Observation of VHE Blazars with the Fermi LAT Telescope.

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To my grandfather Pietro
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Abstract

Blazars are a particular class of Active Galactic Nuclei (AGNs) dominated by a highly variable component of non-thermal radiation produced in relativistic jets close to the line of sight. They exhibit huge apparent luminosities (up to $10^{49}\text{erg s}^{-1}$), irregular and rapid variable emission, strong optical and radio polarization, often superluminal motion and an overall spectrum which can extend from radio to TeV energies.

The Spectral Energy Distribution (SED) of blazars, that is the flux density as a function of energy, is characterized by two emission peaks, the first located at IR/optical frequencies (but in several cases reaching the UV/X-ray band) and the second in the X-ray to $\gamma$-ray energy band. The physical process that is believed to produce the low energy peak is synchrotron emission from relativistic electrons in the jet, while inverse Compton scattering is thought to be at the origin of the higher energy peak.

Inside the blazar class, a particular interest is addressed to the small sub-sample of Very High Energy (VHE) blazars, i.e. those that are detected in the VHE range (GeV-TeV). These objects can be observed by the Large Area Telescope (LAT), the primary instrument on the Fermi Gamma-ray Space Telescope mission (which is designed to study the $\gamma$-ray range, from $\sim 100\text{ MeV}$ to $\sim 300\text{ GeV}$) as well as by Cherenkov detectors, a class of ground-based instruments operating at higher energies. Therefore, to calibrate the Cherenkov telescope, otherwise relying exclusively on MonteCarlo simulations, a viable method could be provided by the study of VHE blazar SEDs. Since blazars are variable sources, we need to identify key parameters to describe and characterize the source state.

This thesis is a work based on nine month LAT data, addressed to observe four VHE sources. In chapter 1, we present the AGN and blazar phenomena concluding with a briefly presentation of the VHE sub-class. In chapter 2, we introduce the LAT instrument and its main characteristics. Chapter 3 deals with the analysis method (i.e. the maximum likelihood and the unfolding method) that we have used to study the blazar SEDs. Analysis results are shown in chapter 4 and finally, in chapter 5, we extract a tentative, joint LAT/Cherenkov SED from a recent multiwavelength campaign.
Introduzione

I blazars sono una particolare classe dei nuclei galattici attivi (AGNs) dominata da una componente di radiazione non-termica, altamente variabile. Quest’ultima è prodotta in jet relativistici il cui asse è orientato (o quasi) con la direzione di osservazione. Le loro principali caratteristiche sono un’elevata luminosità apparenente (può arrivare fino a $10^{49}$ erg s$^{-1}$), un’emissione variabile e rapida, una forte correlazione ottica e radio, presenza di moti superluminali e uno spettro che può estendersi da bande di energie radio fino a quelle gamma. L’intensità spettrale (SED) dei blazars, che è la densità del flusso in funzione dell’energia, mostra due particolari picchi di emissione, il primo posizionato alle frequenze IR/ottico (ma in vari casi può raggiungere anche le UV/X frecuenze) e il secondo nelle bande di energia X/γ. Il processo fisico che sembra essere alla base del picco ad energie inferiori è l’emissione di sincrotone provocata da elettroni relativistici in jet, mentre il secondo picco sembra essere originato dal processo Compton inverso.

All’interno della classe dei blazar, particolare interesse è rivolto al piccolo sottogruppo dei blazars VHE (Very High Energy), gli AGN il cui spettro si estende fino a bande d’energia dell’ordine dei TeV. Questi possono essere osservati sia dal Large Area Telescope (LAT), lo strumento primario del Fermi Gamma-ray Space Telescope (il quale opera nel range di energie da $\sim 100$ MeV a $\sim 300$ GeV) e dai telescopi Čerenkov. Perciò nella calibrazione dei telescopi Čerenkov un utile mezzo può essere proprio lo studio della SED dei VHE blazar. Dato che i blazar sono sorgenti variabili, è necessario uno studio preliminare che permetta di identificare alcuni parametri chiave che descrivano e caratterizzino la SED.

Il lavoro di questa tesi si basa su nove mesi di dati ed ha come scopo la produzione delle SED di quattro VHE blazar. Nel primo capitolo vengono introdotti gli AGN e i blazar; nel secondo è presentato il LAT e le sue principali caratteristiche. Il capitolo terzo invece riguarda i metodi di analisi che verranno usati nel quarto capitolo. Questi sono il metodo della massima verosimiglianza e il metodo dell’unfolding. Infine, nel capitolo quinto verranno presentati alcuni risultati preliminari sulle osservazioni congiunte LAT/Čerenkov.
Chapter 1

Active Galactic Nuclei (AGNs)

Entia non sunt multiplicanda praeter necessitatem. 
Pluralitas non est ponenda sine necessitate. 
Frustra fit per plura quod fieri potest per pauciora.

William of Ockham

The Universe we know is full of galaxies. At first Scientists classified them on a morphological basis, dividing them into spiral, elliptical and irregular galaxies. Later on, astronomers elaborated new, more complex criteria of classification but the lack of an accepted and clear definition led to multiple classifications of the same object.

In addition, the classification would also take into account that galaxies are not simple collections of stars evolving quietly, save the occurrence of rare supernova explosions, but should be able to describe also other particular class of galaxies, such as the one discovered by Carl Seyfert or the quasars (QSO). In 1943, in fact, Seyfert changed abruptly the picture we had of galaxies by compiling a catalogue of galaxies that now carry his name. Seyfert galaxies have peculiar emission lines: since the beginning of the 20th century it had been known that some galaxies showed emission lines in their nuclei, but the emission lines of Seyfert-galaxies are broadened by the Doppler effect, indicating the existence of gas clouds with high relative velocities (∼8000 km/s).

Such high velocities could not be explained by a simple rotation of material around the galactic center and later on they were attributed to the presence of a massive central black hole.

Moreover, in the 1950s, the advances in radio astronomy allowed to detect a whole new universe of violent phenomena and inevitably led to the discovery of quasars (contraction of QUAsi-StellAr Radio source). These were first revealed as radio sources with no corresponding visible counterpart and were subsequently associated with point-like objects of very small angular size, comparable in size with stars, rather than extended sources more similar to galaxies. Nevertheless their large luminosity and high redshifts were too high to be explained by a whole galaxy of stars.

Our current model is that Seyfert galaxies and QSOs are only subclasses of what we call Active Galactic Nuclei (AGNs). All AGNs are most probably powered by the same engine and their different appearance could be caused mainly by the different
viewing angles that the observer has. AGNs may be distinguished by the following characteristics:

- A bright nucleus that overcomes the luminosity of the whole host galaxy, given by the sum of its stars emission.
- Presence of broad or narrow emission lines in the optical spectra produced by non-stellar processes.
- Strong variability of the electromagnetic emission, on time scales from minutes to years.
- Jets propagating from the central core possibly showing superluminal motions.
- Continuum non-thermal emission in several wavelengths, from radio to $\gamma$-ray band.

The term AGN wants to highlight the energetic phenomena occurring in the nuclei or in the central regions which cannot be imputed simply to stars activity. The physical explanation which underlies these extreme sources may be traced back to Zel’Dovich and Novikov (1964) and will be presented in the next section.

1.1 The Central Engine

One of the first puzzles to be solved is to describe the engine that must be capable of producing such an amount of energy in a relatively small volume. To estimate AGN sizes there exist different approaches. First, for nearby AGNs, we can set an upper limit to the size of the order of 1 pc by means of the optical studies. A tighter constraint can be derived from observations of their variability, as special relativity imposes that a system cannot undergo substantial changes in structure on a length scale $l$ in a time shorter than $l/c$. Since AGNs show variations on timescales of few months, weeks, days, or hours, the energy must originate from a very small region. For example the variation timescale observed in BL Lac is 11 minutes, this implies a length-scale of $2 \times 10^{13}$ cm, much less than 1 pc. On the other hand the involved luminosity (taking redshift into account) is bigger than the one of the brightest galaxies. It is not possible to explain such properties by nuclear fusion processes, which powers stars, and so this lead to think at a more efficient mechanism to produce energy: accretion in compact objects. Such large power can be produced continuously only by conversion into electromagnetic energy of gravitational energy in a deep gravitational well (stellar explosions, supernovae and gamma-ray bursts can produce similar powers but only for a limited amount of time). Matter falling toward a massive object releases energy according to

$$L_{\text{acc}} = \eta \dot{M} c^2$$  \hspace{1cm} (1.1)

where $L_{\text{acc}}$ is the source luminosity, $\eta$ is the efficiency of the process, $\dot{M}$ the accretion rate (the amount of matter falling toward the object) and $c$ the speed of light. By
mean of this process, the rest mass energy is converted into electromagnetic energy with an efficiency that can reach up to 10\% (by comparison, nuclear fusion reaches only $\sim 0.7\%$).

Figure 1.1: An outline of the Unified Model for a radio-loud AGN (not to scale) adapted from Urry and Padovani (1995). The black hole with a mass $\geq 10^6 M_\odot$ is located in the center and it has a radius in the range of $10^{-7}$ to $10^{-3}$ pc ($\sim 1$ AU). Surrounding it, the accretion disk which produces radiation through the conversion of potential into thermal energy. Above the disk are orbiting clouds of gas. The clouds nearer the black hole (at a distance of $\sim 3 - 100 \times 10^{-5}$ pc) represented by dark spots, are referred as the BLR, while the farer clouds (located at $\sim 1$ up to few $10^3$ pc) are the light blobs and correspond to the NLR. Either the clouds and (probably) the accretion disk are responsible of the emission lines often observed in AGNs. Instead the lack of this feature in some AGNs bring us to the believe that a thick dusty structure (torus) surrounds the central regions. The torus or warped disk obscures from transverse line of sight and extends from $\sim 0.1$ pc. In the picture are sketched also the radio jets which origin in the region close to the black hole and which can extend as far as 0.1 to several times 100 kpc.
Nowadays the most commonly accepted model is shown in figure 1.1 and consists of a rotating super massive black hole ($M \simeq 10^6 M_\odot - 10^9 M_\odot$) as the central object which can have a Schwarzschild radius of the order of $10^{-7}$ to $10^{-3}$ pc. The black hole is attracting material: the nearer matter is pulled inward by the gravitational potential and forms an accretion disk according to the conservation of the angular momentum. The accretion disk, probably made of a thermal optically-thick plasma which radiates converting potential energy into thermal, can extend to several hundred of thousand Schwarzschild radii and is difficult to be observed separately from the black hole.

Around this central structure, gas clouds ionized by the accretion disk radiation are responsible for the observed strong emission lines. The region close to the black hole is called Broad Line Region (BLR), clouds located here move fast and are dense ($\sim 10^8 - 10^{12} \text{ cm}^{-3}$) so they generate the characteristic broad lines which have a FWHM $> 1000 - 2000 \text{ km s}^{-1}$ and up to $\sim 10000 \text{ km s}^{-1}$. The most noticeable are the permitted Hydrogen ones from Balmer and Lyman series and transition of magnesium and carbon ions. Up to few kpc, in the Narrow Line Region (NLR), are located other clouds with lower densities ($n \sim 10^3 - 10^6 \text{ cm}^{-3}$) and smaller velocities. With typical FWHM $< 1000 - 2000 \text{ km s}^{-1}$ they give rise to narrow emission lines, both permitted and forbidden, the strongest of which are transitions of ionized Oxygen and Neon.

Surrounding this engine there is a torus (or warped disk) made up by dust molecules, that can obscure the central zone. Its presence has been revealed by the study of emission lines: as we can usually observe only narrow and not broad emission lines, it could be that a thick material prevents the observation of the inner regions.

Since all the space around the black hole is deformed by its gravitational potential and spin, the release of energy is highly anisotropic, prevalently collimated along the axis direction. In some cases (radio-loud objects) a strong jet of relativistic plasma (most likely electrons and positrons or electrons and protons) propagates perpendicularly to the plane of the accretion disk. The magnetic field collimates and accelerates the particles from the region close to the black hole until $\sim 100 \text{ kpc}$, forming the so-called radio lobes. The name derives from the fact that in the lobes the energy is released prevalently at radio frequencies. Often, when looking into the jet, there are regions appearing to move away from the center faster than the speed of light (superluminal motion, see appendix A). This can be easily explained by a perspective effect due to the transformation properties of angles in special relativity.

AGNs can be detected over the entire observable electromagnetic spectrum, every band showing contribution of different components. The contribution of the jet is present in all wavebands, though it dominates at radio and $\gamma$-ray frequencies via synchrotron and inverse-Compton process. The expected spectrum of the accretion disk extends from optical to soft X-ray frequencies and peaks in the optical-ultraviolet band. Its radiation excites cloud material giving rise to emission lines while, when absorbed by the dusty torus, it is re-radiated predominantly in the infrared. The hard X-ray continuum is probably due to a corona of hot electrons which, surrounding the black hole, can scatter photons via the inverse-Compton process up to keV energies.
### 1.2 AGN Classification

It is now widely accepted that a vast number of apparently different objects can be explained by the same basic model, their differences due to the different observational perspective. However, the general paradigm of AGN took time before being understood in depth, so it gave rise to a large taxonomy whether one looked to spectral, polarization or variability characteristics. Historically, using empirical observations, it has been possible to group AGNs into classes due to their optical-UV or radio properties.

As a first dividing criterion (see table 1.1), we can divide AGNs according to whether the FWHM of the optical-UV emission lines are greater or not than 2000 km s$^{-1}$. **Type 1** sources show for example bright continua and large Doppler-broadened emission lines. They include low-luminosity Seyfert 1 galaxies and the higher luminosity radio-quiet quasars (QSO) (which rarely show their host galaxy). **Type 2** sources are AGNs with narrow lines or weak continua, including Seyfert 2 galaxies at low luminosities and Faranoff-Riley galaxies, which will be discussed later.

The differences have been well explained by their different orientation effect. Postulating the presence of absorbing material (the torus) that prevents the direct observation of the bright nucleus, we can account for TYPE 0, 1, 2 by assuming that different classes of AGNs are observed at different angles. When looking straight on the plane of the torus we have a Type 2, as only the radiation of the outer region (the NLR) is visible; when the line of sight does not intercept the torus that is the time of Type 1 object: in fact it is possible to observe the regions near the center, located deep in the gravitational well of the black hole, revealing the bright emission of the disk and the

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**Table 1.1: AGNs Unified Model.** Focusing on UV/optical properties (emission line widths) and on radio properties (quiet/loud) it is possible to classify AGN population as illustrated below. The observation angle and the black hole spin are probably the causes of this partition (see text for further details).

<table>
<thead>
<tr>
<th>AGN</th>
<th>Type 2 (Narrow Line)</th>
<th>Type 1 (Broad Line)</th>
<th>Type 0 (unusual spectra)</th>
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<tr>
<td>Black Hole</td>
<td>Seyfert 2</td>
<td>Seyfert 1</td>
<td>BL Lacs (FSRQ)</td>
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<td>Spin?</td>
<td></td>
<td>QSO</td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td>NLRG { FR I, FR II }</td>
<td>BLRG { SSRQ, FSRQ }</td>
<td></td>
</tr>
<tr>
<td>quiet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ Radio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>loud</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>decreasing angle to the line of sight $\Rightarrow$</td>
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BLR. AGNs with unusual spectral properties constitute a special class, Type 0 AGN. Their jets are orientated very close to the observer’s line of sight. Type 0 AGNs lack strong emission or absorption lines (with width $W_{\lambda} < 5\,\text{Å}$), have a strong non-thermal continuum and also variable spectra, such as BL Lacertae objects (BL Lacs).

Another criterion, referring to the radio (5 GHz) - optical (B band) flux ratio $R = F_5/F_B$, divides AGNs into Radio-Loud and Radio-Quiet, depending on whether they have $R$ larger or smaller than 10, respectively. For Radio-Loud objects the luminosity is dominated by the contribution from the powerful relativistic jet(s) and the related lobes (at least at radio frequencies). Nevertheless, also Radio-Quiet objects seem to exhibit outflows with high, but sub-relativistic velocities ($\sim 0.1c$), as revealed in BAL (Broad Absorption Line) quasar (Turnshek, 1984).

As the optical and ultraviolet emission-spectra and the infrared to soft X-ray continuum of radio-loud and radio-quiet are very similar (e.g. Francis et al. (1993)), it has been suggested that they may be produced in the same way. However, it is still not clear if their different behavior is due to an intrinsic dichotomy within the AGN population (Xu et al., 1999), or if it is only the result of some type of observational bias. The second case seems to be supported by recent surveys which discovered a large population of faint intermediate sources (Helfand et al., 1999).

### 1.3 Radio Loud AGNs

Radio Loud AGN sources include radio galaxies, quasars and BL Lacs and make up roughly 10% of the actual AGN population (Ivezić et al., 2002). In the literature they have often been subdivided into two or three subclasses, depending on their physical properties and the complexity and non-spherical symmetry of their innermost region.

