Probe of Lorentz Invariance Violation effects and determination of the distance of PG 1553+113.

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The high frequency peaked BL Lac object PG 1553+113 underwent a flaring event in 2012. The High Energy Stereoscopic System (H.E.S.S.) observed this source for two consecutive nights at very high energies (VHE, $E > 100$ GeV). The data show an increase of a factor of three of the flux with respect to archival measurements with the same instrument and hints of intra-night variability. The data set has been used to put constraints on possible Lorentz invariance violation (LIV), manifesting itself as an energy dependence of the velocity of light in vacuum, and to set limits on the energy scale at which Quantum Gravity effects causing LIV may arise. With a new method to combine H.E.S.S. and Fermi large area telescope data, the previously poorly known redshift of PG 1555+113 has been determined to be close to the value derived from optical measurements.

1. Introduction

PG 1553+113 is a high frequency peaked BL Lac object located in the Serpens Caput constellation. The object has been detected in VHE by H.E.S.S. [2] in 2006 and in high energies (HE, 100 MeV<$E<$300 GeV) by Fermi [1]. The $\gamma$-ray spectrum presents the largest HE-VHE spectral break measured to date [1, 8]. The source has an unknown redshift despite several attempts to measure it. The best estimate to-date, made by spectroscopy [4], is $0.43 < z < 0.58$.

In April 2012, the source underwent a flare reported by the MAGIC collaboration [3]. Subsequently, the source has been observed by the H.E.S.S. telescopes. The data are used in this work to constrain its redshift and to probe a possible Lorentz invariance violation.

2. Data Analysis

2.1. H.E.S.S. data analysis

The H.E.S.S. telescopes have observed PG 1553+113 in April 2012 for two nights. Data were analysed using the Model analysis [3] with Loose cuts. The object has been detected with a significance of 21.5 $\sigma$ in 3.5 hours of live time. The source spectrum is well fitted by a power-law model of the form:

$$F(E) \propto E^{-(4.85\pm0.25)}$$

where $E_*=E/(327\text{ GeV})$ and the flux is found to be 3.5 times higher than the measurements made in 2005-2006 [2].

Indications of intra-night variability have been found with the fit to a constant of the light-curve yielding a $\chi^2$ of 21.34 for 7 d.o.f. ($P_{\chi^2} = 3.3 \times 10^{-3}$).

Data taken in 2005-2006 were re-analysed and the spectrum is, in this case, well fitted by a log-parabola model:

$$F(E) \propto E^{-(5.39\pm0.43)-(3.95\pm1.40)\log_{10}E_*}$$

where $E_* = E/(360\text{ GeV})$. Both spectra (archival and flare) are presented on figure 1.

2.2. Fermi-LAT data analysis

The Fermi-LAT data, from 300 MeV to 300 GeV, have been analysed with the Science-Tools V9R32P5 and instrumental response functions P7REP_SOURCE_V15. A region of interest of 15 degrees has been used and the sky model has been built using the third Fermi catalog [10].

Data contemporaneous to the H.E.S.S. exposures taken in 2012 are well fitted by a power-law of index $\Gamma = 1.72 \pm 0.26$. The pre-flare data are defined by the data taken from August 8, 2008 up to March 1st 2012. The measured spectrum is described by a log-parabola model (Fig. 1).

Variability has been probed before, during and after the flare using a bayesian blocks analysis [9]. No counterpart to the VHE flare was found in the HE light curve.

3. Determination of the redshift

The extragalactic background light (EBL) is a field of infrared photons that interacts with the VHE $\gamma$-rays
A maximum likelihood analysis based on \[ \tilde{Y} \], has been modified to tackle the non-negligible background present in the data.

For \( n_{\text{ON}} \) events recorded in the ON-source region with arrival times \( t_i \) and energies \( E_i \), the likelihood reads:

\[
L(\tau_n) = \prod_{i=1}^{n_{\text{ON}}} P(E_i, t_i | \tau_n) \text{ with:}
\]

\[
P(E_i, t_i | \tau_n) = w_s \cdot P_{\text{sig}}(E_i, t_i | \tau_n) + (1 - w_s) \cdot P_{\text{bkg}}(E_i, t_i)
\]

The probability \( P_{\text{sig}} \) was mainly determined from a parametrization of the light curve at low energies parametrization while \( P_{\text{bkg}} \) was built assuming a constant background. The factor \( w_s \) accounts for the relative weight of signal events with respect to background events.

Constraints on \( \tau_n \) led to lower limits on the Quantum Gravity energy scale \( E_{\text{QG}} \). The 95\% 1-sided lower limits for the subluminal case are: \( E_{\text{QG},1} \geq 4.32 \times 10^{17} \text{ GeV} \) and \( E_{\text{QG},2} \geq 2.11 \times 10^{10} \text{ GeV} \) for linear and quadratic LIV effects, respectively. Figure 3 compares these results with other limits from less distant AGN flares. While the statistics is more limited here, the distance of the source makes the sensitivity to possible LIV effects comparable to previous results.

5. Conclusions

The VHE emitter PG 1553+113 underwent a flaring event in VHE with an increase of its flux by a factor of 3.5. No counterpart of this flare was found in the HE regime by Fermi.

This data set has been used to constrain the redshift of the source to be \( z = 0.49 \pm 0.04 \) using a novel method based on \( \gamma \)-ray data. The flare is also used to put lower limits on the LIV effect with \( E_{\text{QG,1}} \geq 4.32 \times 10^{17} \text{ GeV} \) and \( E_{\text{QG,2}} \geq 2.11 \times 10^{10} \text{ GeV} \) for linear and quadratic effects.

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Figure 2: Posterior probability for the redshift determination and comparison with other measurements.

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Figure 3: Lower limits on $E_{QG,1}$ from linear dispersion (left) and on $E_{QG,2}$ from quadratic dispersion (right) for the subluminal case obtained with AGN as a function of redshift.