LIV analysis: Combination of three BL-Lac flares from LST-1 and PKS2155-304 Chandra flare from HESS

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Outline

Experimentally detectable effects

LIV expected effects:

Model-independent modified dispersion relation:

$$E^2 = p^2 c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{E}{E_{QG,n}} \right)^n \right] \qquad (1)$$

Subluminal or superluminal LIV $\rightarrow \pm$
Experiments are only sensitive to $n = 1, 2$

Note that E_{QG} is often compared to E_{Pl}, but could be very different from it

⇒ Photon speed depends on their energy
⇒ **Time delay** between photons with different energies

$$\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{H_0 E_{QG}^n} \kappa_n(z), \tag{2}$$

with κ_n the source distance parameter (κ_n increases with z and depends on the considered model), for $n = 1, 2$.

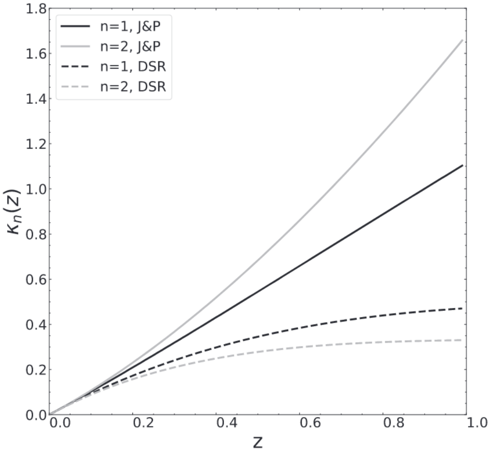


Fig. 1. Different models for κ [Bolmont *et al.* 2022 ApJ]

Time delays

In practice we use the **lag parameter**

$$\lambda_n = \frac{\Delta t_n}{\Delta E_n \ \kappa_n(z)} \simeq \pm \frac{n+1}{2 H_0 E_{QG}^n} \tag{3}$$

so we need sources

- up to **very high energies** and large energy range to maximise $E_h^n - E_l^n$
- **far away**, so that the speed difference is observed as a large enough time delay between photons to be measured: $d > 1$kpc up to $z \sim 0.1$ and more (interaction with the EBL is limiting for higher $z \Rightarrow$ high luminosity sources)
- and **variable**

γ-LIV working group (HESS, MAGIC, VERITAS + LST-1)

Goal

Get a combined limit using all available sources (GRBs, flaring AGNs, pulsars) detected by all IACT experiments, plus some Fermi-LAT GRBs $\rightarrow$ first population study at TeV energies

Already achieved

- Development of an analysis framework, to simulate, analyse and combine results from different experiments: **LIVelihood**
- Code tested on simulated data $\rightsquigarrow$ first paper [Bolmont *et al.* 2022 ApJ]
- Fully compatible with DL3 data format

On going

- Code can now be used on real DL3 data, it is being tested on BL Lac (LST-1) and PKS 2155 Chandra flare (HESS)
- Combination of results from these two sources

PKS2155 Chandra flare lightcurve

To compute the time lag, we need a **template** lightcurve (low energy photons) to compare to high energy photons $\Longrightarrow$ arrange the photons into low and high energy parts, by taking the median energy (with the full flare $E_{med} = 0.61\,\text{TeV}$)

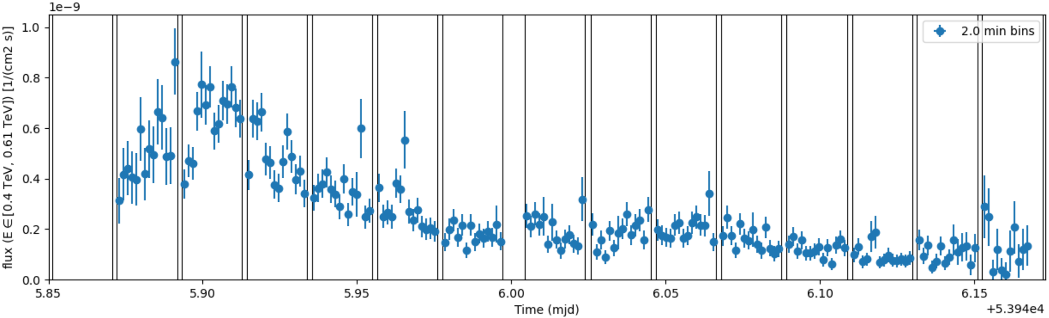
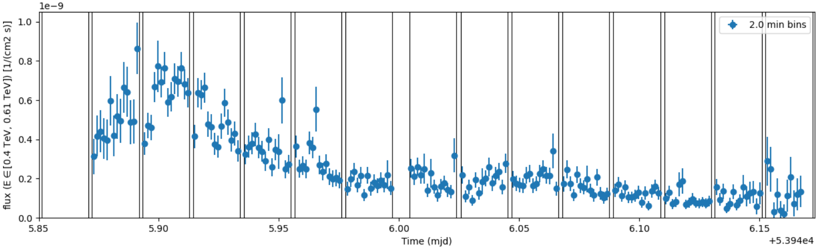


