

Constraining blazar distances with combined *Fermi* and TeV data: an empirical approach

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ABSTRACT

We discuss a method to constrain the distance of blazars with unknown redshift using combined observations in the GeV and TeV regimes. We assume that the VHE spectrum corrected for the absorption through the interaction with the Extragalactic Background Light can not be harder than the spectrum in the *Fermi*/LAT band. Starting from the observed VHE spectral data we derive the EBL-corrected spectra as a function of the redshift z and fit them with power laws to be compared with power law fits to the LAT data. We apply the method to all TeV blazars detected by LAT with known distance and derive an empirical law describing the relation between the upper limits and the true redshifts that can be used to estimate the distance of unknown redshift blazars. Using different EBL models leads to systematic changes in the derived upper limits. Finally, we use this relation to infer the distance of the unknown redshift blazar PKS 1424+240.

Key words: galaxies: distances and redshifts - gamma-rays: observations - radiation mechanisms: non-thermal

1 INTRODUCTION

The extragalactic TeV sky catalogue ($E > 100$ GeV), counts nowadays 35 objects¹. Many of these sources have recently been detected also at GeV energies by the *Fermi* satellite (Abdo et al. 2009), allowing for the first time a quasi-continuous coverage of the spectral shape of extragalactic VHE emitters over more than 4 decades of energy. Except for two starburst galaxies and two radiogalaxies, all the others are blazars, radio-loud active galactic nuclei with a relativistic jet closely oriented toward the Earth, as described in Urry & Padovani (1995). The apparent luminosity of the non-thermal radiation emitted by the jet is then largely enhanced by relativistic beaming and dominates the observed high energy emission. Typically, the spectral energy distribution (SEDs) emitted from these objects, extending from radio waves to gamma-ray frequencies, is composed of two broad humps. In the case of TeV detected blazars, the first component usually peaks in the UV-X-ray band, and the second peak is located at GeV-TeV energies. The first component is identified as electron synchrotron radiation, whilst the second component is widely attributed to inverse Compton scattering of ambient photons by the same synchrotron emitting electrons. Relativistic electrons are accelerated within a region in bulk relativistic motion along the jet (e.g. Tavecchio et al. 1998).

VHE photons emitted by cosmological sources are effectively

absorbed, through the pair production process, $\gamma\gamma \rightarrow e^+e^-$, by the interaction with the so-called Extragalactic Background Light (EBL) (Stecker, de Jager & Salamon 1992). EBL is composed of stellar light emitted and partially reprocessed by dust throughout the entire history of cosmic evolution. The expected EBL spectrum is composed by two bumps at near-infrared and far-infrared wavelengths (Hauser & Dwek 2001). Direct measurement of the EBL has proved to be a difficult task, primarily due to the zodiacal light that forms a bright foreground which is difficult to suppress. Due to the lack of direct EBL knowledge, many models have been elaborated in the last years (Stecker, Malkan & Scully 2006; Franceschini, Rodighiero & Vaccari 2008; Gilmore et al. 2009; Kneiske & Dole 2010). Moreover, for some blazars the derivation of the intrinsic spectrum is also difficult due to the uncertainty or lack of a redshift measurement. In particular a direct spectroscopic measure of the redshift is often difficult in BL Lac objects, which are characterized by extremely weak emission lines (equivalent width < 5 Å).

In this paper we discuss a method to derive upper limits on the redshift of a source based on the comparison between the spectral index at GeV energies as measured by LAT (unaffected by the cosmological absorption up to redshifts far beyond those of interest here) and the deabsorbed TeV spectrum. Basically, for larger distances the deabsorbed spectrum becomes harder. A solid upper limit to the redshift can be inferred deriving the redshift at which

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¹ for an updated list see: <http://www.mppmu.mpg.de/~rwagner/sources/>

