Testing LIV through Delayed Air Shower Development

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Lorentz Invariance Violation (LIV)

LIV may be a hint to reveal new physics beyond the Standard Model and possible quantum-gravity effects.

Particle species for LIV test : photons, electrons, hadrons and neutrinos

Expansion order of LIV : n = 1 linear, n=2 quadratic, ...

Sign of the modification : superluminal ($s_n = 1$) or subluminal ($s_n = -1$)

$$E^2 = p^2 + m_i^2 + s_n \frac{p^{n+2}}{(M_i^{(n)})^n}$$

LIV model in this study

Photon sector, quadratic, subluminal case ($M_{photon}^{(2)} = M$)

Two Typical Method to Detect LIV with Gamma-Ray

ToF : LIV affects the speed of light.

Detect the energy dependence in the arrival time from the transients.

Highest constraints with the method

M > 7.2 x 10^11 GeV (LHAASO collaboration 2024)

EBL : LIV affects the cross section of the pair creation ($2\gamma \rightarrow e^- + e^+$).

Detect the spectrum deformation from the extra galactic sources.

Highest constraints with the method

M > 2.4 x 10^12 GeV (Lang et al. 2019)

New Method : Study LIV with Air Shower

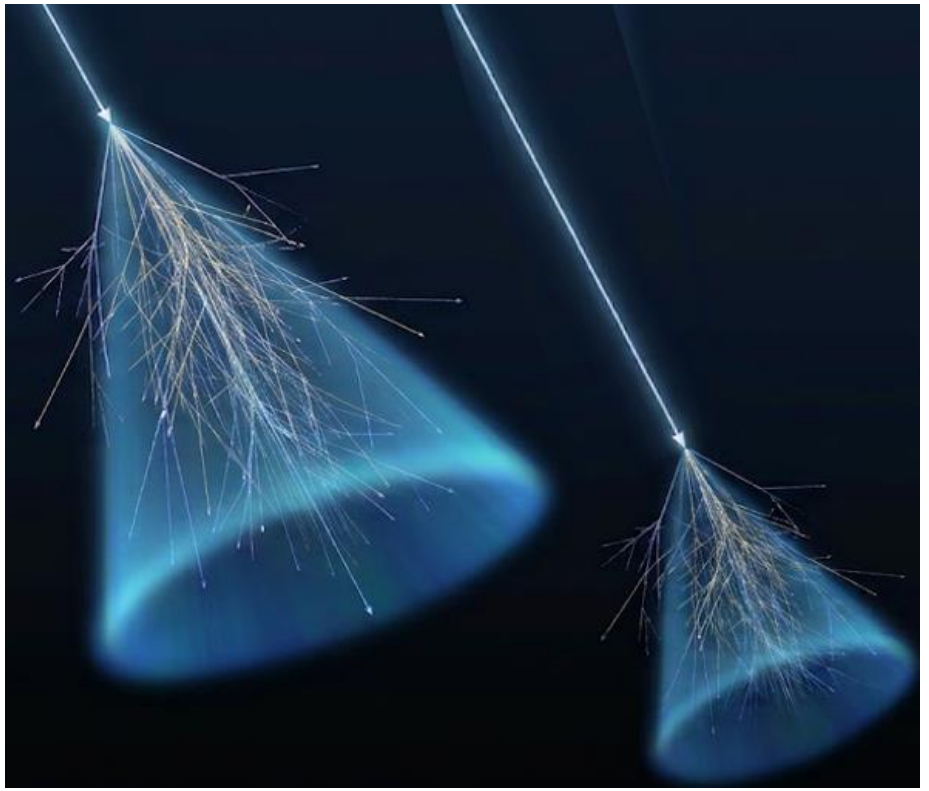
Apply the method shown in Rubtsov et al. 2017 to LST.

Detection Principle :

1. The dispersion relationship of the photon is modified.

$$E_\gamma^2 = p_\gamma^2 - \frac{p_\gamma^4}{M^2}$$

2. Cross section of the Bethe-Heitler process ($\gamma + N \rightarrow e^- + e^+$) decrease rapidly at high energy.
3. Air showers develop deeper in the atmosphere.
4. Too deep showers are no longer observed.
5. The flux at high energy will decrease.



