Spectral Studies of Flaring FSRQs at GeV Energies Using Pass 8 Fermi-LAT Data

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Abstract: Flat spectrum radio quasars (FSRQs) are bright active galactic nuclei surrounded by gas clouds within a UV-visible intense radiation field that form the so-called broad line region (BLR). These objects emit relativistic jets from a region close to the central supermassive black hole and through the BLR. The Fermi-Large Area Telescope (LAT) is sensitive to gamma-ray photons from ~30 MeV to more than 300 GeV. We have performed spectral analysis of bright FSRQs in a 5.5 year (2008-2014) data sample collected by Fermi-LAT data, using the new Pass 8 event selection and instrument response function. Also, our study of flaring episodes in a limited time range brings interesting results while compared to the full 5.5 year data samples.

Project: Studying the spectral shape of flat spectrum radio quasars (FSRQs) in the 0.1-100 GeV energy range to constrain the location of the gamma-ray emission region: within or beyond the broad line region (BLR).

FSRQs is a class of active galactic nuclei with a denser BLR in which gamma rays are absorbed due to electron-positron pair, if produced below the outer shell of the BLR. Indeed, BLR is expected to be denser in FSRQs compared to the BL Lac class.

Operating since 2008, the *Fermi* satellite has amassed more than 6 years of data, continuously surveying the whole sky (Atwood et al. 2009). The energy sensitivity of Fermi-LAT in the 30 MeV-300 GeV range is ideal for the study of the gamma-ray absorption inside FSRQs at high energy and constraining it may yield the location of the gamma-ray emission region.
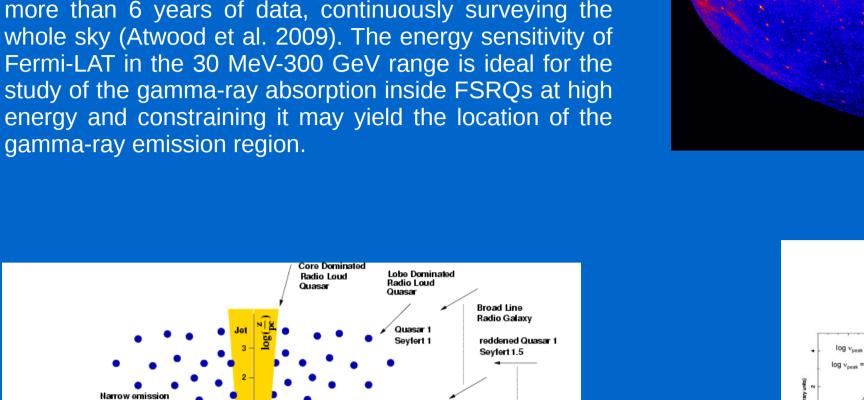
Image Credit: NASA/DOE/Fermi LAT Collaboration

FSRQs versus BL Lacs

Blazars are identified by the position of the synchrotron peak (Low, Intermediate or High) and classified into two classes:

- **Flat Spectrum Radio Quasars (FSRQs)**
  - Always radio-loud
  - Strong emission lines
  - Almost all FSRQs are LSP blazars
  - Leptonic process of gamma ray emission mainly though external Compton
  - Higher luminosity
  - Softer spectral index

- **BL Lacs**
  - Emission lines weak or non existent
  - Leptonic process of gamma-ray emission mainly self-Compton
  - Lower luminosity
  - Harder spectral index

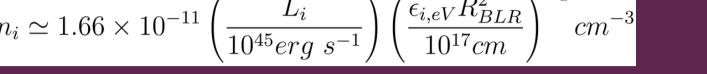Image credit: Christian Zier , Peter L. Biermann (2002)

Modelling the radiation field of the broad-line region

We expect > 10 GeV photons of FSRQ to undergo absorption in the BLR through the two photon pair production process, where the target photon with energy ε is a UV photon from the BLR radiation field. As most of these photons are expected to come from the emission lines, we use a model that includes the 6 strongest lines between ~10 to 41 eV (Telfer et al at 2002). We model these lines using a *Breit-Wigner* distribution, given by:
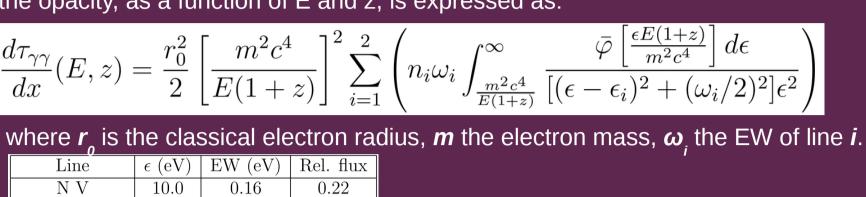
$$BW(\epsilon) = \frac{n_i\ \omega_i}{2\ \pi[(\epsilon - \epsilon_i)^2 + (\omega_i/2)^2]}$$