Fig. 2. Lightcurve from public data at low energies. Vertical lines separate runs.

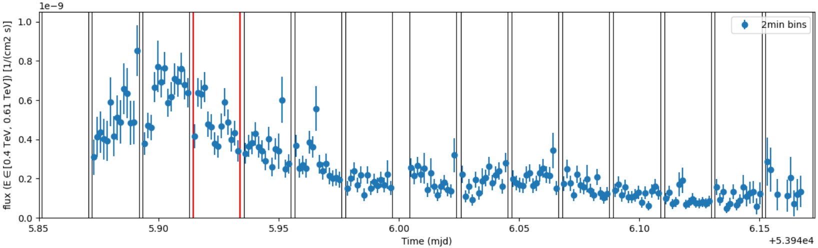
PKS2155 template lightcurve

But hard to fit the whole lightcurve because of the many free parameters



PKS2155 template lightcurve

But hard to fit the whole lightcurve because of the many free parameters
⟶ reduce the analysis to the **4th run** as a first step



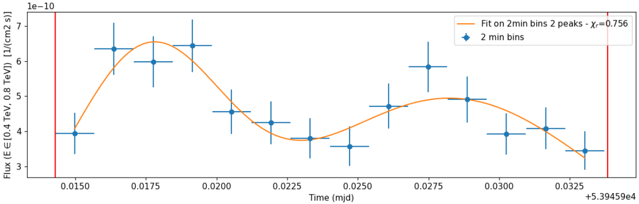
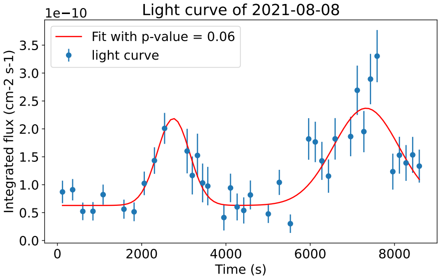
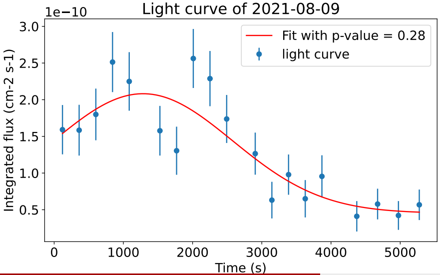
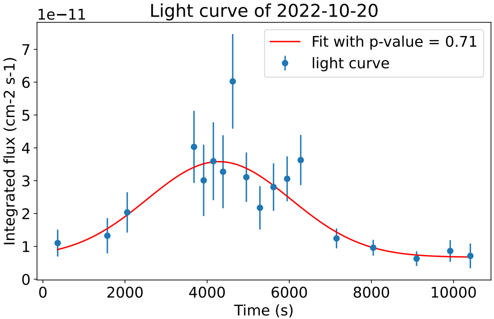


Fig. 3. Analytical fit of the light curve on low energies (in this run [0.4,0.79] TeV)

BL-Lac lightcurves







Likelihood technique

Likelihood formula [Martinez & Errando, 2008 Astrop.Phys.]

$$\frac{dP}{dE_m dt} = \frac{w_s}{N_s} \int A(E_t, \epsilon) M(E_t, E_m) F_s(E_t, t; \lambda) dE_t + \text{bkg. contrib.} \quad (4)$$