Source Name	$z[real]$	<i>Fermi</i> /LAT slope	VHE slope	z^* low EBL model	z^* mean EBL model	z^* high EBL model	$z[rec]$ mean EBL model
Mkn 421	0.030	1.78 ± 0.03	$2.3 \pm 0.1^{(1)}$	$0.101^{+0.021}_{-0.022}$	$0.078^{+0.016}_{-0.018}$	$0.054^{+0.012}_{-0.012}$	$0.009^{+0.012}_{-0.014}$
Mkn 501	0.034	1.73 ± 0.06	$2.3 \pm 0.1^{(2)}$	$0.122^{+0.025}_{-0.024}$	$0.096^{+0.018}_{-0.018}$	$0.067^{+0.013}_{-0.014}$	$0.029^{+0.013}_{-0.013}$
1ES 2344+514	0.044	1.76 ± 0.27	$2.9 \pm 0.1^{(3)}$	$0.248^{+0.080}_{-0.077}$	$0.196^{+0.056}_{-0.060}$	$0.139^{+0.043}_{-0.045}$	$0.105^{+0.041}_{-0.043}$
Mkn 180	0.045	1.91 ± 0.18	$3.3 \pm 0.7^{(4)}$	$0.248^{+0.146}_{-0.150}$	$0.196^{+0.116}_{-0.118}$	$0.147^{+0.091}_{-0.089}$	$0.104^{+0.085}_{-0.086}$
1ES 1959+650	0.047	1.99 ± 0.09	$2.6 \pm 0.2^{(5)}$	$0.111^{+0.055}_{-0.049}$	$0.086^{+0.040}_{-0.040}$	$0.058^{+0.028}_{-0.017}$	$0.022^{+0.029}_{-0.029}$
BL Lacertae	0.069	2.43 ± 0.10	$3.6 \pm 0.5^{(6)}$	$0.299^{+0.152}_{-0.162}$	$0.234^{+0.116}_{-0.116}$	$0.172^{+0.085}_{-0.086}$	$0.132^{+0.085}_{-0.085}$
PKS 2005–489	0.071	1.91 ± 0.09	$3.2 \pm 0.2^{(7)}$	$0.240^{+0.049}_{-0.047}$	$0.186^{+0.036}_{-0.036}$	$0.129^{+0.028}_{-0.027}$	$0.098^{+0.026}_{-0.026}$
W Comae	0.102	2.02 ± 0.06	$3.7 \pm 0.2^{(8)}$	$0.298^{+0.065}_{-0.055}$	$0.234^{+0.046}_{-0.046}$	$0.179^{+0.036}_{-0.033}$	$0.133^{+0.034}_{-0.034}$
PKS 2155–304	0.116	1.87 ± 0.03	$3.4 \pm 0.1^{(9)}$	$0.281^{+0.018}_{-0.017}$	$0.220^{+0.014}_{-0.014}$	$0.162^{+0.011}_{-0.011}$	$0.126^{+0.010}_{-0.010}$
1ES 0806+524	0.138	2.04 ± 0.14	$3.6 \pm 1.0^{(10)}$	$0.281^{+0.180}_{-0.186}$	$0.226^{+0.138}_{-0.152}$	$0.181^{+0.107}_{-0.123}$	$0.126^{+0.101}_{-0.111}$
1ES 1218+304	0.182	1.63 ± 0.12	$3.1 \pm 0.3^{(11)}$	$0.264^{+0.107}_{-0.103}$	$0.212^{+0.080}_{-0.082}$	$0.169^{+0.061}_{-0.067}$	$0.114^{+0.058}_{-0.059}$
1ES 1011+496	0.212	1.82 ± 0.05	$4.0 \pm 0.5^{(12)}$	$0.667^{+0.188}_{-0.193}$	$0.490^{+0.118}_{-0.124}$	$0.348^{+0.112}_{-0.090}$	$0.323^{+0.087}_{-0.092}$
S5 0716+714	$0.310^{*,a}$	2.16 ± 0.04	$3.4 \pm 0.5^{(13)}$	$0.264^{+0.107}_{-0.117}$	$0.210^{+0.086}_{-0.090}$	$0.157^{+0.064}_{-0.068}$	$0.114^{+0.063}_{-0.066}$
PG 1553+113	0.400^b	1.69 ± 0.04	$4.1 \pm 0.2^{(14)}$	$0.779^{+0.075}_{-0.064}$	$0.566^{+0.046}_{-0.046}$	$0.395^{+0.031}_{-0.030}$	$0.338^{+0.029}_{-0.029}$
3C66A	0.444^*	1.93 ± 0.04	$4.1 \pm 0.4^{(15)}$	$0.446^{+0.076}_{-0.069}$	$0.344^{+0.050}_{-0.048}$	$0.265^{+0.038}_{-0.039}$	$0.213^{+0.037}_{-0.035}$
3C279	0.536	2.34 ± 0.03	$4.1 \pm 0.7^{(16)}$	$1.095^{+1.066}_{-1.066}$	$0.746^{+0.716}_{-0.716}$	$0.440^{+0.422}_{-0.422}$	$0.507^{+0.524}_{-0.524}$