Cross section and height distribution

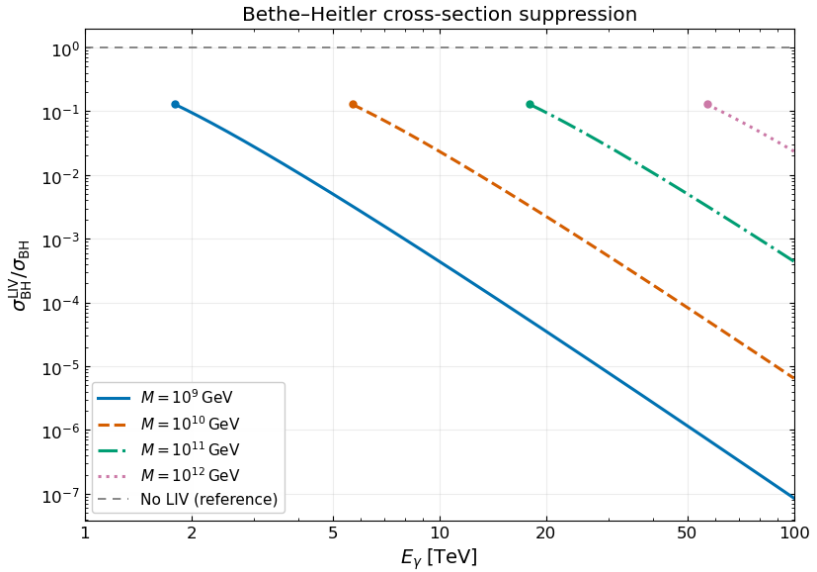
Modified cross section (Rubtsov et al. 2017)

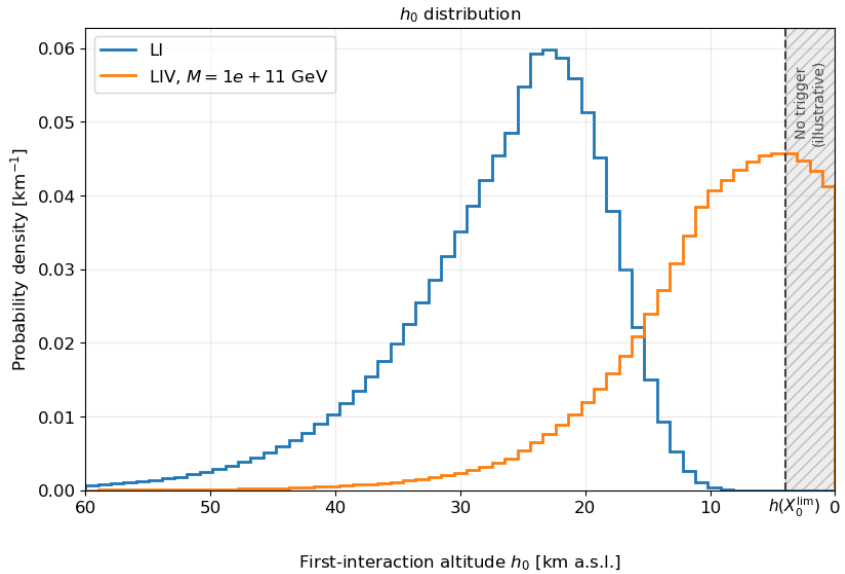
Condition : Energy of the photon is high enough.

$$\chi = \frac{p_\gamma^4}{4m_e^2 M^2} \gg 1$$

Cross section

$$\frac{\sigma_{BH}^{LIV}}{\sigma_{BH}} \approx \frac{12m_e^2 M^2}{7E_\gamma^4} \ln \frac{E_\gamma^4}{2m_e^2 M^2}$$



