

First combined studies on Lorentz Invariance Violation from observations of astrophysical sources

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Lorentz Invariance Violation

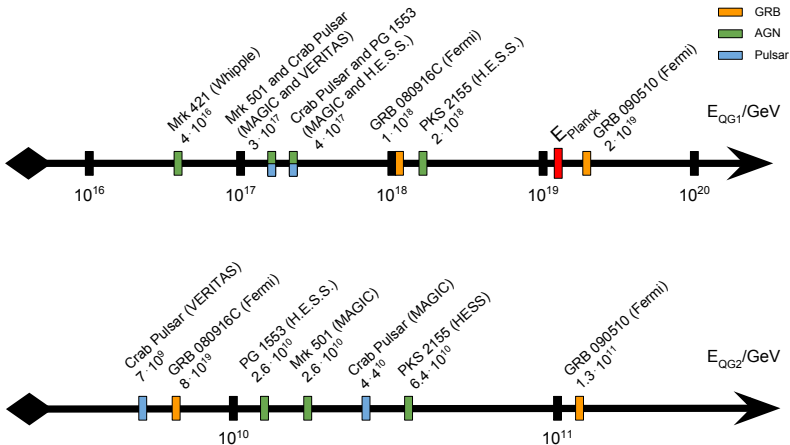
- **Theory** - Aim to build a common theory covering General Relativity and Quantum Mechanics.
- Different approaches, leading to modified dispersion relations inducing LIV.
 - Loop Quantum Gravity.
 - SM extension.
 - Hôrawa's gravity.
- **Experiment** - prove Quantum effects in Space-time structure.
Example: Time-Of-Flight Studies.

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

LIV experimental study

The ToF studies - opportunity to the experimental gamma-ray sector.

- Proportional to E^n and redshift.
- Fast, variable, very energetic, distant sources → Gamma-rays source options.
 - Pulsars, AGNs, GRBs.
- Associated challenges to the study.
 - Low statistic data sets.
 - Few adequate sources for the study.
 - EBL absorption of very energetic photons.
- Solution - Combination between experiments.
 - Increase of the statistics.
 - Intrinsic effects and redshift dependence study.
 - LIV multi-type source combination.



Methodology

Maximum Likelihood analysis (ML) is very adequate

- Supports very low photon statistics.
- Any complex temporal distribution is allowed.
- Unbinned method: maximum use of information.
- Can be adapted in different ways.

Maximization of Likelihood source function.

- Likelihood is created from the event PDFs of the source emission.
- One estimator parameter and some optional nuisance parameters.

$$\frac{dP}{dE dt} = N \int_0^{\infty} \Gamma(E_s) C(E_s, t) G(E - E_s, \sigma_E(E_s)) F_s(t - D(E_s, E_{QGn}, z)) dE_s.$$

ML Combined Analysis

Every source has a Likelihood function - the combination of several of them is straightforward.

- 1 They must share a common estimator parameter.
- 2 The estimator has to be redshift independent.

$$L_{Comb}(\lambda) = \prod_{i=1}^{N_{source}} L_i(\lambda) \longrightarrow -2\log(L_{Comb}(\lambda)) = -2 \sum_{i=1}^{N_{source}} \log(L_i(\lambda)),$$

Typically each likelihood function has a parabolic shape in logarithmic scale.

- Look for the minimum in negative logarithmic scale.
- Easy CLs computation.

Simulation procedure

Simulated sources for the study.

- **Mrk 501** 2005 flare detected by MAGIC.
- **PG 1553+113** 2012 flare detected by H.E.S.S.
- **PKS 2155-304** 2006 flare detected by H.E.S.S.
- **VHE Crab Pulsar** radiation detected by VERITAS.

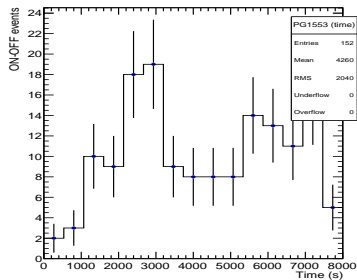
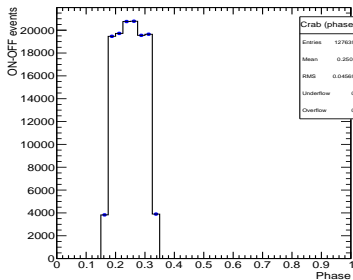
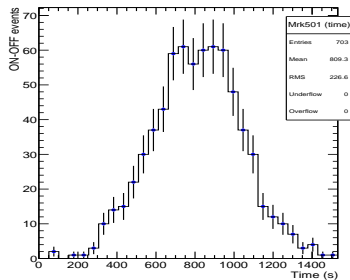
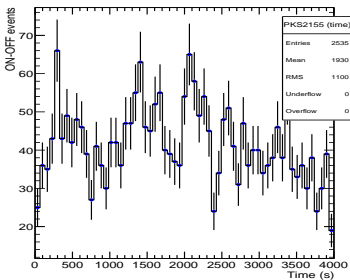
Simulation steps

- 990 simulation sets of each source.
- E_{true} and t_{true}/ϕ_{true} from parametrized published data.
- Injection of LIV effect ($\Delta t \propto E^n$)
- Application of IRFs to obtained measured values.