A is the effective area, M the energy migration matrix, and F_s is the flux

λ is the likelihood parameter

$$L(\lambda) = -\sum_i \log\left(\frac{dP}{dE_m dt}(E_m, i, t_i; \lambda)\right) \quad (5)$$

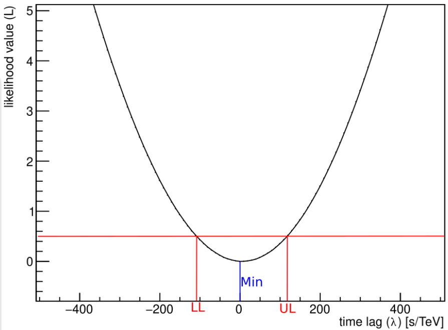


Fig. 4. Likelihood computed from a list of simulated photons following the template time distribution

Reconstruction of the lag from simulations

Process

- **Simulate** high and low energy photons from this template lightcurve at low energies and the energy spectrum
- Compute the likelihood curve for the **time lag parameter** λ
- Find the **minimum** and the lower and upper limits at 1σ

Sanity check: Distribution for $\lambda = 0$

Repeat 1000 simulations to get the distribution of reconstructed lags (for the J&P model and in the n=1 case)

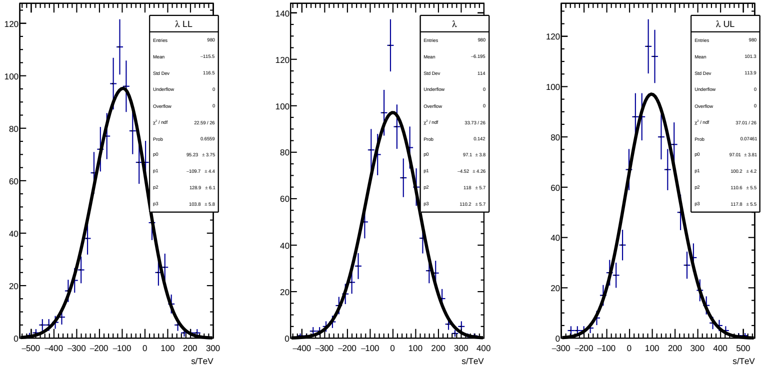


Fig. 5. Distribution of the reconstructed lags from 1000 simulations, with 0 injected lag. Left and right panels are the lower and upper limits of the confidence interval (1σ).

Reconstruction of the lag

Repeat with injected lag in the simulated dataset

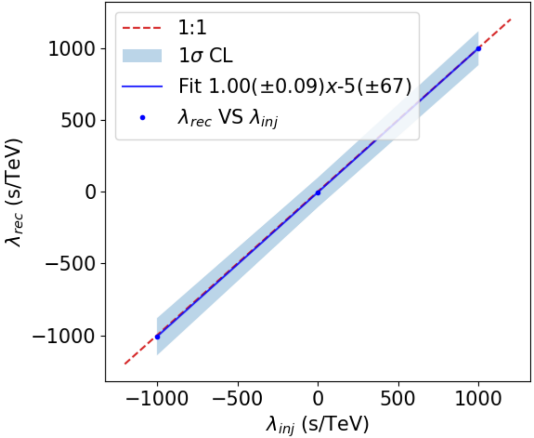


Fig. 6. Plot of the reconstructed VS injected lag

Everything works nicely!