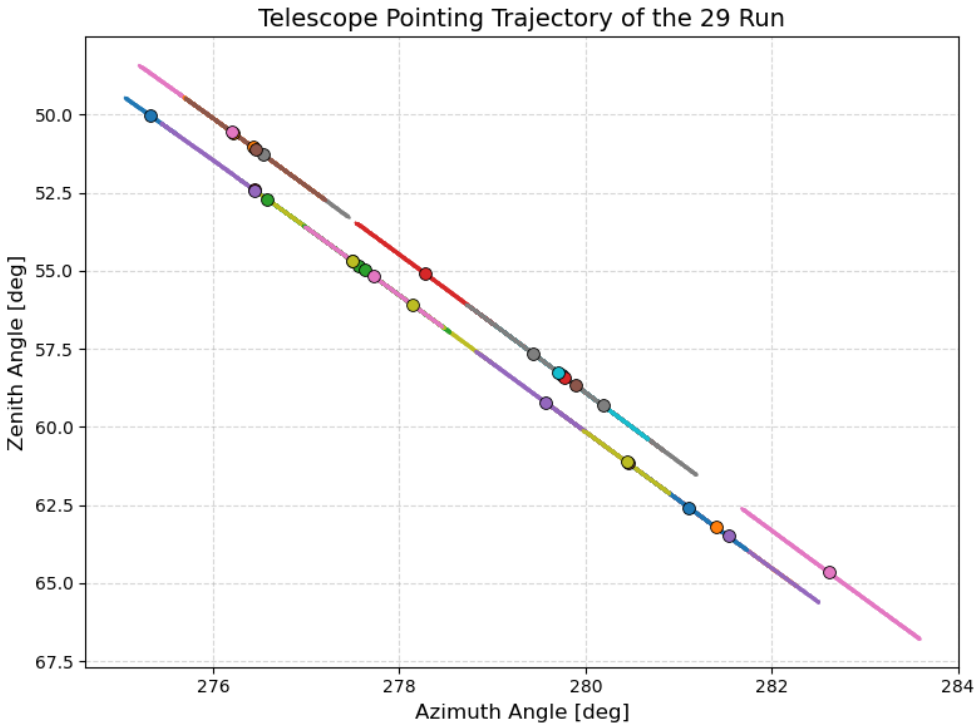


Applied the method to the high zd data

Applied data

- 2022-11-30 to 2023-03-20, Crab, gh efficiency : 0.7
- DL3 files stored in the LST server
- Total live time : 428 min (29 runs)
- Zd : 51 ~ 64 deg

Used high zd data to effectively collect the high energy events



Simplifications and Assumptions in the Analysis

In the paper (Rubtsov et al. 2017), it assumed

1. In the formation of the air shower, they considered the LIV effect until the first interaction of gamma-rays with the atmosphere, and ignored the LIV effect afterword.
2. The distribution of the $\Delta X = X_{max} - X_0$ is gaussian with its mean 250 g/cm^2 and std 50 g/cm^2
3. Air showers which X_{max} exceed the atmospheric depth at the height of telescope ($= X_{max}^{lim}$) is no longer observed.