The original classification of radio galaxies is based on their radio morphology: FR Is show the peak in the edges of the source, and these objects usually display large, diffuse lobes; FR IIs show the peak of the brightness close to the edges of the radio source where the compact, well-defined lobes show clear hotspots and/or bright edges. Faranoff and Riley (1974) have divided them using a correlation between their luminosity properties and their morphology. Setting a “luminosity break” at $L_{178\text{MHz}} \sim 2 \times 10^{25}\,\text{W Hz}^{-1}$, the luminosity of FR Is and FR IIs lies below and above it, respectively. FR I galaxies typically have a lower radio power than FR IIs, however, the transition between the classes is rather smooth and both types of radio morphologies are present in the population of sources around the break. The FR I/FR II break at low redshifts also depends on the luminosity of the host galaxy, as shown by Owen and Ledlow (1994). Optical studies of low-redshift FR nuclei have shown that they are hosted by different populations of galaxies. FR Is are invariably associated with the most massive galaxies (usually cD galaxies, e.g Zirbel (1996), Donzelli et al. (2007)) and are usually located at the center of rich clusters. The morphology of the typical FR I galaxy Centaurus A is shown in figure 1.2. On the other hand, FR IIs are mostly associated with a subclass of ellipticals called “Ngalaxies” and generally found in regions of lower density, while only a few FR II are found in denser groups or clusters.
at redshifts $z > 0.5$ (Zirbel, 1997). However, the most striking difference between the two classes comes from their optical spectrum: while most (if not all) FR Is show only weak (narrow) emission lines, FR IIs can be distinguished in Narrow Line Radio Galaxies (NLRG) and in Broad Line Radio Galaxies (BLRG).

Figure 1.2: A radio (VLA 6cm) and optical image of Centaurus A, the Faranoff-Riley Class I radio galaxy at a distance of only 3.4 Mpc. It is observed to emit over a great extent and is still one of the largest radio galaxies known.

We can also classify Radio Loud AGN setting a division according to the value of the radio spectral index, $\alpha_r (F_\nu \propto \nu^{-\alpha_r})$ between 2.7 and 5 GHz. We call Steep Spectrum Radio Quasars (SSRQ) and Flat Spectrum Radio Quasars (FSRQ) quasars whether $\alpha_r = \alpha$ is greater or lower than 0.5, respectively. Their names reflect the radio continuum spectral shape.

The radio morphology of SSRQs is similar to the one of radio galaxies, though smaller. SSRQs have weaker radio cores and an extended radio emission component, which radiates isotropically and usually shows a double-lobed structure centered on the compact component. FSRQs usually show more rapid variability than SSRQ, high polarization and a radio structure dominated by the compact radio core. The core emission originates in a jet-like structure and is thus highly beamed.

There is another typology of sources which distinguishes itself amongst all others by its odd characteristics. The class bears the name of its prototype, BL Lacertae. BL Lacs are differentiated by the absence of strong (equivalent width $< 5$ Å) emission or absorption lines in their spectra, this feature causing difficulties in the determination of the redshift. They constitute a small subset of the radio-loud class with orientation angles between the radio jet axis and observer’s direction close to zero. A previous distinction was made whether the BL Lac objects were discovered in radio or X-rays observations (RBL/XBL). At the present time both terms “RBL” and “XBL” refer
to the selection band rather than to the intrinsic physical properties and they are reserved for sample membership. They are members of the same object class, the main difference being where the synchrotron emission of their Spectral Energy Distribution (SED) peaks.

Though BL Lacs and FSRQs show very different optical spectra, in other wavebands the spectral features are not at all different from each other. Actually compact radio cores, flat radio spectra, high brightness temperatures, superluminal motion, high polarization, strong and rapid variability are commonly found in both BL Lacs and FSRQs. This is the reason why these sources have been grouped together in the so called “blazar” class. The term blazar is made up combining the words BL (Lac) with (qu)asar and was for the first time introduced by E. Spiegel in 1978, while its use in literature was probably initiated by Angel and Stockman (1980) in the review of optical polarization in extragalactic objects. The current classification was first introduced by Padovani and Giommi (1995) who used the peak energy of the synchrotron emission, or the maximum energy the particles can reach in the jet, to separate BL Lacs into low energy (LBL) and high energy synchrotron peak (HBL) objects. Afterward, a larger number of blazars has been detected and an intermediate class has been recognized as intermediate energy synchrotron peak (IBL) objects.

### 1.4 Unification between Radio Galaxies and Blazars

Radio Galaxies are strong radio sources typically characterized by the largest linear structure at radio frequencies ever found and a well defined spectrum with emission lines. Usually FSRQs have similar range of radio emission and present strong narrow and broad emission lines while, on the contrary, BL Lacs lack or have very weak emission. On the basis of these similarities and differences, a crucial development in understanding AGNs comes with the recognition that at least some types are very similar to others, with differences appearing for those where our view of the innermost region is blocked by a dust- and gas-rich obscuring torus or biased by the presence of jets.

The current unification pattern postulates a connection between BL Lacs, radio loud quasars and radio galaxies (Urry and Padovani, 1995). Many differences could be ascribed to the different orientation of various components of the sources, first of all the jets. This same model has been used to unify radio loud quasars with FR II radio galaxies. Quasars whose radio axes are close to the plane of the sky (thus perpendicular to the line of sight) are not seen as quasars, but as radio galaxies (the “parent population”), so that the jet and the counterjet should be equally spaced and detectable. Similarly, BL Lacs are instead associated with lower-power FR I radio sources (Urry et al., 1991). The first seem to be the face-on version (i.e. the radio source axis is parallel to the line of sight) of the latter: in BL Lacs the jet is pointing very close to the observer so that the radiation produced inside the jet is amplified by relativistic effects. This relativistic beaming causes the non-thermal continuum to be very bright, and the emission lines (emitted isotropically) are weak in comparison. The same object, observed from the side, presents emission lines with usual equivalent
widths, and the radio structure is dominated by the extended lobes rather than the core.

According to this unification scheme, the anisotropy of the jet emission (caused by relativistic beaming) is the basic reason to produce the observed differences. As a direct consequence, we expect that all the isotropic properties of the sources, such as extended radio emission, luminosity of narrow emission lines, host galaxy typology and environment must be similar to those of their parent population.

Regarding host galaxy typology, all radio-loud AGNs are commonly found to be hosted in luminous giant ellipticals (e.g., McLure et al. (1999), Urry et al. (2000)) which supports the unification of blazars and radio galaxies but does not give significant evidence to relate quasars to FR IIIs and BL Lacs to FR Is. Numerous radio-loud environment studies have been made, but none have provided indisputable conclusions. Quasar and FR IIIs are generally detected in clusters of similar richness\(^1\) (e.g., Wold et al. (2000)). On the other hand, BL Lacs seem to be in environment more similar to that of quasars and FR IIIs rather than to FR Is (Wurtz et al., 1997), even if it is yet not understood if FR IIIs environments differ at all from those of FR Is. On the basis of studies made by Prestage and Peacock (1988) on a \(\sim 200\) radio sources sample at \(z < 0.25\), FR I radio galaxies were found in richer clusters than FR II radio galaxies, while when considering higher redshifts radio sources at \(z \simeq 0.5\), FR Is and FR IIIs were found to reside in similar environments (Hill and Lilly, 1991). Subsequent studies, although for a smaller sample of sources, found no significant difference in the richness of the cluster environment also for a low redshifts \(z \simeq 0.2\) sample (McLure and Dunlop, 2001). Even if conflicting results were found, a common feature of all researches remains the wide range spanned by radio-loud AGN cluster properties.

Other physical properties that can be taken into account to test the unified scheme are radio emission and narrow line luminosity. It has been long known that most compact radio cores have extended radio emission (Ulvestad et al., 1981). Since their radio sources radiate fairly isotropically, the presence or absence of this cannot be attributed to orientation. The radio luminosities of quasars and FR IIIs are found comparable (e.g., Murphy et al. (1993); Fernini et al. (1997)) and this reinforces the unification idea. For BL Lacs the situation seems to be a bit more complicated since in some cases they appear to show radio morphologies more similar to with FR IIIs than with FR Is (Kollgaard et al., 1992). Actually, a substantial fraction of BL Lac objects, especially those with redshifts \(> 0.5\), are found to have extended radio emission and luminosities equivalent to that of high-luminosity FR II radio galaxies (Murphy et al., 1993). However, this does not compromise the unification idea but simply underlines the blurriness of the distinction between FR Is and FR IIIs.

Narrow-line luminosity is intrinsically correlated to radio emission (Baum and Heckman (1989); Rawlings and Saunders (1991); Zirbel and Baum (1995)). Narrow emission lines are relatively weak or absent in BL Lacs (as by definition) and often present in FR Is. On the other hand quasars exhibit strong narrow emission lines while FR IIIs can have both weak and strong narrow emission lines (Laing et al., 1994). Although quasars have systematically higher \(\text{O III}\) (that is, the oxygen emission line at

\(^1\)The richness is the measure of the galaxy content of a cluster made with optical observation
\( \lambda = 5007\text{Å} \) luminosities than radio galaxies (Jackson and Browne, 1990) this appears to be due to the anisotropies in the emission of this specific line (Laing et al., 1994). Considering instead the \( \text{O} \, \text{ii} \) line luminosities (that is, the forbidden oxygen emission line at \( \lambda = 3727\text{Å} \)), which emission is argued to be isotropic, the results are consistent with the unification hypothesis (Hes et al., 1993).

Finally a more subtle test to verify the unification pattern is whether the statistical properties of the parent population are consistent with those of the beamed population, once the beaming process is taken into account. For example the total number of beamed objects must be small compared to the number of the (misaligned) parent population, as a consequence of the small viewing angle. Urry and Padovani (1995) found an additional proof studying the luminosity function: applying the beaming effect to the luminosity function of the parent population, they tested if they could find a luminosity function consistent to that of the expected beamed population. This study is quite difficult, as it needs a well-defined, complete sample of both the parent and the beamed population objects. Nevertheless, it is still considered one of the most important evidences in the framework of the AGN unification.

Urry and Padovani were also able to derive the beaming properties of the blazar populations. In particular, the resulting Lorentz factor lays in the range \( 5 < \Gamma < 40 \), both for FR Is and FR IIs, which is consistent with the values measured using the superluminal motion (Vermeulen and Cohen, 1994). The same model applied to the observed radio luminosity functions of sources from the 2 Jy sample gives results well in agreement with the predictions for Quasars (SSRQ and FSRQ) and FR II radio galaxies. A similar study on BL Lac samples is more difficult, as this class suffers from small statistics and problems in the determination of the redshift, nonetheless, results show a good agreement with the beaming model also for BL Lacs and FR Is (Urry et al. (1991); Urry et al. (2000)).

### 1.5 Blazars

BL Lacertae, the prototype for the BL Lac class, is a variable radio source first discovered by Hoffmeister in 1929. It was originally thought to be an irregular variable star in our own galaxy even though it displays a rather unusual optical spectrum. The spectrum is featureless and shows continuum emission increasing steeply to the infrared wavelength. It was only after the discovery of sources with similar characteristics, i.e. OVV quasars, that it had been possible to recognize and explain this particular spectrum as the signature of Doppler-boosted jet emission.

For a long time after its identification, BL Lacertae was thought to lack of broad emission lines. Recently, broad optical emission lines have been detected when the source was in a low-activity state, indicating the existence of the correspondent broad emission line region (Vermeulen et al., 1995). The detection of broad emission lines in BL Lac objects is of fundamental importance since it reveals the similarity in nuclear structure between quasars and BL Lacs. Historically Blazars, like other types of AGN, have been classified according to heterogeneous criteria, often related to observational characteristics and to the energy band where they were first discovered.
1.5 Blazars

Figure 1.3: When the blazar flares a noteworthy feature of the two components is that both peak frequencies shift toward higher energies. As we can see in the case of Markarian 421, the states in which a blazar can be found, faint or flaring, can be very different. On the top of the figure we can have an overview of the source observations in the several energy bands enable by different instruments.

According to the special properties of the objects and their SEDs, blazars are divided into the following three subclasses (Padovani et al., 2001):

- Flat spectrum radio quasars (FSRQs), with the peak frequency of the synchrotron component detected in the IR/optical region and the high-energy $\gamma$-ray component dominating the luminosity;

- High-energy peaked BL Lac objects (HBLs, above all X-ray selected BL Lac objects), with the peak of the synchrotron component generally located in the UV/soft-X-ray region and the high and low energy components showing similar luminosities;

- Low-energy peaked BL Lac objects (LBLs, above all radio selected BL Lac objects) with luminosities and synchrotron peak frequencies intermediate between the above sub classes.

A noteworthy feature of the two components is that both peak frequencies shift toward higher energies (frequencies) when the source flares (see figure 1.3).

Nowadays a more deep comprehension of blazar physics has led to recognize a common origin for most of the peculiar aspects of these sources, so that clearer distinctions can be made simply on the basis of the insight acquired. Thus the term blazar refers
to objects which are clearly beaming toward us and show the dominating signature of beamed emission. Blazars have the following characteristics:

- **compact core-dominated radio emission and flat radio spectral index.** Radio emission has been a key factor in the discovery of AGNs and is a typical characteristic for blazars, since no radio-quiet counterparts have been found until now, although they have been searched for (Stocke et al., 1990).

- **wide broad-band non-thermal spectrum** extending from radio to $\gamma$-rays wavelengths. Probably this component is relativistically beamed synchrotron radiation, originating from inside the jet.

- **strong variability** in time as well as in spectrum amplitudes is seen in all wavebands, especially in the Optical-UV and in X-rays at high energies (MeV and GeV).

- **superluminal motion:** Flat radio spectra and rapid flux variability suggest the presence of structure on small scales, especially in very bright radio cores. Very Long Baseline Interferometry observations, with resolution in the sub-mass range, find that some blazars display multiple components which are getting far apart with transverse velocities apparently in excess of $c$. These apparent superluminal velocities can be ascribed to bulk relativistic motion along the line of sight.

- **one sided radio jets** which are the extension of the radio core emission. The counterjet is thought to be present, but its emission is highly dumped by the relativistic effects.

- **high radio brightness temperatures** often greater than $10^{12}$ K and in some cases even greater than $10^{19}$ K (Quirrenbach et al., 1991).

Variable linear polarization ($> 1 - 2\%$) is another property often found in these objects. It is not really considered among the defining signatures of this class as sometimes sources which behave like blazars (i.e. have all the previous highlighted characteristics) are not polarized. Polarization, when present, can be variable in time (with timescale of about one day), as well as in degree and in position angle, and generally it depends largely on wavelength. In the optical band, polarization varies on a wide range of levels, from almost zero ($< 1\%$, compatible with the levels inferred by dust) up to 60%.

Sources which display only one, or some of these properties, during the first observations generally will show also the others attributes in following observations. This strengthens the hypothesis that all these features are basically related and can be ascribed to a common origin.
1.6 Spectral Energy Distribution

All types of blazars share the basic emission process which determines the overall spectrum shape. The radiation, produced via synchrotron and Inverse Compton (IC) processes, is ascribed to one or both of the following two physical processes:

- **thermal emission** attributed to in-falling matter. Matter inside an accretion disk is highly heated by dissipative forces and it is so close to the black hole that can be captured;

- **non-thermal emission** due to the presence of a relativistic jet. Material ejected from the nucleus at relativistic speed is accelerated in a jet, the radiation is emitted by the highly energetic particles of the jet which are constrained in a magnetic field.

The strong and variable emission which arises from this picture is considered a remarkable feature of blazars, spanning a wide range of energy from radio to $\gamma$-rays. In this concern a crucial rule is played by simultaneous multi-wavelength observations which allow a complete and detailed study of the whole spectrum.

Combined observations are plotted on a Spectral Energy Distribution (SED) diagram, usually represented as $\log \nu F_\nu$ vs. $\log \nu$. This graph gives directly the information on the relative frequency band fueled. Ideally, a complete SED should be based on simultaneous data to investigate the emission mechanism through simultaneous observations of the source status. Unfortunately this is often not possible, but in spite of it our knowledge of the SED has been recently substantially improved by the results of new instruments, such as the Energetic Gamma Ray Experiment Telescope (EGRET, which observed the 100 MeV - 10 GeV band), Cherenkov telescopes (which cover the band $\gtrsim$ 100 GeV) and Fermi-LAT telescope (sensitives to energies from 20 MeV to 300 GeV).

Analysis of these observations have shown that the SED of blazars have a two broad-bumps structure where typically the lower frequency component peaks between the radio and soft X-ray bands, while the higher frequency component peaks in the hard X-ray or $\gamma$-ray band. The two bumps are correlated: the lower the energy of the first, the lower the one of the second component, i.e. if the first peak is located in the infrared band the second is in the X-ray band, while when the first is in the soft X-ray band the second is found in the $\gamma$-ray band.