Table 1. TeV blazars used in this study. In the first column the list of sources, their redshift (second column), their *Fermi*/LAT slope (third column), the VHE slope of the observed spectrum fit (fourth column). The next 3 columns show the redshift values obtained by de-absorbing the VHE spectra until the slope is the one observed by LAT, using three different EBL models, while the last column lists the corresponding reconstructed redshift of each source obtained by using z^* and the fits parameters, as described in the text. *: uncertain. ^a: from Nilsson et al. (2008). ^b: private communication with C. W. Danforth. 1: Acciari et al. (2009d); 2: Albert et al. (2007d); 3: Albert et al. (2007a); 4: Albert et al. (2006); 5: Tagliaferri et al. (2008); 6: Albert et al. (2007b); 7: Acero et al. (2010); 8: Acciari et al. (2009e); 9: Aharonian et al. (2005); 10: Acciari et al. (2009a); 11: Acciari et al. (2009c); 12: Albert et al. (2007c); 13: Anderhub et al. (2009); 14: Prandini et al. (2009); 15: Acciari et al. (2009b); 16: Albert et al. (2008)

the slope of the deabsorbed spectrum coincides with that measured by LAT. Our approach can be considered complementary to those used by Stecker & Scully (2010) and Georganopoulos, Finke & Reyes (2010) (see also Abdo et al. 2009), where the comparison of the spectral slopes at GeV and TeV energies of blazars at known distances is used to derive limits on the EBL. Starting from the derived limits, we find a simple law relating these values to real redshift, that can be used to guess the distance of unknown redshift blazars.

We assume a cosmology with $h = 0.72$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2 BLAZARS SPECTRAL BREAK

We consider the blazar sample containing all the extragalactic TeV emitters located at redshift larger than $z = 0.01$, detected by LAT after 5.5 months of data taking as reported in Abdo et al. (2009). The photon flux emitted by a blazar in both GeV and TeV regimes can be usually well approximated with power laws, of the form $dN/dE = f_0(E/E_0)^{-\Gamma}$, where Γ is the power law index.

Fig. 1 represents the comparison between the power law indices, listed in Table 1, obtained by fitting the photon spectra of sixteen sources measured by *Fermi*/LAT in the GeV regime and the slopes in the TeV regime measured with the new generation of

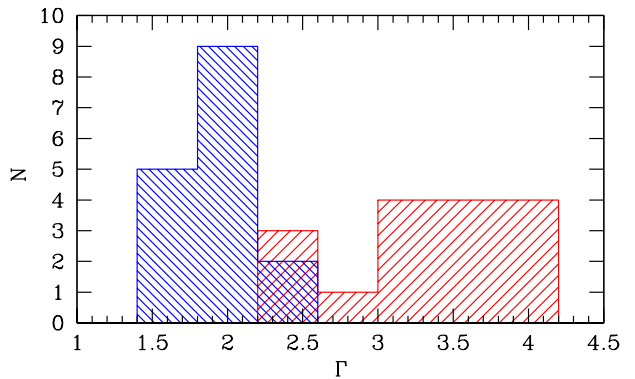


Figure 1. Spectral indices distributions of blazars listed in table 1 as measured by *Fermi*/LAT (blue) and Cherenkov instruments (red).

Cherenkov instruments (H.E.S.S., MAGIC and VERITAS). The spectral slopes Γ in the 0.2 – 300 GeV energy range distribute from 1.63 to 2.43, with a peak around 2, while the VHE spectral slopes show a wider distribution, ranging from 2.28 to 4.12.