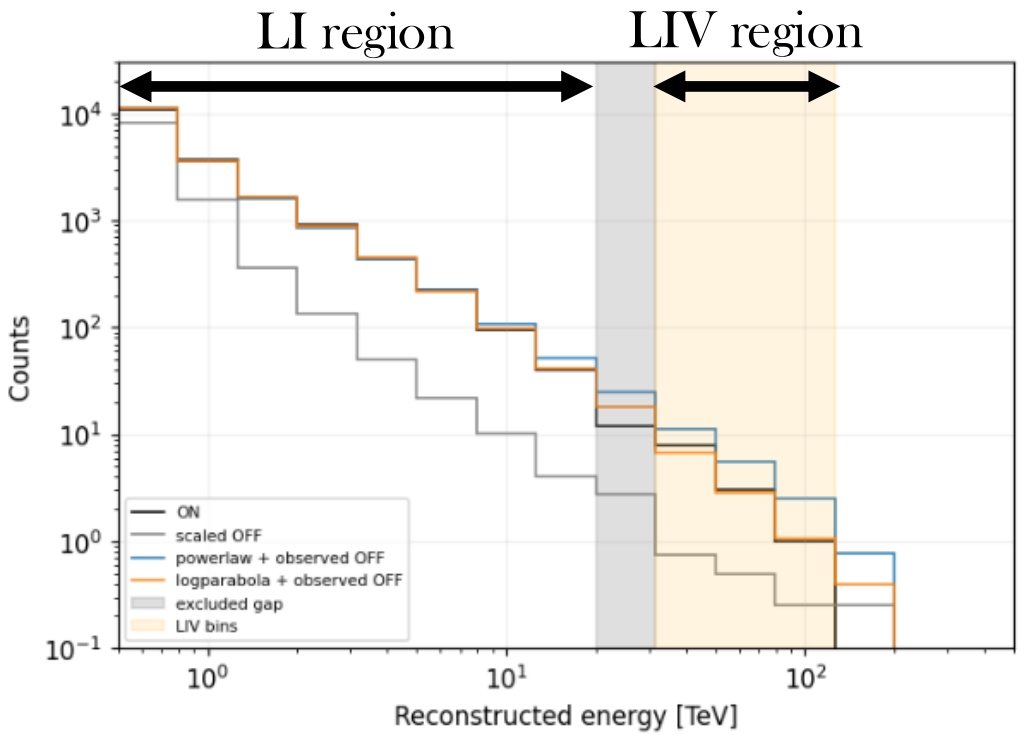
Additional assumption in my analysis

- If $\chi \geq 10$, I considered the LIV effect, but if $\chi < 10$, I ignored the LIV effect.

Outline of the Analysis

Extrapolate the spectrum from the low energy part (LI region) to the high energy part (LIV region), there should be the deviation due to LIV effect.

1. According to the counts map, I used the bins below 19 TeV as LI region and the three bins over 31 TeV as LIV region.
2. Fit the low energy region with power low and log parabola.
3. Compare the expected counts in high energy region (s_LI) and the real count.
4. Derive the lower limit of the LIV parameter, M



Analysis Detail to Obtain the Lower Limit M_min

1. Define the likelihood function in LIV energy region at wobble ON region.

n_H : observed counts at ON region, b_H : observed counts at OFF region, α : ¼ , s_H : expected counts from the source at ON region, b_H, : expected background counts at ON region

$$\mathcal{L}_H(s_H, b_H) = \text{Poisson}(n_H | s_H + b_H)\text{Poisson}\left(m_H | \frac{b_H}{\alpha}\right)$$

2. From the Wilks theorem, the q-value follows chi square distribution (DoF=1).

$$q(s_H) = -2\ln\left(\frac{\mathcal{L}(s_H)}{\mathcal{L}(\hat{s}_H)}\right)$$

3. Find the s_H = s_min, which correspond to the 95% one-sided lower confidence limit.

$$\mathrm{q}(s_{min}) = q_{crit} = 2.7055$$

Analysis Detail to Obtain the Lower Limit M_min

4. Derive the M_min from the s_min

M and s_H are related with these equations.

