The obtained parameters of the PSF are listed in [Table 17](#).

PSF model	
S	$(1.95 \pm 0.03) \times 10^{+2}$
σ_1	$(2.00 \pm 0.03) \times 10^{-2}$
A_2	$(1.03 \pm 0.05) \times 10^{-1}$
σ_2	$(7.81 \pm 0.05) \times 10^{-2}$
A_3	$(9.19 \pm 0.32) \times 10^{-1}$
σ_3	$(4.06 \pm 0.03) \times 10^{-2}$
$R_{68\%}$	$0''.07$
χ^2/ndf	$75/94$

Table 17: Parameters of 1ES 0347-121 PSF model according to [Equation 45](#). S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius of the PSF function.

The position of 1ES 0347-121 was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution, using the test position of $\alpha = 57^\circ.347$, $\delta = -11^\circ.991$ in the J2000 epoch taken from the 2MASS catalogue. The fitted VHE position is $\alpha_{\text{fit}} = 57^\circ.352$, $\delta_{\text{fit}} = -11^\circ.986$ and the angular distance from the test to the estimated best-fit position is $0''.007$.

The VHE emission of the blazar was examined with the circular and elliptical Gaussian models. The width of the source estimated by fitting the former model to the data is $\sigma = 0''.0216$. In the elliptical model, the semi-axes and the position angle are $\sigma_a = 0''.0255$, $\sigma_b = 0''.0185$, $\varphi_{\text{H.E.S.S.}} = 171^\circ.7$, respectively. The morphological parameters derived using *ImPACT* are listed in [Table 18](#).

For comparison, the parameters derived with both Gaussian models using the *M++* technique are shown in [Table 19](#). The circular Gaussian model gives the width parameter $\sigma = 0''.0232$. In case of the elliptical Gaussian

model, the fitted parameters are $\sigma_a = 0^\circ.0289$, $\sigma_b = 0^\circ.0180$, and $\varphi_{\text{H.E.S.S.}} = 166^\circ.5$.

Point-like source model	
α_{fit}	$57^\circ.352 \pm 0^\circ.002$
δ_{fit}	$-11^\circ.986 \pm 0^\circ.001$
N_0	7.68 ± 0.51
D	$0^\circ.007$
Circular Gaussian model	
N_0	5.55 ± 0.70
σ	$0^\circ.0216 \pm 0^\circ.0049$
Elliptical Gaussian model	
N_0	5.50 ± 0.60
σ_a	$0^\circ.0255 \pm 0^\circ.0069$
σ_b	$0^\circ.0185 \pm 0^\circ.0075$
$\varphi_{\text{H.E.S.S.}}$	$171^\circ.7 \pm 6^\circ.5$

Table 18: Morphological parameters calculated by fitting the point-like, circular, and elliptical Gaussian models to 1ES 0347-121 in *ImpACT*. α_{fit} and δ_{fit} are fitted coordinates, N_0 is the normalization parameter, D is the angular distance between test and best-fit source positions, σ is the source width derived from the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

Circular Gaussian model	
N_0	$1.2 \pm 0.1 \cdot 10^{-3}$
σ	$0^\circ.0232 \pm 0^\circ.0036$
Elliptical Gaussian model	
N_0	$1.3 \pm 0.2 \cdot 10^{-3}$
σ_a	$0^\circ.0289 \pm 0^\circ.0049$
σ_b	$0^\circ.0180 \pm 0^\circ.0055$
$\varphi_{\text{H.E.S.S.}}$	$166^\circ.5 \pm 24^\circ.1$

Table 19: Morphological parameters of 1ES 0347-121 calculated with both Gaussian models using *M++* with the std configuration cuts. σ is the source width estimated from the circular Gaussian model fit, σ_a and σ_b are the semi-axes from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The intrinsic structure and the large scale morphology of 1ES 0347-121 were studied with the 8.4 GHz VLBA and 1.5 GHz VLA radio data. The estimated parsec scale position angle is $\varphi_{\text{VLBA}} = 247^\circ.5$ and the large scale position angle is $\varphi_{\text{VLA}} = 313^\circ.8$. Considering the 180° rotational symmetry of an ellipse, the VHE position angle yields $\varphi_{\text{H.E.S.S.}} = 351^\circ.7$. Comparing both radio position angles to the VHE extended structure, radio jets visible in both scales are not compatible with the direction of the extension visible in the VHE data (see [Appendix B](#)).

5.4 VHE STUDY OF THE REFERENCE BLAZAR 1ES 1101-232

The 1ES 1101-232 BL Lac ($\alpha = 11^{\text{h}}03^{\text{m}}36^{\text{s}}.5$, $\delta = -23^{\circ}29'31''.11$) was discovered by the Ariel-5 X-ray satellite and was initially incorrectly identified with the Abell 1146 galaxy cluster (Maccagni et al., 1978). Correct identification of the object came with the multiwavelength observations in the X-ray, optical, and radio ranges. This distant blazar, located at $z = 0.186$, constitutes the centre of a bright elliptical galaxy with an absolute magnitude of $M_R = -24.45$ in the R filter (Falomo & Ulrich, 2000). Optical photometric (taken with several telescopes) and spectroscopic (conducted by the Anglo Australian Telescope) source monitoring showed the intranight variability (Romero et al., 1999), as well as variability on the timescale of months, no absorption features and a set of weak emission [Mg I] and [Na I] lines in the spectra (Remillard et al., 1989).

The 1.5 GHz radio data gathered by the NRAO VLA revealed a diffusive one-sided core-jet structure extending towards the north. This so-called head-tail morphology of the blazar indicates its possible membership to a galaxy cluster (Laurent-Muehleisen et al., 1993). Analysing the 8 GHz VLBA map, Tiet et al. (2012) showed that 1ES 1101-232 possesses a short parsec scale jet extending to the north-west.

PREVIOUS H.E.S.S. ANALYSIS

The TeV observations of the blazar 1ES 1101-232 were performed by the H.E.S.S.-I telescopes between 2004 and 2008. The source was detected with the live time of ~ 63 hours at the significance level of 10.8σ achieved using the std configuration cuts. The spectrum of 1ES 1101-232 is well described by a power law model with the differential photon index $\Gamma = 2.9$. The integral flux at energy > 0.2 TeV is $\Phi = 4.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. The standard data analysis revealed no TeV γ -ray variability in the light curves on any investigated timescales and no extended morphology in the excess distribution in data provided by H.E.S.S. (see Aharonian et al., 2007a; H.E.S.S. Collaboration et al., 2014b, for a more detailed description).

DESCRIPTION OF CURRENT DATA ANALYSIS

The observations of 1ES 1101-232, used in the following analyses, were collected between 24th February, 2004 and 17th January, 2008. The entire dataset consists of 176 and 156 runs lasting 85 and 75 hours of accumulated exposure time in the spatial and spectral analysis, respectively. The selection quality criteria were imposed on this data to extract runs with the optimal quality level. The two datasets, which were eventually used in the spectral and morphological investigations, are characterised by

- 175 runs for the spatial analysis,
- 155 runs for the spectral analysis,
- the offset range of $[0^{\circ}.5, 0^{\circ}.8]$ with the averaged offset of $0^{\circ}.6$,

- the averaged zenith angle of $\sim 22^\circ.6$,
- the averaged azimuth angle of $\sim 222^\circ.8$.

The 1893 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0^\circ.01$ and centred at $\alpha = 165^\circ.91$, $\delta = -23^\circ.49$ coordinates in the J2000.0 epoch taken from the 2MASS catalogue (Cutri et al., 2003). The detection significance achieves $S_{\text{det}} = 22.6 \sigma$ in 78 hours. The spectral significance is $S_{\text{det}} = 20.7 \sigma$ within 68 hours. The results acquired in *M++* and *ImPACT* are consistent with each other and are sufficient to perform spectral and morphological analyses. The statistics of the initial analysis obtained with *ImPACT* and with *M++* are included in Table 20.

Spatial analysis with <i>ImPACT</i>	
Number of On events	1893
Number of Off events	48994
Live time [h]	78
Excess events	830
S_{det}	22.6σ
Rate of γ -rays [min^{-1}]	0.18 ± 0.01
Spectral analysis with <i>ImPACT</i>	
Number of On events	1758
Number of Off events	22507
Live time [h]	68
Excess events	750
S_{spec}	20.7σ
Rate of γ -rays [min^{-1}]	0.18 ± 0.01
Spatial analysis with <i>M++</i>	
Number of On events	2319
Number of Off events	21242
Live time [h]	78
Excess events	888
S_{det}	20.7σ
Rate of γ -rays [min^{-1}]	0.24 ± 0.01

Table 20: Results of 1ES 1101-232 spatial and spectral analyses using *ImPACT* and *M++*.

Figure 32 displays the excess map calculated using *ImPACT* and the PSF distribution generated with respect to the power law index $\Gamma = 2.8$ derived in this work for all accumulated runs. Figure 33 shows the significance maps calculated using *M++* with the std, loose, and hard configuration cuts. The radio and X-ray contours were superimposed on the maps and the source position, taken from the 2MASS catalogue, is marked with the $\times$ symbol.

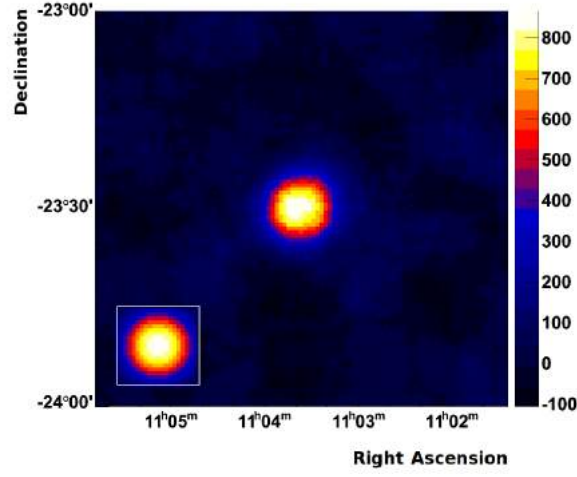


Figure 32: Excess map of 1ES 1101-232. The map was generated using *ImPACT* and smoothed with a Gaussian function of $0''.08$ width. The weighted by excess PSF distribution estimated for the analysed dataset is shown in the inset.

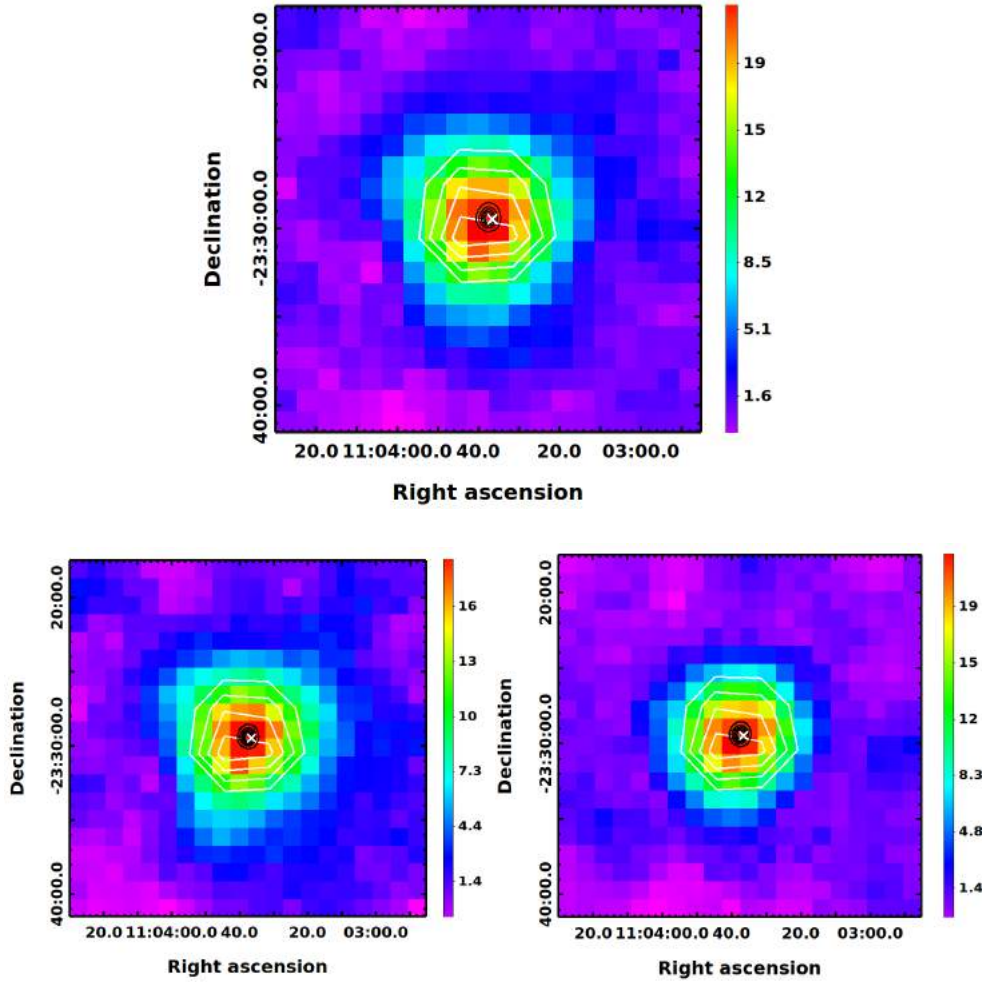


Figure 33: Significance maps of 1ES 1101-232 generated using *M++* with std, loose, and hard configuration cuts.. White X symbol indicates the source position from the 2MASS catalogue. Contours were created with the 1.4 GHz NVSS map (black contours) and the 0.1 – 2.4 keV ROSAT image (white contours).

This multiwavelength test shows that the VHE emission of 1ES 1101-232 is consistent with the emission of this source in radio and X-ray energy bands. The morphology visible at the radio frequency suggests a point-like TeV event distribution, however the VLA maps with better angular resolution revealed a head-tail morphology (Laurent-Muehleisen et al., 1993). The beam size of the considered radio map of the A+C configuration of the VLA array is $1''.3 \times 1''.0$ and rms noise is $89 \mu\text{Jy}/\text{beam}$, while in case of the NVSS map the same parameters yield, respectively, $45'' \times 45''$ and $450 \mu\text{Jy}/\text{beam}$ (Condon et al., 1998).

The maximum of the TeV data significance calculated in all applied cuts matches well with the near-IR position. The region around the maximum significance in all cuts is more compact, as compared to the previous study of 1ES 0414+009, with a clearly marked centre, surrounded by a circular envelope of lower significance. The maximum significance exceeds 19σ , 16σ , and 19σ , while the envelope significance is $[8.5 \sigma, 15 \sigma]$, $[7.3 \sigma, 13 \sigma]$, and $[8.3 \sigma, 15 \sigma]$ in the std, loose, and hard cuts, respectively.

The θ^2 histogram with the PSF comparison, i. e. the distribution of the air shower reconstructed directions, and the significance distribution, i. e. the quality of the background subtraction from the On source region, are shown in Figure 34. The parameters derived by fitting the Gaussian function to the On region in the significance distribution, namely $Mean = 0.00$ and $Width = 1.03$, indicate a high quality background subtraction.

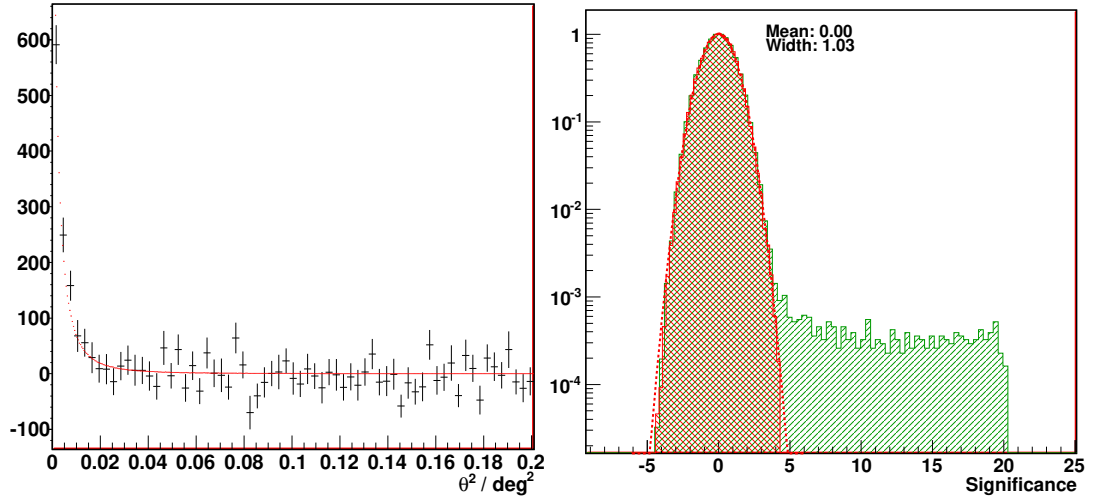


Figure 34: θ^2 and significance distributions of 1ES 1101-232. Left panel: the θ^2 diagram with PSF profile (red dashed line); black crosses indicate data points. Right panel: the significance distribution of the map, wherein red shaded space indicates the significance from the source region, red dotted line shows a Gaussian fit which gives the *Mean* and *Width* values which determines the quality of the fit, and green shaded space is for the entire significance map.

SPECTRAL AND MORPHOLOGICAL ANALYSIS

Spectral analysis of 1ES 1101-232 was performed within the energy range $[0.20, 61.90]$ TeV using the *ImPACT* and *M++* techniques. In the first approach, the TeV differential energy spectrum is well described by both the power law (with $\chi^2/\text{ndf} = 15/19$) and the log parabola (with $\chi^2/\text{ndf} =$

16/18) models, resulting in the photon index $\Gamma = 2.9$ for both models, and the integral flux $\Phi = 5.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and $\Phi = 4.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at $> 0.2 \text{ TeV}$ energy, in case of power law and log parabola models, respectively. The best-fit parameters obtained with both models are summarised in Table 21. The received photon spectra with the fitted models are shown in Figure 35.

Power law model with <i>ImPACT</i>	
Γ	2.9 ± 0.1
N_0	$(4.5 \pm 0.4) \times 10^{-13}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(5.0 \pm 0.3) \times 10^{-12}$
χ^2/ndf	15/19
Log parabola model with <i>ImPACT</i>	
Γ	2.9 ± 0.1
β	0.2 ± 0.1
N_0	$(4.7 \pm 0.4) \times 10^{-13}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(4.9 \pm 0.3) \times 10^{-12}$
χ^2/ndf	16/18
Power law model with <i>M++</i>	
Γ	2.9 ± 0.1
N_0	$(5.4 \pm 0.3) \times 10^{-8}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(3.0 \pm 0.4) \times 10^{-12}$
χ^2/ndf	37/48
Power law with EBL correction model with <i>M++</i>	
Γ	1.7 ± 0.1
N_0	$(1.5 \pm 0.1) \times 10^{-9}$
$\Phi(E > 0.2 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(2.8 \pm 0.4) \times 10^{-12}$
χ^2/ndf	35/46

Table 21: Spectral parameters of 1ES 1101-232 calculated using *ImPACT* and *M++*.

