New constraints on Lorentz invariance violations from H.E.S.S. observations of the blazar PKS 2155-304 flaring period of July 2006

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& γLIV working group

Outline

Lorentz invariance violation

- Some quantum gravity models (QG) allow the modification of photon propagation in vacuum according to their energy = Lorentz invariance violation (LIV)

- Study this phenomenon
  - → determine characteristic QG energy E_{QG}
  - → fix constraints on different models predicting LIV

- Use of a **generic** modified dispersion relation based on a series expansion:

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

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

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

- Photon speed depends on their energy
  $\Rightarrow$ **Time delay** between photons with different energies

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

κ_n = source distance parameter (κ_n increases with z and **encodes the space-time model**) ($n = 1, 2$)

Current status

- For now, the lower limits obtained on E_{QG} are of the order of $10E_{Pl}$ for individual GRBs, and of the order of 10^{17} GeV when combining several GRBs observed by *Fermi*-LAT [Ellis *et al.* 2019 Phys.Rev.D]. The best limit obtained by H.E.S.S. is currently 2.1×10^{18} GeV with the PKS 2155-304 flare on the night of July 28, 2006 [Abramowski *et al.* 2011 Astrop.Phys.] (limits obtained for $n = 1$, 95% CL)
- No population study available at TeV energies yet $\rightsquigarrow$ creation of the γ-LIV working group, which is also preparing CTAO LIV analyses

The γLIV working group (H.E.S.S., MAGIC, VERITAS and 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 → first population study at TeV energies

Already achieved

- **LIVelihood**: analysis framework (likelihood approach), to simulate, analyse and combine results from different experiments
- Code tested on simulated data ⇝ first paper [Bolmont *et al.* 2022 ApJ]

On-going

- Combination of real datasets: 3 BL-Lac flares observed by LST-1, GRB190114C observed by MAGIC, one 1ES 1959+650 flare observed by VERITAS and one PKS2155-304 flare observed by H.E.S.S. (see C. Plard poster at ICRC next week)
- Combination of all the available datasets from the 4 collaborations

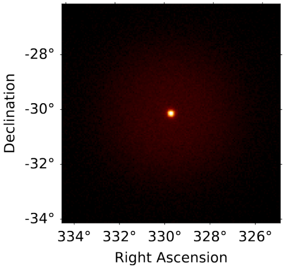
The High Energy Stereoscopic System telescope

- Located in Khomas highlands of Namibia, 1800m a.s.l.
- Array of 5 Cherenkov telescopes (IACT)
- Four 12m mirror telescopes + one 28m mirror telescope
- 100 GeV to 10 TeV

About PKS 2155-304

General information

- BL-Lac object, at z=0.116
- one of the brightest BL-Lac
- enter regular flaring phases
- long term monitoring by H.E.S.S.



In July 2006, H.E.S.S. observed two very bright flaring nights from this source:

- the first night's flare was short and bright and gave the best result on E_{QG} from H.E.S.S.
- the second night's flare benefited from multiwavelength observations and is being analysed

$\Longrightarrow$ **Focus on the LIV analysis of the second flare**

PKS 2155-304 July 2006 second flare data

Why this flare?

- Huge data set, not yet analysed for a LIV search
  - Full night of observation, 15 runs, 32612 excess events, 254σ
  - Zenith angle varied from 53° to 8° to 50°
  - Variability timescale down to $\sim$2 minutes
- Possibility for a good limit on E_{QG} & important addition to the combined multi-instrument analysis

The multiwavelength analysis of this night was published in [Aharonian *et al.* 2009 A&A]

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- Possibility for a good limit on E_{QG} & important addition to the combined multi-instrument analysis
- Part of the H.E.S.S. public data release, which can be used as a benchmark and provide a reproducible analysis with LIVelihood (which will be made public when the second part of the paper is published)

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PKS 2155-304 July 2006 second flare lightcurves