- R_{BLR} : luminosity of the BLR
- R_{BLR} : radius of the BLR
- L_{disc} : luminosity of the accretion disc

The $\gamma\gamma$ opacity in the BLR is calculated assuming the gamma rays are produced within $a \times R_{BLR}$, where R_{BLR} is the outer radius of BLR and $a < 1$. Since this absorption happens at some distance from the supermassive black hole, this corrective factor that we called '**a**' represents the fraction of the BLR responsible for the absorption.

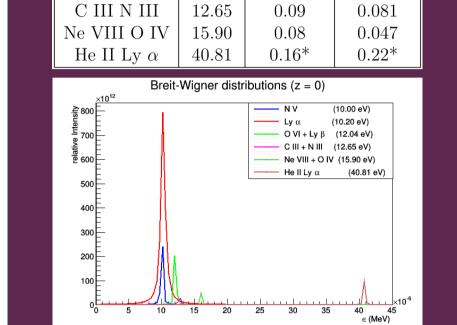Under the commonly used relations $L_{BLR} = 0.1\ L_{disc}$ and $R_{BLR} = \sqrt{L_{disc}}$ (Baldwin & Netzer 1978; Ghisellini & Tavecchio 2009), the photon density n_i of the radiation field for each line i can be written:

$$n_i \simeq 1.66 \times 10^{-11} \left(\frac{L_i}{10^{45}erg\ s^{-1}}\right) \left(\frac{\epsilon_{i,eV} R_{BLR}^2}{10^{17}cm}\right)^{-1}\ cm^{-3}$$

$$\tau_{\gamma\gamma}(E,z) = R_{BLR} \times \frac{d\tau_{\gamma\gamma}}{dx}(E,z)$$

Derived from Gould and Schréder (1967) and Brown, Mikaelian & Gould (1973) the opacity, as a function of E and z, is expressed as:

$$\frac{d\tau_{\gamma\gamma}}{dx}(E,z) = \frac{r_0^2}{2}\left[\frac{m^2c^4}{E(1+z)}\right]^2 \sum_{i=1}^{2} \left(n_i\omega_i \int_{\frac{m^2c^4}{E(1+z)}}^{\infty} \frac{\bar{\varphi}\left[\frac{\epsilon E(1+z)}{m^2c^4}\right]d\epsilon}{[(\epsilon - \epsilon_i)^2 + (\omega_i/2)^2]\epsilon^2}\right)$$

where r_e is the classical electron radius, m the electron mass, ω_i the EW of line i.

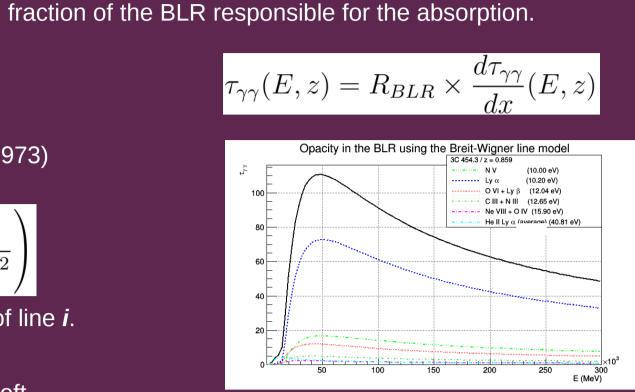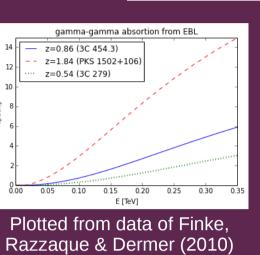| Line	ϵ (eV)	ω (eV)	Rel. flux
N V	10.16	0.16	0.22
Ly α	10.2	0.71	1.00
O VI Ly β	12.04	0.19	0.191
C III N III	12.65	0.09	0.081
N VIII O IV	15.90	0.08	0.047
He II Ly α	40.81	0.16*	0.22*

The table and the figure on the left display the line properties of the average spectrum of quasars we used in our model, as they were compiled in Telfer at al 2002. Due to the uncertainty of these line properties for the He II Ly alpha line, we arbitrary fixed its EW and relative flux to be equal to the ones of N V (uncertainty represented by *).