Applying the *M++* technique, the power law model and the power law with the EBL correction model were fitted with std configuration cuts. The best-fit parameters are listed in Table 21. Both models fit well to the data with $\chi^2/\text{ndf} = 37/48$ and $\chi^2/\text{ndf} = 35/46$ for the power law without and with the EBL correction, respectively. The power law index $\Gamma = 2.9$ and the integral flux $\Phi = 3.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at $> 0.2 \text{ TeV}$ energy are consistent with the power law and the integral flux derived using the *ImPACT* technique above the same energy threshold. The power law with the EBL correction model fit was used to calculate the intrinsic spectral index, giving $\Gamma_{\text{int}} = 1.7$. The integral flux at $> 0.2 \text{ TeV}$ reaches $\Phi = 2.8 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. Comparing these parameters with those determined by the power law model fit, it turns out that at the distance of $z = 0.186$ the EBL emission softens the TeV spectrum and the intrinsic spectrum of 1ES 1101-232 is hard, which allows to suggest that 1ES 1101-232 can be classified as an extreme HBL candidate. The spectral parameters derived in this work are compar-

able within the errors with the previous spectral study of the source, i. e. spectral index $\Gamma = 2.9$ and integral flux $\Phi = 4.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at $> 0.2 \text{ TeV}$ (Aharonian et al., 2007a; H.E.S.S. Collaboration et al., 2014b).

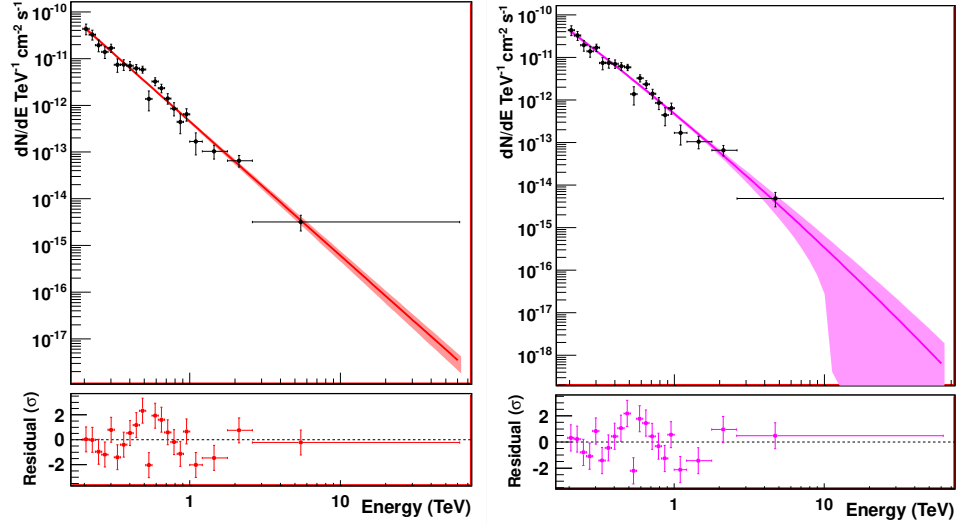


Figure 35: H.E.S.S. spectra of 1ES 1101-232. Left panel: power law model and right panel: log parabola model. In upper panel, the red and pink lines are the best fits of power law and log parabola, respectively, shaded areas mark the match range, and black points are the differential flux points. In bottom panels, the residuals of fitted models are shown.

The power law index Γ was used to derive the PSF parameters (with $\chi^2/\text{ndf} = 54/94$) and to estimate the angular resolution of the detector for the given dataset, which is $R_{68\%} = 0''.07$. The obtained factors of the PSF are listed in Table 22.

PSF model	
S	$(2.14 \pm 0.02) \times 10^{+2}$
σ_1	$(1.83 \pm 0.02) \times 10^{-2}$
A_2	$(9.23 \pm 0.30) \times 10^{-2}$
σ_2	$(8.28 \pm 0.04) \times 10^{-2}$
A_3	$(8.01 \pm 0.18) \times 10^{-1}$
σ_3	$(4.07 \pm 0.03) \times 10^{-2}$
$R_{68\%}$	$0''.07$
χ^2/ndf	$54/94$

Table 22: Parameters of 1ES 1101-232 PSF model according to Equation 45. S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius of the PSF function.

The position of 1ES 1101-232 was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution, with the given test position of $\alpha = 165^\circ 9'07''$, $\delta = -23^\circ 49'2''$ in the J2000 epoch taken from the 2MASS catalogue. The fitted VHE position is $\alpha_{\text{fit}} = 165^\circ 9'06''$,

$\delta_{\text{fit}} = -23^\circ.494$ and the angular distance from the test to the estimated best-fit position reaches $0^\circ.009$.

The extension of the blazar VHE emission was studied using *ImPACT* with the circular and elliptical Gaussian models. The former model gives the width parameter of $\sigma = 0^\circ.0152$, while the parameters derived with the elliptical Gaussian model are $\sigma_a = 0^\circ.0213$, $\sigma_b = 0^\circ.0108$, and $\varphi_{\text{H.E.S.S.}} = 49^\circ.4$ (see [Table 23](#)).

Point-like source model	
α_{fit}	$165^\circ.906 \pm 0^\circ.003$
δ_{fit}	$-23^\circ.494 \pm 0^\circ.003$
N_0	15.08 ± 0.79
D	$0^\circ.0092$
Circular Gaussian model	
N_0	11.73 ± 1.76
σ	$0^\circ.0152 \pm 0^\circ.0054$
Elliptical Gaussian model	
N_0	11.74 ± 1.24
σ_a	$0^\circ.0213 \pm 0^\circ.0045$
σ_b	$0^\circ.0108 \pm 0^\circ.0051$
$\varphi_{\text{H.E.S.S.}}$	$49^\circ.4 \pm 9^\circ.0$

Table 23: Morphological parameters of 1ES 1101-232 calculated by fitting the circular and elliptical Gaussian models using *ImPACT*. σ is the source width from the circular Gaussian model fit, σ_a and σ_b are the semi-axes from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

Circular Gaussian model	
N_0	$1.1 \pm 0.2 \cdot 10^{-3}$
σ	$0^\circ.0202 \pm 0^\circ.0033$
Elliptical Gaussian model	
N_0	$1.1 \pm 0.1 \cdot 10^{-3}$
σ_a	$0^\circ.0218 \pm 0^\circ.0045$
σ_b	$0^\circ.0183 \pm 0^\circ.0048$
$\varphi_{\text{H.E.S.S.}}$	$58^\circ.4 \pm 11^\circ.3$

Table 24: Morphological parameters of 1ES 1101-232 calculated by fitting the circular and elliptical Gaussian models using *M++*. σ is the source width estimated based on the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The circular and elliptical Gaussian models were also used to investigate the blazar emission applying the *M++* technique. The former model gives $\sigma = 0^\circ.0202$, while for the latter model, the parameters are $\sigma_a = 0^\circ.0218$, $\sigma_b = 0^\circ.0183$, and $\varphi_{\text{H.E.S.S.}} = 58^\circ.4$ (see [Table 24](#)).

In addition, the intrinsic and large scale morphology of 1ES 1101-232 were studied with the 8.4 GHz VLBA and 4.8 GHz VLA radio data. The estimated parsec scale position angle is $\varphi_{\text{VLBA}} = 30^\circ.3$ and the large scale position angle is $\varphi_{\text{VLA}} = 345^\circ.6$. Comparing them to the VHE position angle $\varphi_{\text{H.E.S.S.}} = 49^\circ.4$, it turns out that the large scale radio jet is not comparable with the direction of the extension visible in the VHE data, while the parsec scale jet is pointing in a similar direction (see [Appendix B](#)).

5.5 VHE STUDY OF THE REFERENCE BLAZAR 1ES 0229+200

Emission from 1ES 0229+200 ($\alpha = 02^{\text{h}}32^{\text{m}}48^{\text{s}}.62$, $\delta = +20^\circ17'17''.48$) was first detected in the 0.2–4.0 keV X-ray energy range by the Einstein Imaging Proportional Counter Slew Survey ([Elvis et al., 1992](#)). The source was initially classified as an XBL type blazar by [Schachter et al. \(1993\)](#) and subsequently identified as an HBL based on the position of the synchrotron peak $\nu_{\text{peak}}^{\text{S}}$, with the cutoff located at the UV/X-ray frequencies in the $\nu - \nu F_\nu$ SED representation ([Giommi et al., 1995](#)). The blazar, located at $z = 0.14$, constitutes the centre of a bright elliptical galaxy with an absolute magnitude of $M_{\text{R}} = -23.76$ and a black hole mass of $M_{\text{BH}} = 4.8 \times 10^8 M_\odot$ ([Woo et al., 2005](#)). 1ES 0229+200 was used to study the IGMF properties ([Oikonomou et al., 2014](#)) and the EBL emission (e.g. [Kaufmann et al., 2011](#), authors also classified this object as an extreme HBL based on a lack of a cutoff in the synchrotron bump reaching > 100 keV).

[Rector et al. \(2003\)](#) studied 5 GHz VLBA and 1.4 GHz VLA radio maps of 1ES 0229+200. The former map revealed a one-sided jet extending to the south, while in the latter map a two-sided jet extending towards the south–north is visible. The large scale jets are bent to the west. Existence of the radio jets were later confirmed by investigation of the VLA combined maps (A+C configuration), where a symmetric kiloparsec scale structure was found ([Giroletti et al., 2004](#)).

PREVIOUS H.E.S.S. ANALYSIS

The H.E.S.S. observations of 1ES 0229+200 were conducted in 2005 and 2006, resulting in 161 runs lasting 70 hours of accumulated exposure time ([Aharonian et al., 2007c](#)). The source was detected at the significance level 6.6σ . The integral differential flux estimated at energy > 0.58 TeV is $\Phi = 9.4 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to 1.8% of the Crab flux at the same energy threshold. The photon spectrum is described by a power law model with the photon index $\Gamma = 2.5$. The source shows no TeV γ -ray variability on any timescale. Previous investigations have also shown no extension in the VHE emission of this source.

DESCRIPTION OF CURRENT DATA ANALYSIS

Observations of the blazar 1ES 0229+200, which were used in the following analysis, were collected between 11th September, 2004 and 13th December, 2011. The entire dataset consists of 298 and 219 runs lasting 135 and

99 hours of accumulated exposure time, in the spatial and spectral analysis, respectively. The selection quality criteria were imposed on this data to extract the optimal quality runs. The datasets, which were eventually used in the spectral and morphological studies, are characterised by

- 289 runs for the spatial analysis,
- 219 runs for the spectral analysis,
- the offset of $0^\circ.5$,
- the averaged zenith angle of $\sim 45^\circ.15$,
- the averaged azimuth angle of $\sim 9^\circ.3$.

The 1584 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0^\circ.01$ and centred at $\alpha = 38^\circ.20$, $\delta = 20^\circ.29$ in the J2000.0 epoch taken from the 2MASS catalogue (Cutri et al., 2003). The detection significance achieves $S_{\text{det}} = 16.9 \sigma$ in the live time of 124 hours and the spectral significance is $S_{\text{spec}} = 14.3 \sigma$ within 93 hours. The results acquired with *M++* and *ImPACT* are consistent with each other and are sufficient to perform further spectral and morphological investigations of VHE data of 1ES 0229+200. All statistics of the initial analysis obtained in the std configuration cut are included in Table 25.

Spatial analysis with <i>ImPACT</i>	
Number of On events	1584
Number of Off events	46577
Live time [h]	124
Excess events	587
S_{det}	16.9σ
Rate of γ -rays [min^{-1}]	0.08 ± 0.01
Spectral analysis with <i>ImPACT</i>	
Number of On events	846
Number of Off events	16077
Live time [h]	93
Excess events	464
S_{spec}	14.3σ
Rate of γ -rays [min^{-1}]	0.08 ± 0.01
Spatial analysis with <i>M++</i>	
Number of On events	1682
Number of Off events	12717
Live time [h]	124
Excess events	639
S_{det}	17.3σ
Rate of γ -rays [min^{-1}]	0.09 ± 0.01

Table 25: Results of the 1ES 0229+200 spatial and spectral analyses using *ImPACT* and *M++*.

The excess map calculated with *ImPACT* is shown in Figure 36 together with the PSF distribution generated applying the power law index $\Gamma = 2.8$ derived in this work for all accumulated runs. Figure 37 shows the significance maps calculated using *M++* with the std, loose, and hard configuration cuts. The radio contours were calculated based on the 1.4 GHz NVSS map and the X-ray contours from the 0.1 – 2.4 keV ROSAT image. The source position taken from the 2MASS catalogue (Cutri et al., 2003) is marked with the $\times$ symbol.

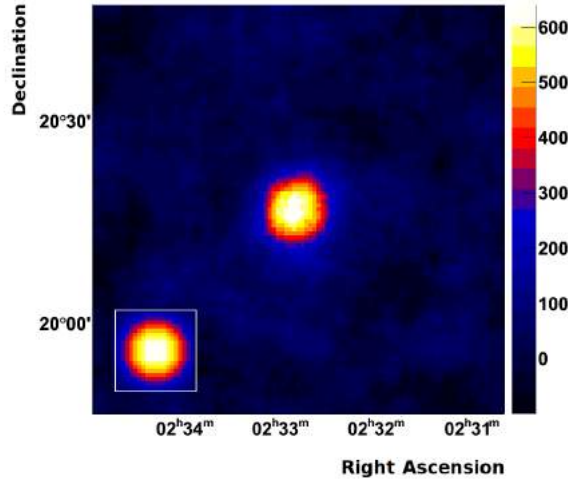


Figure 36: Excess map of 1ES 0229+200 generated with *ImPACT* and smoothed with a Gaussian function of $0''.08$ width. The PSF distribution estimated for the analysed dataset is shown in the inset.

This multiwavelength comparison shows that the TeV emission of 1ES 0229+200 is consistent with the 1.4 GHz radio and 0.1 – 2.4 keV X-ray emission of the source. The maximum of the TeV data significance calculated in all configuration cuts matches well with the near-IR position. In all cuts the regions around these maxima are more compact, as compared to the previously described study of this blazar (see Section 5.1). The clearly marked centre is surrounded by a circular envelope with lower significance. The maximum significance exceeds 18σ , 15σ , and 17σ , while the envelope significance is $[7.8\sigma, 14\sigma]$, $[6.4\sigma, 12\sigma]$, and $[7\sigma, 13\sigma]$ in the std, loose, and hard cuts, respectively. Moreover, the complex parsec and large scale radio structures found by Rector et al. (2003) and Giroletti et al. (2004) additionally suggest to search for source extension in the VHE data.

The θ^2 histogram with the PSF comparison to data is shown together with the significance distribution in Figure 38. The derived parameters from the Gaussian fit to the On region in the significance distribution are $Mean = 0.01$ and $Width = 1.18$, which indicates good background subtraction quality.

In the current study, high level of the detection significance, $S_{\text{det}} = 16.9\sigma$, was reached, while in the previous investigation of the VHE emission of 1ES 0229+200 it reached only $S_{\text{det}} = 6.6\sigma$ (Aharonian et al., 2007c). Higher detection significance allows for a more decent morphological analysis of the source data.

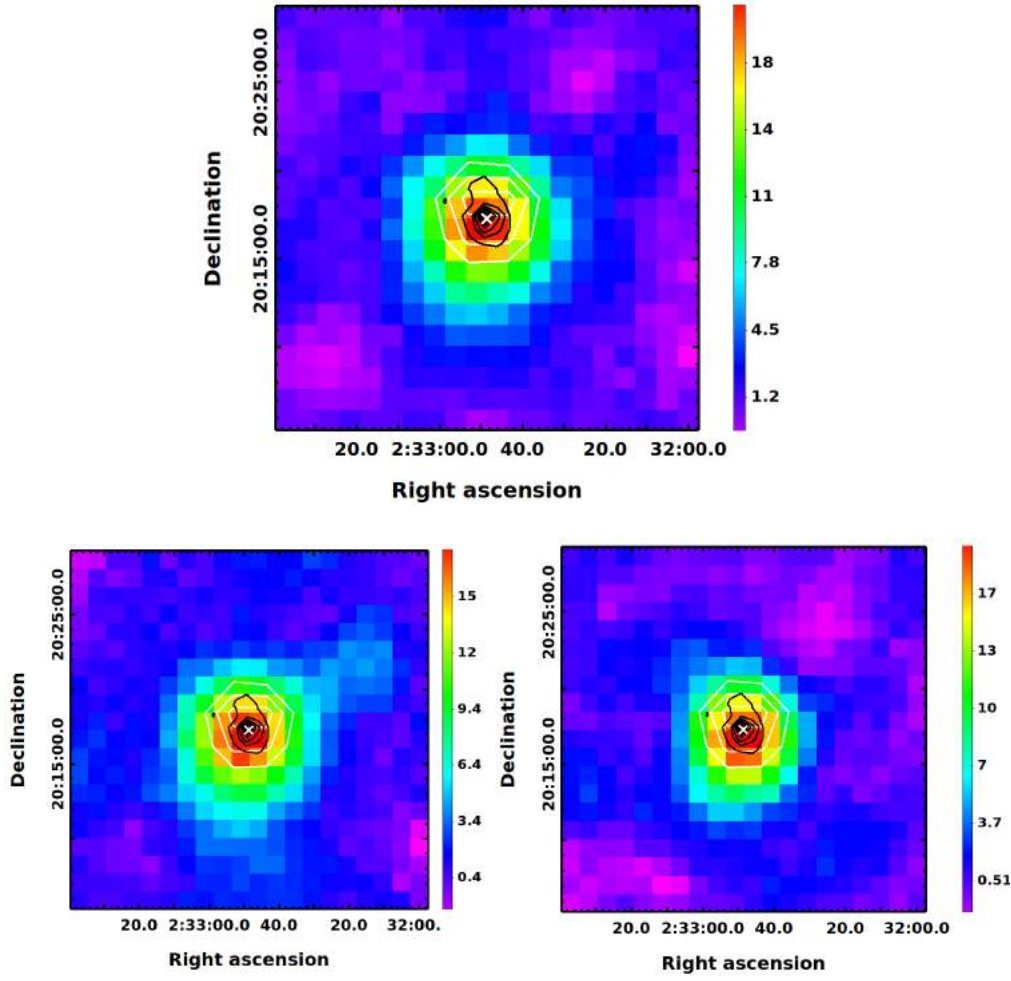


Figure 37: Significance maps of 1ES 0229+200 generated using *M++* with all configuration cuts. White X symbol indicates the source position from the 2MASS catalogue. Contours were created with the 1.4 GHz NVSS map (black contours) and the 0.1 – 2.4 keV ROSAT image (white contours).