It is unanimously accepted that all blazars show the same basic emission processes, i.e. synchrotron and inverse Compton emission. From the high polarization of the radio to optical emission, the lower component of the SED is attributed to synchrotron process, while the higher is widely assumed to be due to Inverse Compton process probably produced by the same population of electrons involved in the synchrotron emission. Various emission models have been suggested and are still competing. The main differences between them are due to the adopted geometry and/or by the nature of the seed photons which are up-scattered by inverse Compton process (see section 1.9).
Blazars are classified in several types by mean of the peak of the synchrotron component $\nu_\text{peak}^S$ peak in their SED. In low energy peaked blazars, or LBL, the $\nu_\text{peak}^S$ peak is located at frequencies lower then $10^{14}$ Hz (e.g. lower dotted line), in the intermediate energy peaked sources, or IBL, peak is $10^{14}$ Hz $< \nu_\text{peak}^S < 10^{15}$ Hz, while for high energy peaked blazars, or HBL, $\nu_\text{peak}^S > 10^{15}$ Hz.

The position of the energy peaks is a feature of every blazar category (see figure 1.4). The synchrotron peak of FSRQ is located in the mm-optical band while for BL Lacs it is observed from IR (LBL objects) to UV/X-ray energies (HBL objects).

Other parameters that can differentiate the blazar classes are the bolometric luminosity and the ratio of the Compton to synchrotron powers, i.e. the power injected in the form of electrons and the power in the external photon component (the Compton dominance, $L_{\text{IC}}/L_{\text{Syn}}$). FSRQs have high Compton dominance (up to 100) and the highest bolometric luminosities, BL Lacs are found on average with lower Compton dominance and bolometric luminosity.

The displacement in peak frequency of the SEDs from the FSRQ to the HBL subclasses could be due to different beaming factors and to intrinsic physical parameters. The SEDs varies in time and also the ratio of intensities in the synchrotron component and the IC component can vary. Notably, this comes when a flare occurs and the SED is shifted from the low luminosity state to the high. For these reasons it is important to define parameters which can give a straight and simple idea of the SED shape. Such tools are provided by the broad spectral indices $\alpha_{\text{ro}}$, $\alpha_{\text{ox}}$ and $\alpha_{\text{rx}}$, which are the ratio of the the radio vs. the optical index, the optical vs. X and the radio vs. X, respectively. Each index is calculated from an assumed power law dependence for flux given by $F_\nu \propto \nu^{\alpha}$. As the changes in SED shape involve different ratios between fluxes at fixed frequencies (i.e. conventionally at 5 GHz, 5500 Å and 1 keV) the broad spectral indices, which allow for that, enable a first distinction of a blazar class only from its monochromatic fluxes at these frequencies (K-corrected, i.e. taking the redshift...
dependence of the object magnitude at a given wavelength band into account). In the 
$\alpha_{\text{ox}}$-$\alpha_{\text{ro}}$ diagram blazars (and AGNs) fill different positions and every class seems to
“prefer” a region. This has been also an helpful tool to study sample selection effect.

1.7 Emission Pattern

As previously underlined, the observation of the emitted radiation is the most direct
diagnostic method for AGNs study. From it, we could be able to trace the wide variety
of mechanisms involved and to constrain emission models in order to understand the
fundamental engine of these sources. The radiation produced by synchrotron and
inverse Compton can be later on scattered, absorbed and re-emitted. Thereby, the
picture of the spectrum that we observe is found to be more complex and also variable
in time. Several injection/acceleration scenarios have been proposed and even if the low
energy emission is fully explained by a synchrotron process, at the higher frequencies
there are still some doubts about which is the most correct model to be adopted.
Actually, the two most accepted models are:

- Synchrotron-Self Compton model (SSC), where the $\gamma$-ray emission is ascribed to
  IC by locally emitted leptons;

- Inverse Compton of Externally Produced Photons model (EC), where the $\gamma$-ray
  emission is ascribed to IC by leptons distributed in external regions.

In the next subsections we are going to review the physics concepts of the basic pro-
cesses involved in order to subsequently discuss emission models.

1.8 Radiative Processes

1.8.1 Synchrotron Radiation

When a charged particle of energy $\gamma mc^2$ moves in a magnetic field $B$ it is accelerated
and loses energy by emitting photons. The resulting spectrum is broad band (in
contrast to the cyclotron radiation of non-relativistic particle) and peaked around the
frequency

$$\nu \approx \frac{4}{3} \lambda^2 \nu_L$$

where $\nu_L$ is the Larmor frequency ($=eB/(2\pi mc)$). If $\alpha$ is the angle between the velocity $v$
and the magnetic field, the power emitted by the particle is

$$P_s = 2\sigma_T cU_B \gamma^2 \beta^2 \sin \alpha^2$$

with $\sigma_T$ is the Thompson cross section and $U_B$ the magnetic energy density. If the
electron distribution function follows a power law, the number density of relativistic
electrons per unit Lorentz factor is given by $N(\gamma) = N_0 \gamma^{-s}$ and the total emissivity can
be obtained by integration, yielding
\[ j_{\text{syn}}(\nu) = B^{1+\alpha} N_0 \nu^{-\alpha} \]  
(1.4)

where \( \alpha = (n-1)/2 \) is the spectral index. The spectrum emitted by such a distribution will have a power law form too.

### 1.8.2 Synchrotron Self-absorption

In presence of a magnetic field an electron can also absorb a photon and acquire energy. In synchrotron self-absorption process a given population of electron can self-absorb part of the synchrotron emission they produce. Upon the characteristic frequency, \( \nu_t \), at which the optical depth is \( \geq 1 \), one must take self-absorption into account. The spectrum resulting will be proportional to \( \nu^2 \) or to \( \nu^{5/2} \) according to whether the thermal equilibrium was reached or not. In the case of an optically thin region (above \( \nu_t \)) instead the spectrum is given by eq. 1.4.

### 1.8.3 Inverse Compton Emission

Since the energy of a typical photon produced via synchrotron process is on average lower than that of the typical electron, the resulting effect of the scattering is the transfer of energy from electrons to photons, the so-called Inverse Compton process. When an electron of energy \( \gamma m_e c^2 \) hits a photon of frequency \( \nu \), the photon is up-scattered to higher frequency \( \nu_c \)

\[ \nu_c \sim \frac{4}{3} \gamma^2 \nu \]  
(1.5)

all this is valid in the Thomson limit (\( \gamma \nu < m_e c^2 / h \)). If the photon energy becomes comparable with the rest mass of the electron, the recoil of the latter cannot be ignored, so the Klein-Nishina cross section must be used and the radiated power is reduced.

Considering the beaming effect, an electron immersed in an isotropic photon bath will see half of the photons (with \( \theta \geq \pi/2 \)) coming inside a cone of angle \( 1/\gamma \). The electron can scatter photons within an angle of \( \pi/2 \) in its rest-frame, which will be emitted inside an angle of \( 1/\gamma \) from the direction of motion in the observer’s frame. The mean electron cooling rate is obtained, averaging on all angles, as the difference between incident and scattered powers. For an isotropic photon field it is

\[ \dot{E} = \frac{4}{3} \sigma T c U_{\text{rad}} \gamma^2 \beta^2 \]  
(1.6)

with \( U_{\text{rad}} \) indicating the seed radiation energy density.

If a power-law electron energy distribution (\( \propto \gamma^{-n} \)) is given, also the emitted spectrum will have the same power-law form and the same slope as for the Synchrotron process. For a monochromatic photon field of energy \( \varepsilon_0 \) and seed photon density \( U_{\text{rad}}/\varepsilon_0 \) the total emissivity is

\[ j_{\text{IC}}(\varepsilon_c) = \frac{1}{4\pi} \frac{(4/3)^\alpha}{2} \frac{\tau_c}{R/c} \frac{U_{\text{rad}}}{\varepsilon_0} \left( \frac{\varepsilon_c}{\varepsilon_0} \right)^{-\alpha} \]  
(1.7)
where $R/c$ is roughly the photon escape timescale, $\tau_c = \sigma_T N_0 R$ is the total number of scattered photons, $\varepsilon_c/\varepsilon_0$ is the gain per scattering and $\alpha = (n - 1)/2$ the spectral index. For a non-monochromatic photon field the emissivity is obtained integrating the previous equation over the frequency range of seed photons

$$j_{IC}(\varepsilon_c) = \frac{1}{4\pi} \frac{(4/3)^\alpha}{2} \frac{\tau_c}{R/c} \varepsilon_c^{-\alpha} \int_{\varepsilon_1}^{\varepsilon_2} \frac{U_{rad}(\varepsilon)}{\varepsilon} \varepsilon^{-\alpha} d\varepsilon$$

(1.8)

It is worth to observe that $\varepsilon_1$ and $\varepsilon_2$ generally depend on $\varepsilon_c$. Actually for a given photon energy $\varepsilon_c$ not all the target photons $\varepsilon$ can be enhanced to that energy but only those for which there are electrons such that

$$\varepsilon = \frac{3}{4} \varepsilon_c \gamma^2$$

(1.9)

### 1.9 SSC and EC Models

Several emission models are still in competition, they differ principally in the adopted geometry (one-zone homogeneous models or inhomogeneous jet models) and/or by the nature of the target photons which are boosted in energy by inverse Compton process. Two major possibilities have been proposed for the source of the seed photons: they can be the same synchrotron photons emitted locally (Synchrotron Self Compton models, SSC, Maraschi et al. (1992); Bloom and Marscher (1996)); or they can come from the external environment, such as from the broad emission-line clouds or from the accretion disk (External Compton models, ERC, Dermer and Schlickeiser (1993)).

In this section we examine these two emission models (SSC and EC) assuming that the radiation is emitted by a single jet of size $R$ in a tangled magnetic field $B$. We consider only the homogeneous case for both scenarios, the radiation is emitted isotropically in its rest frame. We assume that $\Gamma$ is the Lorentz factor of the blob in the observer frame and $\gamma$ is the single particle Lorentz factor in the jet rest-frame.

#### 1.9.1 SSC Model

The photons emitted by the synchrotron process will inevitable be soft targets for Compton scattering and they will be up-scattered to energies close to that of the radiating electrons. In this scenario, a single population of electrons is responsible of the synchrotron emission and of the inverse Compton scattering. What we expect is that the emissivity has a quadratic dependence on the electron density. In the case of an isotropic electron energy distribution, the energy density of the synchrotron photons in the comoving frame is given through the synchrotron luminosity $L(\varepsilon)$:

$$U(\varepsilon) \simeq \frac{3R}{4c} \frac{L(\varepsilon)}{V} = 4\pi \frac{3R}{4c} j_{syn}(\varepsilon)$$

(1.10)

where $3R/4c$ is the mean travel time for a photon to escape a region of radius $R$. Substituting the respective terms and noting that the spectral index $\alpha$ is the same, we obtain

$$j_{SSC} \propto R N_0^2 B^{1+\alpha} \nu^{-\alpha} \ln \Lambda$$

(1.11)
where $\Lambda = \varepsilon_2/\varepsilon_1$. The emissivity is proportional to the square of the electron density as previously observed. In the jet frame the scattered photons can reach the maximum frequency $\nu_{\text{max}}$

$$\nu_{\text{max}} \simeq \frac{4}{3} \gamma_{\text{max}}^2 \nu_s$$  \hspace{1cm} (1.12)

The cooling rate has the same dependence on the parameters (except for the energy density) either for synchrotron and for inverse Compton process, therefore we can obtain the ratio of the two peak luminosity by

$$\frac{L_C}{L_S} = \frac{\dot{E}_c}{\dot{E}_{\text{syn}}} = \frac{U_{\text{syn}}}{U_B}$$  \hspace{1cm} (1.13)

### 1.9.2 EC Model

In the EC scenario, synchrotron and Compton emission originate from different electron populations. The high energy component of the radiation is therefore produced outside the $\gamma$-ray emitting region, even if a contribution from the SSC component is always present. The basic idea is that the gain from UV/optical continuum from the accretion disk is up-scattered in energy by inverse Compton scattering off hot particles surrounding the disk (located in the BLR; Sikora et al. (1994)). The energy density of the external radiation $U_{\text{ext}}$ can be evaluated by the relation

$$U_{\text{ext}} \simeq \frac{L_{\text{ext}}}{4\pi r^2 c} \simeq \frac{\xi L_{\text{disk}}}{4\pi r^2 c}$$  \hspace{1cm} (1.14)

where $\xi$ is the fraction of disk luminosity reprocessed by the BLR, $L_{\text{disk}}$ the luminosity of the central disk and $r$ the distance of the BLR from the nucleus. In its comoving frame the blob will be enhance in energy on account of beaming effects:

$$U'_{\text{ext}} \simeq \Gamma^2 U_{\text{ext}}$$  \hspace{1cm} (1.15)
Combining this equation with 1.8 we get the emissivity in the comoving frame. If we restrict to the case of a monochromatic flux, with the seed photon spectral distribution peaked around the energy $\varepsilon_0$, we obtain

$$j'_{EC}(\varepsilon'_c) \propto N_0 \Gamma^{\alpha+1} \frac{U_{ext}}{\varepsilon_0} \left(\frac{\varepsilon'_c}{\varepsilon_0}\right)^{-\alpha} \quad (1.16)$$

The maximum energy the scattered photons can reach is

$$\varepsilon'_{max} \simeq \frac{4}{3} \gamma_{max}^2 \Gamma \varepsilon_0 \quad (1.17)$$

where $\gamma_{max}$ is the maximum energy of the electron distribution.

### 1.9.3 Comparing Models

We briefly summarize some useful relations for the physics quantities involved in the synchrotron and Compton process in order to discuss critically the observed scenario.

Taking into account the energy of those electron which emit at the peak ($\gamma_{\text{peak}}$), the synchrotron peak frequency is

$$\nu_S = \frac{4}{3} \gamma_b^2 \delta \nu_L \quad (1.18)$$

where $\nu_L = 2.8 \times 10^6 \, B \, \text{Hz}$ is the Larmor frequency. The resulting Compton peak frequency is given by

$$\nu_{SSC} \propto \frac{4}{3} \gamma_b^2 \nu_S \quad (1.19)$$

$$\nu_{EC} \propto \frac{4}{3} \gamma_b^2 \Gamma \delta \nu_0 \quad (1.20)$$

where $\nu_0$ is the frequency of the external radiation. The flux of the two emission processes depend on some basic parameters:

$$F_S \propto \delta^2 N_0 B^2 \quad (1.21)$$

$$F_{SSC} \propto \delta^4 N_0^2 B^2 \quad (1.22)$$

$$F_{EC} \propto \delta^4 N_0 U_{ext} \quad (1.23)$$

We can notice that the SSC flux increases with the intensity of the magnetic field and with the electron densities while the EC flux increases with $\delta$ (which is related to the disk luminosity and to the bulk Lorentz factor). Either $\nu_{SSC}$ and $\nu_{EC}$, and the respective peak luminosities $L_S$ and $L_C$ are fundamental quantities in the pattern of constraining emission models and they can be derived directly from the SED study.

Through considerations on variability timescales, we can instead constrain the size of the emitting region, $R$, imposing the causality condition:

$$R \leq \frac{\delta c t_{\text{var}}}{1 + z} \quad (1.24)$$
In the SSC pattern these parameters are sufficient to describe the model. Actually the latter needs four basic quantities: $\gamma_{\text{peak}}$, $R$, $B$ and $\delta$. $R$ can be derived as a function of $\delta$ while $\gamma_{\text{peak}}$ is directly obtained through the ratio of the peak frequency:

$$\gamma_{\text{peak}} = \left(\frac{3\nu_C}{4\nu_S}\right)^{\frac{1}{2}} \tag{1.25}$$

Combining these equations with those for the synchrotron frequency and the Compton dominance we obtain two relations through which is possible to estimate either $B$ and $\delta$ from observed quantities

$$B\delta = \frac{\nu_s^2}{\nu_c(e/2\pi m_e c)} \tag{1.26}$$

$$B^2\delta^2 = \frac{2L_S^2}{c^3 T_{\text{var}} L_C^2} (1+z)^2 \tag{1.27}$$

In the SSC scenario thus the SED, and some simple variability consideration, allow to fully constrain the parameters and consequently the model (with the uncertainties inferred by possible non simultaneous data).

On the other hand, the EC scenario is more difficult to evaluate since it contains three additional parameters which are $L_{\text{ext}}$, $R_{\text{ext}}$ and $\nu_{\text{ext}}$.

$$\gamma_{\text{peak}} \delta = \left(\frac{3\nu_C}{4\nu_{\text{ext}}}\right)^{\frac{1}{2}} \tag{1.28}$$

$$\frac{B}{\delta} = \frac{\nu_s\nu_{\text{ext}}}{\nu_c(e/2\pi m_e c)} \tag{1.29}$$

As it is not possible anymore to separate $B$ and $\delta$, we have to make some assumption about the nature of the external radiation. In FSRQ the external photon field is attributed to the BLR as evidenced by the detection of lines in optical spectra. The radiation is peaked at optical-UV frequency ($\nu_{\text{ext}} \sim 10^{15}\text{Hz}$) and is approximated by a black-body spectrum. While the luminosity can be determined from these lines or from UV thermal excesses, the size of the BLR is more difficult to constrain, usually it is inferred from the observations of the broad lines variability in radio quiet sources. In BL Lacs much less is known about their radiative environment: their spectrum, without lines, prevents the determination of the potential BLR size.