Poutanen & Stern (2010) and Stern & Poutanen (2014) have reported evidence of absorption in the BLR for some FSRQs.

Very high energy gamma rays travelling from far distances undergo absorption from the extragalactic background light ('EBL', and mainly composed of infrared radiation). This absorption is to be considered above 10 GeV and has been added in our model.

Plotted from data of Finke, Razzaque & Dermer (2010)
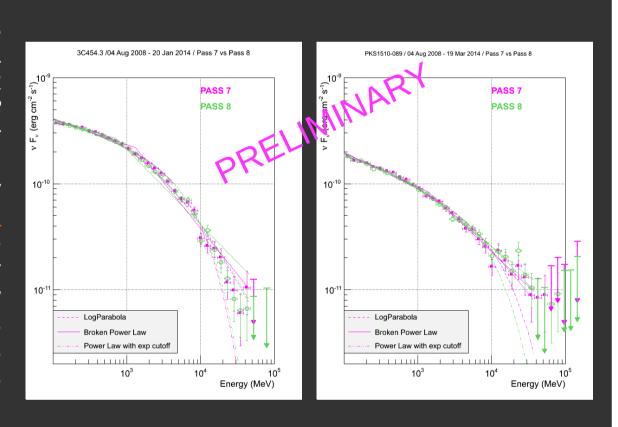
Data processing and model fitting

We have analysed data of 7 bright FSRQs. Data under the label "5.5 years" have been processed from 4 August 2008 till 30 April 2014. The sources we present in this poster are listed below. LII and BII being respectively the Galactic latitude and longitude in decimal degrees.

Name	RA (J2000.0)	Dec (J2000.0)	LII	BII	Redshift	Spectral index 1FGL	Flux 2FGL 1GeV-100 GeV	Flux 1FHL 10GeV-100 GeV
3C 454.3	22 53 57.7	+16 08 53.1	86.11	-38.19	0.859	2.46619	9.65e-8	1.35e-9
PKS 1510-08	15 12 50.5	-09 06 00.9	351.28	40.13	0.360	2.40756	4.06e-8	7.35e-10
4C +21.35	12 24 54.5	+21 22 46.9	255.08	81.65	0.434	2.54717	3.54e-8	7.43e-10
3C 279	12 56 11.0	-05 47 20.1	305.1	57.06	0.536	2.32061	2.56e-8	5.37e-10
PKS 0454-234	04 57 03.1	-23 24 52.0	223.7	-34.9	1.003	2.20649	2.27e-8	2.99e-10
B2 1520+31	15 22 09.8	+31 44 14.3	50.16	57.02	1.484	2.42125	1.76e-8	4.27e-10
PKS B1424-418	14 27 56.2	-42 06 18.6	321.44	17.26	1.522	2.31004	1.47e-8	2.9e-10

Data were processed using the Pass 8 data representation, and the Science Tools version *v9-34-01*. Galactic model *4years_P8_V2_scaled*, isotropic model *4years_P8V3*, no Earth limb template (no expected systematic above 200 MeV). ROI = 10°, SR = ROI + 10°. Signal reconstructed from each source using the unbinned likelihood tool. Considering the absorption models discussed at the previous section, the observed flux will be modelled as:

$$F_{obs}(E) = e^{-a\ \tau_{\gamma\gamma}(E,z)}\ e^{-\tau_{EBL}(E,z)}\ F_{int}(E)$$

The current public release of data representation is Pass 7. In order to test the stability of the data processing of Pass 8 with respect to Pass 7, we first compared the spectral energy distributions of *Pass 8 versus Pass 7* of the two brightest sources of our FSRQ sample: 3C 454.3 and PKS 1510-089. Although some bin-to-bin fluctuations appear due to energy wise event migration, the two SEDs (Pass 7 and Pass 8) for both the sources are compatible. One specific feature remains apparent in the SED (either Pass 7 or Pass 8) of both the sources, that is a narrow dip at 10 GeV. The significance of this feature is currently under investigation. In this poster we discuss spectral features on a wider energy range, such as what we expect from the gamma ray absorption in the BLR above 10 GeV.