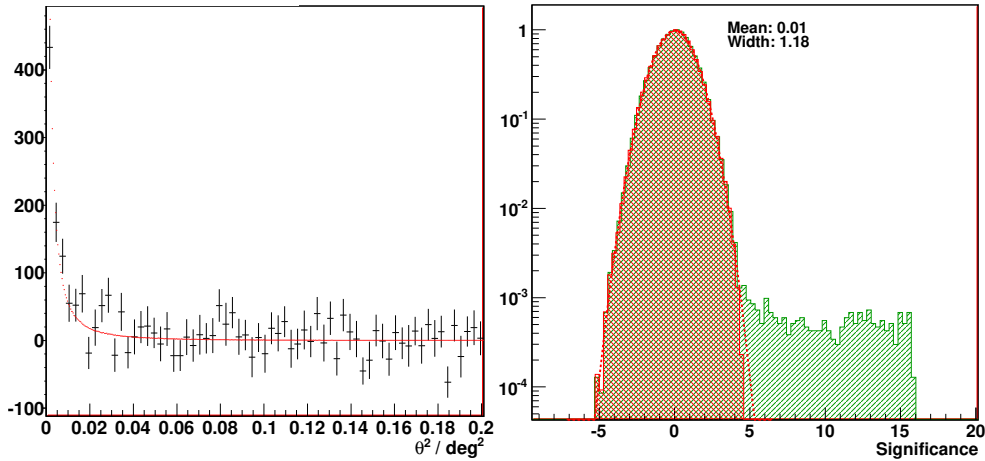


Figure 38: θ^2 and significance distributions of 1ES 0229+200. Left panel: the θ^2 diagram with PSF profile (red dashed line); black crosses indicate data points. Right panel: the significance distribution of the map, wherein red shaded space indicates the significance from the source region, red dotted line shows a Gaussian fit, and green shaded space is for the entire significance map.

SPECTRAL AND MORPHOLOGICAL ANALYSIS

Spectral analysis of 1ES 0229+200 was performed within the energy range [0.58, 61.90] TeV using the *ImPACT* and *M++* techniques. In the first approach, the TeV differential energy spectrum is well described by both the power law (with $\chi^2/\text{ndf} = 10/12$) and log parabola (with $\chi^2/\text{ndf} = 10/12$) models, resulting in the photon indices $\Gamma = 2.9$ and $\Gamma = 2.7$, and the integral fluxes $\Phi = 6.6 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ and $\Phi = 6.5 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.58 TeV energy, respectively. The best-fit parameters obtained by both models are summarised in Table 26. The obtained photon spectra with the fitted models are shown in Figure 39.

Power law model with <i>ImPACT</i>	
Γ	2.9 ± 0.1
N_0	$(4.5 \pm 0.4) \times 10^{-13}$
$\Phi(E > 0.58 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(6.6 \pm 0.6) \times 10^{-13}$
χ^2/ndf	10/12
Log parabola model with <i>ImPACT</i>	
Γ	2.7 ± 0.2
β	0.2 ± 0.1
N_0	$(4.6 \pm 0.4) \times 10^{-13}$
$\Phi(E > 0.58 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(6.5 \pm 0.6) \times 10^{-13}$
χ^2/ndf	10/12
Power law model with <i>M++</i>	
Γ	2.9 ± 0.1
N_0	$(4.9 \pm 0.4) \times 10^{-9}$
$\Phi(E > 0.58 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(6.3 \pm 0.3) \times 10^{-13}$
χ^2/ndf	64/67
Power law with EBL correction model with <i>M++</i>	
Γ	1.9 ± 0.1
N_0	$(2.5 \pm 0.2) \times 10^{-8}$
$\Phi(E > 0.58 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(6.4 \pm 0.3) \times 10^{-13}$
χ^2/ndf	59/62

Table 26: Spectral parameters of 1ES 0229+200 calculated using *ImPACT* and *M++*.

The power law model and the power law with the EBL correction model were also fitted using the *M++* technique. Both models fit well to the data with $\chi^2/\text{ndf} = 64/67$ and $\chi^2/\text{ndf} = 59/62$ for the power law without and with the EBL correction models, respectively. The power law index $\Gamma = 2.9$ and the integral flux $\Phi = 6.6 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.58 TeV are consistent with the power law index and integral flux derived using *ImPACT* above the same energy threshold. The power law with the EBL correction model fit was used to calculate the intrinsic spectral index, resulting in $\Gamma_{\text{int}} = 1.9$ and the integral flux at > 0.58 TeV is $\Phi = 6.4 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$. Comparing the derived parameters, it turns out that at the distance of $z = 0.14$ the

EBL emission softens the TeV spectrum and the intrinsic spectrum of 1ES 0229+200 is hard, which confirms the source's membership to the extreme HBL class of blazars.

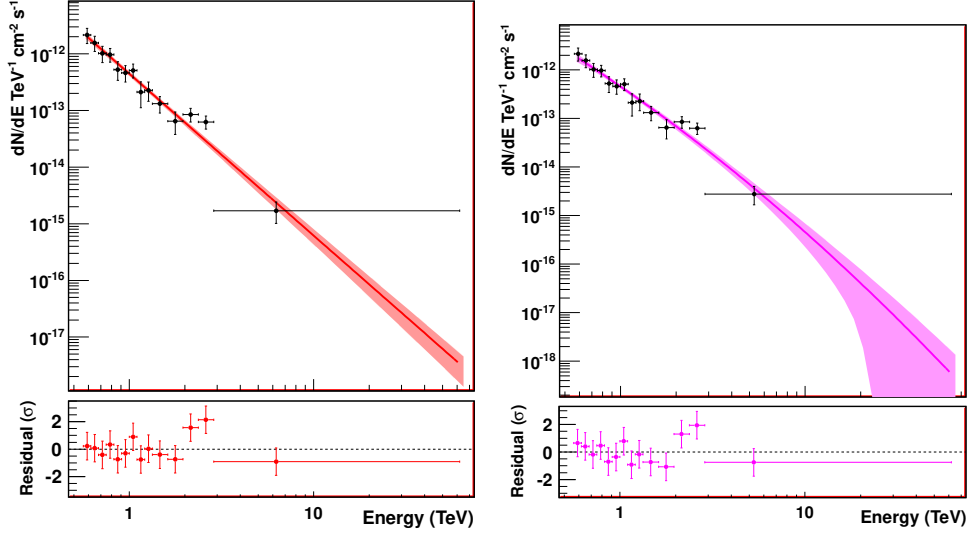


Figure 39: Power law (left panel) and log parabola (right panel) fits to the spectrum of 1ES 0229+200. In the upper panel of each plot, the red and pink lines are the best fits of the power law and log parabola, respectively, shaded areas illustrate the match range, and black points are the differential flux points. In bottom panels, the residuals of fitted models are shown.

The spectral parameters derived in the previous study of the source emission, i.e. index $\Gamma = 2.5$ and integral flux $\Phi = 9.4 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ (Aharonian et al., 2007c) are, respectively, harder and higher than the parameters estimated at the same energy threshold in this study. Such a difference may result from a much larger run list, lasting ~ 7 years, used in the current work, while in the previous study the duration of analysed observations was only ~ 1 year.

PSF model	
S	$(2.54 \pm 0.04) \times 10^{+2}$
σ_1	$(2.45 \pm 0.03) \times 10^{-2}$
A_2	$(5.11 \pm 0.30) \times 10^{-2}$
σ_2	$(9.65 \pm 0.11) \times 10^{-2}$
A_3	$(4.28 \pm 0.23) \times 10^{-1}$
σ_3	$(4.48 \pm 0.06) \times 10^{-2}$
$R_{68\%}$	$0^\circ 07$
χ^2/ndf	$87/94$

Table 27: Parameters of 1ES 0229+200 PSF model according to Equation 45. S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius of the PSF function.

The power law index $\Gamma = 2.9$ was used to derive the PSF parameters (with $\chi^2/\text{ndf} = 87/94$) and to estimate the angular resolution of the detector for the given dataset, which is $R_{68\%} = 0''.07$. The obtained PSF parameters are listed in Table 27.

The position of 1ES 0229+200 was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution, with the test position of $\alpha = 38^\circ.203$, $\delta = 20^\circ.288$ in the J2000 epoch taken from the 2MASS catalogue. The fitted VHE position is $\alpha_{\text{fit}} = 38^\circ.209$, $\delta_{\text{fit}} = 20^\circ.290$ and the angular distance from the test to the estimated best-fit position reaches $0''.007$.

Point-like source model	
α_{fit}	$38^\circ.209 \pm 0''.003$
δ_{fit}	$20^\circ.290 \pm 0''.003$
N_0	10.43 ± 0.65
D	$0''.0067$
Circular Gaussian model	
N_0	8.90 ± 1.26
σ	$0''.0145 \pm 0''.0065$
Elliptical Gaussian model	
N_0	9.18 ± 0.96
σ_a	$0''.0196 \pm 0''.0068$
σ_b	$0''.0100 \pm 0''.0079$
$\varphi_{\text{H.E.S.S.}}$	$93^\circ.4 \pm 5^\circ.0$

Table 28: Morphological parameters of 1ES 0229+200 calculated by fitting the circular and elliptical Gaussian models using *ImPACT*. α_{fit} and δ_{fit} are fitted coordinates, N_0 is the normalization parameter, D is the angular distance between the catalogued and estimated position of the source, σ is the source width estimated based on the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

Circular Gaussian model	
N_0	$0.1 \pm 0.1 \cdot 10^{-3}$
σ	$0''.0172 \pm 0''.0032$
Elliptical Gaussian model	
N_0	$0.1 \pm 0.1 \cdot 10^{-3}$
σ_a	$0''.0197 \pm 0''.0044$
σ_b	$0''.0143 \pm 0''.0049$
$\varphi_{\text{H.E.S.S.}}$	$104^\circ.6 \pm 23^\circ.5$

Table 29: Morphological parameters of 1ES 0229+200 calculated by fitting the circular and elliptical Gaussian models using *M++*. σ is the source width estimated based on the circular Gaussian model fit, σ_a and σ_b are the semi-axes of an ellipse from the elliptical Gaussian model fit, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The morphology of the blazar was examined with the circular and the elliptical Gaussian models. The former model gives $\sigma = 0^{\circ}0145$, while the latter results in $\sigma_a = 0^{\circ}0196$, $\sigma_b = 0^{\circ}0100$, and $\varphi_{\text{H.E.S.S.}} = 93^{\circ}4$ parameters (see Table 28).

The circular and elliptical Gaussian models were also used to investigate the blazar emission with the *M++* technique. The former model gives the width value of $\sigma = 0^{\circ}0172$, while the latter results in $\sigma_a = 0^{\circ}0197$, $\sigma_b = 0^{\circ}0143$, and $\varphi_{\text{H.E.S.S.}} = 93^{\circ}4$. The parameters are summarised in Table 29.

Moreover, the 8.4 GHz VLBA and 1.4 GHz VLA maps were used in order to compare the direction of the VHE energy extension with radio data. The estimated parsec scale position angle is $\varphi_{\text{VLBA}} = 168^{\circ}4$, while the large scale structure consists of two jets with $\varphi_{\text{VLA,N}} = 352^{\circ}5$ and $\varphi_{\text{VLA,S}} = 201^{\circ}6$ (see Appendix B). Considering 180° rotational symmetry of an ellipse, the VHE position angle reaches $\varphi_{\text{H.E.S.S.}} = 273^{\circ}4$, thus the extension direction found in the VHE data is between the radio jets of 1ES 0229+200.

5.6 VHE STUDY OF THE REFERENCE BLAZAR PKS 0548-322

PKS 0548-322 ($\alpha = 05^{\text{h}}50^{\text{m}}40^{\text{s}}.56$, $\delta = -32^{\circ}16'16''.49$), located at $z = 0.069$ (Fosbury & Disney, 1976), is a nearby blazar discovered during a 2.7 GHz survey conducted by the Parkes 64 m radio telescope (Shimmins & Bolton, 1974). The object contains a BH with a mass $M_{\text{BH}} = 3.16 \times 10^8 M_{\odot}$ (Barth et al., 2003), which constitutes the centre of a giant elliptical galaxy with an absolute magnitude of $M_{\text{R}} = -24.2$. The source is classified as an HBL blazar based on the position of $\nu_{\text{peak}}^{\text{S}}$ in the X-ray energy band in the broad-band SED (Padovani & Giommi, 1995).

Studying a low resolution 1.5 GHz VLA map (A+C configuration), Laurent-Muehleisen et al. (1993) revealed a narrow angle tail (NAT) morphology of the blazar, i.e. two jets oriented in south-east and south-west directions. PKS 0548-322 is a member of a rich galaxy cluster, Abell 50549, situated at $z = 0.07$ (Falomo et al., 1995). Most likely, the interactions with the nearby galaxies located in the cluster cause the complex NAT type radio morphology of the blazar. The parsec scale radio structure of PKS 0548-322 seems to be extremely variable in the VLBA data (Piner & Edwards, 2013, 2014, 2018). Its core-jet structure configuration changes in time from the north-east direction towards north.

PREVIOUS H.E.S.S. ANALYSIS

PKS 0548-322 was observed with an accumulated exposure time of 35 hours during observations conducted by the H.E.S.S.-I array of telescopes between October 2004 and January 2008. The detection significance level reached 5.6σ . The differential photon spectrum of PKS 0548-322 is well described by a power law model with a differential photon index of $\Gamma = 2.9$. The integral flux estimated at > 0.25 TeV energy reaches $\Phi = 2.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and corresponds to $\sim 1.3\%$ of the Crab Nebula flux above the same energy threshold. The analysis of PKS 0548-322 H.E.S.S. data has

not shown either flux variability on any analysed timescale or extended morphology of the excess distribution (Aharonian et al., 2010).

DESCRIPTION OF CURRENT DATA ANALYSIS

Observations of PKS 0548-322, which were used in the following analysis, were collected between 17th October, 2004 and 7th November, 2008. The entire dataset consists of 144 and 120 runs lasting 64 and 54 hours of accumulated exposure time, in the spatial and spectral analysis, respectively. The selection quality criteria were imposed on this data to extract the optimal quality runs. The dataset, which was eventually used in the spectral and morphological studies, is characterised by

- 144 runs for the spatial analysis,
- 120 runs for the spectral analysis,
- offset of $0^\circ.5$,
- the averaged zenith angle of $\sim 13^\circ.8$,
- the averaged azimuth angle of $\sim 180^\circ.9$.

Spatial analysis with <i>ImPACT</i>	
Number of On events	789
Number of Off events	25221
Live time [h]	59
Excess events	225
S_{det}	8.8σ
γ -rays rate [min^{-1}]	0.06 ± 0.01
Spectral analysis with <i>ImPACT</i>	
Number of On events	723
Number of Off events	9251
Live time [h]	50
Excess events	211
S_{spec}	8.5σ
γ -rays rate [min^{-1}]	0.07 ± 0.01
Spatial analysis with <i>M++</i>	
Number of On events	1131
Number of Off events	11006
Live time [h]	59
Excess events	214
S_{det}	7.3σ
γ -rays rate [min^{-1}]	0.08 ± 0.01

Table 30: Results of PKS 0548-322 spatial and spectral analyses using *ImPACT* and *M++*.

The 789 γ -ray events were detected in the On source circular region limited by $\theta^2 = 0^\circ 01$ and centred at $\alpha = 87^\circ 67$, $\delta = -32^\circ 27$ in the J2000.0 epoch taken from the 2MASS catalogue (Cutri et al., 2003). The detection significance achieves $S_{\text{det}} = 8.8 \sigma$ within the live time of 59 hours, while in the case of spectral analysis the significance reaches $S_{\text{spec}} = 8.5 \sigma$ in 50 hours. Statistics of the initial analysis obtained using the *ImPACT* and *M++* techniques with the std configuration cuts are included in Table 30.

The excess map calculated using *ImPACT* is shown together with the PSF distribution in Figure 40. The PSF distribution was generated using the power law index $\Gamma = 2.5$ derived in this work for all accumulated runs.

Figure 41 shows the significance maps calculated in the std, loose, and hard configuration cuts. The statistical parameters achieved with *M++*, on the basis of which the maps were calculated, are summarised in Table 30. The radio contours were calculated based on the 1.4 GHz NVSS map and the X-ray contours are from the 0.1 – 2.4 keV ROSAT image. The source position taken from the 2MASS catalogue is marked with $\times$ symbol.

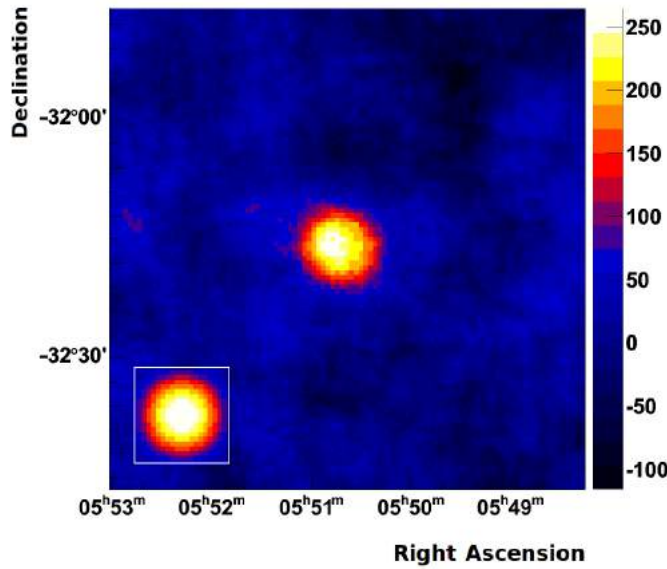


Figure 40: Excess map of PKS 0548-322 generated using *ImPACT* and smoothed with a Gaussian function of $0^\circ 08$ width. The PSF distribution estimated for the analysed dataset is shown in the inset.

The VHE emission of PKS 0548-322 is spatially consistent with its emission in radio and X-ray energy bands. The maximum of the H.E.S.S. data significance calculated in the std cuts matches well with the near-IR position. In case of the loose and hard cuts the region around the significance maximum is wider and its comparison to the catalogue position is ambiguous. In the std cuts the VHE emission is more compact with a clearly marked centre (with a significance of $> 7.2 \sigma$) corresponding well to the near-IR position, surrounded by a narrow circular and less significant γ -ray emission ($> 5.5 \sigma$). In the loose and hard cuts the significance of the TeV emission suggests a point-like morphology of the source with the maximum reaching $\sim 6.8 \sigma$ and $\sim 9.1 \sigma$, respectively.