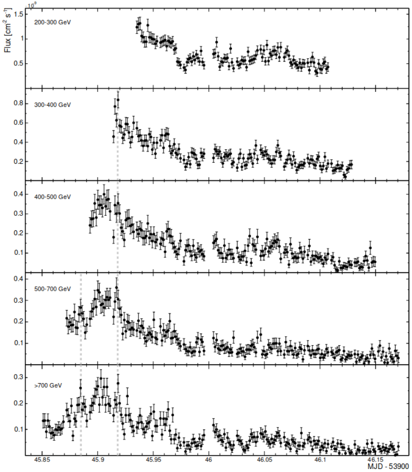


Fig. 1. Lightcurves taken from the original paper [Aharonian *et al.* 2009]

To compute the time lag, we need a **template** lightcurve (from low energy photons) to compare to high energy photons.

In order to remove any bias caused by the absence of low energy photons at higher zenith angles, we apply a cut **E>400 GeV**.

→ split the photons into low and high energy parts, using the median energy (for the full flare $E_{med} = 0.61$TeV)

PKS2155-304 July 2006 Chandra flare lightcurve

Looking at the lightcurve at low energies (cut for E>400GeV because of high zenith observations)

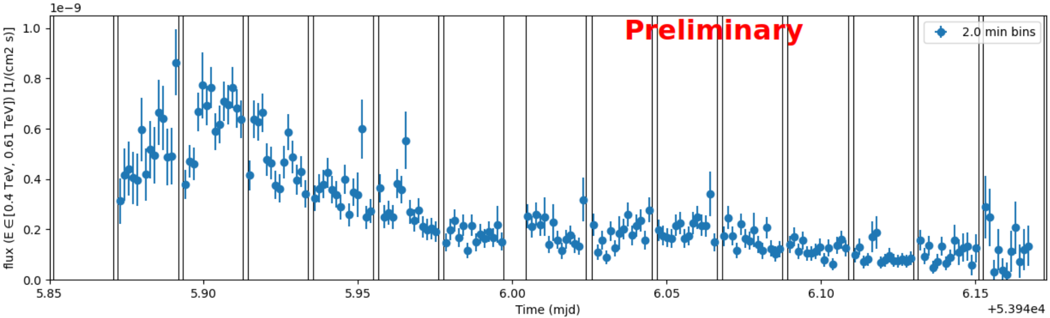
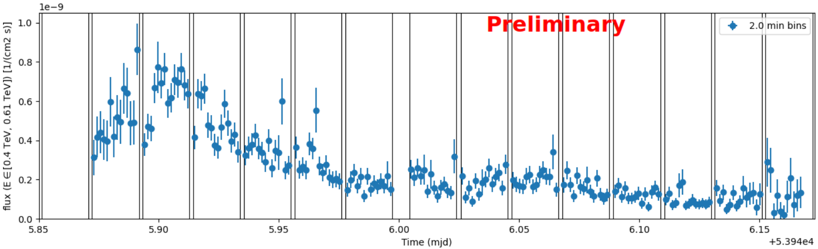


Fig. 2. Lightcurve from H.E.S.S. DR1 at low energies (400-610 GeV). Vertical lines separate runs.

PKS2155-304 July 2006 Chandra flare template lightcurve

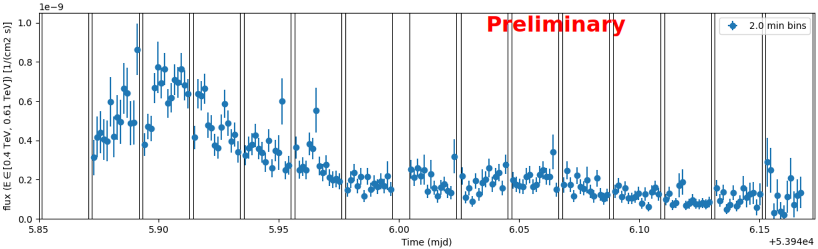
Hard to fit the whole lightcurve because of the many free parameters in the usual fitting method (sum of asymmetric Gaussians)



PKS2155-304 July 2006 Chandra flare template lightcurve

Hard to fit the whole lightcurve because of the many free parameters in the usual fitting method (sum of asymmetric Gaussians)