### 1.10 VHE Blazars

A particular interest is addressed to some sources members of the blazar class which are firmly established by several observations as TeV $\gamma$-ray emitters. We usually refer to them as TeV blazars or VHE (Very High Energy) blazars since their peculiarity is the larger extension of their spectrum at high energies (in the TeV range, actually) with respect to all the other typical AGNs. As representatives of this sub-population we can mention Mrk 421 ($z = 0.031$), Mrk 501 ($z = 0.034$), 1ES 1959+650 ($z = 0.047$), 1ES
1.10 VHE Blazars

1426+428 ($z = 0.129$), 3c66a ($z = 0.444$), PKS 2155-304 ($z = 0.116$), PG 1553+113 ($z < 0.42$), BL Lacertae ($z = 0.069$).

Despite being subjects of intensive studies and several multiwavelength campaigns, we still have relatively poor knowledge of them, especially in the more energetic part of their spectrum. One of the reason is that their spectrum is affected by the interaction with the background light in the gamma energy range and these objects undergo the attenuation due to absorption of VHE photons (Stecker et al. 1992; Hauser and Dwek 2001) by pair production on the extragalactic diffuse component (see section 3.2.4). Over large distances $\gamma$-rays can be absorbed through interaction with low energy photons, as CMB, IR radiation or starlight, producing $e^+ e^-$ pairs. The latter process is possible only above a threshold energy

$$E_{\text{th}} = \frac{2m_e^2c^4}{[1 - \cos \phi](1 + z)^2E_\gamma} \simeq \left(1 + \frac{z}{4}\right)^{-2} \cdot \frac{30 \text{ GeV}}{E_\gamma} \text{ eV}$$  \hspace{1cm} (1.30)

where $\phi$ is the photon scattering angle, $E_\gamma$ the energy of the $\gamma$-ray and $z$ is the source redshift. Therefore it is clear that the VHE blazars are strongly absorbed, as they emit a larger part of energy in the high energy band than the usual blazar.

In addition, to provide a good physical description of them, we have also to account for the particular characteristics of these sources. First of all their broad band spectra can change with time: they are actually a sub-population of blazars and therefore characterized by strong variability. Thus, in principle, we have to be careful combining data of various instrument collected in different periods. Moreover we have to consider also that to obtain the overall spectrum, covering different energies, some instruments need large observation times to detect a signal.

Although generally the overall photon statistics available is rather huge for all frequencies, when moving to the higher band (GeV-TeV) investigated mainly by the Fermi LAT or the Cherenkov telescope, the spectra of these sources can be determined only using data accumulated over long periods of observations and several days could be required when the source is in low state. This is due to the poor sensitivity when studying the high-energy part and probably, as already mention, also to the absorption of VHE photons by pair production on the isotropic component. For this reason, collected data are not usually simultaneous, and most of the blazar behavior relates to the high state of the sources.
Chapter 2

The Large Area Telescope (LAT)

The Gamma ray Large Area Space Telescope (GLAST) has been successfully launched on 11 June 2008 and then renamed the Fermi Gamma Ray Space Telescope after starting its scientific mission on 11 August, 2008. The Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM) are the two instruments on board of the Fermi satellite. Fermi-LAT is a pair-conversion gamma-ray telescope sensitive to photon energies from 20 MeV to 300 GeV. It is a new-generation detector which provides an unprecedented sensitivity in the $\gamma$-ray and which explores the energy range of MeV-GeV band, including a part of the electromagnetic spectrum still not covered by any other instrument. In the so called standard sky survey mode, the LAT monitors all regions of the sky every 3 hours, leading to a highly uniform exposure on longer timescales. Full details of the instrument, onboard and ground data processing, can be found in Atwood and et al. (2009). The second instrument, GBM, aims to recognize $\gamma$-ray-bursts (GRB), detect their position and measure their spectrum. It is made of 12 Sodium Iodide (NaI) scintillation detectors and 2 Bismuth Germanate (BGO) scintillation detectors. GBM covers the lower part of the interested energy range, from few keV to about 1 MeV (NaI), and from 150 keV to 30 MeV (BGO). Overlapping with the LAT, this detector gives a good coverage of the energy range to study GRB spectrum and flares.

2.1 LAT Instrument

The Large Area Telescope is the main instrument of the Fermi observatory. As we can see in the LAT schematic view presented in figure 2.1 the instrument is composed by a segmented anticoincidence detector (ACD) that surrounds the whole instrument to reject the charged-particle background. Inside the ACD $4 \times 4$ towers measuring 43.25 cm $\times$ 43.25 cm $\times$ 84 cm are positioned. A tracker module (TKR) is located in each tower on top of the corresponding calorimeter module (CAL) while on the bottom the Tower Electronics Modules (TEM) are placed with the Data Acquisition electronics (DAQ). The towers are inserted in an aluminium grid, the structural backbone of the LAT, which also conducts the heat away to the radiators. A foam thermal blanket surrounds everything, providing a light-tight cover and preventing damage by micrometeor hits.
2.1.1 The Anticoincidence Detector

The ACD has the purpose to discriminate charged particles and covers a crucial rule in the charged background rejection. Fermi is positioned in a circular low Earth orbit at \( \sim 565 \text{ km} \) and \( 25.6^\circ \) inclination so that the Earth magnetosphere will partially shield the instruments from cosmic rays. Nonetheless, the average particle flux is \( 10^5 \) times the \( \gamma \)-ray flux and this makes the charged background rejection be clearly a significant topic.

LAT orbit is such that it will spend a fraction of time (\( \sim 14.6\% \)) in the South Atlantic Anomaly (SAA), a zone over Brazil characterized by a high density of charged particles; an effect of the offset dipole geometry of the Earth magnetic field. As the LAT will not take data while traversing the SAA, its main effect is the loss of exposure in the southern celestial hemisphere.

As in the previous instruments (e.g. EGRET) the LAT ACD is composed by plastic scintillators which enclose the TKR, but whereas EGRET ACD was a single piece, the LAT ACD has been divided in 89 plastic scintillator tiles, 25 on the LAT top and 16 on each of the four sides. Each tile is read by two interleaved wavelength-shifting fibers (WSFs) by two photomultiplier tubes. For a better coverage, the ACD tiles overlap in one direction, while 8 scintillating fiber ribbons seal the gaps in the other.

The segmented system considerably reduces self veto effect and background noise with respect to EGRET. Since the LAT ACD allows the rejection of charged particles with an efficiency of at least 3000 : 1 for a minimum ionizing particle, problems could arise when electromagnetic showers develop in the calorimeter. When a low energy photon (\( \sim 1 \text{ MeV} \)) produced in the CAL hits an ACD tile, the released energy is
roughly comparable with that of a minimum ionizing particle; thus it could be mistaken to be a charged particle and the whole event rejected. By ACD segmentation the ACD firing tiles can be identified and associated with the direction of the primary particle. This let to reduced self veto effect in LAT to < 20% (while in EGRET the efficiency loss was 50%) for 10 GeV incident photons with respect to 1 GeV. The significant improvements consist in a higher instrument sensibility and a wider observable energy band.

### 2.1.2 The Tracker

Each tracker module is composed by 18 trays one above each other. For the backbone structure of the trays carbon has been chosen because of its large radiation length, high modulus (stiffness) to density ratio, good thermal conductivity, and thermal stability.

All trays are of similar construction, every one consists of a $x - y$ couple of Silicon Strip Detector (SSD) planes and, depending on its position, a tungsten (W) foil of variable thickness. Tungsten was chosen for its high $Z$, in order to improve photon conversion in electron-positron couples as the conversion probability is proportional to $Z^2$. The first 12 couples of SSD (counting from top) have a W conversion foil of 0.03 radiation lengths (r.l.), the following 4 couples have a W foil of 0.18 r.l. and the last 2 couples have no converters. The trays on the top have thin converters to optimize the PSF at low energy. On the other hand, the trays with a higher W thickness allow to maximize the effective area, and thus to increase the conversion probability (even if in this way angular resolution is degraded due to the Coulomb multiple scattering). Finally the last 2 trays, without W foils, maintain a good precision in the determination
of the CAL entering point. The total TKR depth is about 1.5 radiation lengths.

Each SSD plane contains 16 units (4×4): four adjacent ladders, each one made up by four square SSDs bonded edge to edge. Each SSD sensor has 384 strips on a single side, with a pitch (i.e. distance between centers of adjacent strips) of 228 \( \mu m \).

The tracker contributes to the first-level trigger for the LAT. Each detector layer generates a logical signal OR of all of its 1536 channels, and the coincidence of successive layers (typically 3 \( x \)-\( y \) planes) provides a trigger request that will be used by subsequent subsystems (see section 2.1.4). Finally, to reconstruct the track from the SSD hits, an iterative procedure based on a Kalman filter is used (see section 2.2).

![Figure 2.3:](image)

### 2.1.3 The Calorimeter

Each tower contains a CAL module with a total depth of \( \sim 8.6 \) radiation lengths. A CAL module is segmented both in depth and lateral directions to improve energy resolution, in each module there are 8 layers and every layer is made up of \( 12 \times 1.3 \times 2.1 \) CsI(Tl) crystals read by photodiodes at both ends. Crystals are arranged in a hodoscopic configuration so that each layer is aligned 90° with respect to the previous one, forming an \( x \), \( y \) array, as were TKR Silicon detectors. One long side of each log is slightly rugged, and the point along the crystal where energy has been deposited is determined from asymmetry in the light collected at the two ends of each crystal. The lateral uncertainty is given by the log thickness: \( \sim 2 \) cm for both \( x_0 \) and \( R_m \). Through the information of the CAL we can calculate various quantities:

- the released energy and its distribution in CsI(Tl) crystals, both longitudinal and transverse;
- the direction of the electromagnetic shower axis;
• combining the previous information the energy of the incident photon which has product the tracked electron-positron couple.

The segmentation allows spatial imaging of the shower and accurate reconstruction of its direction: the events in the TKR are correlated with energy deposition in the CAL, and the direction of high energy photons not converting in the TKR could be detected (obviously with a lower resolution).

### 2.1.4 Data Acquisition and Triggering

The Data Acquisition System (DAQ) elaborates the data from the other subsystems and provides a first on-board science analysis. Its primary function is to collect information from the LAT subsystems, read out the event data from the LAT channels and analyze them to reduce the number of downlinked events. In addition, it allows a quick search and alert system for transients (mainly Gamma Ray Burst and solar flares).

The hardware trigger has the purpose to minimize the effects of the background signals (mostly charged particles and earth albedo) on the instrumental deadtime associated with reading out the LAT in order to maximize the amount of “good” events (i.e. celestial γ-ray) that can be downlinked within the available bandwidth.

The first part of the acquisition is managed by the Tower Electronics Module (TEM). A TEM is present in each tower and it relates the information from the tower subsystems collecting the signals from the TKR and from the CAL;
Five hardware trigger primitives (at tower level)

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKR</td>
<td>three x-y tracker planes hit in a row</td>
</tr>
<tr>
<td>CAL LO</td>
<td>single log with more than 100 MeV</td>
</tr>
<tr>
<td>CAL HI</td>
<td>single log with more than 1 GeV</td>
</tr>
<tr>
<td>ROI</td>
<td>MIP signal in a ACD tiles close to a triggering tower</td>
</tr>
<tr>
<td>CNO</td>
<td>heavy ion signal in the ACD</td>
</tr>
</tbody>
</table>

subsequently it can communicate a trigger request to the following trigger instruments in a very short time since it is a combination of simple logic signals from the subsystems. The main primitives generated are resumed in the table below and are: “TKR”, generated when a track is detected in at least 3 TKR plains (x-y); “CAL LO” generated when a released of > 100 MeV energy is measured in one calorimeter log; “CAL HI” generated when a released of > 1 GeV energy is measured in one calorimeter log; “ROI”, a MIP signal is detected in an ACD tile adjacent to a triggering tower; “CNO”, which corresponds to the detection of a signal in the ACD compatible with the passage of a heavy ion.

With these primitives several triggers can be built: e.g. “gamma”, “Heavy Ion”, “periodic”. To “gamma”, that contains principally gamma-events, most of the bandwidth is reserved (≈ 360 Hz), while “Heavy Ion” events (≈ 10 Hz) are downlinked as they are useful for calibration. The “periodic” trigger (≈ 2 Hz), instead, is built on its correspondent primitive: it consist on a trigger input not based on the detection of events and downlinked data are used for calibration and diagnostic purposes.

The final part of acquisition process is managed by the Spacecraft Interface Unit (SIU): the SIU contains the command interface to the spacecraft and also performs the basic functions to control the LAT. It gathers data from all the towers, reconstructs tracks which have passed through different towers and send the resulting data to the Solid State Recorder (SSR) for downlink (the downlink takes place every two orbits).

Since the data volume that can be downlinked within the allocated bandwidth is limited, a first selection of the events on board is required. As for triggers there are several channels, also for filters we can have various channels for different purposes: e.g. Gamma, Heavy Ion etc. The procedure is as follow: for each triggered event a filter (i.e. a cut on high-level variable) is applied, the conditions which require less time are tested to optimize the available resource. When an event fails one condition the process stops, the event is rejected and the elaboration proceeds with the next event. When filter algorithms have reduced the event rate from 2-4 kHz to ≈ 400 Hz, the elaborated information are sent to SIU. Currently there is also a high energy pass: events with energy greater than 20 GeV are downlinked with no filtering at all (as they are few and do not take up so much bandwidth).

### 2.2 LAT Event Reconstruction

When an event is classified as a photon, the next step (performed on ground) is to reconstruct the primary track and estimate its energy. The development of the re-
construction is fundamentally based on the Monte Carlo simulation of the events and correlates the information from the various components assuming a single event hypothesis. In the following subsections, we report the basic steps of the reconstruction.

### 2.2.1 Track Reconstruction

For photons with energy greater than 20 MeV we can neglect photoelectric effect and Compton process and consider pair production as the only interaction process. The $e^-$ and $e^+$ produced, passing through the TKR, lose energy in the SSDs allowing a first estimate of their energy, their angle of incidence with respect to telescope zenith and their position. For the $k$-th plane we can define a state vector $v_k$ which contains all the previous information

$$v_k = \begin{pmatrix} \text{position} \\ \text{track slope} \\ \text{energy} \end{pmatrix}$$  \hspace{1cm} (2.1)

If $H_k$ is the matrix which transforms the state vector into the vector of the measurable quantities $m_k$, and $\varepsilon_k$ is the error vector we find

$$m_k = H_k v_k + \varepsilon_k$$  \hspace{1cm} (2.2)

State vector temporal evolution is described as

$$v_{k+1} = F_k v_k + w_k$$  \hspace{1cm} (2.3)

where $F_k$ is the deterministic evolution and $w_k$ the stochastic component due to Coulomb Multiple Scattering. We can assume that $\varepsilon_k$ and $w_k$ are independent and that their average is null. As we can see in figure 2.5 the track reconstruction is based on a two step process:

- the estimation of $v_k$ from $m_{k-1}$ in each TKR plane;
- the Kalman filter smooths the track from the bottom to the top, estimating again $v_k$ from $v_{k+1}$.

The trajectory provided by the candidate track is related with the CAL information (see 2.2.2). Then the CAL entering point is automatically related with the best hypothesis track using combinatoric algorithms and the track reconstruction process takes place again.

For every track four algorithms are applied. The first consist in the search of the "best" track, which is always available as the result of the Kalman filter. The second consists in a search of a vertex (not always present) and it is computed simply looping over the tracks. If the distance of closest approach between the starting track and the candidate second track is within a specified distance (default: 6 $\mu$mm), and the angle between the two is compatible with the (correspondent) energy released in the CAL, a vertex solution is generated. The last two algorithms apply to the tracks the same processes, but assuming that a significant part of energy has been subtracted by a photon (thus, the Bremsstrahlung process has taken place.)
2.2.2 Energy Release Reconstruction

To reconstruct the energy deposition the total energy in the crystal is calculated for each calorimeter crystal by combining the signals from the two ends. In the same way it is determined the position along the crystal where the energy was released. Afterwards, the shower development is taken into account and related to the whole released energy. The latter is in a first time simply estimated as the total sum of the crystal energies and then improved with the information given by the TKR. Actually, we have to consider also the leakage from the later and back sides of the CAL and through the internal gaps between CAL modules. To quantify the energy correction necessary, the trajectory provided by the best track is the input for three different algorithms:

- a parametric correction (PC), which operates in the whole phase space of the LAT and is based on the barycenter of the shower;
- a fit to the shower profile (SP), which works in the range beyond 1 GeV and considers the longitudinal and transverse development of the shower;
- a maximum likelihood (LK) fit, which operates below 300 GeV and correlates the overall total energy deposited with the number of hits in the TKR and with the energy seen in the last layer.
Each event is elaborated by the three algorithms, but for low energies (∼100 MeV), one more method is necessary as in this case a significant amount of the energy (∼50%) can be released in the TKR. The TKR energy is determined from the SSD signals, i.e. the amount of the energy deposition at certain depth in a tracker layer is evaluated from the number of hit silicon strips.