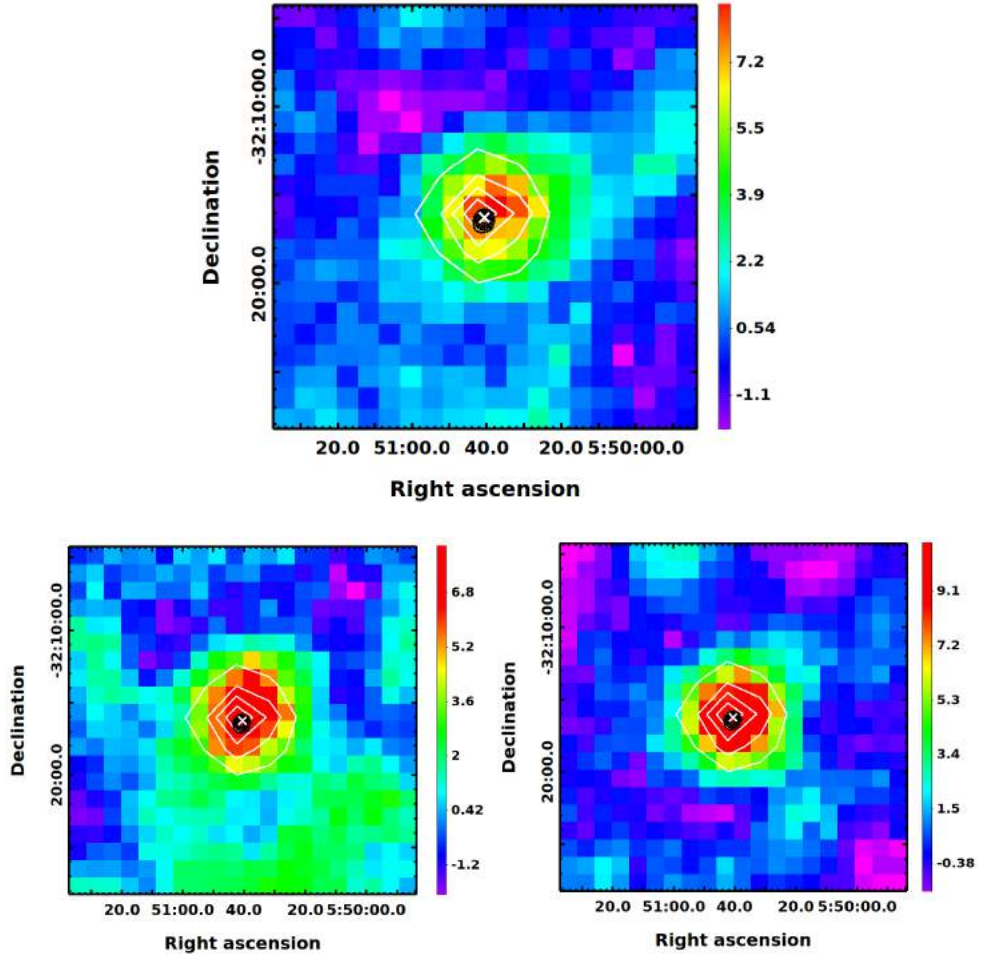


Figure 41: Significance maps of PKS 0548-322 generated in the std, loose, and hard configuration cuts with *M++*. White X symbol indicates the source position from the near-IR catalogue. Contours were created with the 1.4 GHz NVSS map (black contours) and the 0.1 – 2.4 keV ROSAT image (white contours).

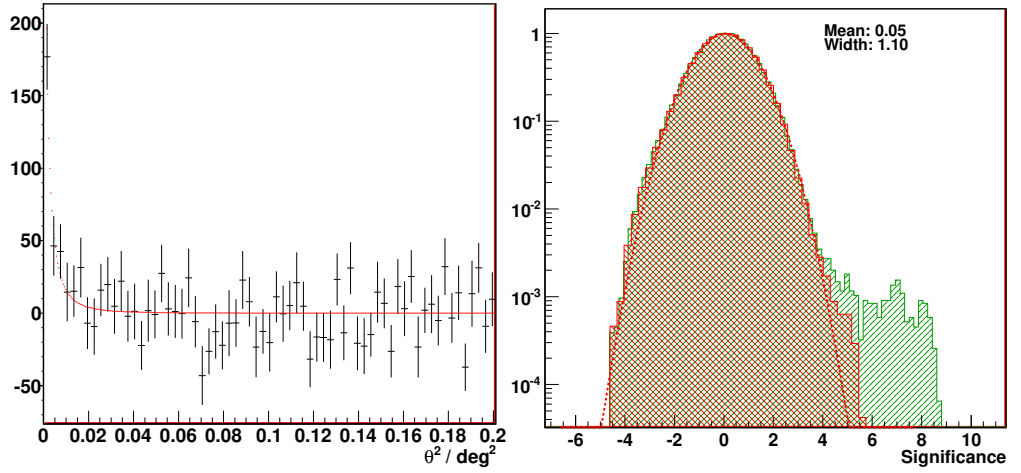


Figure 42: θ^2 and significance distributions of PKS 0548-322. Left panel: the θ^2 diagram with PSF profile (red dashed line); black crosses indicate data points. Left panel: the significance distribution of the significance map, wherein red shaded space indicates the significance from the source region, red dotted line shows a Gaussian fit, and green shaded space is for the entire significance map.

The θ^2 histogram with the PSF comparison to data is shown together with the significance distribution in Figure 42. The derived parameters from the Gaussian fit to the On region in the significance distribution are $Mean = 0.05$ and $Width = 1.10$, which indicate the good quality background subtraction.

SPECTRAL AND MORPHOLOGICAL ANALYSIS

Spectral analysis of PKS 0548-322 was performed within the energy range [0.25, 56.23] TeV using the *ImPACT* and *M++* techniques. In the first approach, the TeV differential energy spectrum is well described by both the power law (with $\chi^2/\text{ndf} = 5/6$) and the log parabola (with $\chi^2/\text{ndf} = 4/5$) models, resulting in the photon indices $\Gamma = 2.5$ and $\Gamma = 2.4$, and the integral flux $\Phi = 1.6 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.25 TeV in both cases. The best-fit parameters obtained by both models are summarised in Table 31. The obtained photon spectra with the fitted models are shown in Figure 43.

Power law model with <i>ImPACT</i>	
Γ	2.5 ± 0.1
N_0	$(2.9 \pm 0.3) \times 10^{-13}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.6 \pm 0.2) \times 10^{-12}$
χ^2/ndf	5/6
Log parabola model with <i>ImPACT</i>	
Γ	2.5 ± 0.1
β	0.2 ± 0.1
N_0	$(3.0 \pm 0.5) \times 10^{-13}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.5 \pm 0.3) \times 10^{-12}$
χ^2/ndf	4/5
Power law with <i>M++</i>	
Γ	2.4 ± 0.2
N_0	$(6.6 \pm 0.9) \times 10^{-9}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(1.5 \pm 0.4) \times 10^{-12}$
χ^2/ndf	47/49
Power law with EBL correction with <i>M++</i>	
Γ_{int}	1.8 ± 0.2
N_0	$(1.2 \pm 0.1) \times 10^{-9}$
$\Phi(E > 0.25 \text{ TeV}) [\text{cm}^{-2} \text{ s}^{-1}]$	$(2.7 \pm 0.4) \times 10^{-12}$
χ^2/ndf	44/47

Table 31: Parameters of PKS 0548-322 spectral analysis using *ImPACT* and *M++*.

The power law and the power law with the EBL correction models were fitted to the PKS 0548-322 data using also the *M++* technique. Both models fit well to the data with $\chi^2/\text{ndf} = 47/49$ and $\chi^2/\text{ndf} = 44/47$ for the power law without and with the EBL correction models, respectively. The power law index $\Gamma = 2.4$ and the integral flux $\Phi = 1.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at > 0.25

TeV are comparable within errors with the power law index and integral flux derived using *ImPACT*. The power law with the EBL correction model gives the spectral index $\Gamma_{\text{int}} = 1.8$ and the integral flux at > 0.25 TeV is $\Phi = 2.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$.

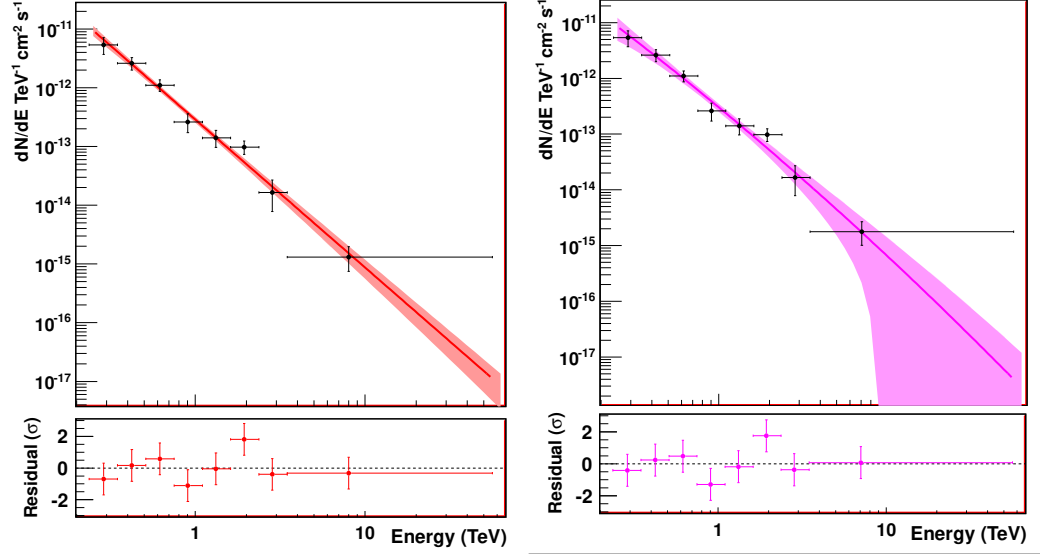


Figure 43: H.E.S.S. spectra of PKS 0548-322. Left panel: power law and right panel: log parabola models fit to the PKS 0548-322 data. In the upper panel of each plot, the red and pink lines are the best-fits of the power law and the log parabola, respectively, the shaded areas illustrate the match range, and the black points are the differential flux points. In the bottom panels, the residuals of fitted models are shown.

The power law index $\Gamma = 2.5$ was used to derive the PSF parameters (with $\chi^2/\text{ndf} = 64/94$) and to estimate the angular resolution of the detector for the given dataset, reaching $R_{68\%} = 0''.07$. The PSF parameters estimated in this work are listed in Table 32.

PSF model	
S	$(3.71 \pm 0.02) \times 10^{+2}$
σ_1	$(1.63 \pm 0.01) \times 10^{-2}$
A_2	$(5.24 \pm 0.13) \times 10^{-2}$
σ_2	$(7.76 \pm 0.04) \times 10^{-2}$
A_3	$(5.30 \pm 0.08) \times 10^{-1}$
σ_3	$(3.78 \pm 0.02) \times 10^{-2}$
$R_{68\%}$	$0''.07$
χ^2/ndf	64/94

Table 32: Parameters of PKS 0548-322 PSF model according to Equation 45. S is the scale factor, A_2 and A_3 are the amplitudes, σ_1 , σ_2 , and σ_3 are the standard deviations of the Gaussian functions, and $R_{68\%}$ is the 68% containment radius of the PSF function.

The power law index $\Gamma = 2.5$ estimated in this investigation is softer than the power law index $\Gamma = 2.9$ derived in the previous study of PKS 0548-322 (Aharonian et al., 2010). Also, the integral flux previously estimated at > 0.25 TeV reaches $\Phi = 2.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ and is higher than in case of the current analysis. This discrepancy can be caused by different run lists used in both investigations.

The position of PKS 0548-322 was estimated using the point-like source model by fitting it to the excess map convolved with the PSF distribution with the test position of $\alpha = 87^\circ 669$, $\delta = -32^\circ 271$ in the J2000 epoch from the 2MASS catalogue. The fitted position is $\alpha_{\text{fit}} = 87^\circ 674$, $\delta_{\text{fit}} = -32^\circ 270$ and the angular distance from the test to the estimated best-fit position reaches $0''.012$.

Point-like source model	
α_{fit}	$87^\circ 674 \pm 0''.005$
δ_{fit}	$-32^\circ 270 \pm 0''.005$
N_0	5.77 ± 0.63
D	$0''.0121$
Circular Gaussian model	
N_0	5.09 ± 1.02
σ	$0''.0085 \pm 0''.0034$
Elliptical Gaussian model	
N_0	4.57 ± 1.54
σ_a	$0''.0148 \pm 0''.0082$
σ_b	$0''.0124 \pm 0''.0045$
$\varphi_{\text{H.E.S.S.}}$	$64^\circ 2 \pm 4^\circ 6$

Table 33: Summary of morphology fits of the point-like, circular Gaussian, and elliptical Gaussian models to PKS 0548-322 data in *ImPACT*. α_{fit} and δ_{fit} are fitted coordinates, N_0 is the normalization parameter, D is the angular distance between the test and best-fit position of the source, σ is the source width from the circular Gaussian model, σ_a and σ_b are the semi-axes from the elliptical Gaussian model, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

Circular Gaussian model	
N_0	$0.1 \pm 0.1 \cdot 10^{-3}$
σ	$0''.0191 \pm 0''.0047$
Elliptical Gaussian model	
N_0	$0.1 \pm 0.1 \cdot 10^{-3}$
σ_a	$0''.0207 \pm 0''.0066$
σ_b	$0''.0153 \pm 0''.0071$
$\varphi_{\text{H.E.S.S.}}$	$56^\circ 7 \pm 11^\circ 5$

Table 34: Morphology parameters of PKS 0548-322 calculated using the circular and elliptical Gaussian models in *M++* with the std configuration cuts. σ is the source width from the circular Gaussian model, σ_a and σ_b are the semi-axes from the elliptical Gaussian model, and $\varphi_{\text{H.E.S.S.}}$ is the position angle.

The extension of the blazar was examined with the circular and the elliptical Gaussian models. The former model gives $\sigma = 0''.0145$, while the latter results in $\sigma_a = 0''.0148$, $\sigma_b = 0''.0124$, and $\varphi_{\text{H.E.S.S.}} = 64''.2$ parameters (see Table 33).

The circular and elliptical Gaussian models were also used to investigate the blazar emission in the *M++* technique. The former model gives $\sigma = 0''.0191$, while the latter results in $\sigma_a = 0''.0207$, $\sigma_b = 0''.0153$, and $\varphi_{\text{H.E.S.S.}} = 56''.7$ (see Table 34).

5.7 ADDITIONAL MORPHOLOGICAL ANALYSIS

In the following section, the morphological analysis of the studied AGN was performed using the *Mathematica 10.4* software. The VHE data was prepared with the standard reconstruction procedure (see Section 3.2.2) performed in *ImPACT* and cross-checked with *M++*. The spectral analysis was also conducted within the H.E.S.S. software as described in Section 4.3. Fits of the circular and elliptical Gaussian models to the VHE model maps generated based on the H.E.S.S. data according to Equation 49 were done in order to verify the results obtained with the *ImPACT* and *M++* techniques and to test the reliability of the fits performed with the H.E.S.S. software. The signal, to which both Gaussian models are fitted, is limited by the significance levels $\geq 5\sigma$. The sets of parameters derived during the fitting process, i. e. σ , σ_a , σ_b , and $\varphi_{\text{H.E.S.S.}}$, as well as the ratios of the semi-axes and their errors (see Section A.2.2), are listed in Table 35 and Table 36.

Source	σ	σ_a	σ_b	$\varphi_{\text{H.E.S.S.}}$
(1)	(2)	(3)	(4)	(5)
1ES 0414+009	$0''.0509 \pm 0''.0005$	$0''.0557 \pm 0''.0005$	$0''.0457 \pm 0''.0004$	$166''.8 \pm 1''.5$
Centaurus A	$0''.0428 \pm 0''.0002$	$0''.0532 \pm 0''.0006$	$0''.0341 \pm 0''.0003$	$37''.5 \pm 0''.9$
1ES 0347-121	$0''.0555 \pm 0''.0002$	$0''.0577 \pm 0''.0002$	$0''.0531 \pm 0''.0004$	$170''.4 \pm 1''.7$
1ES 1101-232	$0''.0472 \pm 0''.0002$	$0''.0494 \pm 0''.0002$	$0''.0449 \pm 0''.0002$	$129''.7 \pm 1''.7$
1ES 0229+200	$0''.0480 \pm 0''.0002$	$0''.0500 \pm 0''.0002$	$0''.0460 \pm 0''.0002$	$157''.7 \pm 2''.4$
PKS 0548-322	$0''.0473 \pm 0''.0004$	$0''.0476 \pm 0''.0005$	$0''.0469 \pm 0''.0005$	$36''.9 \pm 31''.2$

Table 35: Parameters of the fits in *Mathematica*. Columns: (1) source designation, (2) width of the source estimated from the circular Gaussian model, (3)–(4) lengths of major (σ_a) and minor (σ_b) semi-axes of the ellipse calculated based on the elliptical Gaussian model, respectively, and (5) position angle $\varphi_{\text{H.E.S.S.}}$.

The majority of the examined sources seem to be only slightly extended. Two objects, i. e. 1ES 0414+009 and Centaurus A, are the exceptions which possess clearly elongated elliptical shapes. In case of the former object, the semi-axes attain values of $\sigma_a = 0''.0557$ and $\sigma_b = 0''.0457$, and the ratio of the semi-axes yields 1.219. The position angle $\varphi_{\text{H.E.S.S.}} = 166''.8$ and this result is consistent with that obtained with the *ImPACT* technique (see Section 5.1 and Appendix B for details). Centaurus A is the most extended AGN in the sample, with $\sigma_a = 0''.0532$, $\sigma_b = 0''.0341$, and the ratio of the semi-axes equals 1.561. Its angle $\varphi_{\text{H.E.S.S.}} = 37''.5$, which is consistent with the values

obtained using the *ImPACT* as well as *M++* techniques (see [Section 5.2](#) and [Appendix B](#)). On the other hand, PKS 0548-322 is nearly circular, with $\sigma_a = 0''.0473$, $\sigma_b = 0''.0469$, and the ratio of 1.015 ± 0.016 . Its angle, $\varphi_{\text{H.E.S.S.}} = 36^\circ.9$, has a large error of $31''.2$, which results from fitting the elliptical Gaussian model to a circular source.

Source	$\frac{\sigma_a}{\sigma_b}$	$\Delta\left(\frac{\sigma_a}{\sigma_b}\right)$	z
(1)	(2)	(3)	(4)
1ES 0414+009	1.219	0.014	0.287
Centaurus A	1.561	0.016	0.002
1ES 0347-121	1.086	0.005	0.188
1ES 1101-232	1.101	0.006	0.186
1ES 0229+200	1.086	0.008	0.14
PKS 0548-322	1.0	—	0.069

Table 36: Ratios of the semi-axes and their errors. Columns: (1) source designation, (2) ratio of the semi-axes of the fitted ellipse, (3) errors of the semi-axes ratios, and (4) redshift z .

[Figure 44](#) shows an interesting linear dependence of the ratio of semi-axes of the ellipse from the redshifts of the studied blazars listed in [Table 36](#). The red line is an $y = az + b$ relation with $a = 0.849 \pm 0.082$ and $b = 0.941 \pm 0.006$. The statistical significance of this correlation, taking into account five points only, is insufficient. However, the observed relation of the blazar extension with redshift can give a potential substantial impact to the current knowledge, but this dependence still requires detailed study in the future.

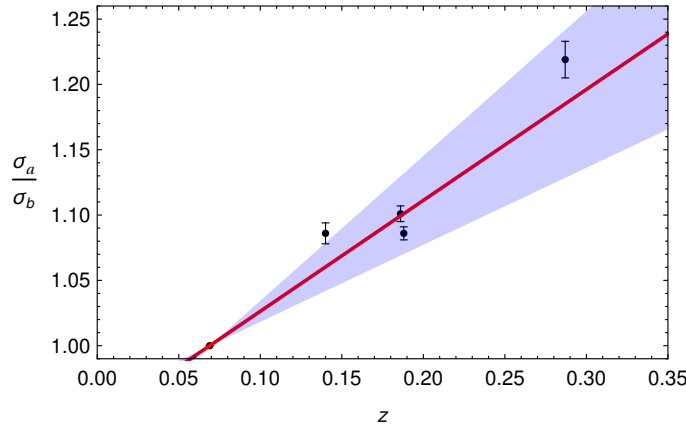


Figure 44: Relation of semi-axes ratio versus redshift for the examined blazars. The red line is the fitted linear relation and the blue shadowed area is the 95% mean prediction band.