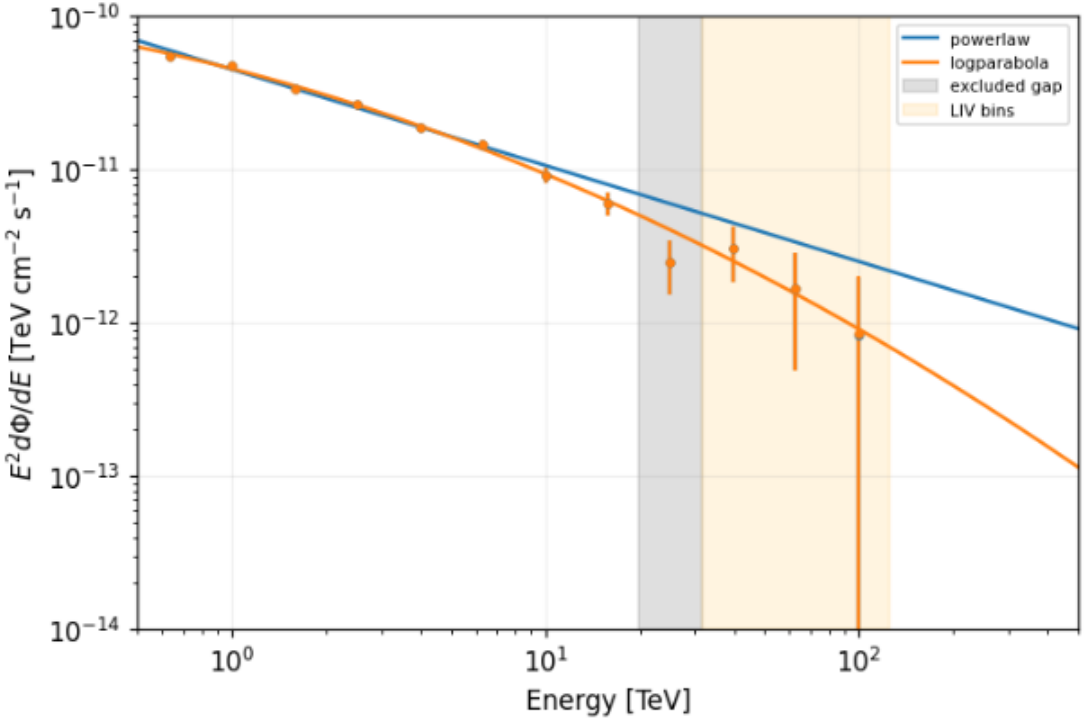
The expected counts in a bin

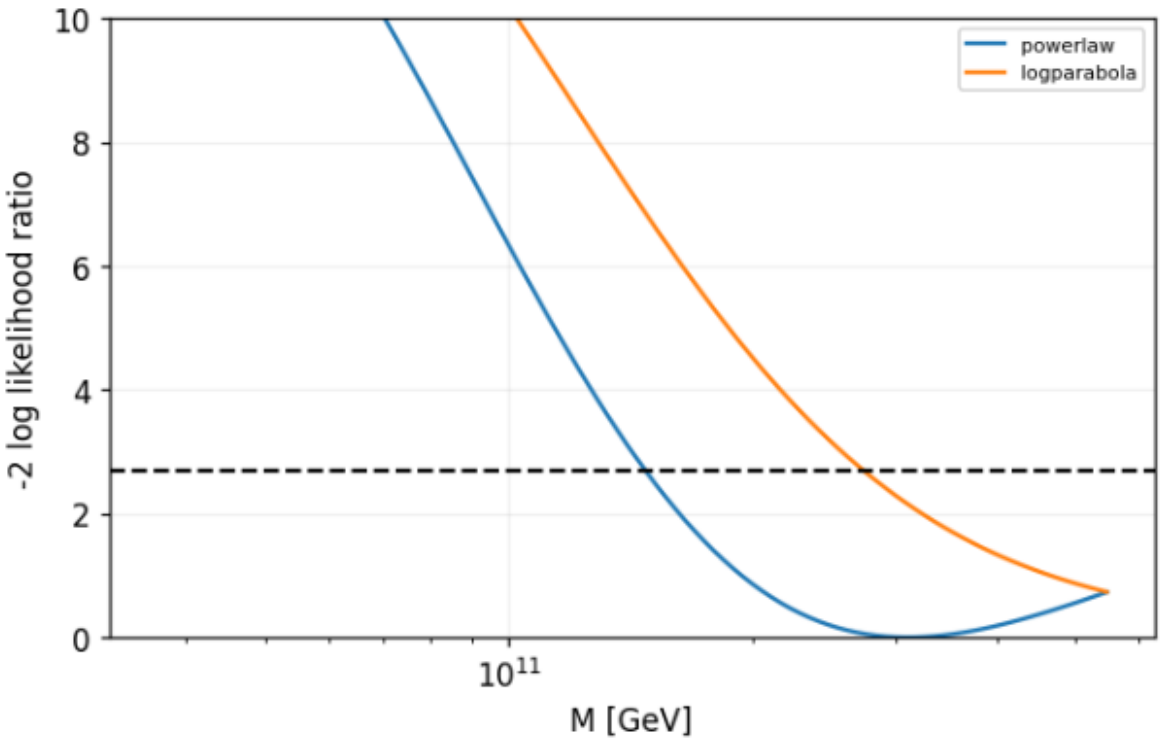
$$s_H(M) = \sum_r T_r \int dE_{\gamma,\mathrm{true}} \phi(E_{\gamma,\mathrm{true}};\hat{\theta}) A_{\mathrm{eff},r}(E_{\gamma,\mathrm{true}}) P_{reg}(E_{\gamma,\mathrm{true}}, M) \int_{E^{min}_{\gamma,\mathrm{reco},H}}^{E^{max}_{\gamma,\mathrm{reco},H}} dE_{\mathrm{reco}} D_r(E_{\gamma,\mathrm{reco}}|E_{\gamma,\mathrm{true}})$$