Fit functions

Fits were performed from 100 MeV till the last energy point, using:

- a log-parabola (LP);
- A broken power law (BPL);
- A power law with an exponential cutoff (PLEC).

In each of these functions we can include:
- EBL absorption
- EBL + opacity of the BLR (→ LPτ, BPLτ, PLECτ.)

Fitting procedure:

- A first standard LP fit is performed while keeping all parameters fixed to the values obtained by the unbinned likelihood analysis and χ^2/ndf is returned;
- A second standard LP fitting is performed with N0, α and β kept free, while E_b kept fixed to the unbinned likelihood fit value;
- We compare the fit;
- We fit LP, BPL and PLEC that all now include EBL;
- We fit LPτ, BPLτ, PLECτ $(= LP/BPL/PLEC \times exp(-a\ \tau_{\gamma\gamma}) \times exp(-\tau_{EBL}))$
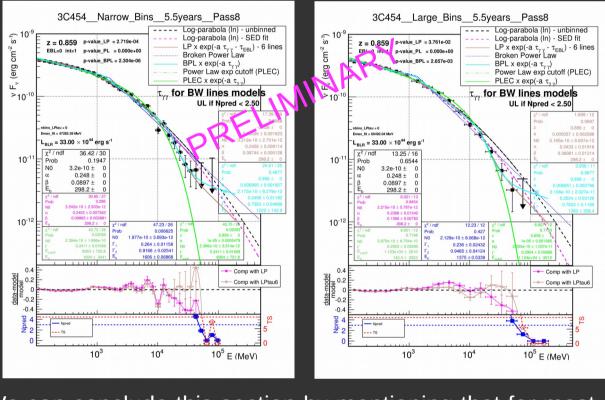
Parameter a is kept free in the [10^-5, 1] range to account for the fraction of radius of the BLR in which gamma rays may be absorbed.

The fitting procedure using the absorption models is implemented by interpolation of both the τ_{EBL} and $\tau_{\gamma\gamma}$ graphs. While comparing each **"EBL + BLR absorption"** fit (*LPτ, BPLτ or PLECτ*) with the **"no absorption fit"** (*LP, BPL or PLEC*), and if both fits have a χ^2/ndf <~ 1, we obtain a **p-value** which indicates the discrepancy between the fit with model and the fit without model, for a given function.

Investigation of systematic effects on fitting data points

Fit parameters of a set of predefined fitting functions are returned by the unbinned likelihood analysis, according to a specified energy range. We do not include any absorption effect there. On the other hand, fits presented in the "Results" section include absorption models, but are binning dependant, so that the results of the fit parameters may vary from one choice of binning to another. In this "Investigation of systematic" section, we investigate how a LP fit can be affected by the choice of binning, by comparing a unbinned LP fit returned by the unbinned likelihood program, with a binned SED LP fit.

In the two figures below are presented two different choices of binning ("Narrow" versus "Large"). We do not include absorption effect, in order to establish qualitative comparison of the fits. We can expect the "Narrow" binning to give results closer to the unbinned process, and we observed that some spectral features may be hidden by the "large" binning, but we also noticed the following effects with the narrow binning: more fluctuations due to low statistic data points, a lower energy of the last significant data point, and appreciable departure from the original sets of "unbinned fit parameters".