[Figure 45](#) displays the model maps of all analysed objects. Contours indicate both employed fit models, with the black lines denoting the circular Gaussian model, while the white lines are for the elliptical Gaussian model. Both sets of contours were generated every 0.5σ based on the standard deviation of the fits. Just like in case of the parameters derived with the *ImPACT* and *M++* techniques, it is clearly visible that 1ES 0414+009 and

Centaurus A are more extended than other objects, while PKS 0548-322 can be very well approximated as a circular source.

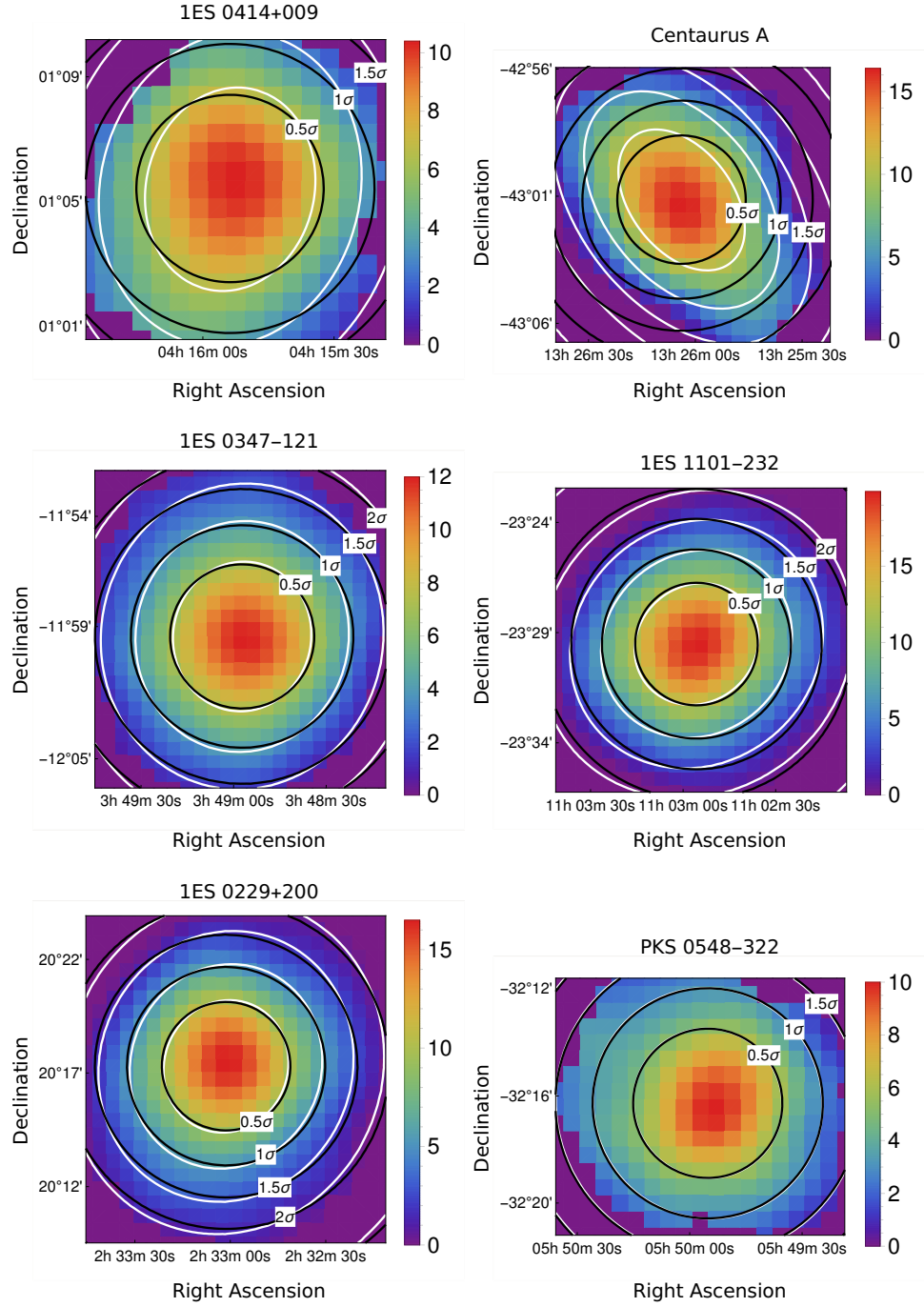


Figure 45: Model maps with superimposed contours of fitted circular and elliptical Gaussian models. The color scale is for the area with significance of $\geq 5\sigma$ to which both models were fitted. The black contours denote the circular Gaussian model, while the white contours are for the elliptical Gaussian model. Both sets of contours were generated every 0.5σ based on the standard deviation of the fits. In case of PKS 0548-322, both models give nearly identical results.

5.8 COMPARISON OF APPLIED MODELS

To assess which model, i.e. the circular or elliptical Gaussian, is a better description of the data, two approaches were employed, including the F-test (with the significance level $\alpha = 0.05$) and the information criteria (IC): Akaike IC (AIC), small-sample AIC (AIC_c), and Bayesian IC (BIC).

5.8.1 Information criteria

Following Akaike (1974), the AIC is defined as

$$AIC = 2p - 2\mathcal{L}_p, \quad (50)$$

where $\mathcal{L}_p$ is the log-likelihood and p denotes the number of parameters. For a regression problem,

$$\mathcal{L}_p = -\frac{1}{2}n \ln \frac{RSS}{n}, \quad (51)$$

where n is the number of fitted points and RSS is the residual sum of squares; p is an implicit variable in the log-likelihood. A preferred model is the one that minimises the AIC. The formulation of the AIC penalises the use of an excessive number of parameters, i.e. it prefers models with fewer parameters as long as the others do not provide a substantially better fit. The expression for the AIC consists of two terms, where the first measures the model complexity, i.e. the number of free parameters, and the second measures the goodness of a fit. Among candidate models with AIC_i , let $AIC_{\min}$ denote the smallest, i.e. corresponding to the preferred model.

The AIC is suitable when n/p is large, i.e. $n/p > 40$ (Burnham & Anderson, 2004). If this condition is not fulfilled, a correction is introduced, resulting in a small-sample version of the AIC, called AIC_c (Hurvich & Tsai, 1989):

$$AIC_c = 2p - 2\mathcal{L}_p + \frac{2(p+1)(p+2)}{n-p-2}. \quad (52)$$

The AIC_c converges to the AIC when n is large.

What is essential in assessing the goodness of a fit in the AIC method is the difference $\Delta_i = AIC_i - AIC_{\min}$ (or $\Delta_i = AIC_{c,i} - AIC_{c,\min}$), not the absolute value of an AIC_i (or the $AIC_{c,i}$). If $\Delta_i < 2$, then there is substantial support for the i -th model, and the proposition that it is a proper description is highly probable. If $2 < \Delta_i < 4$, then there is a strong support for the i -th model. When $4 < \Delta_i < 7$, there is considerably less support and models with $\Delta_i > 10$ are essentially not even worth a bare mention (Burnham & Anderson, 2004).

The BIC (Schwarz, 1978) is defined as

$$BIC = p \ln n - 2\mathcal{L}_p. \quad (53)$$

As was in case of the AIC and the AIC_c , a preferred model is the one that minimises the BIC, which also penalises the usage of an excessive number

of free parameters. The difference is that the penalisation in case of the BIC is much more stringent, especially for large samples.

The support for the i -th model (or evidence against it) also depends on the differences, $\Delta_i = \text{BIC}_i - \text{BIC}_{\min}$ in a way that if $\Delta_i < 2$, then there is substantial support for the i -th model (or the evidence against it is worth only a bare mention). When $2 < \Delta_i < 6$, then there is positive evidence against the i -th model. If $6 < \Delta_i < 10$, the evidence is strong, and $\Delta_i > 10$ yields very strong evidence against the i -th model (essentially no support; Kass & Raftery 1995). When two models with similar $\mathcal{L}$ are considered and $\frac{\Delta_i}{2\Delta p} < 1$, the relative improvement is due to actual improvement of the fit, not to increasing the number of parameters only.

Despite apparent similarities between the AIC (AIC_c) and the BIC, they answer different questions, as they are derived based on different assumptions (Tarnopolski, 2016a,b). The AIC tries to select a model that most adequately describes reality in the form of the data under examination. This means that in fact the model being a real description of the data is never considered. On the contrary, the BIC tries to find the true model among the set of candidates. In view of the fact that the BIC is more stringent, it has a tendency to underfit, while the AIC, as a more liberal method, is inclined towards overfitting. Occasionally, this pointing at different models by the two criteria, which happens rarely, is due to the fact that they try to satisfy different conditions. All of the above IC can be applied to nested as well as non-nested models.

F-TEST

The F-test for regression (Rawlings et al., 1998) compares two nested models and is based on the test statistic given by

$$F = \frac{\left(\frac{\text{RSS}_1 - \text{RSS}_2}{p_2 - p_1} \right)}{\left(\frac{\text{RSS}_2}{n - p_2} \right)}, \quad (54)$$

where indices 1,2 denote the models under examination in a way that model 1 is nested within model 2, RSS_i is the residual sum of squares and p_i is the number of parameters. The null hypothesis H_0 is that model 1 is a better description of the data. F is distributed according to the F -distribution with $(p_2 - p_1, n - p_2)$ degrees of freedom (dof); it is compared with the critical value F_{crit} for the given dof and the chosen significance level α . H_0 is rejected if $F > F_{\text{crit}}$, or equivalently, if the associated p -value does not exceed α (see Figure 46).

5.8.2 Results of model comparison

For all instances, $n/p \approx 40$ for the elliptical model, so to be on the safe side, the AIC_c was employed together with the AIC. For five objects, i.e. Centaurus A, 1ES 0229+200, 1ES 0347-121, 1ES 1101-232, and 1ES 0414+009, the ΔIC ranged roughly from ~ 100 to ~ 400 in favour of the elliptical model, hence the circular one is confidently rejected. The remaining object, i.e. PKS 0548-322, yielded the circular model as the better one, with

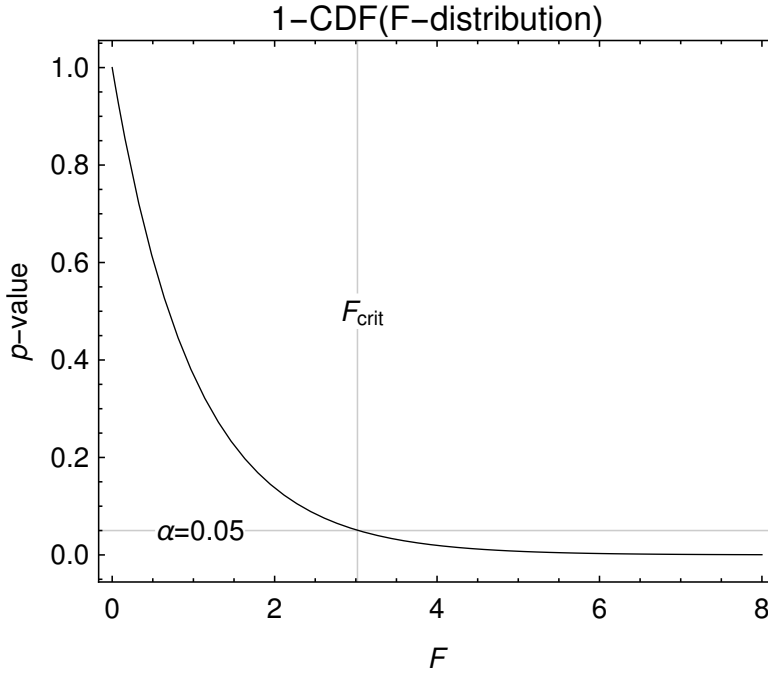


Figure 46: The F-distribution. 1–CDF is the so called survival function. There are in fact six curves in the plot, for n ranging from 227 to 453, i. e. the sizes of the data sets for the objects of interest, but they are indistinguishable from each other and for all $F_{\text{crit}} \approx 3.02$.

$\Delta\text{AIC} = 3.05$, $\Delta\text{AIC}_c = 3.24$, and $\Delta\text{BIC} = 10.02$. Note that the comparison was performed between two fitted models and in case of PKS 0548-322 the parameters of the elliptical model make it nearly circular, hence the difference between the two, quantified by ΔAIC and ΔAIC_c , is relatively small, which makes perfect sense for the ΔIC values (i.e., $\frac{\Delta_i}{2\Delta p} < 1$, due to $\Delta p = 2$). The penalisation term of the BIC makes it more stringent, hence it is more harsh on models with very similar performance. Therefore, the conclusion that the circular model is significantly better than the elliptical one, is strongly justified.

The F-test yielded results entirely consistent with the IC approach: for the same five objects, the value of F from Equation 54 range from ~ 70 to ~ 430 , which is $\gg F_{\text{crit}} \approx 3.02$. This implies a rejection of H_0 , stating that the objects have a circular morphology, and accepting the alternative hypothesis that their shape is elliptical. On the other hand, in case of PKS 0548-322, $F = 0.46 < 3.02$, hence the hypothesis that this object has a circular shape can not be rejected.

These results show that only PKS 0548-322 can be truly considered circular and the other objects (in particular, the other four blazars), cannot be described appropriately as circular even though the ellipticity of these blazars is small, hence describing them as circular is unjustified on the basis of statistical inference. They are elliptical objects with small axes-ratio.

SUMMARY AND DISCUSSION

6.1 SUMMARY AND CONCLUSIONS

The main purpose of the presented research was to study the VHE emission of the extreme HBL blazar 1ES 0414+009 and the FR I radio loud galaxy Centaurus A in order to understand the extended morphology of both sources. The detailed analysis was based on the observations collected by the H.E.S.S. telescopes. The careful spectral and morphological analyses of the four reference blazars, including 1ES 0347-121, 1ES 1101-232, 1ES 0229+200, and PKS 0548-322, which are expected to be point-like sources, were performed for comparison.

The objects of interest were observed by the H.E.S.S.-I array of telescopes. The collected data were first calibrated and then prepared for further analysis with standard H.E.S.S. methods using two independent techniques, i.e. *ImPACT* and *M++*, based on different calibration and event reconstruction procedures in order to cross-check the compatibility of obtained results. The analysis resulted in the high quality spectra, which are well described by power law and log parabola models. The intrinsic spectra corrected for the EBL absorption were fitted with a power law model. Using such fits, the parameters describing the VHE spectrum were estimated. The derived spectral index Γ was applied in the morphological data analysis with the circular and elliptical Gaussian models convolved with the PSF distribution estimated for each data set. The results of this analysis are listed in [Table 37](#).

During the morphological studies, it turned out that the fitting procedures implemented in both *ImPACT* and *M++* are extremely sensitive to the input parameters. Even a slight change in any input parameter, i.e. semi-axes, position angle, or normalisation, generates radically different results. Therefore, an independent analysis using *Mathematica 10.4* software was conducted.

Furthermore, the VHE position angles derived based on the morphological investigation of the H.E.S.S. data were compared with the VLBA or VLBI parsec scale and the VLA large scale radio jets.

The performed analyses showed that:

- The comparable results obtained in both *ImPACT* and *M++* techniques confirm the reality of the extension of 1ES 0414+009 in the VHE data. The detailed analysis with additional cuts imposed on the data, i.e. in the years of observations, the zenith angle ranges, and the selected energy ranges, reveals that the asymmetry of the source is stable between different cuts, with essentially the same position angles of the extension. On the other hand, the extension of 1ES 0414+009 is not compatible with the directions of the parsec or large scale radio jets visible in the VLBA and VLA data. This inconsistency could be

possibly explained by a precession of the jet direction close to the line of sight, where small variations of the jet can lead to large changes in the position angle. If the observed extended γ -ray emission was generated earlier than the VLBA radio jet and later than the bulk VLA emission, the observed VHE position angles can be different.

- The extended VHE morphology of Centaurus A is confirmed by the results obtained in both *ImPACT* and *M++* techniques and the analysis using additional cuts imposed on the run list. This revealed the extension of the source and quite similar position angles derived in each cut. The orientation of the VHE extension is compatible with the directions of the VLBI parsec scale and the VLA large scale jets.

The analysis of the four reference blazars revealed that their VHE extensions are smaller than the asymmetries of 1ES 0414+009 and Centaurus A. Furthermore, the circular Gaussian model is a better description of PKS 0548-322 than the elliptical Gaussian model, so that this blazar can be truly considered as a point-like source, while the three other objects are slightly extended.

Source	Morphological parameters			
	σ	σ_a	σ_b	$\varphi_{\text{H.E.S.S.}}$
1ES 0414+009	$0^\circ 0113 \pm 0^\circ 0063$	$0^\circ 0385 \pm 0^\circ 0064$	$0^\circ 0163 \pm 0^\circ 0072$	$174^\circ 4 \pm 6^\circ 2$
Centaurus A	$0^\circ 0145 \pm 0^\circ 0064$	$0^\circ 0427 \pm 0^\circ 0098$	$0^\circ 0137 \pm 0^\circ 0026$	$38^\circ 4 \pm 7^\circ 1$
1ES 0347-121	$0^\circ 0216 \pm 0^\circ 0049$	$0^\circ 0255 \pm 0^\circ 0069$	$0^\circ 0185 \pm 0^\circ 0075$	$171^\circ 7 \pm 6^\circ 5$
1ES 1101-232	$0^\circ 0152 \pm 0^\circ 0054$	$0^\circ 0213 \pm 0^\circ 0045$	$0^\circ 0108 \pm 0^\circ 0051$	$49^\circ 4 \pm 9^\circ 0$
1ES 0229+200	$0^\circ 0145 \pm 0^\circ 0065$	$0^\circ 0196 \pm 0^\circ 0068$	$0^\circ 0100 \pm 0^\circ 0079$	$93^\circ 4 \pm 5^\circ 0$
PKS 0548-322	$0^\circ 0085 \pm 0^\circ 0064$	—	—	—

Table 37: Morphological parameters of the studied AGN using *ImPACT*. σ is estimated based on the circular Gaussian model, while σ_a , σ_b , and $\varphi_{\text{H.E.S.S.}}$ are calculated based on the elliptical Gaussian model.

6.2 DISCUSSION

The morphological parameters estimated based on the H.E.S.S. data were then compared with parsec and large scale radio morphologies to verify possible coincidence between the orientation of the VHE emission and the radio jets and to evaluate the reality of the studied extensions. The VLBA/VLBI parsec scale jets are often misaligned with the large scale radio structures visible in the VLA maps, thus the considered VHE extensions were compared with both radio data (see [Appendix B](#)).

[Figure 47](#) shows a comparison of the parsec scale VLBA/VLBI radio structures $\varphi_{\text{VLBA,VLBI}}$ with the VHE extensions $\varphi_{\text{H.E.S.S.}}$ of the studied AGN, while the same comparison for the large scale position angles φ_{VLA} is illustrated in [Figure 48](#). This investigation revealed that the position angles, $\varphi_{\text{H.E.S.S.}}$, estimated in this work do not correlate well with the radio jets of studied blazars. In case of Centaurus A, radio φ_{VLBI} and φ_{VLA} as well as the VHE $\varphi_{\text{H.E.S.S.}}$ angles are comparable.