$\longrightarrow$ introduce new method to get rid of the fit $\Longrightarrow$ **Spline interpolation**



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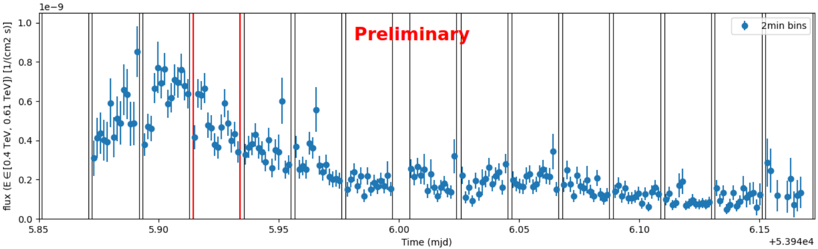
$\longrightarrow$ method validated on the analysis of the **4th run**, where both the fitting method and the spline are usable (results presented at TMEX25 in January)



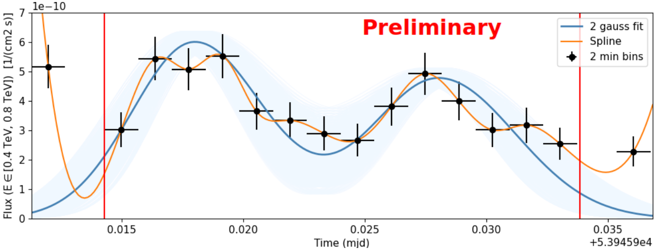
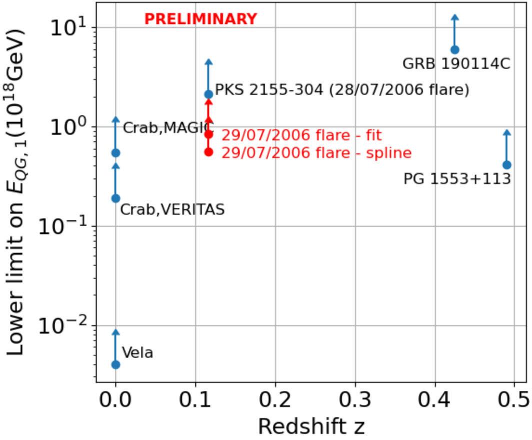


Fig. 3. Two templates for the lightcurve on low energies (in this run [0.4,0.79] TeV)

Results on the run#4

- Analysis on run 4 provided a **good limit** with one run
- **Allowed to compare** the spline interpolation and fitting methods → comparable systematic errors ✓



PKS2155-304 July 2006 Chandra flare template lightcurve

Now **expand** to the main part of the flare (high flux and stable spectral index)

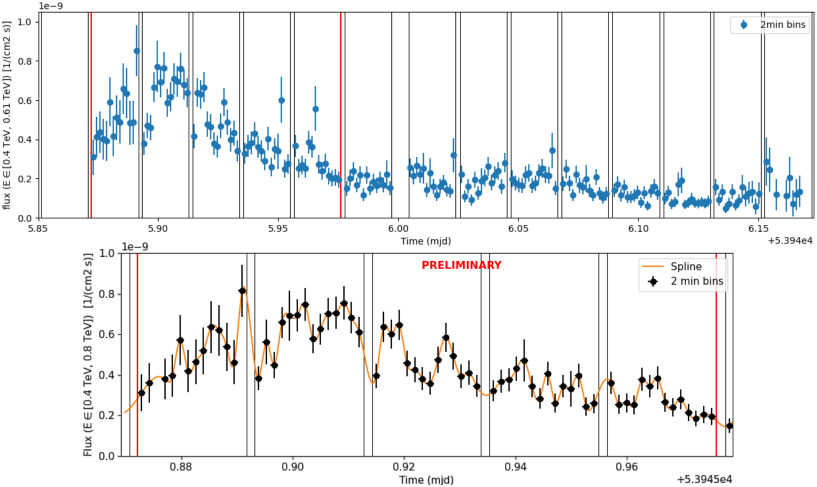


Fig. 4. Template for the lightcurve on low energies (in these runs [0.4,0.75] TeV)