From all these methods the best one is selected with automated techniques trained on Monte Carlo samples.

### 2.3 Instrument Response Functions

#### 2.3.1 IRF Definition

In high energy astrophysics the Instrument Response Functions (IRFs) represent a high-level model of the instrument response that enable the data analysis. IRFs are used for two different purposes:

- instrument analysis is complex and can be hardly manageable by the external astrophysics community. For this reason data are released in form of photons tables (e.g. “.fits” files), which are made up by few estimated quantities like energy, direction, inclination angle with respect to the telescope axis, . . . ;

- IRFs enable a direct comparison of data from different instruments in different energy ranges, allowing a multi-wavelength analysis.

The instrument response relates the true photon energy $E'$ and direction $\hat{p}'$ with the measured quantities $E$ and $\hat{p}$ and it is usually factorized into three functions, plus a temporal scaling factor:

$$R(E, \hat{p}|E', \hat{p}'; t) = T(t)A(E', \hat{p}')D(E|E', \hat{p}')P(\hat{p}|E', \hat{p}')$$  \hspace{1cm} (2.4)

The scaling factor $T(t)$ accounts for temporal effects (e.g. instrument failures, temporary switching off, thermal expansion, . . . ) while we assume that we can neglect temporal variations which cannot be expressed as a scaling factor, over a large time interval. The three functions describing the IRFs are:

- the effective area $A(E', \hat{p}')$, which is the efficiency multiplied for the geometrical area of the detector $A_0$

$$A = A_0 \cdot \frac{N_{\text{detected}}}{N_{\text{incident}}}$$

- the energy dispersion $D(E|E', \hat{p}')$, i.e. the probability density that a photon with energy $E'$ and direction $\hat{p}'$ is detected with energy $E$.

- the Point Spread Function (PSF) $P(\hat{p}|E', \hat{p}')$, i.e. the probability density that a photon with energy $E'$ and direction $\hat{p}'$ is detected with direction $\hat{p}$. 

If $S(E', \hat{p}', t')$ is the source model (i.e. the differential flux $d\Phi/dE'$ of our model) the expected observed distribution of count hits is

$$M(E, \hat{p}, t) = \int dE' d\hat{p}' R(E, \hat{p} | E', \hat{p}'; t) S(E', \hat{p}', t)$$  

(2.5)

IRFs have been evaluated using Monte Carlo simulations and validated by means of accelerator beam tests mainly carried out at CERN in 2006. Furthermore, during the assembly of the instrument, cosmic ray triggers were recorded to control the proper functioning of the various components as they were added to the LAT. The performance parameters are finally improved as all algorithms are optimized during the on-orbit operations of Fermi.

### 2.3.2 Background Rejection and Event Classification

The wide range of analysis that can be done with LAT observations (from GRBs to extended diffuse radiation) requires a particular optimizations of the event selections and different rates of residual backgrounds. The background rejection has been thus developed to create 3 analysis classes, each one optimized for specific science topics. In all of these analysis classes the charged-particle background entering within the field of view has mostly been rejected.

Table 2.3.2 shows the analysis classes that have been defined taking into account the performance of the LAT, the background expected in orbit and the current knowledge of the $\gamma$-ray sky. What distinguishes the classes is an increasingly tighter requirement that the candidate events in both the tracker and the calorimeter was produced by a celestial photon. This information can be directly evaluated looking to the expected electromagnetic showers induced by the candidate event.

The loosest cuts are applied to the Transient class, which has a permitted background rate of $< 2$ Hz, so that the we expect no more than one background event every 5 sec inside a $10^6$ radius about a source. The background rejection in the Source class instead is set to allow residual background similar to that expected from the extragalactic $\gamma$-ray background flux, when considering the entire field of view. Finally, the Diffuse class has the best background rejection as its signal to noise would not significantly improve with harder cuts.

As we can see these analysis classes are hierarchical, this means that all events in the Diffuse class are contained in the Source class and all events in the Source class are in the Transient class. For the Diffuse class, which will be selected in this study, the resulting rejection factor is $\sim 1:10^6$ at energies $\sim 10$ GeV while maintaining $> 80\%$ efficiency for retaining $\gamma$-ray events.
### Table 2.1: LAT analysis classes

<table>
<thead>
<tr>
<th>Analysis class</th>
<th>Residual background rate (Hz)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient</td>
<td>2</td>
<td>Maximize effective area, particularly at low energy, at the expense of higher residual background rate; suitable for study of localized, transient sources</td>
</tr>
<tr>
<td>Source</td>
<td>0.4</td>
<td>Residual background rate comparable to extragalactic diffuse rate estimated from EGRET; suitable for study of localized sources</td>
</tr>
<tr>
<td>Diffuse</td>
<td>0.1</td>
<td>Residual background rate comparable to irreducible limit and tails of PSF at high-energy minimized; suitable for study of the weakest diffuse sources expected</td>
</tr>
</tbody>
</table>
Chapter 3

Analysis Methods

The analysis performed in this work accounts for 9 month data collected by the LAT instrument since the August 4th, 2008. There are two main steps to perform: chapter 3.1 deals with the selection of the events, while the two different approaches to analyze the data, the likelihood and unfolding methods, are discussed in chapter 3.2 and 3.3, respectively. For all the sources, data were taken while the LAT was in scanning mode: every orbit the LAT covers 75% of the sky sweeping by 35° from the local zenith towards the celestial poles. At the end of the orbit Fermi rocks to 35° on the other side of the orbital plane and continue to observe. In this way, the whole sky is scanned every three hours and no time is lost due to Earth occultation.

3.1 Selection of Events

Before running the analysis on a particular source, a selection in the event files has to be done, both to avoid excessive computational time losses and to ensure a good data quality.

Energy Selection and Region of Interest

A first selection is done on the energy of the detected $\gamma$-ray: only events in the energy range between 250 MeV – 250 GeV are considered as at lower energies the systematic uncertainties to date are not well understood. Regarding the region extension to account for the analysis a useful limit can be inferred by the PSF. Referring to figure 3.1 where the LAT containment radius is displayed versus energy at normal incidence and at 60° incidence, we see that for the lower energy range selected $\sim 68\%$ of photons is contained in 2 degrees, in a Gaussian approximation, and in about 5 degrees we have $\sim 99\%$ of photons. Therefore in fitting we can restrict the analysis to a region of interest (ROI) of 5 degrees (see section 3.2.2) ensuring a not excessive loss of events.

Gamma-event Selection

Additionally there are two further quality cuts:
we choose the events class level, one of the three classes presented in section 2.3.2. For this work the diffuse class is always selected, as it ensures the best background rejection (though with a loss of statistics);

- we make a cut to remove albedo gammas (i.e. photons produced by interaction of \(\gamma\)-rays with the Earth atmosphere). This is performed by removing from analysis the time intervals when the analyzed source angle with respect to the detector zenith was > 105\(^\circ\) (and thus in the range of the Earth albedo).

### 3.2 The Likelihood Analysis for LAT Data

The official analysis method of the Fermi collaboration to date is the maximum likelihood analysis, which has already been used in previous experiments, e.g. by COMPTEL and EGRET. The maximum likelihood analysis described in the following section is applied to photon counts and is used to estimate to what extent the observed data are consistent with a statistical hypothesis.

#### 3.2.1 The Extended Maximum Likelihood Method

To derive information from the measured events, e.g. the flux or spectral index of a source we use the maximum likelihood method. This estimates the values of the set of parameters maximizing the likelihood that the chosen source model fits the collected data.

Assuming the source model has \(m\) free parameters \(\lambda_1, \lambda_2, \ldots, \lambda_m\) the expected observed distribution of count hits given by Eq. 2.5 can be written

\[
M(E, \hat{p}, t, \{\lambda_k\}) = \int dE\, d\hat{p} R(E, \hat{p} | E', \hat{p}'; t) S(E', \hat{p}', t, \{\lambda_k\})
\]

where \(S\) is the differential flux of the model \(S = d\Phi/dE' = dN/(dt \, dA \, dE')\), and therefore \(M = dN/dt\).
In the best case, which however requires powerful computing facilities, we can bin events in energy $E$, direction $\hat{p}$ and arrival time $t$ in such a way that each bin contains only one single photon (unbinned analysis). If the time binning width is $\Delta t$, in each bin the expected number of photons can be calculated with Eq. 3.1

$$N_{\text{exp}}(E, \hat{p}, t, \{\lambda_k\}) = M(E, \hat{p}, t, \{\lambda_k\}) \cdot \Delta t$$

(3.2)

Indicating with $P$ the set of bins containing one photon and $Q$ the set of bins containing no photons, we assume that the probability of observing a photon follows the Poisson distribution\(^1\)

$$f(n, \nu) = \frac{\nu^n}{n!} e^{-\nu}$$

the likelihood function associated with the parameters set $\{\lambda_k\}$ is defined as (Mattox et al., 1996)

$$L(\{\lambda_k\}) = \prod_P N_{\text{exp}}(\{\lambda_k\}) \prod_Q e^{-N_{\text{exp}}(\{\lambda_k\})} = \prod_P N_{\text{exp}}(\{\lambda_k\}) \prod_{P \cup Q} e^{-N_{\text{exp}}(\{\lambda_k\})}$$

(3.3)

As the term “likelihood” usually refers to a Gaussian distribution function, the latter is called “extended likelihood function”. Calculating the logarithm of Eq. 3.3, using the definition in Eq. 3.2, yields

$$\ln L(\{\lambda_k\}) = \sum_P \ln N_{\text{exp}}(\{\lambda_k\}) - \sum_{P \cup Q} N_{\text{exp}}(\{\lambda_k\}) = \sum_P \ln M(\{\lambda_k\}) + \ln \Delta t^{N_{\text{obs}}} - N_{\text{tot}}(\{\lambda_k\})$$

(3.4)

where $N_{\text{obs}}$ is the number of observed photons and $N_{\text{tot}}(\{\lambda_k\})$ is the total number of photons expected from the model $S(\{\lambda_k\})$. Since we want to find the maximum of the likelihood $L$, i.e. the maximum of $\ln L$, we can omit the constant term $\ln \Delta t^{N_{\text{obs}}}$, and so we find

$$\ln L(\{\lambda_k\}) = \sum_P \ln M(\{\lambda_k\}) - N_{\text{tot}}(\{\lambda_k\})\]$$

(3.4)

The maximum of the likelihood $L$ corresponds to the minimum of $-\ln L$. The most probable set of parameters $\{\lambda_k\}$ to minimize $-\ln L$ are estimated by this value and the likelihood function (eq. 3.3) allows to determine the parameter covariances. In fact, the Cramer-Rao’s lower bound allows to give an upper limit for the covariance matrix terms

$$\sigma_{ij}^2 = \left[ -\frac{\partial^2 \ln L}{\partial \lambda_i \partial \lambda_j} \right]^{-1}_{\lambda_k = \bar{\lambda}_k}$$

\(^1\)With $n$ being the observed number of photons per bin, thus 0 or 1, while $\nu$ is the predicted number from the model $M$ calculated in each bin using Eq. 3.2.
This method allows also the comparison of different models for which the likelihood ratio test is found to be the most powerful criterion. According to Wilks’ theorem, if we consider a model \( M \) with \( m \) parameters and a second model \( M_0 \) with a subset of \( h < m \) parameters, the test statistic

\[
T_S = 2 (\ln \mathcal{L} - \ln \mathcal{L}_0)
\]

is distributed asymptotically as a \( \chi^2 \) with \( k = m - h \) degrees of freedom. This comparison can be applied only within the likelihood analysis, so that the result we will have is which of the models tested with the likelihood method is more consistent with the data.

### 3.2.2 The Unbinned Analysis

The unbinned analysis uses the likelihood method discussed in section 3.2.1 to process the LAT data of point-sources. Detailed information about LAT software is given in the User Workbook\(^2\). In this paragraph the main steps of the unbinned analysis procedure are summarized:

1. spatial and temporal selection of events, in part already discussed in section 3.1; in our analysis we have selected events in a ROI of 5\(^\circ\) radius centered at the source position derived from Fermi data, available in the LAT bright source list\(^3\). Since we are interested in point-source objects, such ROI is suitable as it is larger than the 68% containment angle of the PSF at lowest energies (\( \sim 3\)\(^\circ\)). This ensures most photons coming from the source to be detected with a good suppression of background.

2. creation of a count map of the studied region; as we can see in figure 3.2 for the two sources PG1553 + 113 and PKS 2155–304, this procedure allows to have a first overview of the other possible sources within the extraction region.

3. creation of the exposure map which is used to calculate the number of events expected for each bin. The exposure \( \mathcal{E} \) is calculated as the integral of the total response over the entire ROI extension and is defined as

\[
\mathcal{E} = \int_{\text{ROI}} dt \, dE' \, d\hat{p}' \, T(t) A(E', \hat{p}')
\]

in bins of time, logarithmic energy and cosine of incidence angle\(^4\). In each bin one can obtain the expected number of photons from the source by multiplying the model flux with the corresponding exposure:

\[
N_{\text{exp}} = \mathcal{E} \frac{d\Phi}{dE}
\]

\(^2\)http://glast-ground.slac.stanford.edu/workbook/sciTools_Home.htm  
\(^3\)http://fermi.gsfc.nasa.gov/ssc/data/access/lat/bright_src_list  
\(^4\)The grid used for the exposure calculation is much wider than the one used to calculate the likelihood.
Figure 3.2: Count map for the ROI (5° radius centered in the source position) of PG1553+113 and PKS 2155–304. The bright central dot represents the interested source while other bright points (when present) are due to sources located nearby; in the analysis development we must account also for them.

Generating the exposure map requires two steps. First the calculation of the lifetimes as a function of energy and cosine of inclination angle (expCube, this provides the information about how long a single position of the sky has been observed). With this quantity we can compute the map (expMap) choosing an acceptance cone with radius larger than the ROI of the event selection (15° centered in the source coordinates). An acceptance cone larger than the ROI is necessary to ensure that photons located outside the ROI, but still coming from the source, can be accounted of in calculating the size of the instrument PSF.

4. develop a source model \( S(\{\lambda_k\}) \), taking into account the radiation emitted in a region larger than the ROI to avoid systematics effects. This model has to contain all the sources in the extraction region that have to be fit: the galactic diffused emission the isotropic components (see section 3.2.4) and point-source objects located nearby.

5. fit the model parameters \( \{\lambda_k\} \) to the detected counts. As discussed in section 3.2.1, first we obtain the expected distribution of observed photons \( M \) (eq. 3.1) by convolving the source model \( S \) with the IRFs, then we calculate the likelihood logarithm (eq. 3.4) and maximize it to find the most probable set of parameters \( \{\hat{\lambda}_k\} \) with their covariance matrix.

These are the guidelines to perform the unbinned analysis according with the provided Science Tools v.9.r12 as part of the LAT software. The analysis here presented uses the post-launch IRFs P6.V3_DIFFUSE while the optimizer used to find the parameters
estimation is MINUIT.

### 3.2.3 The Binned Analysis

For completeness, we briefly sketch also the other available method using the likelihood approach to analyze data, i.e. *binned analysis*. It is designed to analyze data in a large region of the sky, not being particularly interested in achieving a very high precision in source position. For example, in the case of extended sources such as the diffuse emission from molecular clouds in our galaxy, the unbinned analysis would require excessive computing times, thus the binned likelihood analysis is used, which is less accurate but much faster than former.

The main steps for a binned analysis are:

1. produce a count map ny binning data according to their direction and energy;
2. as for the unbinned analysis, calculate lifetimes as a function of energy and cosine of inclination angle (expCube);
3. as for the unbinned analysis, develop a source model \( S(\{\lambda_k\}) \);
4. calculate the binned exposure,
\[
\mathcal{E} = \int dt \int dE' \int dp' \ T(t) A(E', \hat{p}')
\]
where the same bin size is used as in the counts map;
5. produce a source map (i.e. a map of the predicted counts in each bin) by convolving the source model with IRFs;
6. calculate the likelihood \( \mathcal{L}(\{\lambda_k\}) \) (the formula is different from that in eq. 3.3, as it refers to the generic definition of the likelihood function\(^5\)) and fitting the model parameters to obtain the most probable values \( \{\bar{\lambda}_k\} \) and their covariances.