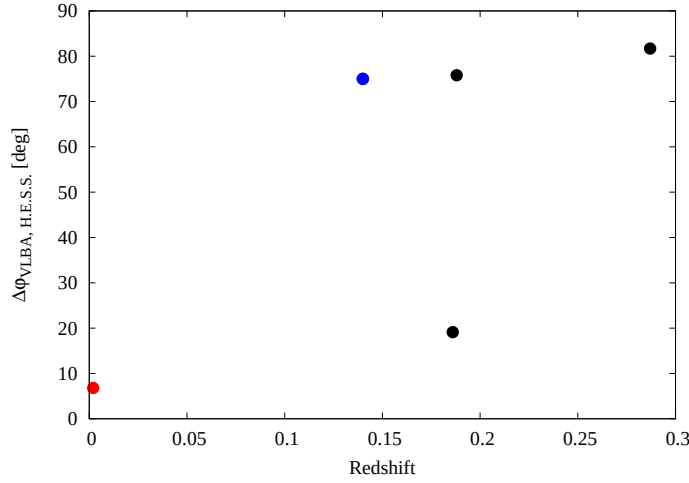


Figure 47: Comparison of the parsec scale VLBA/VLBI radio structure with the VHE extension of the studied blazars: $\Delta\phi_{\text{VLBA, H.E.S.S.}}$ versus redshift; a red circle denotes Centaurus A, blue circle indicates 1ES 0229+200, and black circles stand for the extreme HBLs with the one-sided VLA radio emission.

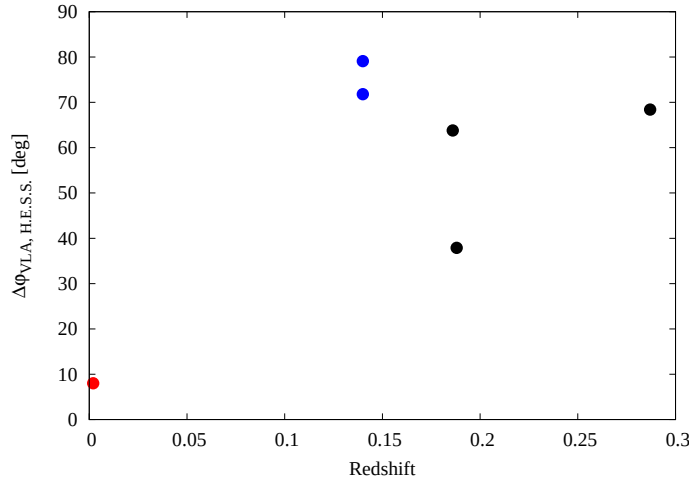


Figure 48: Comparison of the large scale VLA radio structure with the VHE extension of the studied blazars: $\Delta\phi_{\text{VLA, H.E.S.S.}}$ versus redshift; red circle denotes Centaurus A, blue circles indicate two jets of 1ES 0229+200, and black circles are for the extreme HBLs with the one-sided VLA radio emission.

A short additional consideration is presented, testing if the measured extensions of VHE emission of the studied blazars can be real and whether the asymmetries systematically change with distance. The correlation presented in Figure 44 (in Section 5.7) was initially checked with relation of the fitted emission centre shift D calculated from the position catalogued in lower frequencies to the estimated best-fit VHE position of the studied AGN, versus redshift z (Figure 49). A decreasing trend of $D(z)$ is noticeable, which can mean that a real physical effect is measured, not the one arising from signal and background fluctuation. Figure 50 displays a distribution of the significance S_{det} versus z , examining if flux fluctuations of more distant sources could be responsible for the observed trends. However, this distribution seems to be random and do not confirm such suspicions.

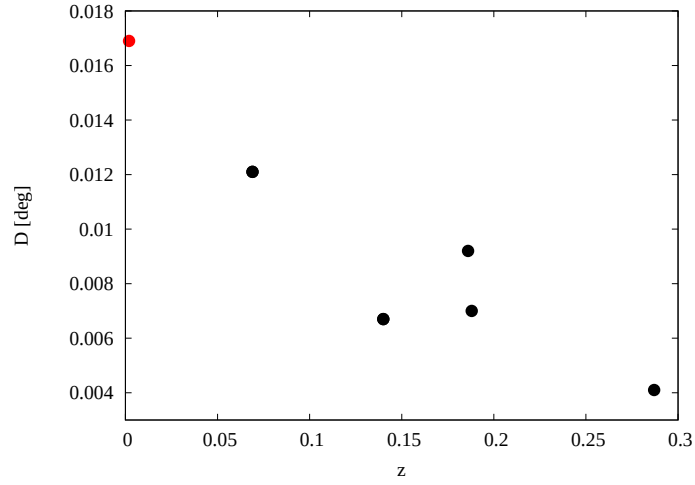


Figure 49: Relation of the angular distance between the catalogued and estimated VHE position versus redshift of examined AGN. A red circle denotes Centaurus A and black circles stand for the extreme HBLs.

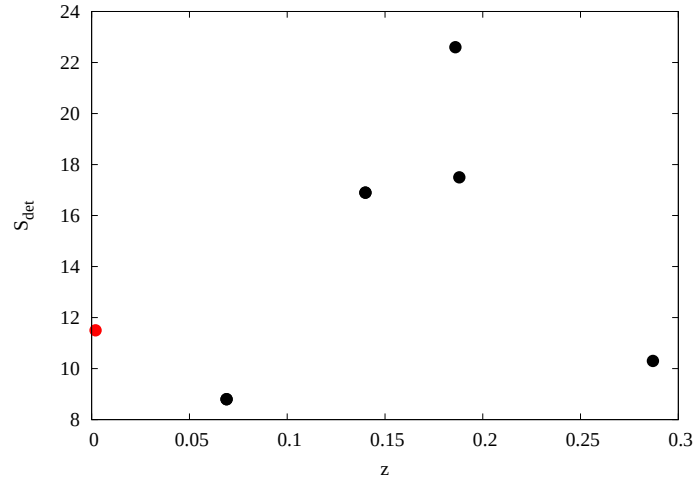


Figure 50: Relation of the detection significance of the examined AGN versus their redshift. A red circle denotes Centaurus A and black circles stand for the extreme HBLs.

In spite of all, a small sample containing only five objects makes the significance of the discussed trends inadequate. Therefore, additional preliminary spectral and morphological analyses of all HBL blazars available in the H.E.S.S. database were performed to get better insight into this issue. The analyses were conducted in the same way as described in [Chapter 4](#), the resulting parameters are listed in [Table 38](#), while the relation of semi-axes ratio versus z is plotted in [Figure 51](#). The visual inspection of this relation for the 15 blazars reveals non-random distribution. However, a clear systematic trend can not be pointed out due to two highly extended blazar outliers at $z \sim 0.1$, i. e. RGB J0152+017 ($z = 0.08$) and 1ES 1312-423 ($z = 0.105$).

Source	α_{J2000}	δ_{J2000}	S_{det}	S_{spec}	Γ_{PL}	$\frac{\sigma_a}{\sigma_b}$	$\Delta\left(\frac{\sigma_a}{\sigma_b}\right)$	z
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Mrk 421	11:04:19.0	38:11:41.0	66.5	61.5	2.2	1.008	0.003	0.031
PKS 2005-489	20:09:27.0	-48:49:52.0	42.7	39.8	3.2	1.035	0.005	0.071
RGB J0152+017	01:52:33.5	01:46:40.3	13.0	11.5	3.2	1.233	0.012	0.080
1ES 1312-423	13:14:58.5	-42:35:49.0	6.9	6.0	3.1	1.161	0.013	0.105
PKS 2155-304	21:58:52.7	-30:13:18.0	464.9	438.7	3.3	1.019	0.003	0.116
TeV J1010-313	10:10:15.0	-31:18:18.4	8.1	7.5	3.2	1.012	0.016	0.140
HESS J2359-306	23:59:09.4	-30:37:22.7	28.5	24.7	3.1	1.024	0.005	0.165
PKS 0301-243	03:03:23.5	-24:07:35.9	4.01	7.2	5.2	1.160	0.030	0.266
PKS 0447-439	04:49:28.2	-43:50:12.0	12.7	13.4	4.2	1.093	0.010	0.343
1ES 1553+113	15:55:44.7	11:11:41.0	19.4	18.7	4.7	1.099	0.003	0.500

Table 38: Statistical, spectral, and morphological parameters of ten additionally analysed HBLs. Columns: (1) source designation, (2 – 3) Right Ascension and declination in the J2000.0 epoch, (4) detection significance, (5) spectral significance, (6) power law spectral index, (7) semi-axes ratio, (8) error of the semi-axes ratio, and (9) redshift.

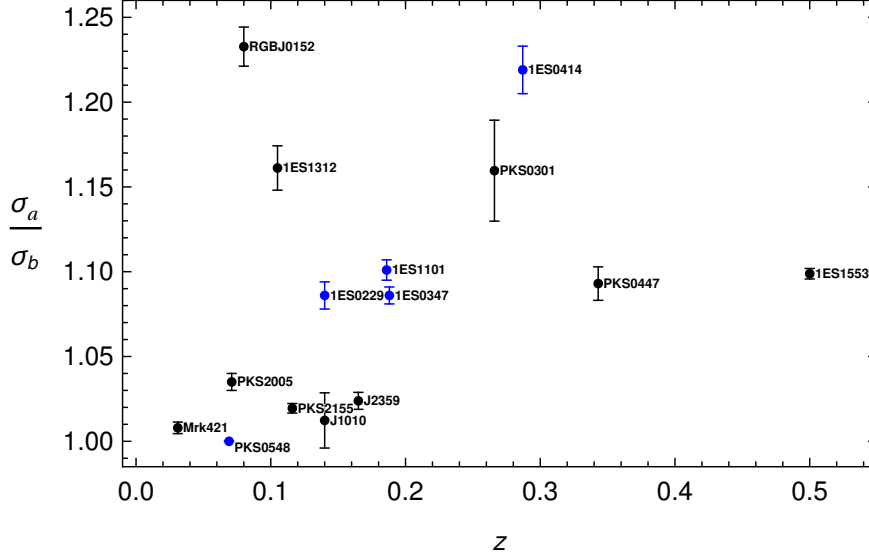


Figure 51: Relation of semi-axes ratio versus redshift for HBL (black points) and extreme HBL blazars (blue points).

6.3 EXTREME HBL BLAZARS?

The investigation of the intrinsic VHE spectra of the five blazars, including 1ES 0414+009, 1ES 0347-121, 1ES 1101-232, 1ES 0229+200, and PKS 0548-322, confirmed that they are relatively hard with the EBL corrected power law index Γ_{int} in the range of [1.7, 2.3]. This fact, together with the lack of variability in the TeV energies, suggests possible membership of the studied objects to the extreme HBL class of blazars (see [Section 2.2](#)). The power law index Γ_{int} estimated from data can also be used for further research, including modelling of the broadband SED of these blazars taking into account the TeV energy part of the spectrum. Such modelling should allow

to study the physical mechanisms responsible for the extreme conditions prevailing in blazars of this subclass.

6.4 FUTURE CTA PERSPECTIVES

The results presented in this work show that 1ES 0414+009, Centaurus A, 1ES 0347-121, 1ES 1101-232, and 1ES 0229+200 possess an extended morphology in the TeV H.E.S.S. data. The extension in the excess distribution of these sources makes them good candidates for observations and morphological investigations with the forthcoming ground-based IACT CTA observatory. The angular resolution of CTA is expected to reach $\sim 1'$, while it is only $\sim 6'$ in case of the H.E.S.S. telescopes.

Part III

APPENDIX

MONTE CARLO SIMULATIONS

In order to validate the fitting procedure performed in [Chapter 5](#), two types of Monte Carlo (MC) simulations were implemented to verify the reliability of error propagation of the position angle (φ) in relation to the axes ratio ($\frac{\sigma_a}{\sigma_b}$) of an elliptical Gaussian function using purely artificial (i.e. numerically generated) and real data of the six objects of interest.

A.1 GENERATION OF ARTIFICIAL OBJECTS

In order to generate the artificial data, a total number of 10^3 MC simulations were performed according to the following steps:

1. Parameters of the exact elliptical Gaussian were randomly drawn as follows:
 - σ_a from a $\mathcal{U}(7, 10)$ distribution,
 - σ_b from $\mathcal{U}(\sigma_a, 2\sigma_a)$,
 - φ from $\mathcal{U}(0, \pi)$,
 - A from $\mathcal{U}(10, 20)$,

where $\mathcal{U}(x_1, x_2)$ denotes the continuous uniform distribution with support in $[x_1, x_2]$. These parameters are coined as *true* and are treated as exact. Such values were chosen to mimic the possible range of parameters of the six examined objects, including the $\geq 5\sigma$ significance level. The units of σ_a and σ_b are in pixels.

2. From such a Gaussian function, points on a 501×501 grid were generated (with the means located in the center of the grid) and each point was subject to an additive random fluctuation, i.e. *background noise*, drawn from $\mathcal{U}(-A/5, A/10)$. This range was also inferred from the values observed for the examined objects.
3. Such a signal map was then subject to a convolution with the PSF modelled by [Equation 45](#), with its σ 's drawn independently from $\mathcal{U}(1.2, 1.5)$ each.
4. Finally, a fit of an elliptical Gaussian was performed to the points with values > 0 ; due to the above framework, this mimics the condition of a $\geq 5\sigma$ significance level.
5. The obtained parameters of each fit were used to infer:
 - the *true* axes ratio (this ranges from 1 to 2 due to the constraints on σ_a and σ_b),
 - the ratio of the fitted axes,
 - the error of the fitted ratio according to [Equation 55](#),

- the original and fitted angles, φ ,
- the errors $\Delta\varphi$ of the fitted angle.

The aim of this MC simulaton is twofold. First, it will be used in [Section A.3](#) to analyze the dependence of the ratio $\frac{\sigma_a}{\sigma_b}$ on $\Delta\varphi$ and second, it is used to examine the influence of noise on the axes ratio. [Figure 52](#) displays the relation between the fitted and true axes ratios. The black dashed line marks the ideal case of equality of the two, while the solid red line is the best fit line, $y = ax + b$, with parameters $a = 1.259 \pm 0.005$ and $b = -0.251 \pm 0.007$. It turns out that the true ratio is slightly higher than the one obtained via fitting, e. g. in case of Centaurus A the fitted ratio of 1.561 (see [Section 5.7](#)) becomes 1.654.

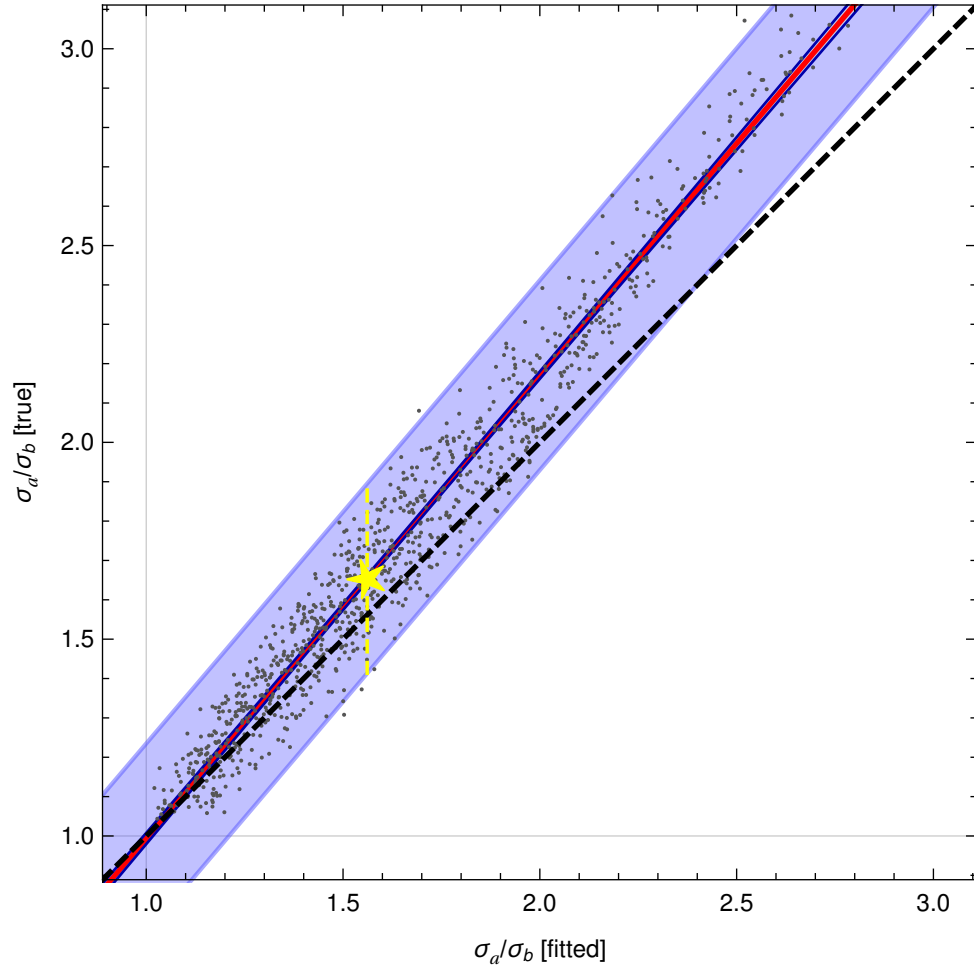


Figure 52: Relation between the fitted and true ratios of the axes. The red line is the best fit line, while the thin blue lines around it mark the 99% mean prediction band and the light-blue shaded area marks the 99% single prediction band. Location of Centaurus A is denoted with the yellow star and the vertical dashed yellow line symbolizes the 99% single prediction interval (1.413, 1.895) of the true value. The *true* ratio here is given by [Equation 56](#) and is computed from the parameters of the generated 2D Gaussian function. The *fitted* ratio is the one obtained from the fitting.

A.2 TRANSFORMATION OF THE REAL OBJECTS

A.2.1 The procedure

For each of the six objects of interest listed in [Chapter 4](#) (more specifically, for the areas with significance $\geq 5\sigma$; see [Section 4.2](#)), 10^3 MC simulations were performed in the following framework:

1. The data points were rotated first by an angle α randomly chosen from $\mathcal{U}(0, \pi)$.
2. A stretch by a factor r_i from $\mathcal{U}(1, 2)$ was performed in a randomly chosen direction, either vertically or horizontally.
3. The transformed points were rotated again by an angle β drawn from $\mathcal{U}(0, \pi)$.
4. An elliptical Gaussian was fitted to the modified dataset.
5. The axes ratio and its error were recorded together with φ and $\Delta\varphi$.

The original data points are located on a quadratic grid, hence a vertical or horizontal stretch would not impact the relative layout of the points. The rotation by an angle α is introduced to make the layout a bit less ordered after the stretching. The second rotation by an angle β is to introduce a further level of randomization before the fitting is performed. In total, 6×10^3 simulations were accomplished.

The mode, for 10^3 simulations for each object, of $\Delta\varphi$ falls roughly in the range $[0.5^\circ - 1^\circ]$, and the mean is at $\sim 1^\circ$. An exception is a highly circular PKS 0548-322 for which the mean is at 3.7° . It is worth to mention that the obtained distributions of $\Delta\varphi$ are rather severely skewed, with skewness ranging from ~ 5 to ~ 11 .