Reconstruction of the lag from simulations - Sanity check

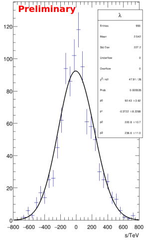
Process

- **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

$\rightarrow$ then repeat the process for 1000 simulations

$\rightarrow$ get the distributions of minimum values and lower and upper limits

$\rightarrow$ extract the mean values of each distribution



$\rightarrow$ reconstructed at -1$\pm$100s/TeV

Template, calibration and application to real data

Procedure: define lightcurve template, check the calibration, apply to real data and study systematics

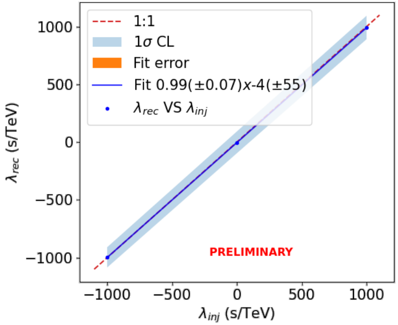


Fig. 5. Calibration plot for the spline template.

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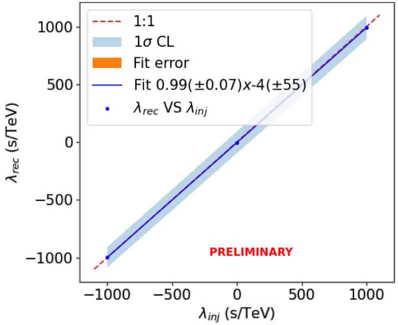

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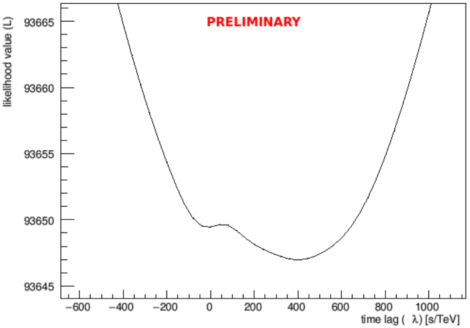


Fig. 6. Likelihood curve from real data.

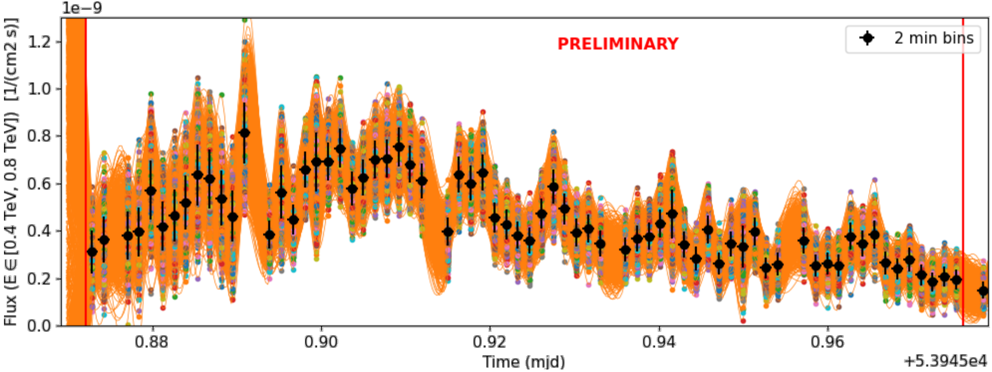
Real data likelihood

Minimum: 389 s/TeV
1σLL: -113 s/TeV
1σUL: 699 s/TeV

Systematic error from the spline template

Method

Interpolate splines (1000) from the fluctuations of the flux points within their error bars



Generate photon lists (1000) as before
Associate randomly each spline to one photon list to calculate the likelihood

All systematic errors

Using this method, but taking all the nuisance parameters into account, the distribution of the minima becomes:

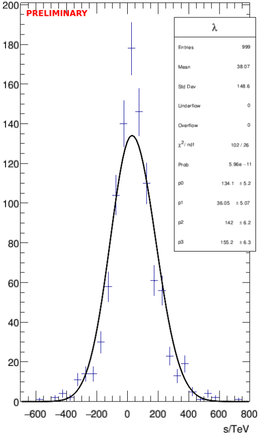


Fig. 7. Distribution of $\lambda_{\rm rec}$ from 1000 simulations following the real photon list time and energy distribution.