### 3.2.4 Diffuse \(\gamma\)-ray Emission

As discussed in the previous section, in the likelihood analysis an important step consists of developing a model which accounts for the radiation emitted in the selected ROI. Therefore, to analyze both galactic and extragalactic sources, a crucial point is to provide an accurate determination of the diffuse emission in the interstellar space, since it dominates the \(\gamma\)-ray sky, constituting almost 90% of the total luminosity at

\(^5\)In general, given a stochastic variable \( x \) distributed according to a density probability \( f(x, \{\lambda_k\}) \), and a sample of observations \( x_1, x_2, \ldots, x_N \), the likelihood function associated with the set of parameters \( \{\lambda_k\} \) is
\[
\mathcal{L}(\{\lambda_k\}) = \prod_{i=1}^{N} f(x_i, \{\lambda_k\})
3.2 The Likelihood Analysis for LAT Data

GeV energies. The diffuse $\gamma$-ray emission consists of two components: the galactic diffuse emission and the isotropic component. In the following subsections we briefly introduce these two components and also report about the background models assumed for the likelihood analysis.

**Diffuse Galactic $\gamma$-ray Emission**

Diffuse galactic $\gamma$-ray emission (DGE) comes mainly from the galactic plane and is produced by interactions of high energy cosmic rays (CRs) with the interstellar gas and the interstellar radiation field. The energetic particles involved are primarily protons and electrons: the former interact via $\pi^0$-production with the interstellar gas, while the latter interact via Bremsstrahlung with the interstellar medium and via IC scattering with the radiation field.

Therefore, determining the DGE requires a model of CR propagation and must account for the distribution of the target gas and the interstellar radiation field. Such models are based on the theory of particle transport and interactions in the interstellar medium and can exploit data provided by different observations. An important contribution to the development of these models has been given by EGRET, even if it provided a deceptive view of the GeV energy range leading to a strong debate about the so called “GeV excess” (Hunter et al. (1997), Strong et al. (2004)).

The DGE model used to analyze LAT data has been developed in the pre-launch period and it is now constantly updated and improved (Porter et al., 2008). The model is based on GALPROP, a numerical method and the corresponding computer code to calculate galactic CR propagation and $\gamma$-ray production. The GALPROP run used for this work, $54_{77Xvarh7S}$, includes the cosmic ray electron spectrum measured by Fermi (Abdo et al., 2009), improved description of interaction process and tuning to $\gamma$-ray emission seen by Fermi itself. In particular this model is consistent with the cosmic ray spectrum measured at Earth and the non-detection of the GeV excess by Fermi (Abdo et al. submitted 2009).

**Isotropic Component**

The isotropic background is difficult to disentangle from the intense galactic diffuse foreground because it is relatively weak and has a continuum spectrum with no strong (distinguishing) features. Moreover, its modeling is more complex with respect to DGE, since all the components which may contribute are still not well determined. The isotropic model should account for:

- the true extragalactic diffuse emission (the equivalent of the cosmic microwave background in the gamma energy range), which potentially can provide important information about the early Universe (e.g. the phase of baryon-antibaryon annihilation, dark matter annihilation, evaporation of primordial black holes);

- contributions from the population of faint and unresolved sources (e.g. AGN, normal galaxies..) and from further potential sources (such as galaxy clusters and $\gamma$-ray burst events);
• background from charged cosmic rays misclassified by the LAT background rejection as $\gamma$-rays.

Besides, determination of the isotropic component depends on the adopted model for the DGE spectrum, which itself is not yet firmly established. However for the source analysis described here we do not care to separate these various contributions and thusly we use an isotropic spectrum inferred from LAT data themselves, assuming the galactic model previously described.

### 3.3 Unfolding Analysis

An alternative method to analyze LAT data is the “unfolding analysis” which is based on Bayes’ theorem (D’Agostini, 1995). Given the observed gamma photons, one is actually interested in the true physical quantities of the real events, taking into account all the distortion that can be inferred by the detector. The Bayes approach is quite simple: starting from a Monte Carlo simulation we can fill a matrix which takes into account the overall effect of these distortions on the initial quantities and relates the true and observed quantities. This approach is a useful tool to unfold experimental distributions in order to get the best knowledge of the true ones and it can be improved by using an iterative procedure.

#### 3.3.1 Bayes’ theorem

Let us assume that we observe a single effect $E$ which can be produced by several independent causes $(C_i, i=1,2,\ldots,n_c)$; the initial probability of the causes $P(C_i)$ and the conditional probability of the $i$th cause to produce the effect $E$, $P(E|C_i)$ is known. The Bayes theorem says that:

$$P(C_i|E) = \frac{P(E|C_i)P(C_i)}{\sum_{l=1}^{nc} P(E|C_l)P(C_l)}$$  \hspace{1cm} (3.5)

The probability that the observed effect $E$ was due to the $i$th cause is proportional to the probability of the cause (to be observed) times the probability of the cause to produce the effect.

At first sight Bayes’ formula seems to be unuseful: to calculate $P(E|C_i)$ we need to know the initial probability of the causes, meaning we have to know the initial distribution of the data which is exactly what we want to determine but in reality the weak point of this approach can be overcome with the increasing number of observations. If we cannot guess the initial distribution, we can start from a uniform distribution and increase the knowledge on $P(C_i)$ by an iterative procedure (see next section).
3.3 Unfolding Analysis

3.3.2 Unfolding the Data

When we measure \( n(E) \) events (with \( E \) being the effect), the expected number of events that can be inferred by each cause \( C_i \) can be written as

\[
\hat{n}(C_i) = n(E)P(C_i|E)
\]  

(3.6)

since for a given cause we can have several effects \( E_j \). The term \( P(C_i|E) \) is estimated with Monte Carlo methods and is the conditional probability: i.e. the probability that the effect \( E \) was produced by the \( i \)th cause. With \( P_0(C_i) \) being the initial probability of each cause, Bayes’ formula (eq. 3.5) allows to calculate the quantity \( P(C_i|E) \) for each of the \( E_j \) effects

\[
P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l)P_0(C_l)}
\]  

(3.7)

This quantity is called the *smearing matrix* and gives the probability that each effect \( E_j \) has been due to the \( i \)th cause. We have to note that:

- the overall sum of the initial probabilities of all the causes is 1;
- this means that if a cause has an initial probability set to zero it will never change (as a new cause cannot be introduced);
- each effect must be the product of one or more of the considered causes; thus, if the detected data contain also background, the latter must be included among the causes as well;
- we have to account for the efficiency \( \epsilon_i \) of observing the cause \( C_i \) in any of the possible effects; a priori not all the causes have to produce at least one of the observed effects.

After we have made \( N_{\text{obs}} \) observations we obtain a distribution of frequencies \( n(E) \equiv \{n(E_1), n(E_2), \ldots, n(E_{n_E})\} \). The predicted number of events inferred by each cause can be evaluated by eq. 3.6 and, taking into account the efficiency, it yields to derive the best estimation of the true number of events which is

\[
\hat{n}(C_i) = \frac{1}{\epsilon_i} \sum_{j=1}^{n_E} n(E_j)P(C_i|E_j) \quad \epsilon_i \neq 0
\]  

(3.8)

On the basis of this unfolded quantities the overall true number of events, the final probabilities of the causes and the final efficiency are calculated:

\[
\hat{N}_{\text{true}} = \sum_{i=1}^{n_c} \hat{n}(C_i)
\]  

(3.9)

\[
\hat{P}(C_i) \equiv P(C_i|n(E)) = \frac{\hat{n}(C_i)}{\hat{N}_{\text{true}}}
\]  

(3.10)
\[ \hat{\epsilon} = \frac{N_{\text{obs}}}{N_{\text{true}}} \] 

(3.11)

If the initial distribution is not consistent with the data, it will be different to the final one. It is important to stress that the closer the initial distribution is to the true one, the smaller the difference is. This suggest to proceed iteratively, with the main steps being:

1. start from an initial distribution which exploits all the knowledge of the studied process;
2. calculate \( \hat{n}(C) \) and \( \hat{P}(C) \);
3. make a \( \chi^2 \) comparison between \( \hat{n}(C) \) and \( n_0(C) \);
4. substitute \( P_0(C) \) with \( \hat{P}(C) \) and \( n_0(C) \) with \( \hat{n}(C) \), and restart again; if, after the second iteration, the \( \chi^2 \) is “small enough” we stop the iteration; otherwise we re-run the analysis from step two.

When the iterative procedure has converged, the unfolded distribution \( \hat{n}(C) \) is obtained. After the procedure has converged, statistical errors on the spectrum are evaluated taking into account both data and MC statistical errors. The error on the flux is therefore determined as the sum of all entries of the covariance matrix.

### 3.3.3 Unfolding Procedure for LAT Data

Following the iterative procedure previously discussed the unfolding method allows to reconstruct the true photon energy spectra from the observed ones. The spectrum of the source is reconstructed without any assumption on its shape but rather just by exploiting the observed photon energy spectrum from the source (acquired data) and the smearing matrix (SM), that represents the detector response function (evaluated from Monte Carlo simulations). For each source the SM is evaluated from the whole simulated gamma sample accounting for the satellite pointing history (IRF).

#### Data selection

The data are selected as presented in section 3.1: they are selected only in a sample of diffuse events within the energy range of 250 MeV-250 GeV and they are then refined with the cuts for albedo gammas described in section 3.1.

#### Smearing Matrix

The smearing matrix (SM) represents the set of probabilities \( P(E_{\text{obs}}|E_{\text{true}}) \), i.e. the probability that the detector observes a photon with energy \( E_{\text{obs}} \) when its true energy is \( E_{\text{true}} \). The SM is evaluated for each source because observed photons have their own angular distribution in the detector reference system that usually differs from the angular distribution of photons from other sources. It also accounts for the detection
efficiency and the detector effective area: for each given value of the true energy $E_{\text{true}}$, the sum of $P(E_{\text{obs}}|E_{\text{true}})$ on the observed energies $P(E_{\text{obs}})$ could be less than 1.

The SM for a given source is reconstructed in the few steps summarized below:

- the expected angular distribution of photons coming from the source within a given ROI is evaluated from the satellite pointing history;
- from the simulated gamma-ray data, a sample of events is selected according to the expected angular distribution;
- the probabilities $P(E_{\text{obs}}|E_{\text{true}})$ are afterwards estimated as the ratio
  \[ \frac{N(E_{\text{obs}}|E_{\text{true}})}{N(E_{\text{true}})} \]
  where $N(E_{\text{true}})$ is the number of simulated gammas with true energy $E_{\text{true}}$ and $N(E_{\text{obs}}|E_{\text{true}})$ is the number of events with true energy $E_{\text{true}}$ that are observed with energy $E_{\text{obs}}$.

### Background Subtraction

One of the main differences between the unfolding and the likelihood method is that in the unfolding method the background evaluation can be done without the use of any model distribution: it is simply evaluated from the same event sample used in the source analysis. Several methods have been developed to estimate the background; amongst them the following two:

- in the same sky region of the source, events are selected in an off-pulse phase for the study of pulsars while, in the case of GRBs, events are selected in “ad-hoc” time windows (prior to the burst);
- the other possibility is to choose events in a sky region far from the ROI centered on the source. This choice can be done for any source but works better for sources with $|b| > 10$, where the effects of the DGE are smaller.

The latter procedure is the one used in this work: to evaluate the background a ring centered on the source, but far from the ROI, is selected, the internal and external radius are $10^\circ$ and $15^\circ$ degree, respectively.

### Unfolding the Spectra

The unfolding procedure followed in this study can be divided in these steps: a trial spectrum $P(E_{\text{true}})$ is assumed as starting point (usually a flat distribution);

1. the smearing matrix is inverted with the Bayes theorem: the probabilities $P(E_{\text{true}}|E_{\text{obs}})$ are evaluated with the trial spectrum $P(E_{\text{true}})$;
2. from the observed spectrum $P(E_{\text{obs}})$ and the probabilities $P(E_{\text{true}}|E_{\text{obs}})$ a new “true” spectrum $P'(E_{\text{obs}})$ is reconstructed;
3. the new reconstructed spectrum is used as starting point for the next iteration;
4. the iterations are terminated when the difference between the reconstructed spectrum after the $(n-1)$-th iteration and the reconstructed spectrum after the $n$-th iteration are small enough\(^6\).

We want to stress that the reconstructed spectrum does not depend on the input trial spectrum. Actually, it is worth noticing that the choice of the trial spectrum determines only the number of iterations needed for the procedure to converge. Anyway, in most cases, the method converges after a few iterations.

### 3.4 Discussion

The next chapter describes a first attempt to perform an analysis on LAT data with the purpose to provide a proper description of each source under study. The analysis that will be presented in the next chapters are obtained by means of the likelihood approach as the unfolding method still needs to be implemented and tested.

The unfolding method, anyway, allows us to perform a first characterization of the spectra and seems more suitable for our aim as it provides all the necessary ingredients for drawing the SED at high energies.

On the other hand, as we will see in the analysis the likelihood method has still several problems in modeling the AGNs. First of all we must assume one of the build-in model for the interested source and it relies on the model for the isotropic component that we feed in; thus, it is affected by all the uncertainties on the modeling of the diffuse components. This is the main cause also for the other basic problem with the likelihood approach which is present also in this study: the bad residuals behavior, especially at higher energies.

Moreover, this method allows the determination of the spectral shape parameter for the source but does not allow the direct estimation of the points of the spectrum and the covariance matrix between them (which are exactly what we are interested in). On the other hand all these information may be obtained with the unfolding approach, but, until now it is still under commissioning and all the results shown later on are to be regarded as preliminary.

\(^6\)The comparison between the spectra is done with a $\chi^2$ test.
Chapter 4

Observation of a Blazar Sample

The Fermi-LAT is designed to address several different scientific objects which will enlarge our knowledge of the $\gamma$-ray sky. It aims at a detailed study of different astrophysical topics such as: galactic sources (e.g. pulsars, supernovae remnants, X-rays binaries and sources of the solar system) diffuse sources and molecular clouds, extragalactic sources such as galaxy clusters and AGNs. Moreover, the progress in several areas requires (coordinated) multi-wavelength observations with both ground and space-based telescopes. In particular, with regard to the higher energy range covered by the LAT data, an important and crucial topic is the calibration of the Cherenkov telescopes (such as MAGIC, HESS and the forthcoming CTA) in order to merge the information collected in the GeV-TeV energy range by different instrument and to extend our understanding of the TeV energy range.

VHE blazars (together with pulsars) offer the main contribution to this latter aim as their spectrum can extend up to energies of the order of several TeV band. As pointed out in the previous sections (e.g. in section 1.6), blazars are variable sources and their emitted radiation arises from a complex and still not clear set of physical interactions (see section 1.7 and following). Therefore, in particular, we need to identify key parameters to describe and characterize the source state and notably their SED.

4.1 Source Sample

Blazars are a class of powerful but highly variable $\gamma$-ray emitters, according to the unified model of AGNs, which describes them as super-massive black holes surrounded by accretion disks and characterized by outflowing jets. Although they represent only several per cent of the overall AGN population, they largely dominate the high-energy extragalactic sky. The reason is that most of the non-thermal power, which arises from relativistic jets that are narrowly beamed and boosted in the forward direction, is emitted in the $\gamma$-ray band.

This study presents the observation of a sample of 4 sources detected with a high confidence TS by Fermi LAT in the first 6 months of its mission. They are all VHE blazars located at a high galactic latitude ($|b| > 10^\circ$). These sources are Mrk 421, PKS2155 − 304, PG1553 + 113 and 3C66A.
4.2 Data Analysis

Data Sample

Events of the diffuse class between 250 MeV-250 GeV are selected. Only the ones with energy larger than 250 MeV are chosen, as at lower energies the systematic uncertainties, to date, are not well understood (the S/N ratio of the LAT is low due to the PSF broadness, see section 3.1).

As stressed previously the aim of this analysis is to recognize the “best” SED for each source studied. In this section we report the fundamental steps done for each source in order to obtain this best SED that could be later on used for calibration purpose. The first step consist in produce a spectrum exploiting the whole data sample available for the source, obtaining the spectral shape averaged in the whole observed period. Using the Fermi LAT “Science Tools” we perform all the necessary analysis steps as described in section 3.2.2. In particular, for each source an appropriate source model is chosen and then used to fit the spectrum of the 9 month sample: in this fit the parameters relative to all the components are set free to have a better estimation of all the contributions.

Various spectral functions are available to model the spectra of the sources within the ROI. Regarding the diffuse components we assume that they are uniform at high galactic latitude (as such is the exposure of the instrument) and thus, for the galactic component, the spectrum is fitted with a constant function (and the spatial part is modeled with the GALPROP code 54.77Xvarh7S), while for the isotropic component we use the code provided by the Diffuse Fermi Group up to date.