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└ Simulations

└ Simulated distributions



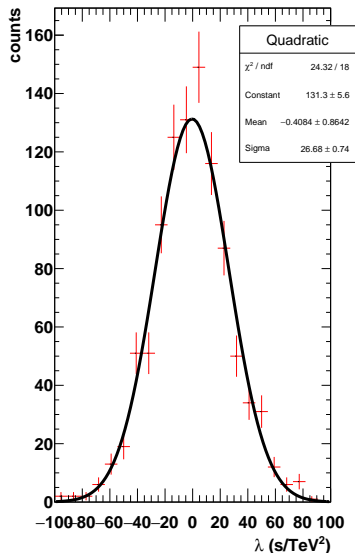
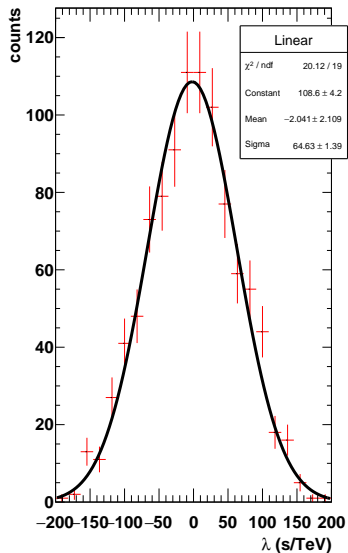
The analysis, applied over the 990 sets of simulations, uses λ as a fit parameter, that is related to the QG energy scale E_{QG} ,

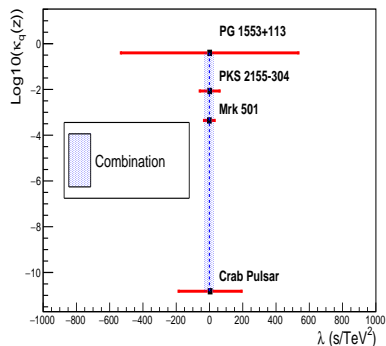
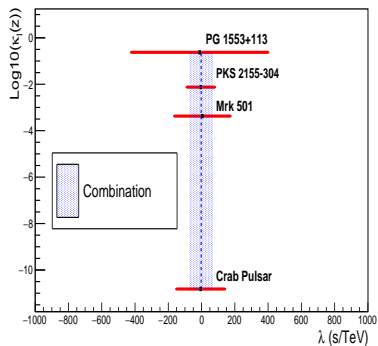
$$\frac{\Delta t_n}{E_h^n - E_l^n} \simeq s_{\pm} \frac{n+1}{2H_0} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz' = s_{\pm} \frac{n+1}{2H_0} \frac{1}{E_{QG}^n} \kappa(z),$$

$$\lambda = \frac{\Delta t_n}{\Delta E^n \kappa(z)} = \frac{1}{E_{QG} H_0},$$

From every analysis, for individual and combined cases and for linear and quadratic case, we get:

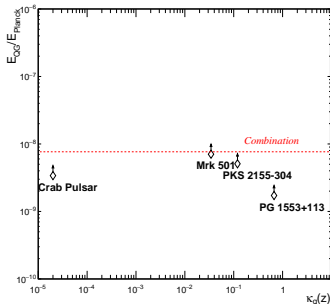
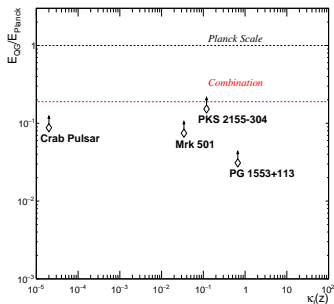
- Distribution of best fit value of the parameter λ .
- Distribution of 1-sided 95% CLs.
- Upper limits on E_{QG} .