The systematic difference between the two distributions is pri-

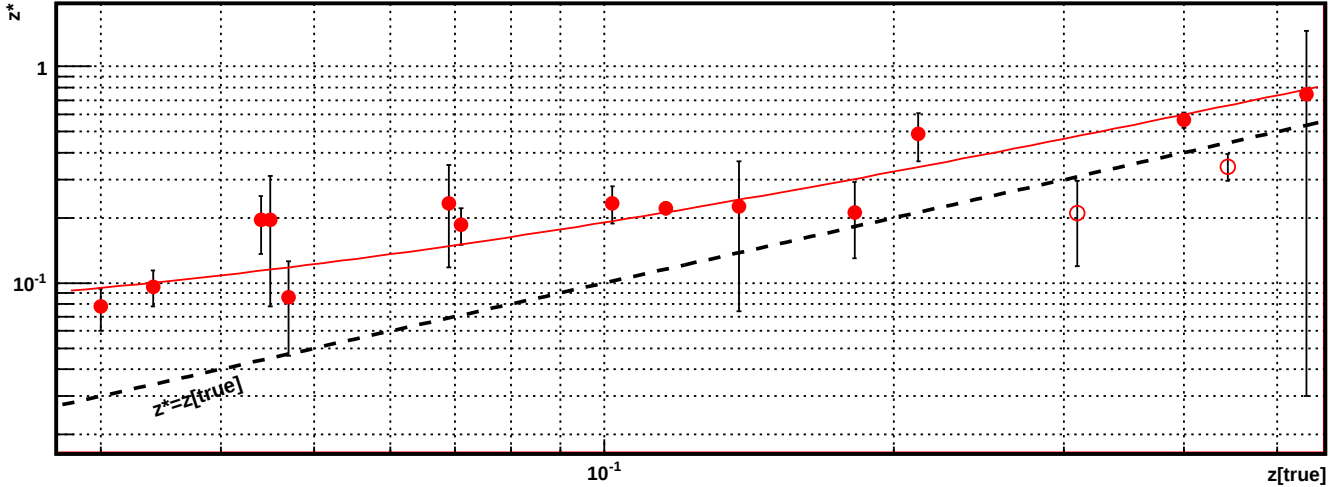


Figure 2. True redshifts vs z^* derived with the procedure described in the text for the Franceschini et al. (2008) EBL model. The open points were not used in the fit calculation (red line) since their redshift is uncertain (sources 3C 66A and S5 0716+714). The dashed line is the bisector: only for the sources 3C 66A and S5 0716+714 the limits on the redshift estimated in this work are below the true (even if uncertain) redshifts.

marily due to an intrinsic break in the spectrum emitted by the source. In fact the peak of the high-energy component in the SED of TeV blazars is commonly located between GeV and thousands of GeV (e.g. Tavecchio et al. 2010): LAT observes mainly the photons of energy below the energy of the IC peak, in the hard portion of the spectrum, while Cherenkov instruments probe the steeper part of the peak (e.g. Aharonian et al. 2009).

A second effect influencing the distribution of TeV slopes is the interaction of VHE photons with EBL and the consequent reduction of the flux which depends on the distance. This dependence is likely responsible for the observed spread of the TeV spectral indices not present in the well peaked GeV indices distribution.

Quantitatively, the effect of the interaction of VHE photons with EBL is an exponential attenuation of the flux by a factor $\tau(E, z)$, where τ is the optical depth, function of both photon energy and source redshift. Thus, the observed differential energy spectrum from a blazar is related to the emitted one according to $F_{\text{obs}}(E) = e^{-\tau(E)} F_{\text{em}}(E)$. In principle it is possible to derive the emitted (or intrinsic) spectrum by deabsorbing the observed spectrum. This procedure depends on the absorption coefficient $\tau(E, z)$ and the redshift z of the source. Vice versa, if the intrinsic source spectrum is known, given the absorption coefficient τ , the redshift z can be estimated comparing the absorbed spectrum with the observed one.