The same model is used for all the point-source objects within the ROI, i.e. a power law function described by the following equation:

\[
\frac{dN}{dE} = \frac{N(\gamma + 1)E^\gamma}{E_{\text{max}}^{\gamma+1} - E_{\text{min}}^{\gamma+1}}
\]

where \( \gamma \) is the spectral index and \( \frac{dN}{dE} \) is the differential flux (for point sources is expressed in units of \( \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \) while for extended sources is considered per solid angle and so expressed in units of \( \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \text{sr}^{-1} \)). The integrated flux \( N \) is treated as a free parameter, together with the index, to be evaluated over the fixed energy range \( E_{\text{max}} - E_{\text{min}} \) (that in our analysis is the selected energy range). The errors are calculated in the minimization procedure and they do not account for the systematics.

In the particular case of the interested source, we make a first attempt to fit its spectrum with a power law function. The fit results show a problem with the spectral shape (especially evident in the case of Mrk 421), highlighted in the behavior of residuals at high energies. Therefore, accounting for the spectrum shape, we decide to try to fit it with a broken power law function, i.e. a power law spectrum with a spectral index \( (\gamma^1) \) from \( E_{\text{min}} = 250 \text{ MeV} \) to \( E_b \) (break energy), and a different spectral index \( (\gamma^2) \) from \( E_b \) to \( E_{\text{max}} = 250 \text{GeV} \):
4.2 Data Analysis

Figure 4.1: Fit spectral results for Mrk 421 accounting for the 9 month data sample performed with the likelihood method using the power law model (top panel), and the one using the broken power law (bottom panel): on the left counts versus fit model, on the right residuals.

\[
\frac{dN}{dE} = \left[ \int_{E_{\text{min}}}^{E_b} \left( \frac{E}{E_b} \right)^{\gamma_1} dE + \int_{E_b}^{E_{\text{max}}} \left( \frac{E}{E_b} \right)^{\gamma_2} dE \right]^{-1} \cdot \left\{ \begin{array}{ll} \left( \frac{E}{E_b} \right)^{\gamma_1} & \text{if } E \leq E_b \\ \left( \frac{E}{E_b} \right)^{\gamma_2} & \text{if } E \geq E_b \end{array} \right. \tag{4.2}
\]

In this function, in addition to the flux and index parameters, also the \( E_b \) is treated as free. The results of the fits with the two different models of eq. 4.1 and 4.2, in the case of Mrk 421, are shown in figure 4.1, while the estimated parameters are presented in table 4.1.

As we can see, for the broken power law the two indices are compatible within the errors: this means that the source does not significantly change between the lower and higher energy range to require this particular modeling. In addition, we notice that they are compatible with index of the power law model as well. Thus, as we find no statistical preference for a broken power law in the data sets, we choose the power law model. The power law model is also more suitable than the other one since in the
Table 4.1: Fit results using the power law and broken power law function for Mrk 421.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>Power law</th>
<th>Broken power law</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FLUX</td>
<td>γ</td>
</tr>
<tr>
<td>Mrk 421</td>
<td>0.7 ± 0.2</td>
<td>−1.7 ± 0.2</td>
</tr>
<tr>
<td>differential flux</td>
<td>(10^{-7}) cm(^{-2}) s(^{-1})</td>
<td>differential flux</td>
</tr>
<tr>
<td>galactic</td>
<td>0.7 ± 0.2</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>isotropic</td>
<td>1.2 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

latter both the value of the integrated flux and the value of \(E_b\) (\(E_b = 1451 ± 1244\)) are not well defined due to the large estimated errors.

Performing the fit, we have now obtained the values of the integrated flux and the spectral index. Clearly we have to pay attention on what we remarked in previous sections: it is fundamental to take into account that the variability of these objects can be very strong and as we consider a rather large, in time, data set, the source SED can undergo deep changes during the whole observation. The parameters estimated in such a way are just the average values in the whole period, therefore it is necessary to analyze smaller sets of data samples to verify if the source spectrum changes. A good compromise between having enough event statistics and having sufficiently small time interval is to select event sub-samples of a week length, so that we obtain 42 sub-samples.

Now, when performing the fit, we decide that the parameters relative to the galactic and extragalactic diffuse components can be fixed to the value estimated in the first overall fit of the whole period, as they should change on a weekly scale. Since the diffuse components are difficult to determine because of the still poor knowledge of their spectral shapes and since their estimations can have large fluctuations during small time intervals, the values of our interested parameters can be affected by its variations. On the other hand the estimations obtained from the 9 month fit can be a good approximations for the real values. Thus our way to proceed fixing both diffuse components at their average values, ensures that the recorded variations of the spectrum are caused by the studied source and not by fluctuations of these components.

Once we obtain the desired values in every week, we produce the light curve to verify the source behavior. As expected, the light curve shows a dynamic trend (for each source studied) so that we have to check if there is correlation between the integrated flux and the index. For each of the 42 weeks the fluxes are estimated between the energy range 250 MeV – 10 GeV as at this threshold we are in the Compton bump and, hence, we can measure the Compton spectral index.

The correlation has been calculated as the ratio between the covariance of the two parameters and the square root of their variance product:

\[
\text{Corr}(\text{flux}, \text{index}) = \frac{\text{Cov}(\text{flux}, \text{index})}{\sqrt{\text{Var}(\text{flux}) \text{Var}(\text{index})}}
\]
The results that will be presented in the following section show small value of correlation (in all the sources). Therefore we can divide the 42 sub-samples in classes according with the value of the flux: each class will represent a different source state. Thus, starting from the lower recorded value, we take four classes containing 7, 14, 14 and 7 data weeks. Then we verify the data homogeneity within the bunches: we analyze the (weekly) spectral shapes inferring the integrated flux and spectral index, we use these values to plot the function in eq. 4.1 and check if the sub-samples are homogeneous within the same class.

Afterwards each class sample is fitted with the same procedure of the 9 month sample (the time interval of every sample is now rather large) and the four spectral shapes relative to the different source states are evaluated. In the following section we report about the analysis and the results for every source. We stress that when performed the unfolding method more data were available and thus the additional point in all the unfolding light curve is just due to including a week more.

4.3 Analysis Results

4.3.1 Markarian 421

Mrk 421 is the closest known TeV blazar \((z = 0.030)\) and was the first extragalactic object discovered as TeV emitter (Punch et al., 1992). It is detected by the LAT with a statistical significance of \(\sim 47\) sigma. Moreover it is known to be one of the fastest varying gamma-ray sources. Mrk 421 has been extensively monitored in VHE gamma rays where it highlights a complex behavior, showing a low-level quiescent state with flaring on timescales as short as 30 minutes (Gaidos et al., 1996). In addition, it has been noticed that when the source extends to the TeV range, its flux can reach values larger than the Crab flux, as it was during a giant flare in 2004 (3 times the crab flux).

Recent observations of this source during 2003-2005 by VERITAS (Whipple) and MAGIC found the source to be very dynamic, showing evidence of spectral hardening with flux increase in both X-rays and \(\gamma\)-rays as well as a loose correlation between X-rays and gamma-rays (Rebillot et al., 2006).

Spectrum and Light Curve

Checking the counts map for the ROI of Mrk 421 we do not find any other source beside Mrk 421 itself, therefore, the adopted model for the fit includes only its spectrum and the diffuse components. The likelihood results for the fit parameters are reported in table 4.2 while in figure 4.1 the likelihood spectrum of Mrk 421 for the 9 month data sample and the corresponding residuals are displayed. Figure 4.2 displays the light curve performed with the likelihood analysis (blue points) and the preliminary results obtained with the unfolding analysis (red points). The integrated flux has been divided by its mean value to highlight the source variability and, as we can see, there is a good agreement between the values calculated with the two methods. This is also confirmed by the high correlation estimated \( \text{Corr} (\text{flux}_L, \text{flux}_U) = 0.858 \) which corresponds to a
Figure 4.2: The light curve of Mrk 421. The values of the daily integrated fluxes are divided by the mean value to display the source variability. The blue points correspond to the values calculated with the likelihood analysis while the red points are the one with the unfolding analysis.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>Integrated flux (10^{-7} \text{ cm}^{-2} \text{ s}^{-1})</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 421</td>
<td>0.7 ± 0.2</td>
<td>−1.7 ± 0.2</td>
</tr>
</tbody>
</table>

| differential flux (\text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} \text{ sr}^{-1}) |
|---------------------------------|---|
| galactic                        | 1.197 ± 0.004 |
| isotropic                       | 1.20 ± 0.16 |

Table 4.2: Fit results in the ROI centered in Mrk 421 for the 9 month data sample.

Variability Investigation

From the light curve we notice that the source has been quite low in the observed period, anyway we proceed verifying if there is correlation between the flux and the spectral index as discussed in section 4.2. Referring to figure 4.3 the distribution of the values do not show any particular trend and indeed the calculated value for the correlation is rather low: \text{Corr}(\text{flux, index}) = 0.045.

\[ t = 10.575^1. \]

\[ t = r[(N - 2)/(1 - r^2)]^{1/2}, \] where \( r \) is the correlation between the two flux and \( N \) the number of freedom degrees.
4.3 Analysis Results

Figure 4.3: Referring to the source Mrk 421, the left panel shows the integrated flux vs. spectral index evaluated for each of the 42 weeks, while the right panel shows the histogram of the integrated flux.

Classes for Different Source State

After having verified that there is no correlation between the flux and the spectral index, we can split the sample into 4 classes, according to the flux values, as previously explained in 4.2. Figure 4.3 shows the histogram of the flux values for Mrk 421 and while in figure 4.17 we can instead verify the homogeneity of the 4 classes created with this procedure.

Spectra for Different Source State

Once we have obtained the 4 classes we analyze them with the procedure described in section 4.2. The estimated values for the integrated flux and spectral index are reported in table 4.3.1 while referring to the figure 4.4 we find the resulting four spectra with the correspondent residuals: from the top to the bottom the first, second, third and fourth classes are displayed.

<table>
<thead>
<tr>
<th>MRK 421</th>
<th>Integrated flux $(10^{-7} \text{ cm}^{-2} \text{ s}^{-1})$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1</td>
<td>0.315 ± 0.039</td>
<td>$-1.65 \pm 0.059$</td>
</tr>
<tr>
<td>class 2</td>
<td>0.407 ± 0.034</td>
<td>$-1.68 \pm 0.041$</td>
</tr>
<tr>
<td>class 3</td>
<td>0.559 ± 0.040</td>
<td>$-1.80 \pm 0.041$</td>
</tr>
<tr>
<td>class 4</td>
<td>0.663 ± 0.070</td>
<td>$-1.88 \pm 0.065$</td>
</tr>
</tbody>
</table>

Table 4.3: Integrated flux and spectral index for the 4 classes data sample of Mrk 421.
Figure 4.4: Fit spectral results for the four classes of Mrk 421 (performed with the likelihood): from the top to the bottom we find the first, second third and fourth class, respectively. The left panel reports counts versus fit model, the right panel the residuals fit.
4.3.2 PKS 2155−304

At a redshift of \( z = 0.12 \), the HBL PKS 2155-304 was first detected at TeV energies in 1999 by the Durham telescopes, with a statistical significance of 6.8 standard deviations and now it is one of the most distant well-established sources of TeV gamma rays. The LAT detected it with a statistical significance of \( TS \sim 44 \sigma \). It is associated with a compact radio source and exhibits an essentially featureless continuum from radio to X-ray frequencies. The maximum power emitted by PKS 2155-304 is between the UV and soft X-ray range, and it is the brightest BL Lac detected in the UV regime as reported in Wandel and Urry (1991).

Recently observation of this object has been made by a multiwavelength campaign that included Fermi and H.E.S.S. telescope (Aharonian et al., 2009). During this period the source was detected close to the lowest archival X-ray and very high energy (> 100 GeV) state. A particularly noteworthy result of this detection is that it highlighted a probable optical/VHE correlation and evidence for a correlation of the X-rays with the high energy spectral index while, on the contrary, in previous observations when the source was in flaring state, no correlation between the X-ray and VHE components was found. This results yields an evidence that its spectral and variability properties are significantly different than its flaring, high state behavior.

Spectrum and Light Curve

The counts map of PKS2155−304 evidences another object within the selected ROI: this is the source NMS1139 classified by Fermi as a blazar and detected with \( TS = 115 \). Therefore, the fit function includes the (power law) model that accounts for it and the usual functions which account for to the studied source and the diffuse components as well. The likelihood results for the fit parameters are reported in table 4.4 while in figure 4.5 the likelihood spectrum of the source for the 9 month data sample and the corresponding residuals are displayed. Referring to figure 4.6 which presents the light curve, we find the likelihood values for the (daily) integrated flux divided by the mean value (blue points) which show a behavior in agreement with the preliminary correspondent quantity estimated by the unfolding method (red points). The correlation estimated yields in this case to \( \text{Corr} (\text{flux}_L, \text{flux}_U) = 0.83 \) which corresponds to a \( t = 9.4 \).

Variability Investigation

After a first overview of the source behavior provided by the light curve, we proceed verifying the correlation between the integrated flux and the spectral index. The distribution of the values, represented in figure 4.7, apparently shows a linear trend, from lower to higher flux values. In fact, the evaluation of the correlation yields the largest value with respect to the studied sources, \( \text{Corr} (\text{flux}, \text{index}) = 0.181 \).
<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>Integrated flux ((10^{-7} \text{ cm}^{-2} \text{ s}^{-1}))</th>
<th>(\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS2155 − 304</td>
<td>0.931 ± 0.027</td>
<td>−1.88 ± 0.02</td>
</tr>
<tr>
<td>NMS1139</td>
<td>0.38 ± 0.11</td>
<td>−2.46 ± 0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>differential flux ((\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}\text{sr}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>galactic</td>
<td>1.38 ± 0.17</td>
</tr>
<tr>
<td>isotropic</td>
<td>0.87 ± 0.14</td>
</tr>
</tbody>
</table>

Table 4.4: Fit results in the ROI centered in PKS 2155-304 for the 9 month data sample

![Figure 4.5](image1)

Figure 4.5: Fit spectral results for PKS 2155 − 304 accounting for the 9 month data sample performed with the likelihood: on the left counts versus fit model, on the right fit residuals.

Classes for Different Source State

We split the sample into 4 classes, according with the flux values, as previously discussed. Figure 4.7 shows the histogram of the flux values for PKS 2155−304 and in figure 4.17 we can instead verify the homogeneity of the 4 classes created with this procedure.

Spectra for Different Source State

With the usual procedure of section 4.2 we fit the four class samples and obtain the resulting spectra with the correspondent residuals: from the top to the bottom the first, second, third and fourth classes are displayed in figure 4.8. The estimated values for the integrated flux and spectral index are reported in table 4.5.
4.3 Analysis Results

Figure 4.6: The light curve of PKS 2155 – 304. The values of the daily integrated fluxes are divided by the mean value to underline the source variability. The blue points correspond to the values calculated with the likelihood analysis while the red points are the one with the unfolding analysis.

Figure 4.7: Referring to the source PKS 2155 – 304, the left panel shows the integrated flux vs. spectral index evaluated for each of the 42 weeks, while the right panel shows the histogram of the integrated flux.

<table>
<thead>
<tr>
<th>PKS2155 – 304</th>
<th>Integrated flux $(10^{-7} \text{ cm}^{-2} \text{s}^{-1})$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1</td>
<td>$0.565 \pm 0.056$</td>
<td>$-1.766 \pm 0.067$</td>
</tr>
<tr>
<td>class 2</td>
<td>$0.775 \pm 0.045$</td>
<td>$-1.864 \pm 0.042$</td>
</tr>
<tr>
<td>class 3</td>
<td>$0.937 \pm 0.051$</td>
<td>$-1.853 \pm 0.040$</td>
</tr>
<tr>
<td>class 4</td>
<td>$1.470 \pm 0.079$</td>
<td>$-1.950 \pm 0.044$</td>
</tr>
</tbody>
</table>

Table 4.5: Integrated flux and spectral index for the 4 classes data sample of PKS2155 – 304.
Figure 4.8: Fit spectral results for the four classes of PKS2155 – 304 (performed with the likelihood): from the top to the bottom we find the first, second third and fourth class, respectively. The left panel reports counts versus fit model, the right panel the residuals.
4.3 Analysis Results

4.3.3 PG1553 + 113

PG1553+113 (Ra = 238.938, dec = 11.188) is classified as an HBL with the redshift still essentially unknown (the lower limit estimated is $z < 10.42$) as up to now no emission or absorption lines have been detected. Another difficulty in the redshift estimation is due to the fact that the host galaxy is not resolved. The source is detected by the LAT with a statistical significance of $\sim 31$ sigma and in addition, in the GeV-TeV energy range can be observed both by H.E.S.S. and MAGIC. Its very high energy spectrum shows features that can be due to absorption by the low-energy photon field of the extragalactic diffuse component (see section 1.10).

