Constraining blazars distances with combined GeV and TeV data

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Recently, a new method to constrain the distances of blazars with unknown redshift using combined observations in the GeV and TeV regimes has been developed. The underlying assumption is that the Very High Energy (VHE, E > 100 GeV) spectrum corrected for the absorption of TeV photons by the Extragalactic Background Light (EBL) via photon-photon interaction should still be softer than the gamma-ray spectrum observed by Fermi/LAT. The constraints found are related to the real redshifts by a simple linear relation, that has been used to infer the unknown or uncertain distance of blazars. The sample is revised with the up-to-date spectra in both TeV and GeV bands and the method applied to the unknown distance blazar PKS 1424+240 detected at VHE.

I. INTRODUCTION

A. TeV Blazars

The large majority of extragalactic TeV photons emitters belongs to the class of blazars: radio-loud Active Galactic Nuclei (AGN) with a relativistic jet closely oriented towards the Earth [12].

The typical spectrum emitted by a blazar is non thermal and covers the entire electromagnetic spectrum, as sketched in Fig 1. It is composed by two bumps: at low energies the emission is synchrotron radiation by relativistic electrons, while at higher energies the origin of the radiation is more uncertain. The most credited models, referred as leptonic models, involve the inverse Compton scattering mechanism to explain the high energy emission. However, alternative models taking into account the presence of a hadronic component in the emission are not ruled out.

At GeV and TeV regimes, the photon energy flux emitted by a blazar is usually well approximated with a power law of the form \( dN/dE = f(E/E_0)^{-\Gamma} \).

B. EBL absorption

An important effect involving VHE photons emitted by blazars is the production of electron-positron pairs \( (\gamma\gamma \rightarrow e^+e^-) \), caused by the interaction with the EBL [11]. EBL is composed of stellar light emitted and partially reprocessed by dust throughout the entire history of cosmic evolution.

Due to the lack of direct EBL knowledge, many models have been elaborated in the last years [5–7, 10], but the uncertainties remains quite large.

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 \( \tau \) is the optical depth, function of both photon energy and source redshift.

This is represented in Fig. 1, where, due to the absorption, the observed TeV spectrum (continuous line) differs significantly from the emitted spectrum (dashed line). The observed differential energy spectrum from a blazar is related to the emitted one according to

\[
F_{\text{obs}}(E) = e^{-\tau(E, z)} F_{\text{em}}(E).
\]

In principle it is possible to derive the emitted (or intrinsic) spectrum by deabsorbing the observed spectrum. This procedure depends on the absorption coefficient \( \tau \) and the redshift \( z \) of the source. Vice versa, if the intrinsic source spectrum is known, given the absorption coefficient \( \tau \), the redshift \( z \) can be estimated comparing the absorbed spectrum with the observed one. Here, we use the second approach.

II. THE METHOD

In a recent paper, we have proposed a method to derive an estimate on the distance of a blazar [8]. The
TABLE I. List of TeV blazars used in this study. Source name (first column), $\Gamma_{\text{LAT}}$ reported in the first year catalogue (second column), $z^*$ and $z_{\text{rec}}$ values obtained with the Franceschini EBL model (fourth and fifth columns). $^\ast$: uncertain.

| Source Name | $z_{\text{true}}$ | $\Gamma_{\text{LAT}}$ | $z^*$ | $z_{\text{rec}}$ |
|-------------|-------------------|----------------------|-------|------------------|
| Mkn 421     | 0.030             | 1.81 ± 0.02          | 0.07 ± 0.02 | 0.02 ± 0.05 |
| Mkn 501     | 0.034             | 1.85 ± 0.04          | 0.08 ± 0.02 | 0.03 ± 0.05 |
| 1ES 2344+514| 0.044             | 1.57 ± 0.17          | 0.19 ± 0.03 | 0.09 ± 0.05 |
| Mkn 180     | 0.045             | 1.86 ± 0.11          | 0.21 ± 0.11 | 0.11 ± 0.05 |
| 1ES 1959+650| 0.047             | 2.09 ± 0.05          | 0.07 ± 0.03 | 0.02 ± 0.05 |
| BL Lacertae | 0.069             | 2.37 ± 0.04          | 0.27 ± 0.14 | 0.14 ± 0.05 |
| PKS 2005−489| 0.071             | 1.90 ± 0.06          | 0.18 ± 0.03 | 0.09 ± 0.05 |
| W Comae     | 0.102             | 2.06 ± 0.04          | 0.24 ± 0.05 | 0.13 ± 0.05 |
| PKS 2155−304| 0.116             | 1.91 ± 0.02          | 0.22 ± 0.01 | 0.11 ± 0.05 |
| RGB J0710+591| 0.125            | 1.28 ± 0.21          | 0.21 ± 0.06 | 0.11 ± 0.05 |
| 1ES 0806+524| 0.138             | 2.09 ± 0.10          | 0.23 ± 0.15 | 0.12 ± 0.05 |
| H 2356−309  | 0.165             | 2.10 ± 0.17          | 0.16 ± 0.07 | 0.08 ± 0.05 |
| 1ES 1218+304| 0.182             | 1.70 ± 0.08          | 0.21 ± 0.08 | 0.11 ± 0.05 |
| 1ES 1101−232| 0.186             | 1.36 ± 0.58          | 0.23 ± 0.11 | 0.12 ± 0.05 |
| 1ES 1011+496| 0.212             | 1.93 ± 0.04          | 0.60 ± 0.18 | 0.35 ± 0.05 |
| SS 0716+714 | 0.310$^\ast$      | 2.15 ± 0.03          | 0.23 ± 0.10 | 0.12 ± 0.05 |
| PG 1553+113 | 0.400             | 1.66 ± 0.03          | 0.75 ± 0.07 | 0.45 ± 0.05 |
| 3C 66A      | 0.444$^\ast$      | 1.92 ± 0.02          | 0.39 ± 0.05 | 0.22 ± 0.05 |