It was verified, as an extension of the performed simulations, that the rotations and stretching do not affect the shape of the fitted Gaussian. Hence, the manipulations of the observed data described above do not introduce additional biases, but allow to examine the axes ratio–angle dependence for real objects, that are subject to less controlled distortions than imposed in [Section A.1](#).

A.2.2 The formulae

The ratio of the axes is $\frac{\sigma_a}{\sigma_b}$, with $\sigma_a > \sigma_b$. The error of the ratio, from the propagation of uncertainty law, is

$$\begin{aligned} \Delta\left(\frac{\sigma_a}{\sigma_b}\right) &= \left[\left(\frac{\partial\left(\frac{\sigma_a}{\sigma_b}\right)}{\partial\sigma_a} \right)^2 (\Delta\sigma_a)^2 + \left(\frac{\partial\left(\frac{\sigma_a}{\sigma_b}\right)}{\partial\sigma_b} \right)^2 (\Delta\sigma_b)^2 \right]^{1/2} \\ &= \sqrt{\left(\frac{\Delta\sigma_a}{\sigma_b} \right)^2 + \left(\frac{\sigma_a \Delta\sigma_b}{\sigma_b^2} \right)^2} \end{aligned} \quad (55)$$

Given an ellipse with a position angle φ and an initial axes ratio $r = \frac{\sigma_a}{\sigma_b}$, subject to rotation by an angle α , and stretching in the horizontal and vertical directions by factors r_1 and r_2 , respectively, the axes ratio $r' = \frac{\sigma'_a}{\sigma'_b}$ of the resulting ellipse follows:

$$r' = \frac{\sqrt{X + \sqrt{Y}}}{\sqrt{X - \sqrt{Y}}}, \quad (56)$$

where

$$X = [r^2 + 1 - (r^2 - 1) \cos 2(\alpha + \varphi)] r_1^2 + [r^2 + 1 + (r^2 - 1) \cos 2(\alpha + \varphi)] r_2^2 \quad (57)$$

and

$$Y = 4(r^2 - 1)^2 \sin^2 2(\alpha + \varphi) r_1^2 r_2^2 + [(r^2 + 1)(r_1^2 - r_2^2) - (r^2 - 1)(r_1^2 + r_2^2) \cos 2(\alpha + \varphi)]^2. \quad (58)$$

Note that the second rotation by an angle β does not change the axes ratio, hence β is absent in Equation 56–Equation 58.

Figure 53 is a visualisation of the dependence of the axes ratio r' on α and φ , for given r_1 and r_2 . The light yellow plane indicates the case of $r' = 1$, i. e. a circle.

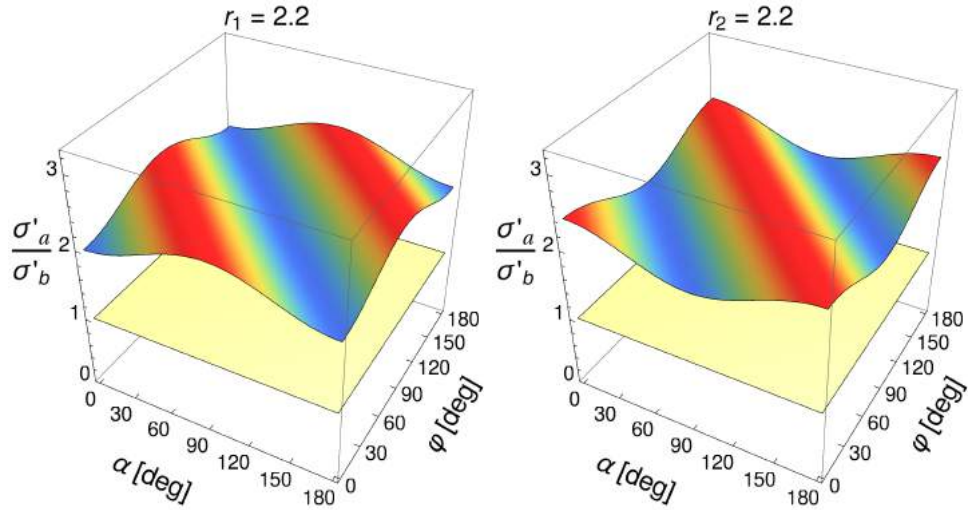


Figure 53: Dependence of the ratio $\frac{\sigma'_a}{\sigma'_b}$ on α and φ for a horizontal stretch by a factor of $r_1 = 2.2$ (left panel) and a vertical stretch by a factor of $r_2 = 2.2$ (right panel). The initial ratio is $r = 1.1$ in both cases.

A.3 RESULTS OF THE FITS OF OBJECTS AND THE MC SIMULATIONS

The results of both types of the MC simulations are gathered in Figure 54, which displays a relationship of the axes ratio of the fitted elliptical Gaussian function and the errors of the fitted angles, $\Delta\varphi$. The blue and red points denote Centaurus A and the examined blazars, respectively. Grey points, with error bars obtained via Equation 55, mark the results of the MC simulations based on transformation of the observations of the six objects,

as described in Section A.2. The purely artificial MC simulations from Section A.1 are depicted by black points. The horizontal dashed line denotes the axes ratio equal to 1, i.e. a purely circular model. The inset exhibits a magnification of the area surrounded by the orange dashed frame in order to highlight the region where the separation of the trends is most visible and to better distinguish the individual objects. Overall, there is a clear tendency that the more circular the object, the bigger the error $\Delta\varphi$ of the fitted angle φ . The particular values obtained for the six objects of interest are in very good agreement with both types of simulations.

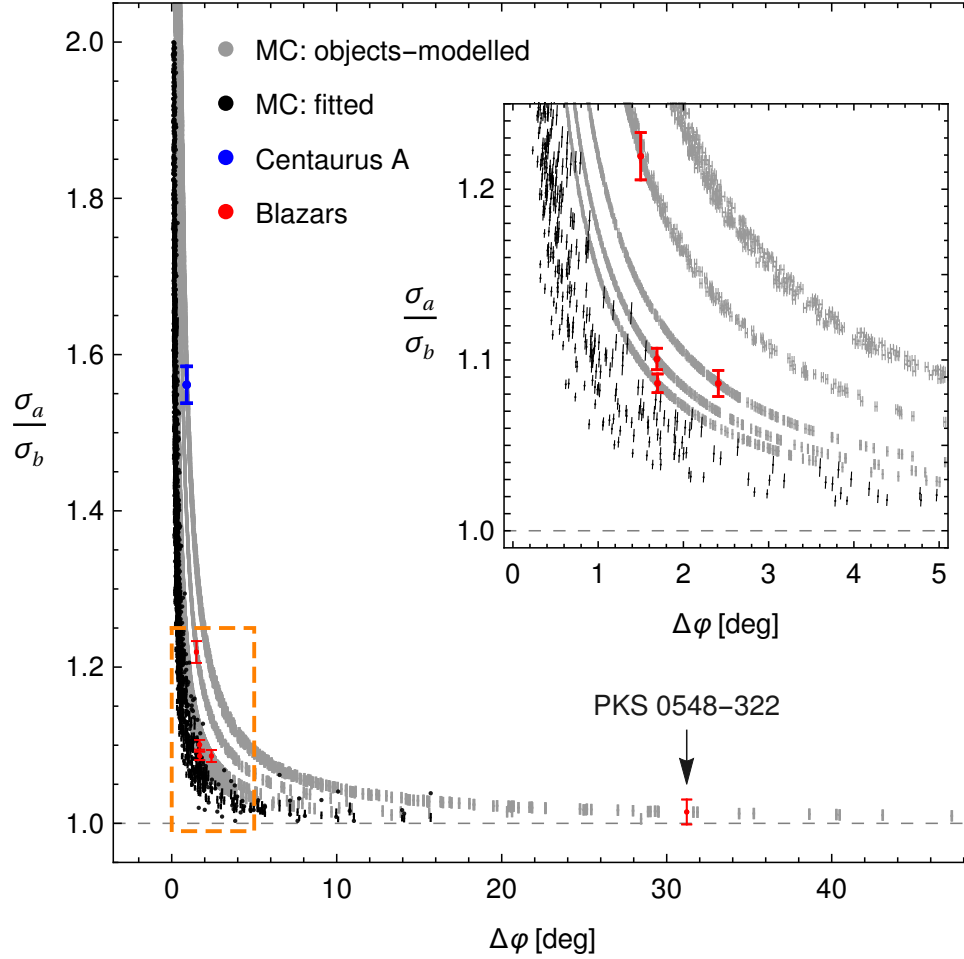


Figure 54: A relationship of the ratio of ellipse axes and errors of the fitted angle φ . The blue point denotes Centaurus A, while the red points stand for the blazars. Grey points mark the results of the MC simulations based on transformation of the real H.E.S.S. data of the six objects. The black points indicate the fitted values. The dashed horizontal line marks a purely circular model.

Radio data collected by the Very Long Baseline Array (VLBA) and the Very Long Baseline Interferometry (VLBI) were used to study the intrinsic radio morphology of six analysed AGN. The investigation includes comparison between the position angles ϕ_{VLBA} or ϕ_{VLBI} of the parsec scale jets derived from 8.4 GHz maps and the position angles $\phi_{\text{H.E.S.S.}}$ of the VHE extension estimated based on the elliptical Gaussian model fitted to the H.E.S.S. data (see Chapter 5).

The contour maps of the examined blazars, presented in Figures 55, 59, 61, 63, and 65, were generated with the *Astronomical Image Processing System* (AIPS)¹ based on the interferometric observations conducted by the VLBA. The FITS files were taken from the webpage of *VLBA Observations of TeV Blazars*² with the consent of the authors. The contours start at $3 \times \text{rms}$ estimated for each map separately, and increase by a factor of 2 for each subsequent contour. Figure 57 shows the contour map of Centaurus A generated by the *Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry* group (TANAMI)³ and taken from Müller et al. (2014). The contours mark flux density levels starting at $3 \times \text{rms}$ level, scaled logarithmically, and increased by a factor of 3 for each subsequent contour. The grey dashed lines indicate negative flux density level. Based on these maps, the position angles ϕ_{VLBA} and ϕ_{VLBI} of the jets were derived using the *SAOImage DS9*⁴ data visualisation application (see Table 39).

In order to study the large scale ($\sim$ kiloparsec scale) morphology of the sources of interest, the high resolution Very Large Array (VLA) radio maps were analysed. The derived radio position angles ϕ_{VLA} were estimated using *SAOImage DS9* and then compared with the VHE position angles $\phi_{\text{H.E.S.S.}}$. The contour maps of individual sources, i. e. Figures: 56, 58, 60, 62, 64, and 66, were prepared with *AIPS* in similar fashion as the VLBA contour maps.

To visualise the comparison between the radio and VHE extensions, lines which represent the position angles $\phi_{\text{H.E.S.S.}}$ are superimposed on all radio contour maps but the VLBA and VLA maps of PKS 0548-322 (since the VHE emission of this blazar is described by the circular Gaussian model, see Section 5.8.2), i. e. purple line denotes the position angle derived with *ImPACT*, blue line — with *M++*, and red line — with *Mathematica 10.4* software.

¹ <http://www.aips.nrao.edu/index.shtml>; date of access: 15.06.2018

² <http://www2.whittier.edu/facultypages/gpiner/research/archive/archive.html>; date of access: 12.06.2018

³ <http://pulsar.sternwarte.uni-erlangen.de/tanami/>; date of access: 20.06.2018

⁴ <http://ds9.si.edu/site/Home.html>; date of access: 12.06.2018

Source	$\phi_{\text{VLBA,VLBI}}$	ϕ_{VLA}	$\phi_{\text{H.E.S.S.}}$		
			$\phi_{\text{H.E.S.S.,ImPACT}}$	$\phi_{\text{H.E.S.S.,M++}}$	$\phi_{\text{H.E.S.S.,Mathematica}}$
(1)	(2)	(3)	(4)	(5)	(6)
1ES 0414+009	92°:7	62°:8	174°:4	146°:8	166°:8
Centaurus A	45°:2	46°:4	38°:4	38°:6	37°:5
1ES 0347-121	247°:5	313°:8	171°:7	166°:5	170°:4
1ES 1101-232	30°:3	345°:6	49°:4	58°:4	129°:7
1ES 0229+200	168°:4	352°:5 (N) 201°:6 (S)	93°:4	104°:6	157°:7
PKS 0548-322	2°:9	147°:1 (SE) 218°:3 (SW)	–	–	–

Table 39: Position angles of the sources of interest estimated based on the VLBA, VLBI, VLA, and H.E.S.S. data. Columns: (1) source name; (2) parsec scale position angle from the VLBA or VLBI radio maps, (3) large scale position angle from the VLA radio maps, and VHE structure position angle from the H.E.S.S. data derived with: (4) *ImPACT*, *M++*, and (6) *Mathematica*. (N) stands for north and (S) – south jet of 1ES 0229+200, while (SW) denotes south-west and (SE) – south-east jet of PKS 0548-322. Since the VHE emission of PKS 0548-322 is described by the circular Gaussian model, the position angle $\phi_{\text{H.E.S.S.}}$ is not included in this comparison.

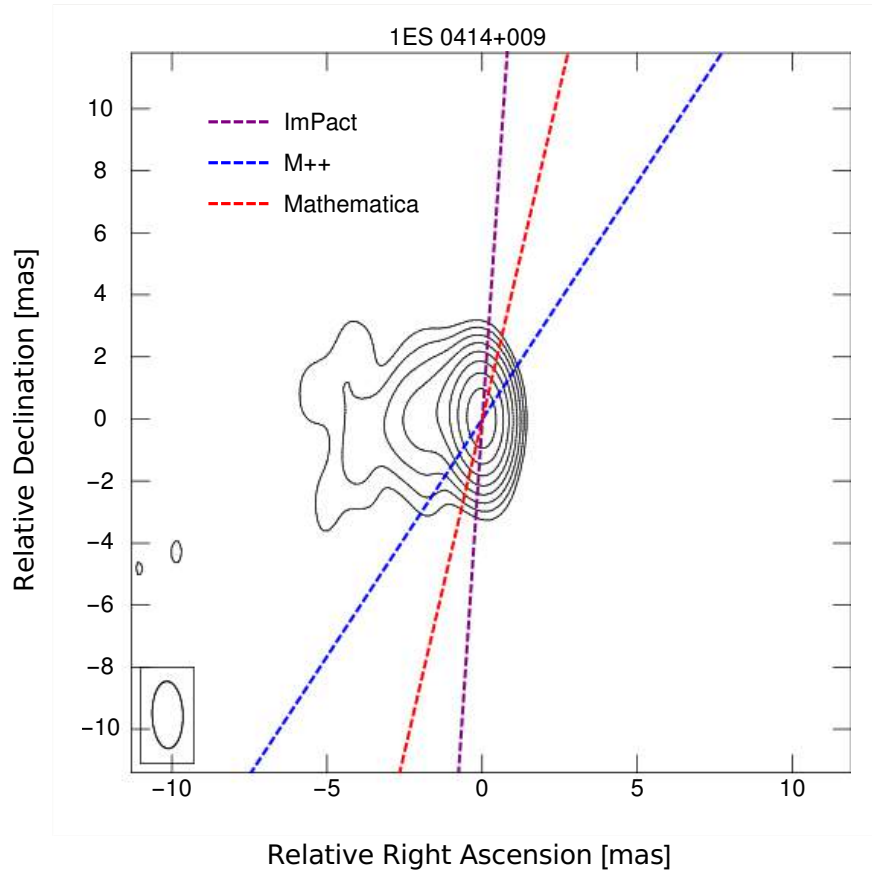


Figure 55: VLBA 8.4 GHz contour map of 1ES 0414+009; the FITS file was taken from the website of *VLBA Observations of TeV Blazars*² (Piner & Edwards, 2018).

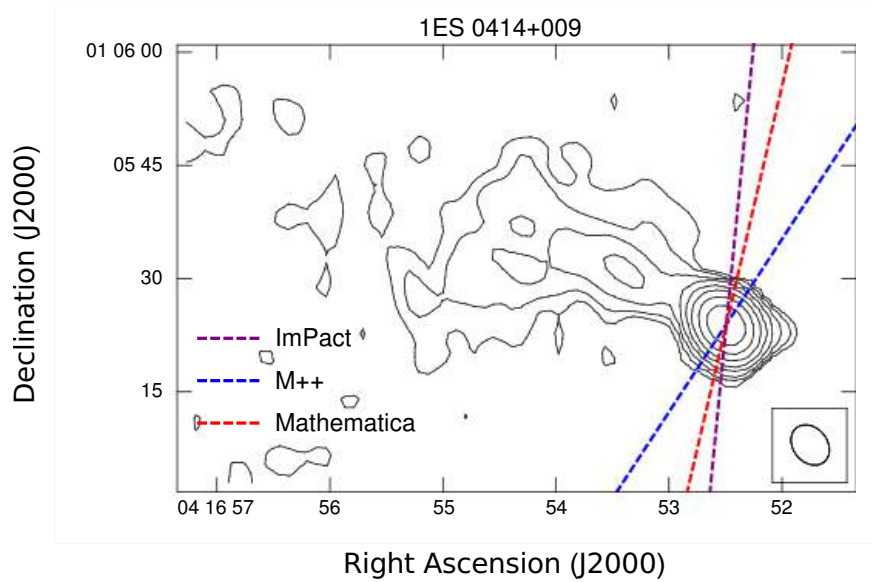


Figure 56: VLA 1.4 GHz contour map of 1ES 0414+009; the FITS file was taken from the website of *National Radio Astronomy Observatory (NRAO)*⁵.

⁵ <http://www.aoc.nrao.edu/~vlba/d/>; date of access: 12/06/2018

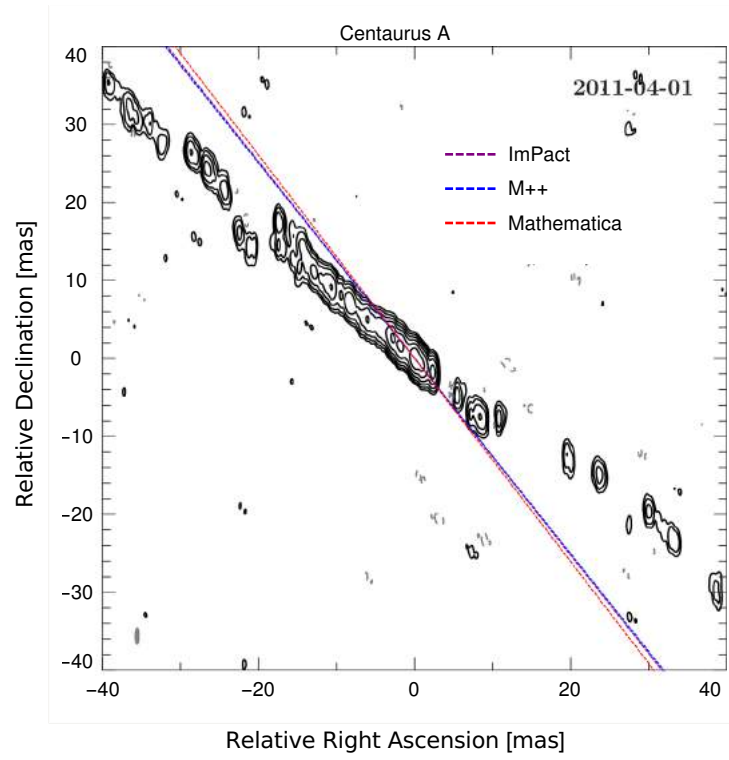


Figure 57: VLBI 8.4 GHz contour map of Centaurus A; credit: TANAMI³ (Müller et al., 2014). The contour map was modified to unify it to the maps of other objects (merely the axis labels were changed from the relative RA [mas]/Relative DEC [mas] to the Relative Right Ascension [mas]/Relative Declination [mas]).