Spectrum and Light Curve

The count map for the ROI of PG1553 + 113 shows the presence of several sources in addition to the interested one. These are NMS0788 (still unidentified TS = 49), NMS0792 (blazar, TS = 983), NMS0808 (a blazar associated with the 3EG J1608+1055 source TS = 127) and NMS0796 (blazar, TS = 957). This latter in particular shows from the fit a quite high value of the (integrated) flux in respect to PG1553 + 113 (see table 4.6) but considering also the correspondent spectral indexes we can see that for the higher energy band is dominant the contribution of our source. As usual all the extra sources have been included in the modeling which is displayed in figure 4.9. As regard the light curve (see figure 4.10), also for this source the trend of the weekly fluxes estimated with the two analysis methods are in well agreement. The correlation estimated for PG1553 + 113 yields to $\text{Corr}(\text{flux}_L, \text{flux}_U) = 0.253$ which corresponds to a $t = 1.677$.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>Integrated flux ($10^{-7}$ cm$^{-2}$ s$^{-1}$)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG1553 + 113</td>
<td>0.36 ± 0.0197</td>
<td>$-1.68 \pm 0.03$</td>
</tr>
<tr>
<td>NMS0788</td>
<td>0.170 ± 0.065</td>
<td>$-2.17 \pm 0.17$</td>
</tr>
<tr>
<td>NMS0792</td>
<td>0.13 ± 0.09</td>
<td>$-2.28 \pm 0.32$</td>
</tr>
<tr>
<td>NMS0796</td>
<td>1.44 ± 0.13</td>
<td>$-2.34 \pm 0.053$</td>
</tr>
<tr>
<td>NMS0808</td>
<td>0.69 ± 0.20</td>
<td>$-2.82 \pm 0.19$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>differential flux (cm$^{-2}$s$^{-1}$MeV$^{-1}$sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>galactic</td>
</tr>
<tr>
<td>isotropic</td>
</tr>
</tbody>
</table>

Table 4.6: Fit results in the ROI centered in PG1553 + 113 for the 9 month data sample
Variability investigation

When we proceed in verify if there is correlation between the flux and the spectral index as discussed in section 4.2 (see figure 4.11) we find a low correlation value, \( \text{Corr}(\text{flux}, \text{index}) = 0.044 \).
4.3 Analysis Results

Figure 4.11: Referring to the source PG1553 + 113, the left panel shows the integrated flux vs. spectral index evaluated for each of the 42 weeks, while the right panel shows the histogram of the integrated flux.

Classes for different Source State

As usual we divide the sample into 4 classes, according with the flux values, as previously discussed. Figure 4.11 shows the histogram of the flux values for PG1553 + 304 and in figure 4.17 we can instead verify the homogeneity of the 4 classes created with this procedure.

Spectra for different Source State

With the usual procedure of section 4.2 we fit the four class samples and obtain the resulting spectra with the correspondent residuals: from the top to the bottom the first, second, third and fourth classes are displayed in figure 4.12. The estimated values for the integrated flux and spectral index are reported in table 4.7.

<table>
<thead>
<tr>
<th>Class</th>
<th>Integrated flux (10^{-7} \text{ cm}^{-2} \text{ s}^{-1})</th>
<th>\gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1</td>
<td>0.245 ± 0.013</td>
<td>-1.707 ± 0.033</td>
</tr>
<tr>
<td>class 2</td>
<td>0.291 ± 0.031</td>
<td>-1.610 ± 0.061</td>
</tr>
<tr>
<td>class 3</td>
<td>0.445 ± 0.038</td>
<td>-1.659 ± 0.050</td>
</tr>
<tr>
<td>class 4</td>
<td>0.605 ± 0.063</td>
<td>-1.877 ± 0.071</td>
</tr>
</tbody>
</table>

Table 4.7: Integrated flux and spectral index for the 4 classes data sample of PG1553 + 113.
Figure 4.12: Fit spectral results for the four classes of PG1553+113 (performed with the likelihood): from the top to the bottom we find the first, second third and fourth class, respectively. The left panel reports counts versus fit model, the right panel the residuals fit.
3C66A is classified as a low frequency peaked BL Lac (LBL) at redshift \( z = 0.444 \). Its low frequency spectral component peaks at optical/UV while the high frequency component peaks in MeV-GeV range. In the same region there is the radio galaxy 3C66B \( (z=0.021) \) separated from the blazar by about 8 arc minutes. At microwave frequencies the emission of the radio galaxy dominates the one of the blazar, while vice versa, at higher energies it is the blazar that dominates. The radio galaxy 3C66B has been thus excluded as a possible source of the VHE emission, even if MAGIC observation seems to prefer as the actual VHE source the location of 3C66B (Aliu et al., 2009). However, 3C66A is a promising candidate for observation at very high (> 100 GeV) energies by the new generation Cerenkov telescopes. It is detected by the LAT with a statistical significance of \( TS \sim 47 \).

**Spectrum and Light Curve**

In the modeling of the observed spectra we have to include three additional sources. These are NMS0122 (a source associated with the AGN QSO B3 0224+393, \( TS = 31 \)), NMS0124 (a source associated with the blazar QSO B3 0227+403, \( TS = 77 \)) and PSRJ0218+4232 (a pulsar with \( TS = 273 \)). We can see the spectrum of the 9 month data sample in figure 4.14 and the fit results in table 4.8. Figure 4.13 displays the light curve performed with the likelihood analysis (blue points) and the preliminary results obtained with the unfolding analysis (red points). The integrated flux has been divided by its mean value to highlight the source variability and as we can see there is a good agreement between the values calculated with the two methods. This is also confirmed by the very high correlation estimated \( \text{Corr} (\text{flux}_L, \text{flux}_U) = 0.957 \) which corresponds to a \( t = 20.763 \). For this source the trend of the weekly fluxes estimated with the two analysis methods is clearly in well agreement showing an increasing activity of the source especially in the final detected weeks.

<table>
<thead>
<tr>
<th>Component</th>
<th>flux ((10^{-7} \text{ cm}^{-2} \text{ s}^{-1}))</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C66A</td>
<td>0.939 ± 0.032</td>
<td>−1.914 ± 0.024</td>
</tr>
<tr>
<td>NMS0122</td>
<td>0.20 ± 0.11</td>
<td>−2.68 ± 0.30</td>
</tr>
<tr>
<td>NMS0124</td>
<td>0.260 ± 0.089</td>
<td>−2.35 ± 0.17</td>
</tr>
<tr>
<td>PSRJ0218+4232</td>
<td>0.89 ± 0.13</td>
<td>−2.30 ± 0.076</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>differential flux ((\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}\text{sr}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>galactic</td>
<td>0.724 ± 0.064</td>
</tr>
<tr>
<td>isotropic</td>
<td>1.67 ± 0.14</td>
</tr>
</tbody>
</table>

**Table 4.8:** Fit results in the ROI centered in 3C66A for the 9 months data sample
Chapter 4 – Observation of a Blazar Sample

Figure 4.13: The light curve of 3C66A. The blue points are the likelihood values for the daily integrated fluxes while the red points are the one for the unfolding.

Figure 4.14: Fit spectral results for 3C66A accounting for the 9 months data sample performed with the likelihood: on the left counts versus fit model, on the right fit residuals.

Variability investigation

Proceeding with the analysis we calculate correlation between the integrated flux and the spectral index which yields a low value: Corr(flux,index) = -0.04. Referring to figure 4.15 which reports the distribution of the values, we can see that also for this source the distribution do not show any particular trend.
4.3 Analysis Results

**Figure 4.15:** Referring to the source 3C66A, the left panel shows the integrated flux vs. spectral index evaluated for each of the 42 weeks, while the right panel shows the histogram of the integrated flux.

### Classes for different Source State

After having verified the correlation between the flux and the spectral index, we can split the sample into 4 classes, according to the flux values, as previously explained in 4.2. Figure 4.15 shows the histogram of the flux values for 3C66A while in figure 4.17 we can verify the homogeneity of the 4 classes created with this procedure.

### Spectra for different Source State

Following the procedure of section 4.2 we fit the four class samples and obtain the resulting spectra with the corresponding residuals: from the top to the bottom the first, second, third and fourth classes are displayed in figure 4.16. The estimated values for the integrated flux and spectral index are reported in table 4.9.

<table>
<thead>
<tr>
<th>3C66A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated flux $ \left(10^{-7} \text{ cm}^{-2} \text{ s}^{-1}\right)$</td>
</tr>
<tr>
<td>class 1</td>
</tr>
<tr>
<td>class 2</td>
</tr>
<tr>
<td>class 3</td>
</tr>
<tr>
<td>class 4</td>
</tr>
</tbody>
</table>

**Table 4.9:** Integrated flux and spectral index for the 4 classes data sample of 3C66A.
Figure 4.16: Fit spectral results for the four classes of 3C66A (performed with the likelihood): from the top to the bottom we find the first, second third and fourth class, respectively. The left panel reports counts versus fit model, the right panel the residuals fit.
Figure 4.17: The four classes for Mrk 421, PKS 2155-304, PG1553 + 113 and 3C66A, respectively. They are here plotted as function of energy to display the homogeneity of samples within every class. The integrated flux is estimated between 250 MeV-10 GeV. The black lines correspond to the first class (lowest value of integrated flux observed), the red lines correspond to the second class (middle-low value of integrated flux observed), the green lines correspond to the third class (middle-high value of integrated flux observed), the blue lines correspond to the fourth class (highest value of integrated flux observed).
Chapter 5

Conclusion and Future Perspectives

This thesis presents a first attempt to provide a description of VHE blazar SEDs. Although blazars constitute the most numerous class of extragalactic $\gamma$-ray sources, only few of them are detected in the VHE range. In addition, the components of the VHE class are of crucial importance in the study of the GeV-TeV energies as they can enable a significant progress both in the comprehension of the blazar physics and in the understanding of extragalactic $\gamma$-ray interactions. Since the large dynamic range of VHE blazars is covered by several instruments, multi-wavelength campaigns are necessary to provide complete (and simultaneous) observations of the sources and, moreover, to display the evolution of their spectra.

The spectral analysis of chapter 4 is performed with the standard method provided by the Fermi Science tools (v9r12). This method, by means of the standard LAT analysis software, performs a maximum likelihood fit of the model parameters for each observed source which accounts also for additional objects, if detected in the selected ROI. The diffuse components are fit with the data as well, hence taking into account also the residual instrumental background. The galactic diffuse emission is derived using the GALPROP code, while the extragalactic diffuse emission is modeled with an isotropic power law component (these are both presented in section 3.2.4).

The likelihood results for the light curves (on weekly time interval) have been compared with the results of a preliminary analysis performed using the unfolding technique based on Bayes theorem. The latter method allows to reconstruct the energy spectrum of the source from the observed data after background subtraction, without assuming any parametric model, and including the energy dispersion effect of the instrument response. The results obtained are in good agreement with the one of the standard analysis; however, we want to remark that unfolded results are just preliminary as the method has to be tested and implemented.

As we are dealing with highly variable sources, the spectrum evaluated for a large time sample is rather useless for our purposes. This spectrum can actually be substantially different from the one observed in the extreme source states, i.e. when the source flares. Therefore, after estimating the correlation flux/index, we proceeded dividing each 9 month source data into 4 classes by observing the values of the integrated flux in every week, and then we verified the homogeneity within each class. Afterwards we
fitted the spectrum of each class, thus obtaining the correspondent SED for the various source states. For every source the results showed a very good agreement between model and spectrum at lower energies, and also when considering the higher energies the residuals have still a good distribution even if the statistic is quite low.

5.1 GeV-TeV Calibration

In this thesis we have just started to work in the challenging field of the GeV-TeV calibration. We made a splitting of the large time samples based only on the integrated flux values which is clearly just a first approximation of what should be an accurate analysis. Actually an accurate analysis should account also for the detected events energy to produce homogeneous data set. Moreover, to be useful for the calibration of Cherenkov telescope, it should allow us to relate directly the data collected in the different bands by several instruments. From this point of view, as we have seen in the previous chapters, the likelihood method is rather incomplete, since it provides the modeled spectrum of the source but not the covariance matrix among the data points. This is the reason for which we are trying to implement an alternative procedure, i.e. the unfolding analysis, which has all the main ingredients needed by this topic:

- provides points and not parameters of a template spectrum;
- provides a covariance matrix among these points;
- does not depend from the “isotropic model” used.

Anyway, with the likelihood approach some interesting results are already available. Figure 5.1 displays the observation results of a multi-wavelength campaign on Markarian 421, organized by the Fermi/LAT team, which covered the period from the end of January 2009 until the end of May 2009. The data points of TeV Cherenkov telescope (MAGIC, open circle) show an excellent agreement with the Fermi LAT data points (filled circle). A noteworthy feature of the spectral shape suggests a turn over of the spectrum around 100 GeV. At these energies, the energy bins for the LAT have large statistical error bars and could hide the curvature in the spectrum.

This is a preliminary result but it leads to exiting perspectives. The LAT data allow a deep study on individual sources in the (new) high energy band where we can understand the physical processes occurring inside blazars, on the other hand, multi-wavelength observations are of fundamental importance, as well, allowing to outline all their complex aspects. To merge all these information thus, the joint calibration with Fermi LAT and the Cherenkov instruments will be crucial and extend our knowledge of blazar behavior also to the GeV-TeV range.
Figure 5.1: Results of a multi-wavelength campaign on Markarian 421 for the MeV-TeV energy range. Filled circles indicates the LAT data points, open circles the one detected with MAGIC. Notice the good agreement between the two experiments.
Appendix A

Superluminal Motion

Observations made by Very Large Baseline Interferometry show that at radio frequencies in the AGNs are present very compact components, moving apart with apparent transverse speeds greater than the velocity of light. The phenomenon, known as superluminal motion, is due to relativistic beaming and can be explained considering small inhomogeneities that move alongside with the jet, the latter pointing at small offset angles with respect to our line of sight. We will consider the simplest demonstration of superluminal motion which is provided by a two source (blob) model.

Suppose to have initially two sources at the point B at time $t_1$ and afterward, at time $t_2$, one blob has moved a distance $v \Delta t$ from the other (see figure A.1).

![Figure A.1: Observational scheme of superluminal motion. This phenomenon is due to relativistic beaming explained by considering small inhomogeneities that move alongside with the jet, the latter pointing at small offset angles with respect to our line of sight.](image)

The observer detects an initial signal at time $t_1'$ (when the blobs are both in the same position): in this case their signal will have traveled the distance $D + v \Delta t \cos \theta$. At later time $t_2'$ the observer records again information about the light-travel time between him and the two sources: one is still at the distance $AB$ but now the other is approximately at distance $D$. The angular separation between the two blobs at time $t_2'$ is

$$\Delta \phi = \frac{v \Delta t \sin \theta}{D}$$

If $\Delta t$ indicates the time that the observer measures between the two detections it can
be easily calculated by noting

\[ t'_1 = t_1 + \frac{D + v \delta t \cos \theta}{c} \]

and

\[ t'_2 = t_2 + \frac{D}{c} \]

thus, the time elapsed between the two observations is

\[ \Delta t = t'_2 - t'_1 = t_2 - t_1 - \frac{v \delta t \cos \theta}{c} = \delta t (1 - \beta \cos \theta) \]

where \( \beta = \frac{v}{c} \) in the usual convention. We can finally compute the transverse velocity

\[ \beta_T = \frac{v_T}{c} = \frac{D}{c} \frac{\Delta \phi}{\Delta t} = \frac{v \sin \theta}{c(1 - \beta \cos \theta)} = \frac{\beta \sin \theta}{1 - \beta \cos \theta} \quad (A.1) \]

Now we want to express \( \beta_T \) as a function of the angle to the line of sight \( \theta \), and find for which angle \( \beta_T \) is maximized; thus, we differentiate eq. A.1 with respect to \( \theta \) and set the result equal to zero:

\[ \frac{\partial \beta_T}{\partial \theta} = \frac{\beta \cos \theta}{1 - \beta \cos \theta} - \frac{(\beta \sin \theta)(\beta \sin \theta)}{(1 - \beta \cos \theta)^2} = 0 \]

and then this yields \( \theta_{\text{max}} = \cos^{-1} \beta \). By inserting this in eq. A.1 and noting that

\[ \sin(\cos^{-1}\beta) = (1 - \beta^2)^{1/2} \]

the maximum value of \( \beta_T \) can be obtained as function of the Lorentz factor, \( \gamma = \frac{1}{(1 - \beta^2)^{-1/2}} \)

\[ \beta_{\text{Tmax}} = \frac{\beta (1 - \beta^2)^{1/2}}{(1 - \beta^2)} = \beta \gamma \quad (A.2) \]

It is worth notice that for \( \beta \to 1 \) \( \beta_{\text{Tmax}} \approx \gamma \), and thus, in the case of relativistic motion close to the line of sight (i.e. \( \theta \approx \cos^{-1}\beta \)), the observer detects transverse separation velocities apparently greater than \( c \).
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Few people live.
It is true life only to realize one’s own perfection,
to make one’s every dream a reality.

Oscar Wilde

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Poche persone vivono.
La vera vita consiste nel realizzare la propria perfezione,
fare di ogni proprio sogno una realtà.

Oscar Wilde

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