Parameter	PKS 2155	Mrk 501	PG 1553	Crab	Combination
λ_{best} (s/TeV)	-4.5±2.6	4.9±5.6	-11.3±13.4	-5.4±4.7	-2.37±2.2
1σ CL (s/TeV)	84.6±2.1	168.6±4.4	412.0±9.7	146.0±3.8	67.6±1.6
λ_{LL} (s/TeV)	-154.9	-296.6	-687.7	-254.2	-118.2
RMS_{LL} (s/TeV)	88.8	169.9	414.5	150.4	67.52
λ_{UL} (s/TeV)	142.5	299.5	658.6	244.7	117.8
RMS_{UL} (s/TeV)	83.72	171.6	421.4	151.3	66.1

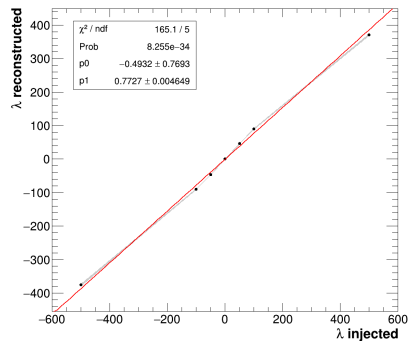
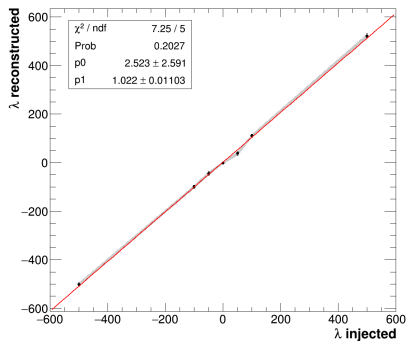
Parameter	PKS 2155	Mrk 501	PG 1553	Crab	Combination
λ_{best} (s/TeV ²)	1.3±1.9	-0.8±1.1	1.0±17.5	3.8±6.4	-0.6±0.9
1σ CL (s/TeV ²)	59.8±1.7	31.85±1.0	533.7±13.2	189.5±5.6	26.7±0.7
λ_{LL} (s/TeV ²)	-104.4	-59.2	-912.1	-326.6	-49.5
RMS_{LL} (s/TeV ²)	69.2	33.2	542.1	351.0	28.9
λ_{UL} (s/TeV ²)	100.0	56.8	921.1	354.2	48.1
RMS_{UL} (s/TeV ²)	67.9	34.1	554.2	355.0	28.0



Source	$E_{QG_linear} (10^{18} \text{ GeV})$	$E_{QG_Quadratic} (10^{10} \text{ GeV})$	Redshift
PKS 2155	1.86	6.20	0.116
Mrk 501	0.91	8.57	0.034
PG 1553	0.38	2.08	0.5
Crab	1.07	4.14	2kpc
Combination	2.31	9.34	-

Conclusions and prospects

- Combination - Improvement visible at λ parameter level.
- Energy limits.
 - Linear
 - Dominated by the PKS 2155-304 limit.
 - Combination - 24% improvement respect to best individual case.
 - Quadratic
 - Dominated by Mrk 501 limit.
 - Combination - 10% improvement respect to best individual case.
- PG 1553 contributes with redshift and Crab Pulsar with statistics.
- The list of used sources - constantly increasing with publications.
- Predictions and preparation for Cherenkov Telescope Array (CTA).

Case $\lambda \neq 0$ for AGN combination.

Systematic effects

Limits and CLs in presence of Nuisance Parameters.

Procedure in construction will follow.

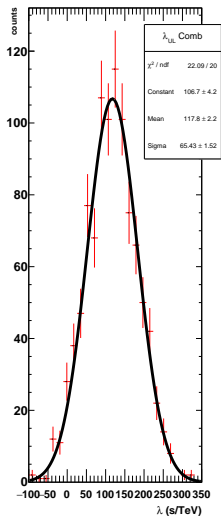
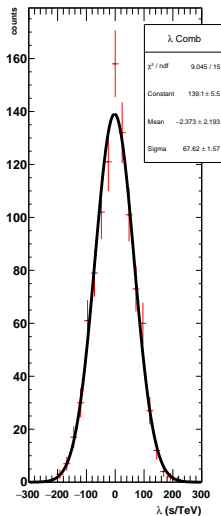
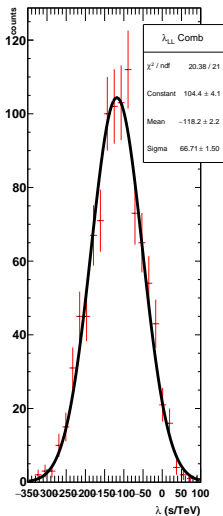
Rolke, Lopez & Conrad (2009) arXiv:0304059

Systematic uncertainties	Typical range per source (%)
Selection cuts	5 - 10
Background contribution	1 - 5
Acceptance factors	2 - 5
Energy resolution	2 - 5
Energy resolution	2 - 5
Energy calibration	10
Spectral index	5
Calibration systematics (constant, shift)	10
Time template parametrization	5 - 30

Due to limited statistics for certain sources:

Time template uncertainties → dominate systematic effects

Combination plots - Linear case



Combination plots - Quadratic case