Here, we use the second approach, developing an empirical method to estimate a safe upper limit to the source distance based on the reasonable assumption that the intrinsic spectrum at TeV energies cannot be harder than that in the adjacent GeV band. Indeed, from the brightest objects studied at both GeV and TeV energies it appears that the SED is continuous with a broad peak not requiring additional spectral components (e.g. Aharonian et al. 2009). Hence, a natural assumption is to require that the slope measured in the GeV energy range is a limit value for the power law index of the deabsorbed TeV spectrum. This condition, satisfied when the IC peak maximum extends beyond the VHE spectral points, has never been observed in nearby blazars, for which the EBL absorption effect is negligible.

In order to estimate the redshift z^* for which the TeV spec-

tral slope equals the GeV one, the measured spectral points of each source have been corrected for the corresponding absorption factor starting from $z = 0.01$, and the resulting spectrum fitted with a power law. This procedure, applied in fine steps of redshift, is iterated until the slope of the deabsorbed spectrum equals the one measured by LAT. The corresponding redshift, z^* , is the limit value on the source distance.

3 RESULTS

Of the sixteen sources considered in this study, 14 blazars have well known redshift and are used to test the method, while the remaining two blazars (3C 66A and S5 0716+714) have uncertain redshift, and are considered separately. The central columns of Table 1 reports the z^* calculated following the method described in the previous section, using three different EBL models: a low limit model (Kneiske & Dole 2010), a mean (Franceschini et al. 2008) and a high level one (Stecker et al. 2006, baseline model). The absorption coefficients of the last model were obtained from a simple extrapolation of the values given for fixed redshifts in Stecker et al. (2006) (F. Stecker, private communication). The errors on z^* are estimated taking into account both errors on the TeV and LAT slopes.

Fig. 2 shows the comparison between the real redshift, x-axis, and the estimated one, y-axis, obtained with the mean EBL density model. All the z^* lie above the bisector (dashed line) meaning that their values are larger than the real redshift ones. This is expected since we are not considering the presence of the intrinsic break in the blazar spectra. This result confirms that the method can be used to set safe upper limits on blazars distance. The only exceptions are the two sources with uncertain distance, S 0716+714 and 3C 66A (open circles).

Stecker and Scully (2010) derived a linear expression for the steepening of the observed TeV slope due to EBL absorption. Since in our procedure z^* is related to this steepening, it is natural to assume that also z^* and $z[\text{true}]$ are related by a linear function,