III. ANALYSIS AND RESULTS

The sample presented in this study is composed by all the extragalactic TeV emitters located at redshift larger than $z = 0.01$ and detected by LAT after the first year of data taking $^1$. In total, there are 16 sources with well known redshift and two additional sources with uncertain redshift, namely 3C 66A and SS 0716+714. In the first column of Table $^1$ we list the sources used in the study. The second column represents the list of sources measured by LAT after the first year of data taking, in the energy range 0.1–100 GeV. Three new sources are added to the sample considered in the original study, namely: RGB J0710+591, H 2356–309 and 1ES 1101−232, located at redshifts 0.125, 0.165 and 0.186, respectively. The last two sources were not detected by LAT in the first 5.5 months, while the spectrum of RGB J0710+591 has only recently been published by the VERITAS collaboration $^4$. With respect to the 5.5 months catalogue, the new LAT determination of the spectral slopes is characterized by smaller errors, due to the increased statistics.

With this enlarged data set, we estimate the quantity $z^*$, redshift at which the deabsorbed TeV spectrum exhibits the same slope measured by LAT at lower energies. We adopt the energy density EBL model $^6$, hereafter Franceschini model $^{14}$. The $z^*$ values obtained are listed in the fourth column of Table $^1$.

Figure $^2$ represents the distribution $z_{\text{true}} - z^*$ ob-
FIG. 2: $z^*$ versus true redshift derived with the procedure described in the text. The open symbols represent the two sources with uncertain redshift, 3C 66A and S5 0716+714, not used in the fit. The dashed line is the bisector, while the continuous line is the linear fit to the data.

TABLE II: – Parameters of the linear fitting curve ($z^* = A + Bz_{\text{true}}$).

| A       | B       |
|---------|---------|
| 0.036 ± 0.014 | 1.60 ± 0.14 |

All the $z^*$ values distribute above or on the bisector. This confirms that $z^*$ can be considered an upper limit on the source redshift, hence the maximum hardness hypothesis is confirmed also in this study. The linear curve drawn represents the fit of the data. The linear trend of the distribution is less evident here than in the previous study. The probability of the fit is, in fact, ~6%, well below the previous value (58%).

The reason for this behaviour can be related to the new sources introduced, but also to the new LAT determination of the slopes. In order to investigate such alternatives, we have fitted the distribution excluding the three new sources. The new fit returns a probability of 9%, close to the value obtained with the full sample. This result suggests that the low probability found is mainly due to the smaller error bars characterizing the determination of the new slopes in the GeV band with respect to previous estimates. The parameters obtained are listed in Table II.

Following the first study, we investigate the distribution $\Delta z$, difference between the values $z_{\text{rec}}$, listed in the last column of Table II obtained by inverting the linear formula $z_{\text{rec}} = (z^* - A)/B$, and the true redshifts, $z_{\text{true}}$. The histogram obtained, Figure 3, is well fitted by a Gaussian of $\sigma = 0.05$, which can be assumed as the error on the reconstructed redshift, $z_{\text{rec}}$, estimated with this method. In the histogram, the two sources with uncertain redshift, not used for the Gaussian fit, lie outside the expected interval. This result confirms that the behaviour of S5 0716+714 and 3C 66A is different from that found for other sources and suggests that or these sources are peculiar, or their redshift is incorrect.

In conclusion, we can say that with an enlarged data set the results previously found are confirmed. However, the linearity of the $z^*-z_{\text{true}}$ relation has a smaller probability, due to the reduced errors of the new $\Gamma_{\text{LAT}}$ determinations.
IV. THE REDSHIFT OF PKS 1424+240

As a final application, we use our method on PKS 1424+240, a blazar of unknown redshift recently observed in the VHE regime by VERITAS [3]. The slope measured by Fermi/LAT in the energy range 0.1 – 100 GeV is $1.83 \pm 0.03$.

The corresponding $z^\ast$ at which the slope of the deabsorbed TeV spectrum becomes equal to it is $0.45 \pm 0.15$, filled circles in Fig. 4. This result is in agreement with the value of $0.5 \pm 0.1$, reported in [3], calculated by applying the same procedure but using only simultaneous LAT data.

Our estimate on the most probable distance for PKS 1424+240 is $0.26 \pm 0.05$, where the error is the $\sigma$ of the Gaussian fitting the $\Delta z$ distribution. The deabsorbed spectrum of PKS 1424+240 assuming this distance is drawn in Fig 4, filled squares.

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[13] Indeed, this is true at a reasonable distance from the peak maximum.
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