Values

Minimum $=$ 36s/TeV
1σLL $=$ -106s/TeV
1σUL $=$ 191s/TeV

↓

Systematic error

$\pm \binom{155}{142}$ **s/TeV**

All errors

J&P

$$\lambda_1 = 389 \pm \binom{229}{243}_{stat} \pm \binom{155}{142}_{syst} \text{ s/TeV}$$

Results (Preliminary) - Jacob&Piran n=1

Limits on E_{QG} at 95% CL (subluminal)

Big flare	2.1e18 GeV
Chandra flare Run 4 (Fit)	8.4e17 GeV
Chandra flare Run 4 (Spline)	5.6e17 GeV
Chandra flare Run 2-6 (Spline)	4.6e17 GeV

Limits on E_{QG} at 95% CL (superluminal)

Big flare	2.1e18 GeV
Chandra flare Run 4 (Fit)	1.2e18 GeV
Chandra flare Run 4 (Spline)	3.74e18 GeV
Chandra flare Run 2-6 (Spline)	2.7e18 GeV

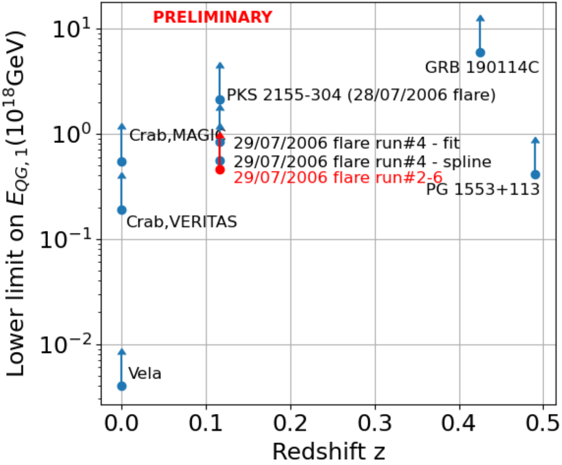


Fig. 8. Current limits on $E_{QG,1}$ (subluminal).

Conclusions and next steps

Spline interpolation method

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Runs 2-6

- Analysis is final and provides a new **stringent limit**
- Taking all runs added fluctuations of the likelihood curve, increasing the statistical error even with more photons
- Hence this limit is lower, but more robust than the run 4 only
- Also shows that fluctuations between runs do not significantly change the result on E_{QG}

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Now:

- Combine the data within the γLIV WG: first results presented next week at ICRC 2025

Thank you!

Source intrinsic effects

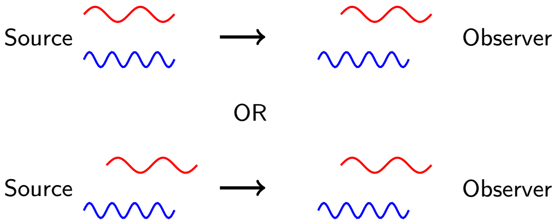


Fig. 9. LIV or intrinsic effect?

Examples

Acceleration mechanism, source extension...