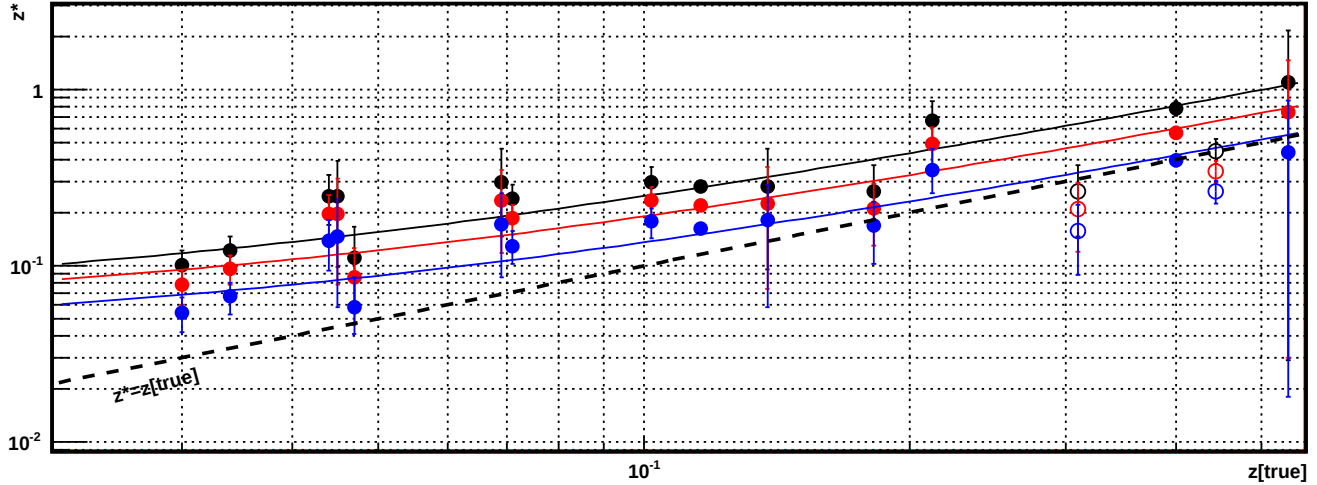


Figure 3. Comparison of the true redshift vs z^* in log scale using three different EBL models: black points Kneiske et al. (2010) model (low level), red line Franceschini et al. (2008) model (mean level), blue line Stecker et al. (2006) model (high level). The open points were not used in the fit calculation since their redshift is uncertain (sources 3C 66A and S5 0716+714).

EBL Model	A	B
Low level	0.062 ± 0.017	1.86 ± 0.17
Mean level	0.054 ± 0.012	1.36 ± 0.14
High level	0.040 ± 0.009	0.96 ± 0.08

Table 2. Parameters of the linear fitting curves ($z^* = A + Bz[\text{true}]$) plotted in Fig. 3

$z^* = A + Bz[\text{true}]$. The meaning of the coefficients is rather transparent: basically A is a measure of the intrinsic spectral break of the sources, while, following Stecker & Scully (2010), B is a measure (increasing values for decreasing EBL level) of the optical depth of the EBL model used.

We interpolate with this linear function the data with well known distance of Fig. 2. The linear fit (continuous line) describes very well the data, as confirmed by the reduced chi-squared value of the fit, $\chi^2/d.o.f. = 9.9/12$, and corresponding probability of 62%. The results obtained with the other two EBL models are drawn in Fig. 3. It is evident that with a low photon density EBL model (black circles), the estimated redshifts are all shifted at higher values, while with a high photon density model (blue circles) the shift is downwards. Even if the optical depth evolution is different between the EBL models used here, the linear behaviour is evident also in the two extreme cases. The parameters are listed in Table 2.

Having derived this empirical relation we can try to use it to *derive the redshift* of sources with uncertain distance. This can be done under the assumption that the source of interest shares similar spectral properties with the sources used to derive the fit (basically they have similar values of the spectral break measured by A).

To demonstrate the feasibility of such a method, in the last column of Table 1 we report the values of the *reconstructed* redshift, $z[\text{rec}]$, obtained by applying the inverse formula ($z[\text{rec}] = (z^* - A)/B$) to the z^* estimated with the Franceschini et al. EBL model. In order to avoid a bias, the parameters A and B are each time calculated excluding from the fit the source for which we es-

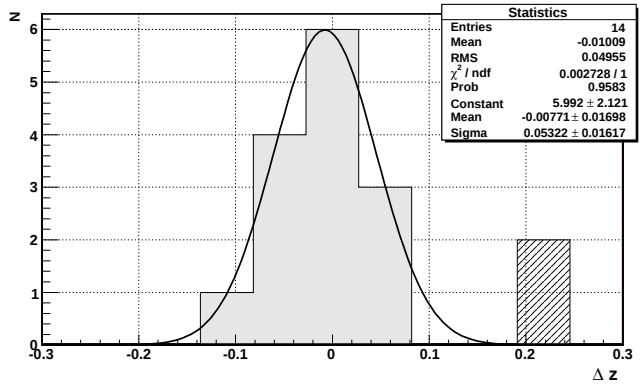


Figure 4. Δz plot ($z[\text{true}] - z[\text{rec}]$) (filled histogram) and superimposed the two sources with uncertain redshift (S5 0716+714 and 3C 66A), not used for the Gaussian fit.

timate the redshift $z[\text{rec}]$. The differences between the real and the reconstructed redshifts, Δz is drawn in Figure 4, filled area. Despite the low statistic, the distribution is quite well described by a Gaussian centered in zero with a σ of 0.05. The separated shaded histogram represents the Δz of the uncertain redshift sources.

4 DISCUSSION AND CONCLUSIONS

We presented a method that allows the estimation of the quantity z^* , upper limit on the redshift of a TeV emitting blazar with a GeV counterpart observed by *Fermi*/LAT, obtained by deabsorbing the observed TeV spectrum.