Flux suppression probability due to LIV $\left(\frac{d\Phi}{dE}\right)_{LIV} = P_{\mathrm{reg}}(E_\gamma) \cdot \left(\frac{d\Phi}{dE}\right)_{LI}$

$$P_{reg}(E_\gamma, M) = \int_0^{X^{lim}_{max}} dX_{max} \int_0^{X_{max}} dX_0 \frac{\exp\left(-\frac{X_0}{\langle X_0\rangle_{LIV}}\right)}{\langle X_0\rangle_{LIV}} \cdot \frac{\exp\left(-\frac{(X_{max}-X_0-\langle\Delta X\rangle)^2}{2\Sigma^2_{\Delta X}}\right)}{\sqrt{2\pi}\Sigma_{\Delta X}}$$

Results : SED and q-M Map





From the right figure, I got the result

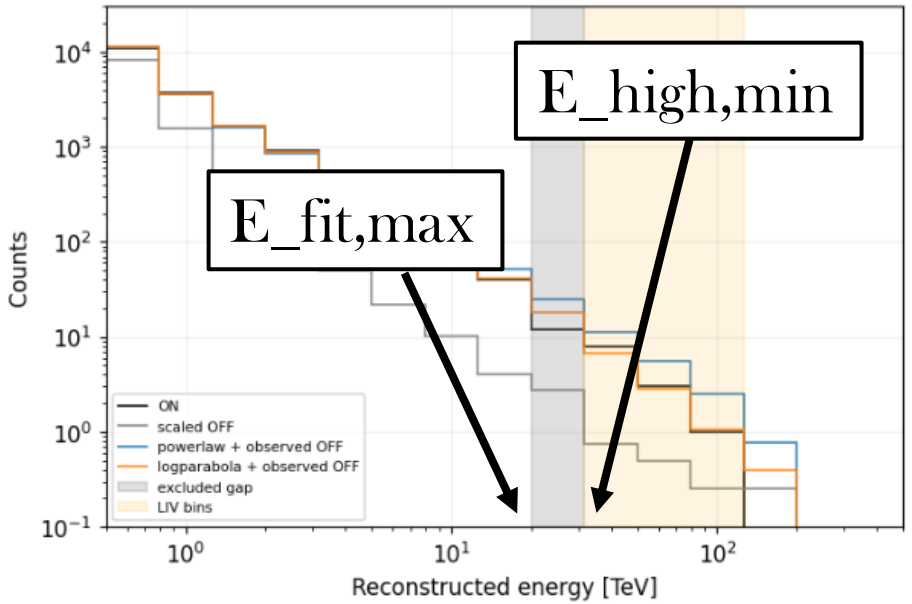
$$M \geq 2.74 \times 10^{11}\ \text{GeV} \quad \text{(Logparabola)}$$

$$M \geq 1.47 \times 10^{11}\ \text{GeV} \quad \text{(Powerlow)}$$

Self-Consistency Check

In the analysis, I assumed

1. Below E_fit,max, LIV effect is ignored.
2. Above E_high,min, LIV effect appears.



Model	M_{low} [GeV]	$E_{\mathrm{fit,max}}$ [TeV]	$\chi(E_{\mathrm{fit,max}})$	$E_{\chi=10}$ [TeV]	$E_{\mathrm{high,min}}$ [TeV]	$\chi(E_{\mathrm{high,min}})$
Power law	1.473431×10^{11}	19.905359	6.923413	21.821768	31.547867	43.683784
Log-parabola	2.736017×10^{11}	19.905359	2.007901	29.736128	31.547867	12.669001