Solution

- **population study**: mitigate the intrinsic effects influence by looking at sources of the same type but at different distances
- **modelisation**: constrain intrinsic effects with modelisation of acceleration mechanisms

Lag-redshift models

J&P

$$\kappa_n^{J\&P}(z) = \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz' \tag{2}$$

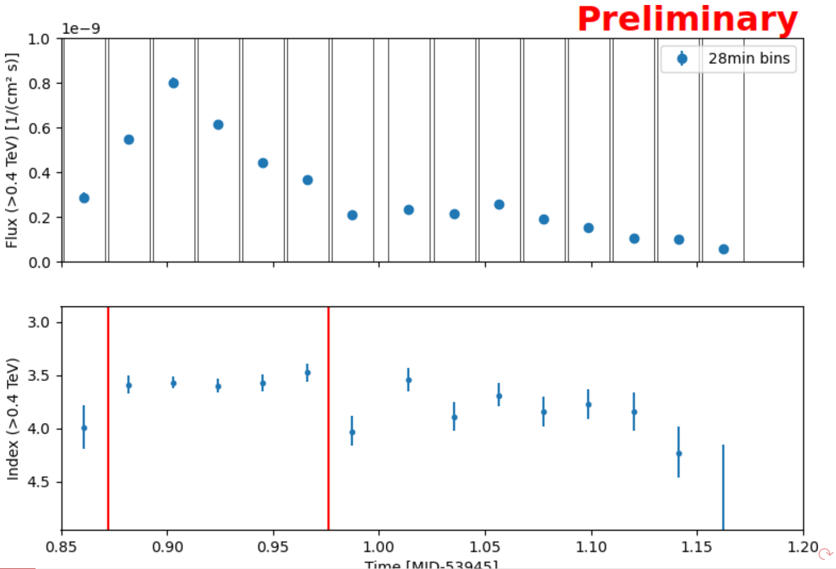
Doubly Special Relativity

$$\kappa_n^{DSR}(z) = \int_0^z \frac{h^{2n}(z')}{(1+z')^n\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz' \tag{3}$$

with

$$h(z') = 1+z' - \sqrt{\Omega_m(1+z')^3+\Omega_\Lambda} \times \int_0^{z'} \frac{dz''}{\sqrt{\Omega_m(1+z'')^3+\Omega_\Lambda}} \tag{4}$$

Template lightcurve (preliminary)

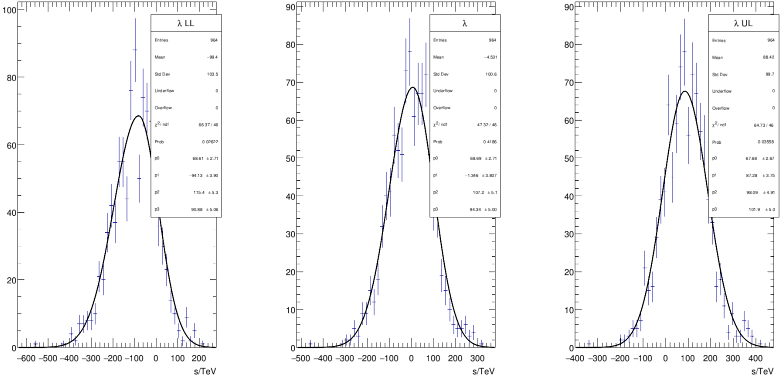


Hard to fit the whole lightcurve $\rightarrow$ focus the analysis to the main flare, where the spectral index is constant

Fit - 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)

Preliminary



Mean values

Min = -1s/TeV
1σLL = -99s/TeV
1σUL = 88s/TeV

Fig. 11. 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).

Spline - More details on the template lightcurve systematic error

For the spline

1. Start with the flux lightcurve derived from real data, where each flux value has an associated error. We can draw a **random value for each time** bin using a Gaussian distribution. This distribution is centered around the mean flux value, with the standard deviation equal to the associated error. Then we can interpolate a **spline from this new set**.