In the table below are presented the fit parameters of the 'unbinned' and 'binned' fits of the data using the log-parabola function without EBL absorption.
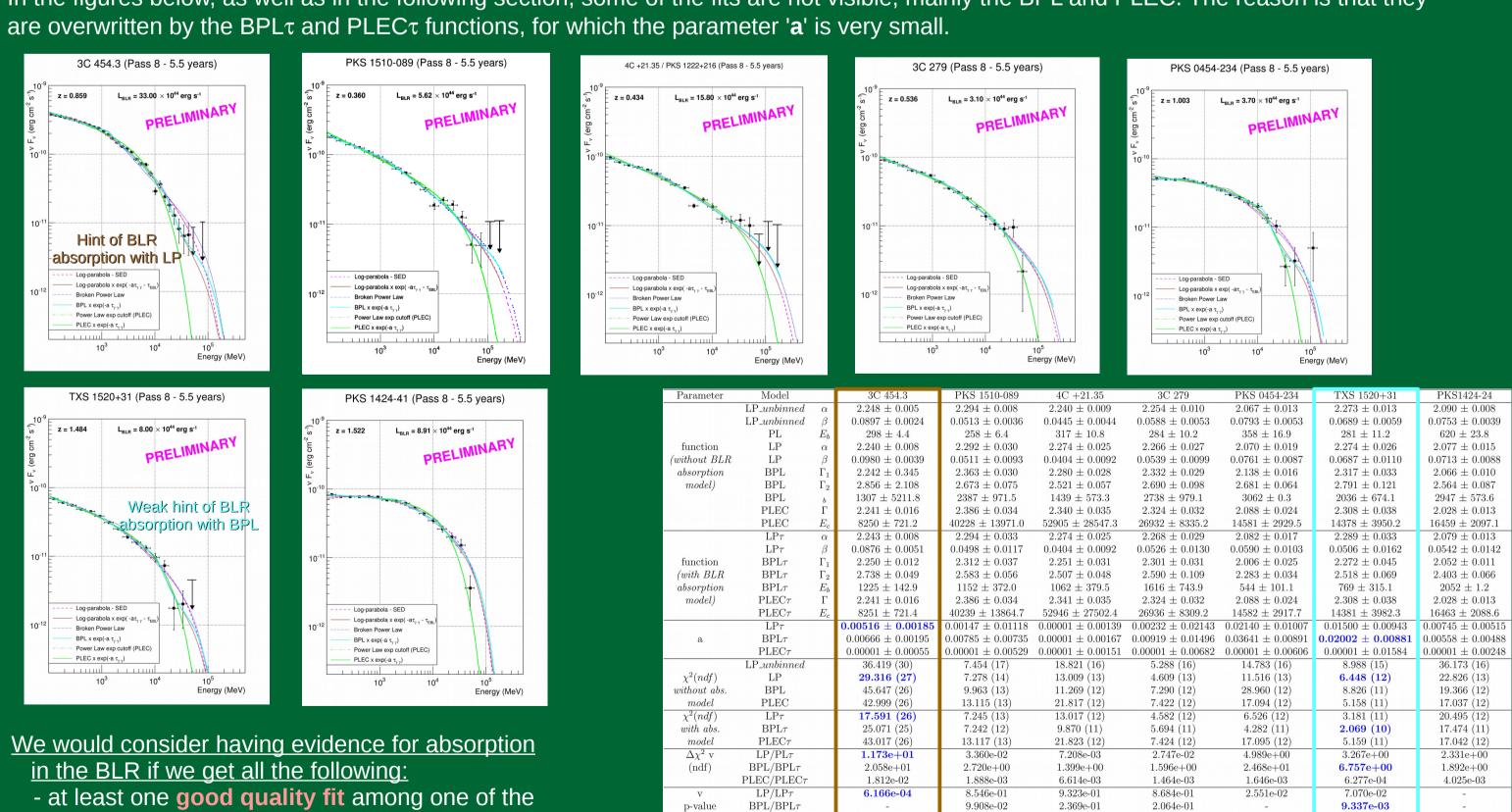
We can conclude this section by mentioning that for most of these sources, we need to find a binning for which our LP fit has to be similar to the unbinned one, in order to have a relatively good confidence in comparing the fits presented in the next sections. Depending on the source, either the 'narrow bin', or the 'large bin' option might give a fit closest to the unbinned likelihood. For now we assume that this binning effect on the standard LP fit is can be extrapolated to other fits (with or without absorption). This is to be checked in further work.

Results on the 5.5 years of data

We present now the results on the 7 bright FSRQs. Data under the label "5.5 years" are processed from 4 August 2008 till 30 April 2014. Sources are presented in the same order of decreasing flux in the 1-100 GeV energy range as in Table 1. Values of the luminosity in the broad line region (L_{BLR}) is given on the plots, as taken or derived from Pacciani et al (2014) and Xiong & Zhang (2014)

In the figures below, as well as in the following section, some of the fits are not visible, mainly the BPL and PLEC. The reason is that they are overwritten by the BPLτ and PLECτ functions, for which the parameter 'a' is very small.