The result is consistent with the assumption

Compare the Result with Rubtsov et al. 2017

Their result : Applied the method to Crab observation with HESS and HEGRA

- For HEGRA data : **M > 2.1 x 10^11 GeV**

(Highest energy bin centered at 75 TeV)

- For HESS data : **M > 1.3 x 10^11 GeV**

(Highest energy bin centered at 40 TeV)

My result is consistent with the study

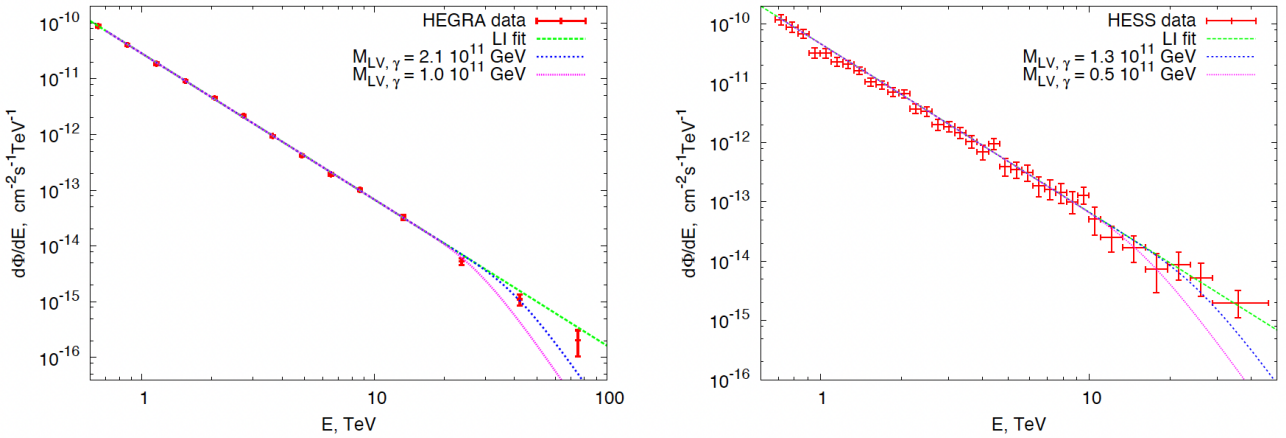


Figure 1: Photon spectrum of the Crab nebula obtained by collaborations HEGRA (385 hours of data from 1997 to 2002) [63] (left) and H.E.S.S. (4.4 hours of data during the flare of March 2013) [64] (right). The dashed line corresponds to the best power-law fit of the spectrum while the dotted lines show the prediction for the flux under the hypothesis of Lorentz violation with a given $M_{LV,\gamma}$.

Cited from Rubtsov et al. 2017

Summary and Future works

The constraint obtained in this study is within a factor of ten of the current best constrains from other methods.

This paper (Rubtsov et al. 2017) suggests observing Xmax and more directly detect the LIV effect.

Advantages

1. No need to assume the distribution of $\Delta X = X_{max} - X_0$
2. No need to assume the observable maximum atmospheric depth (X_{max}^{lim})
3. We can see the LIV effect more directly compared to the flux suppression.