Now let's try on real data

Likelihood from real data

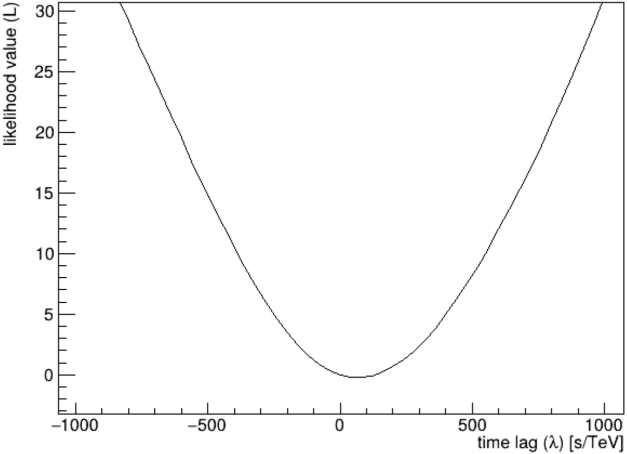


Fig. 7. Likelihood computed from real data

- Minimum: 86 s/TeV
- LL: -57 s/TeV
- UL: 220 s/TeV

Calibrated statistical error

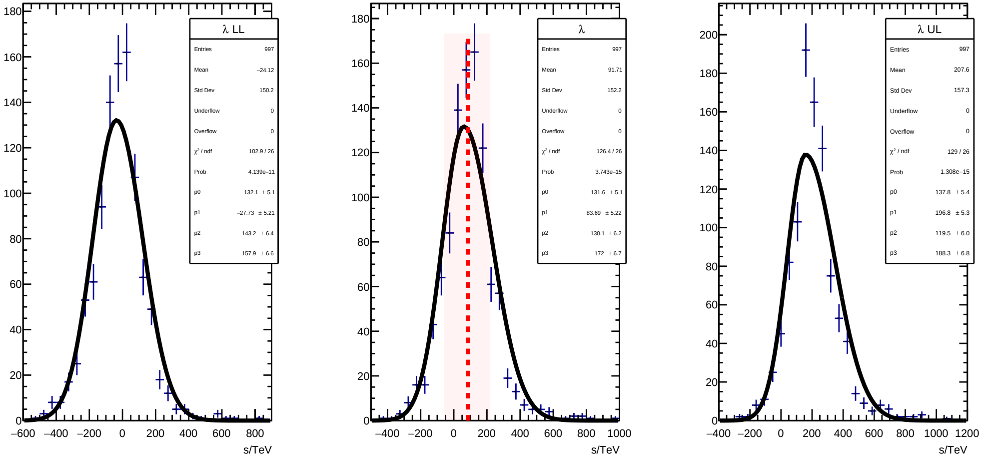


Fig. 8. Simulations based on real data → extract the **statistical error**

Systematic errors

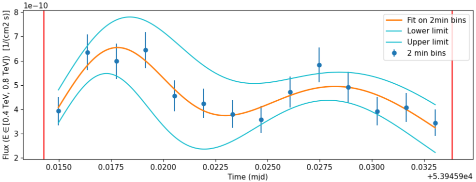


Fig. 9. Errors on lightcurve parameters

Spectral index	Redshift	Background	Energy Scale
± 0.02	$\pm 10^{-5}$	$\pm 20\%$	$\pm 10\%$

$$L(\lambda, \vec{\theta}) = L_S(\lambda) + L_{template}(\vec{\theta_{LC}}) + L_\gamma(\theta_\gamma) + L_B(\vec{\theta}_B) + L_{ES}(\theta_{ES}) + L_z(\theta_z) \quad (6)$$

with

$$L_x(\vec{\theta}_x) = \sum_i \frac{(\theta_{x,i} - \bar{\theta}_{x,i})^2}{2\sigma_{x,i}^2}, \quad (7)$$

assuming a normal distribution.

Then, re-do the whole process with these nuisances → get a mean value + errors → get a limit

Results

Limits

- J&P $\lambda_1 = 86 \pm \binom{114}{110}_{stat} \pm \binom{344}{357}_{syst}$
  $E_{QG,1} = 0.63\text{e}18$ GeV (95% CL)

Chandra flare	3.1e17 GeV
BL-Lac combination	3.8e16 GeV
Combination	6.3e17 GeV

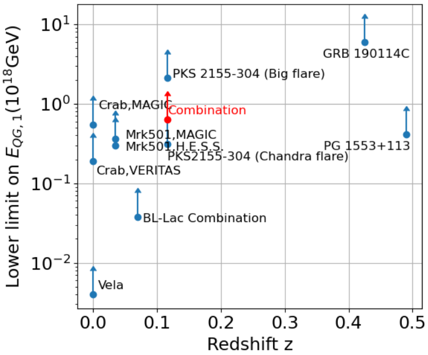


Fig. 10. Current limits on $E_{QG,1}$

Conclusions and next steps

- Successful test of combination of real data
- Good limit obtained
- Improvement could come from better analysis of the sources, or adding more sources
- Combine this result with other results in the γLIV working group
- The final result should be published and then be used in the HESS/MAGIC/VERITAS/LST-1 working group