We would consider having evidence for absorption in the BLR if we get all the following:
- at least one **good quality** fit among one of the fits with EBL+BLR absorption (LPτ, BPLτ and PLECτ);
- a **good quality fit** of the corresponding function with only EBL absorption (LP, BPL or PLEC);
- parameter 'a' with a relatively **small error bar**;
- a **small p-value.**

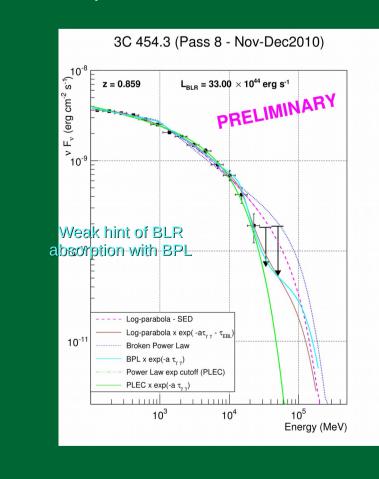In Tab. 2 are presented the fit parameters. In *blue bold face* are the parameters that **suggest a possible BLR absorption**, as some of the above conditions are partially met for **3C 454.3** (with a *p-value* of 6.2x10^-4 / **3.9 sigma C.L.**) and for **TXS 1520+31** (with a smaller significance). We have no hint of absorption for the other sources we studied.

Results on high state/flaring episodes

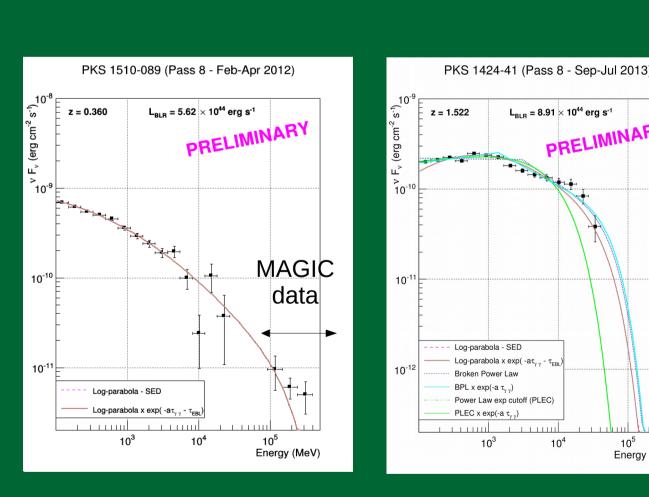Data were analysed during flaring/high state periods for the following sources:

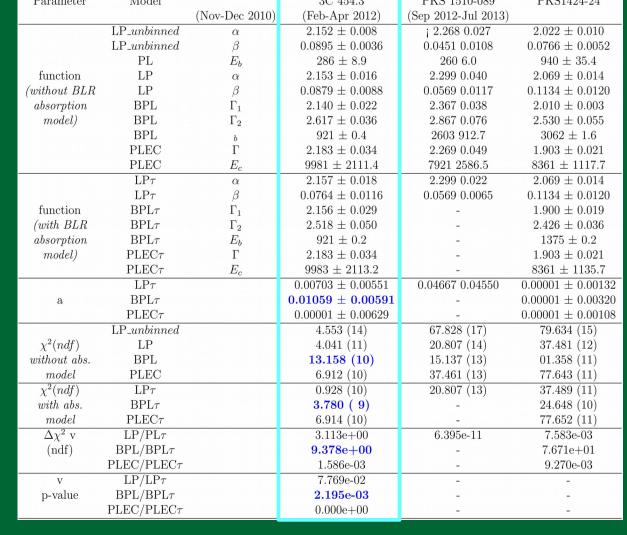- **3C 454.3** (high state and giant flare) during Nov-Dec 2010 (Abdo et al 2011);
- **PKS 1510-089** during Feb-Apr 2012 (Aleksic et al 2014) ;
- **PKS 1424-41** during Sep 2012-Jul 2013 (series of 4 successive radio flares).

During these outburst episodes, the gamma-ray emission region can have a different location compared to the quiescent state. In this section we present the results obtained on these three high states. Under the same criteria than the ones used in the previous section, we still find **no evidence of BLR absorption**, though we still have a **hint** of it for **3C 454.3** with a p-value of around 2.2x10^-3 for the discrepancy between the BPL and BPL fits (significance of **almost 3 sigma**).

Though we dispose of less photons in the data analysis of flaring episodes, during strong and long flares, it could be possible to constrain the location of the gamma-ray production region if it is deep enough inside the BLR.

Conclusions and perspectives

We find that the gamma-gamma absorption in the BLR is not significant for the models of BLR and spectral functions we have investigated. An implication of our results is that the gamma-ray emission zone in FSRQs might be located outside or at the outer edge of the BLR. However, further investigation on binning effects on the SED fits are required. Further work is also expected to improve the modelling of the BLR.

Acknowledgements

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