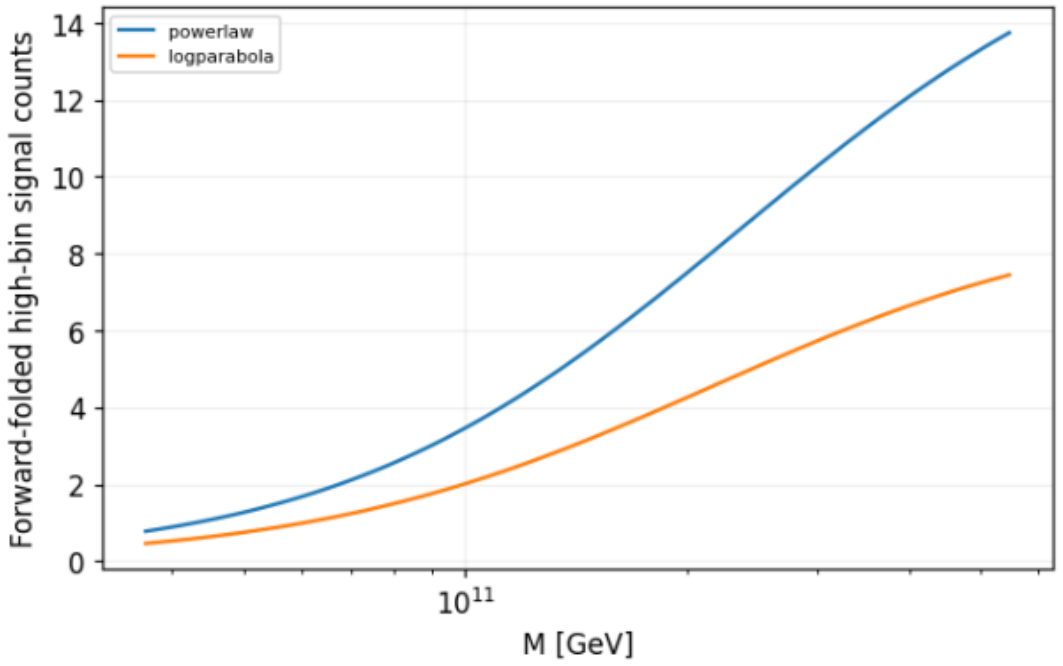
Accurate and sensitive to LIV

We can possibly explore a previously untested parameter space for LIV with LST+MAGIC or future LST stereo observation.

Back up

Quantity	Reconstructed energy [TeV]	Power law [%]	Log-parabola [%]
$f_{\mathrm{mis\,reco,l,1}}$	0.500–0.792	0.000000	0.000000
$f_{\mathrm{mis\,reco,l,2}}$	0.792–1.256	0.000000	0.000000
$f_{\mathrm{mis\,reco,l,3}}$	1.256–1.991	0.000000	0.000000
$f_{\mathrm{mis\,reco,l,4}}$	1.991–3.155	0.000000	0.000000
$f_{\mathrm{mis\,reco,l,5}}$	3.155–5.000	0.000000	0.000000
$f_{\mathrm{mis\,reco,l,6}}$	5.000–7.924	0.006187	0.000000
$f_{\mathrm{mis\,reco,l,7}}$	7.924–12.559	0.181465	0.014143
$f_{\mathrm{mis\,reco,l,8}}$	12.559–19.905	7.522110	0.385109
$f_{\mathrm{mis\,reco,h}}$	31.548–125.594	0.297788	6.310175

s_H


powerlaw
logparabola
Forward-folded high-bin signal counts
0
2
4
6
8
10
12
14
10^{11}
M [GeV]

Problem of the Analysis in Rubtsov et al. 2017

Bethe Heitler process $\gamma + N \rightarrow e^- + e^+ + N$

Triplet pair production $\gamma + e^- \rightarrow e^- + e^+ + e^-$

The cross section

$$\sigma_{pair}^{LI} = \sigma_{BH}^{LI} + \sigma_{Tri}^{LI}$$

The correct LIV-introduced cross section

$$\sigma_{pair}^{LIV} = \sigma_{BH}^{LIV} + \sigma_{Tri}^{LIV}$$

In this paper

$$\lambda^{LIV} = \frac{\sigma_{BH}^{LI}}{\sigma_{BH}^{LIV}} \lambda^{LI}$$

Triplet pair production is not considered.
This term should be

$$\frac{\sigma_{BH}^{LI} + \sigma_{Tri}^{LI}}{\sigma_{BH}^{LIV} + \sigma_{Tri}^{LIV}}$$