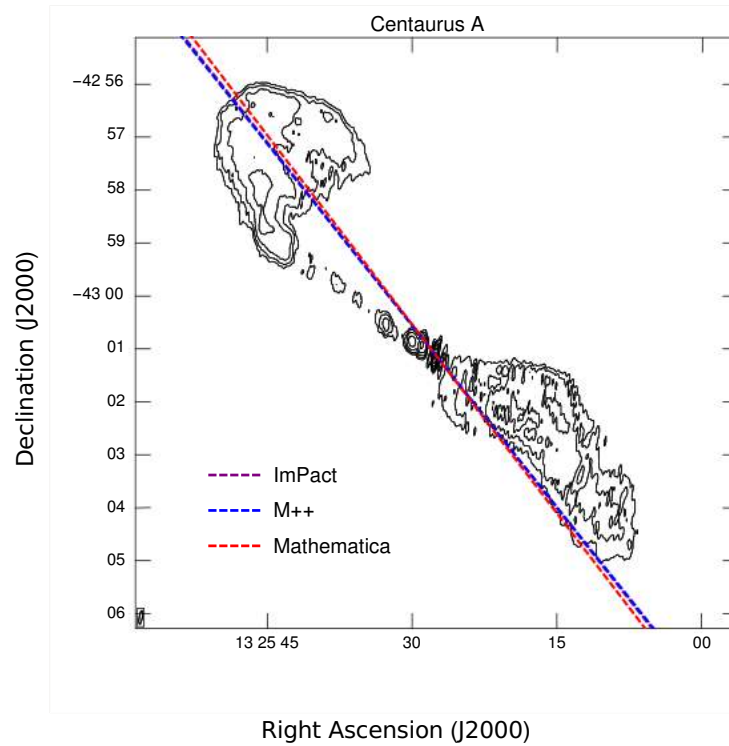


Figure 58: VLA 1.4 GHz contour map of Centaurus A; the FITS file was taken from the website of NRAO⁵.

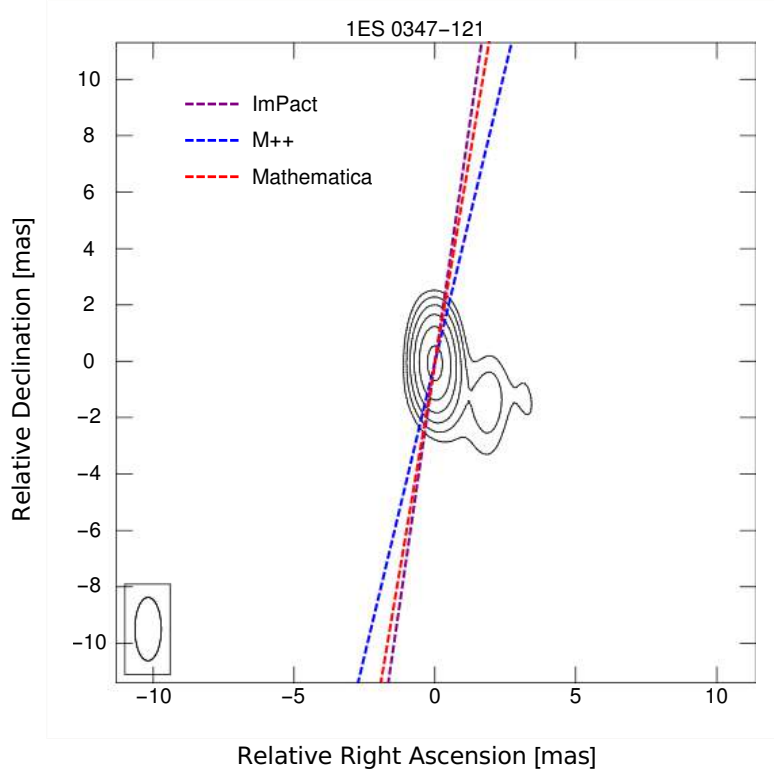


Figure 59: VLBA 8.4 GHz map of 1ES 0347-121; the FITS file was taken from the website of *VLBA Observations of TeV Blazars*² (Piner & Edwards, 2018).

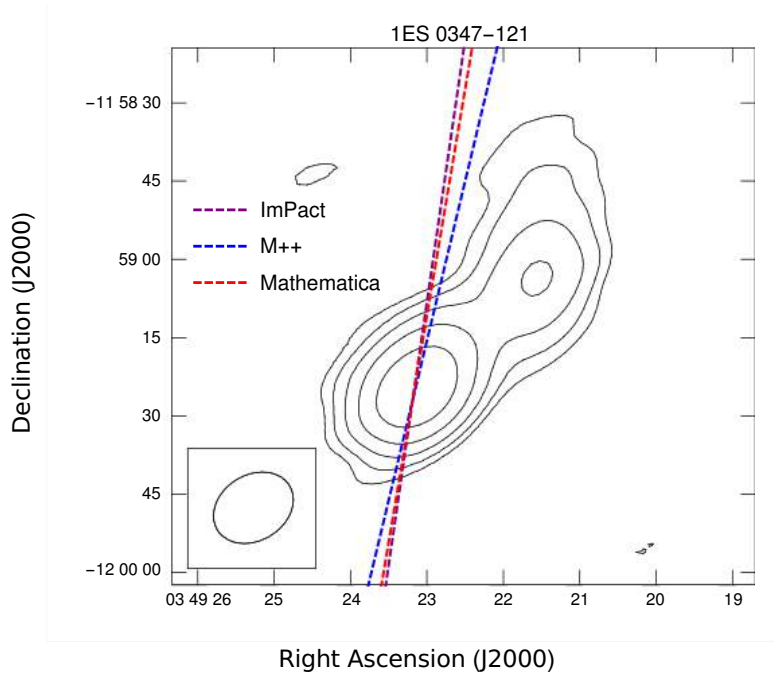


Figure 60: VLA 1.4 GHz map of 1ES 0347-121; the FITS file was taken from the website of NRAO⁵.

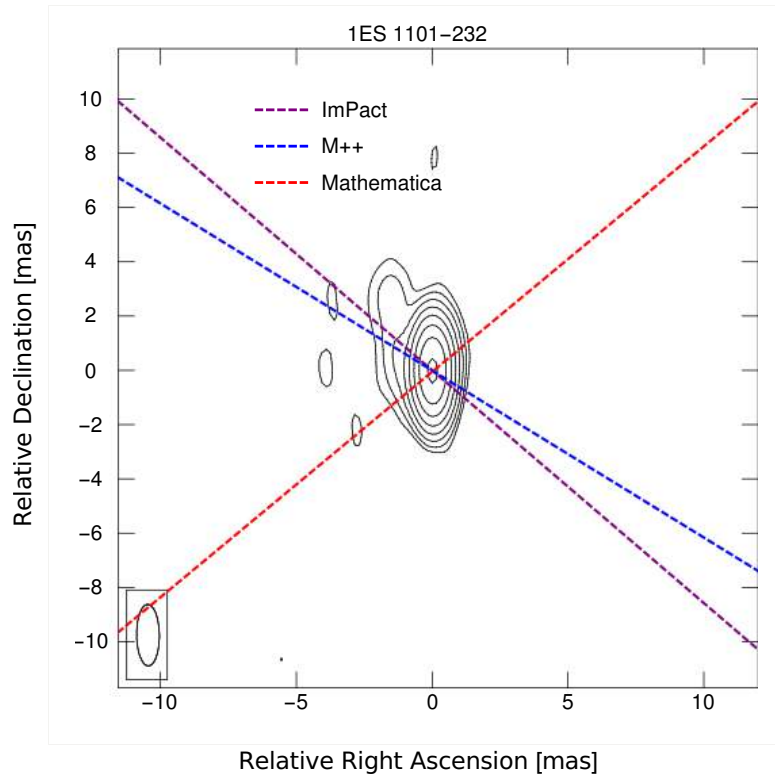


Figure 61: VLBA 8.4 GHz map of 1ES 1101-232; the FITS file was taken from the website of *VLBA Observations of TeV Blazars*² (Tiet et al., 2012).

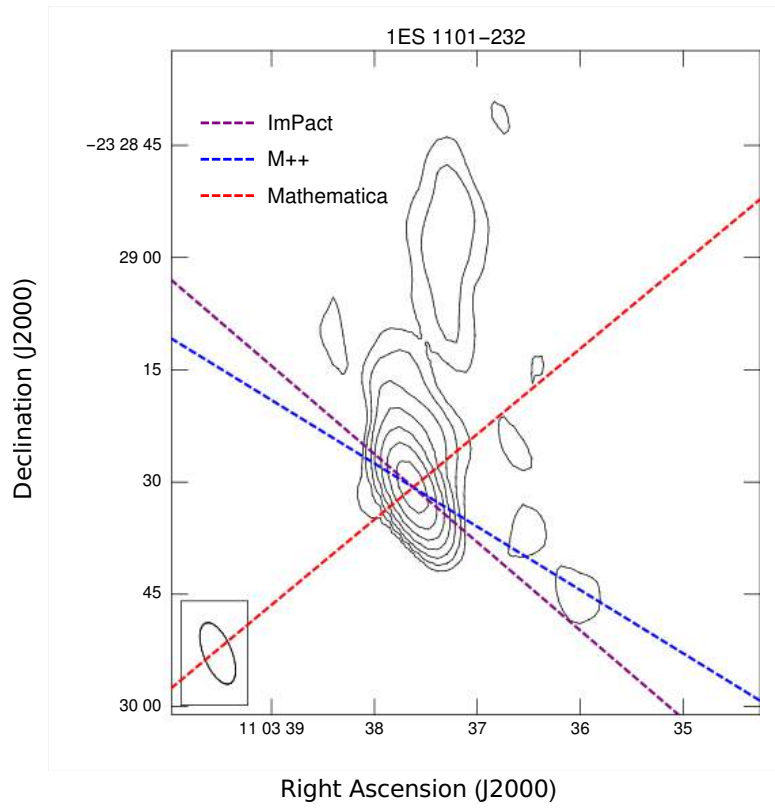


Figure 62: VLA 4.8 GHz map of 1ES 1101-232; the FITS file was taken from the website of NRAO⁵.

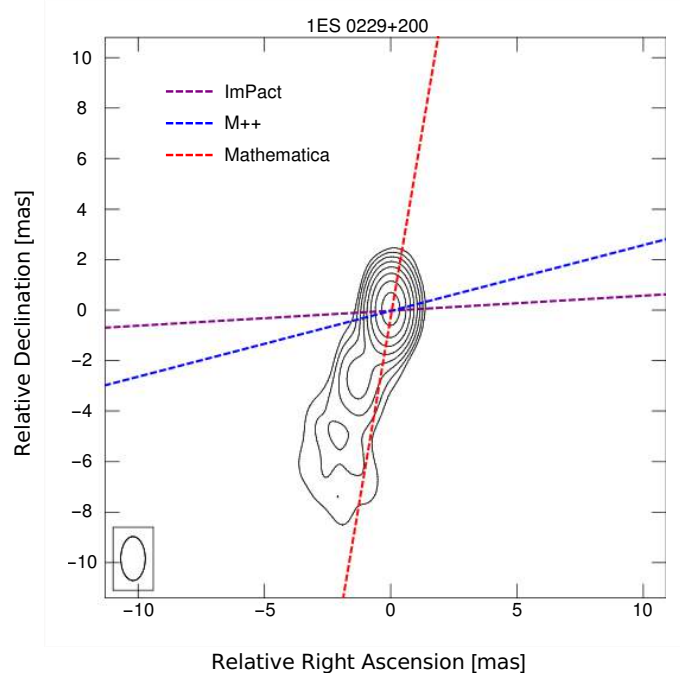


Figure 63: VLBA 8.4 GHz map of 1ES 0229+200; the FITS file was taken from the website of VLBA Observations of TeV Blazars² (Piner & Edwards, 2018).

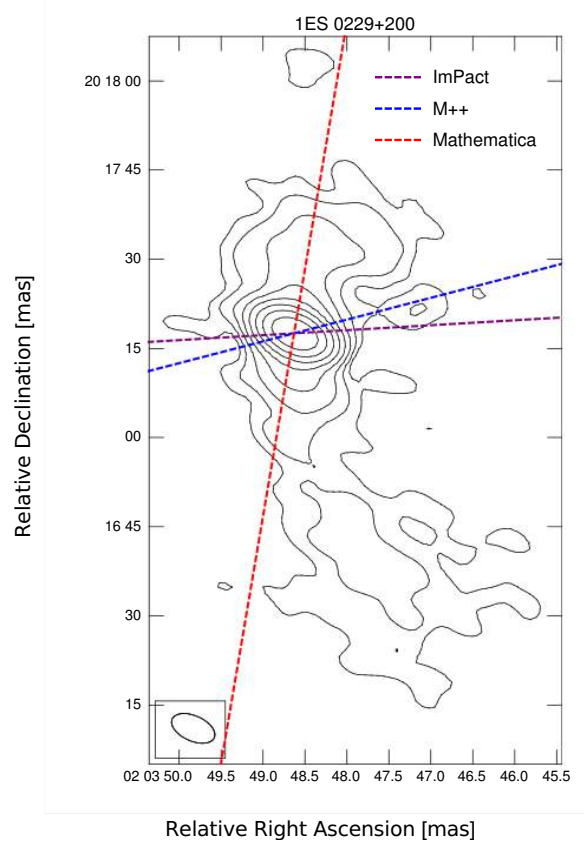


Figure 64: VLA 1.4 GHz map of 1ES 0229+200; the FITS file was taken from the website of NRAO⁵.

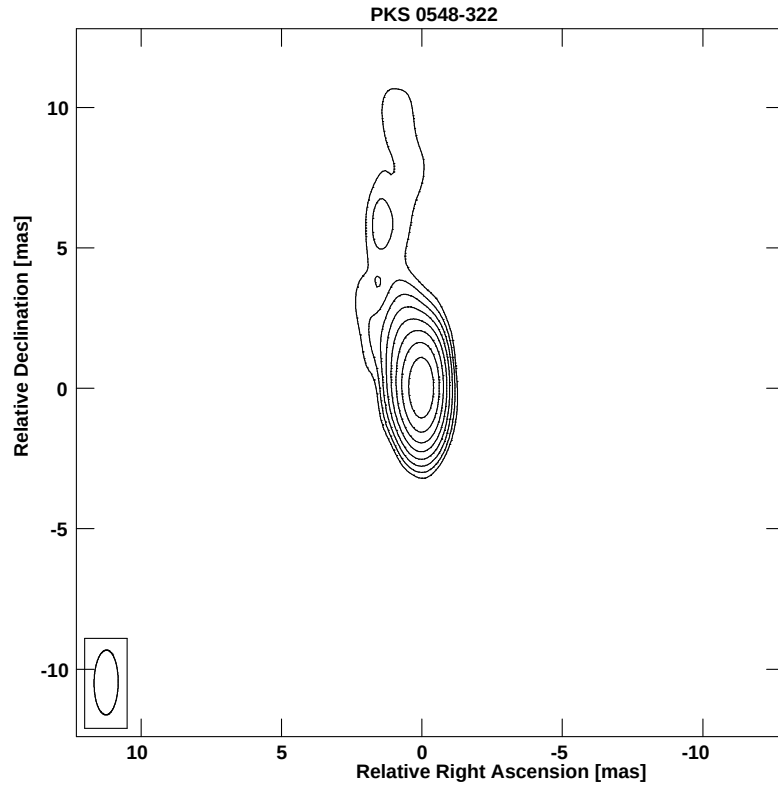


Figure 65: VLBA 8.4 GHz map of PKS 0548-322; the FITS file was taken from the website of *VLBA Observations of TeV Blazars*² (Piner & Edwards, 2018).

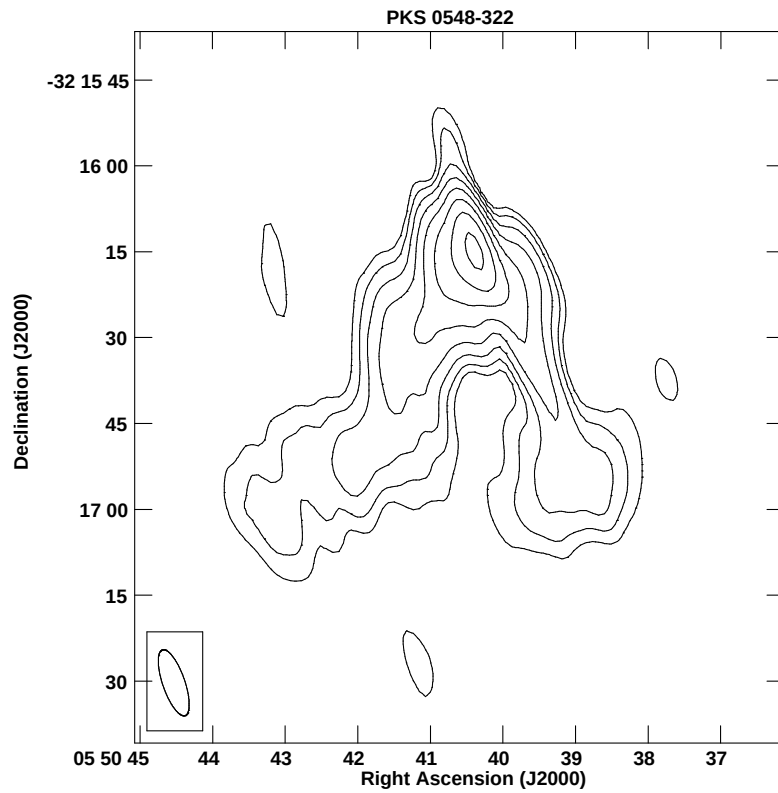


Figure 66: VLA 1.4 GHz map of PKS 0548-322; the FITS file was taken from the website of NRAO⁵.

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OŚWIADCZENIE

Uniwersytet Jagielloński
Wydział Fizyki, Astronomii i Informatyki Stosowanej
Obserwatorium Astronomiczne

Ja, niżej podpisana Natalia Żywucka-Hejzner, nr indeksu: 1105711, doktorantka Wydziału Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego, oświadczam, że przedłożona przeze mnie rozprawa doktorska zatytułowana:

“Morphological study of TeV emission from 1ES 0414+009 and Centaurus A with H.E.S.S. data”

jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem Prof. dr hab. Michała Ostrowskiego. Pracę napisałam samodzielnie.

Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami).

Jestem świadoma, że niezgodność niniejszego oświadczenia z prawdą ujawniona w dowolnym czasie, niezależnie od skutków prawnych wynikających z ww. ustawy, może spowodować unieważnienie stopnia nabytego na podstawie tej pracy.

Natalia Żywucka-Hejzner
Kraków, sierpień 2018