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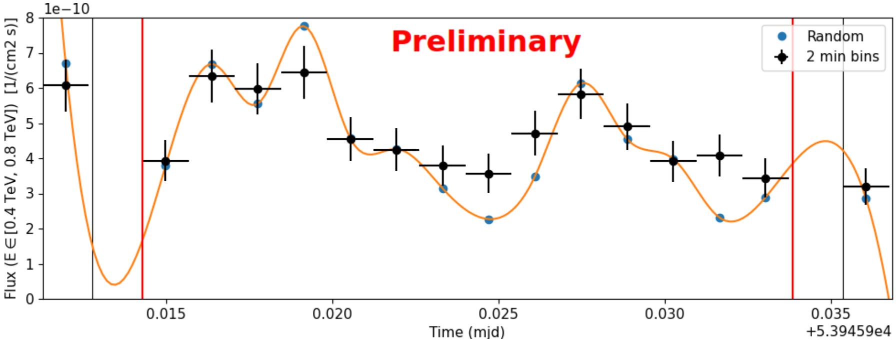

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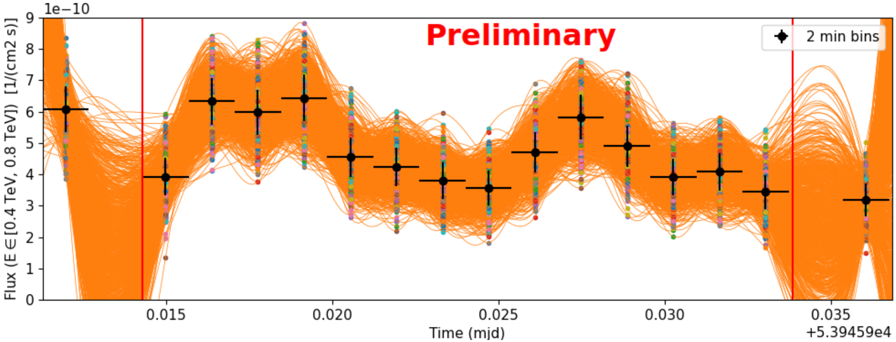
2. **Repeat** for 1000 splines.



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2. Repeat for 1000 splines.
3. Generate 1000 photon lists **with LIVelihood** from the spline template extracted from real data. Compute the likelihood for each list: **one spline for one photon list**. The minimization process finds the best values for the lag, the normalization and the other nuisance parameters (spectral index, background proportion, etc)

Note

Then, because the splines are **not used freely** with each photon list, we don't expect the likelihood shape to be widened. However, we can also read the error from the **width of the distribution**.

All systematic errors

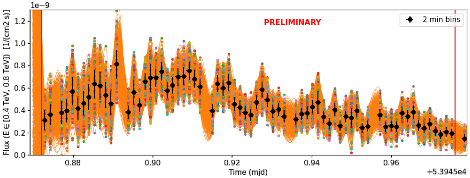

Fig. 12. Error from lightcurve template.

	Template	Spectral index	Redshift	Background proportion	Energy scale
Values	$\pm 1\sigma$	± 0.07	$\pm 10^{-3}$	$\pm 1\%$	$\pm 10\%$
Contribution (s/TeV)	144	29	11	~ 1	17

Finally, compute the energy limit from the mean value and systematic error

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

$$\frac{dP}{dE_m dt} = \frac{w_s}{N_s} \int A(E_t, \epsilon) M(E_t, E_m) \Gamma_s(E_t) C_s(t, E_t; \lambda) dE_t + \text{bkg. contrib} \quad (5)$$

A is the effective area, M the energy migration matrix, Γ_s the spectrum of the source and C_s is the lightcurve
λ is the likelihood parameter to be measured or constrained

$$L(\lambda) = -\sum_i \log\left(\frac{dP}{dE_m dt}(E_{m,i}, t_i; \lambda)\right) \quad (6)$$

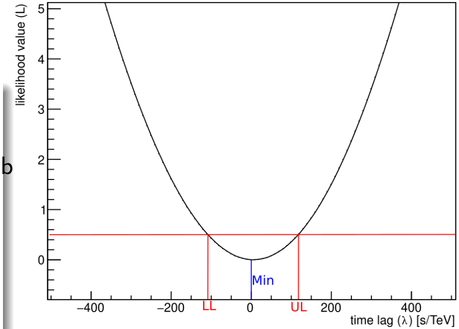

Fig. 13. Likelihood computed from a list of simulated photons following the template time distribution. Minimum and confidence interval at 1σ ($L = 0.5$) are indicated.