In order to use the largest sample of spectra for this study, we made several assumptions: first of all we combined GeV and TeV data even if the observations in the different energy bands were not simultaneous. The impact of this choice, however, is probably moderated by fact that we do not use the flux but only the values of the slopes, less variable than the flux (unless in extreme states). For example the spectral slope of the HBL 1ES 1218+304 recently measured by the Veritas Collaboration (Acciari et al. 2010b) during

a high flux level, matches within the errors the slope determined during its quiescent state.

Secondly, in this work we use TeV spectra observed with various Cherenkov experiments, characterized by different sensitivities. This difference, especially at high energies, could affect the result, leading to systematic effects in the distance limit determination. Another possible cause of systematics could be the use of all the blazar sample, independently from the nature of the source: we didn't apply any distinction between HBL, LBL and FSRQ, characterized by a different position of the IC peak.

Despite all these approximations, the method presented in this paper applied to a sample of test sources gave satisfactory results. The z^* values obtained by correcting the spectra from the EBL absorption, are, in fact, all above the real redshift values if we use a mean background photon level. This suggests the use of this method for constraining the distance of unknown redshift sources.

We applied the z^* estimate also to two sources with uncertain distance: in both cases the limit lies below the quoted values. This result could be due to some intrinsic properties of the sources (specifically, a more moderate intrinsic spectral break between the GeV and TeV bands than that of the other sources), or to a wrong estimate of their distances. In the latter case, our method would constrain the redshift of S5 0716+714 below 0.21 ± 0.09 and that of 3C 66A below 0.34 ± 0.05 . It can be pointed out that in the case of S5 0716+714, the redshift of 0.31 used in this work, recently reported by Nilsson et al. (2008), is estimated by assuming the luminosity of its host galaxy. Another estimate on the blazar distance, based on the spectrography of the three galaxies close to this source, gives the value of ~ 0.26 for its redshift, more in agreement with our derived limit.

The same procedure was applied to our sample using two extreme EBL models. The low density one gives even safer upper limits on the sources distances, while the z^* obtained with the high density model are closer to the real redshift values. Even with this model, all the estimates are above or on the bisector, confirming our assumption that the deabsorbed TeV slope cannot be harder than the GeV slope reported by *Fermi*/LAT.

Following previous works, we tested the possibility of a linear relation between our z^* estimates and the real distances of the sources. We found that the linear fit describes quite well our results, independently on the EBL model considered, although the slope and intercept of the fits are different in the three cases (Table 2).

The relation found suggests to use the z^* estimate not only to set an upper limit on unknown distances of blazars, but also, via the inverse-formula, to try an evaluation of this distance. In order to investigate this opportunity, we tested it on our sample of sources using the mean EBL model, paying a special attention to avoid biases in the calculation. The distribution of the difference Δz between the reconstructed and the real redshift is well described by a Gaussian peaked in zero with a σ of 0.05. Once again, the uncertain redshift sources are outside the expected interval. The value of the redshift of S5 0716+714 obtained with this method is 0.11 ± 0.05 , where the error quoted is the σ of the Δz distribution. For 3C 66A, the same procedure leads to a redshift estimate of 0.213 ± 0.05 .

As a final example of application, we use our procedure to PKS 1424+240, a blazar of unknown redshift recently observed in the VHE regime by Veritas (Acciari et al. 2010a). The *Fermi*/LAT spectrum slope measured between 0.2 to 300 GeV is 1.85 ± 0.05 and the corresponding z^* redshift at which the deabsorbed TeV spectrum slope equals it is 0.382 ± 0.105 , using Franceschini et al. EBL model. This result is in agreement with the value of 0.5 ± 0.1 , reported by Acciari et al. (2010a), calculated applying the same

procedure but only simultaneous *Fermi* data. Our estimate on the most probable distance for PKS 1424+240, obtained by inverting the z^* formula, is $z[rec] = 0.24 \pm 0.05$, where the error, as before, is assumed as the σ of the Gaussian fitting the Δz of Fig. 4.

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