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

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Outline

Lorentz Invariance Violation

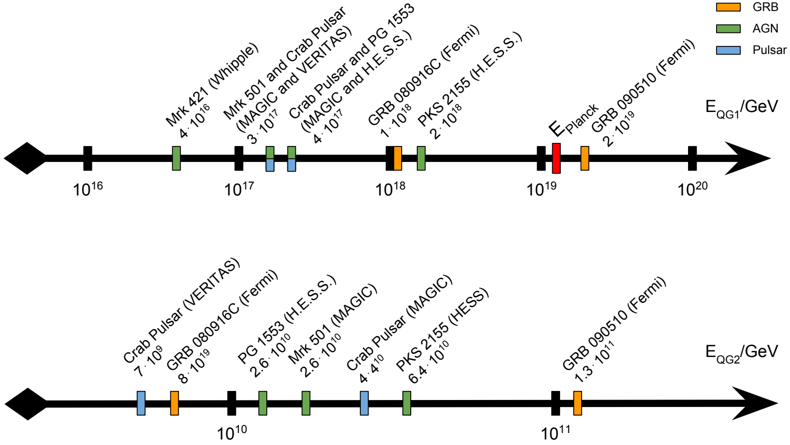
- **Theory** - Aim to build a common theory covering General Relativity and Quantum Mechanics.
- Different approaches, leading to modified dispersion relations inducing LIV.
  - Loop Quantum Gravity.
  - SM extension.
  - Hôrawa's gravity.
- **Experiment** - prove Quantum effects in Space-time structure.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


GRB
AGN
Pulsar
Mrk 421 (Whipple) 4·10^16
Mrk 501 and Crab Pulsar (MAGIC and VERITAS) 3·10^17
Crab Pulsar and PG 1553 (MAGIC and H.E.S.S.) 4·10^17
GRB 080916C (Fermi) 1·10^18
PKS 2155 (H.E.S.S.) 2·10^18
E_Planck
GRB 090510 (Fermi) 2·10^19
E_QG1/GeV
10^16
10^17
10^18
10^19
10^20
Crab Pulsar (VERITAS) 7·10^9
GRB 080916C (Fermi) 8·10^19
PG 1553 (H.E.S.S.) 2.6·10^10
Mrk 501 (MAGIC) 2.6·10^10
Crab Pulsar (MAGIC) 4·4^10
PKS 2155 (HESS) 6.4·10^10
GRB 090510 (Fermi) 1.3·10^11
E_QG2/GeV
10^10
10^11

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.

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

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.

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

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

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

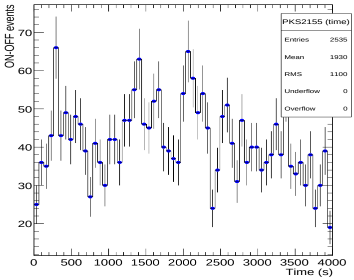
Simulation procedure

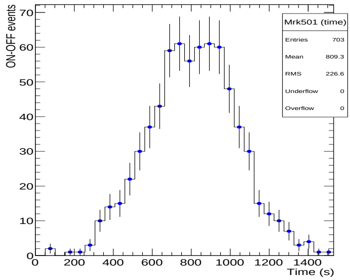
Simulated sources for the study.

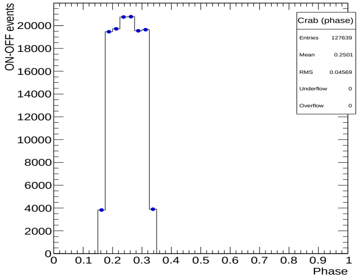
- **Mrk 501** 2005 flare detected by MAGIC.
- **PG 1553+113** 2012 flare detected by H.E.S.S.
- **PKS 2155-304** 2006 flare detected by H.E.S.S.
- **VHE Crab Pulsar** radiation detected by VERITAS.

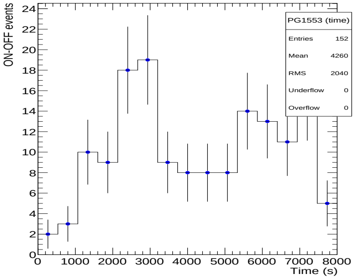
Simulation steps

- 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.


ON-OFF events
Time (s)
PKS2155 (time)
Entries 2535
Mean 1930
RMS 1100
Underflow 0
Overflow 0


ON-OFF events
Time (s)
Mrk501 (time)
Entries 703
Mean 809.3
RMS 226.6
Underflow 0
Overflow 0


ON-OFF events
Phase
Crab (phase)
Entries 127639
Mean 0.2501
RMS 0.04569
Underflow 0
Overflow 0


ON-OFF events
Time (s)
PG1553 (time)
Entries 152
Mean 4260
RMS 2040
Underflow 0
Overflow 0

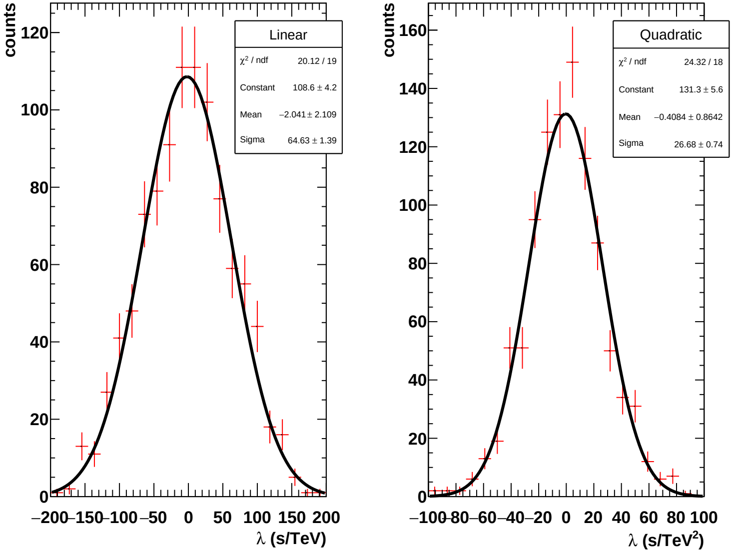
The analysis, applied over the 990 sets of simulations, uses λ as a fit parameter,that is related to the QG energy scale E_{QG},

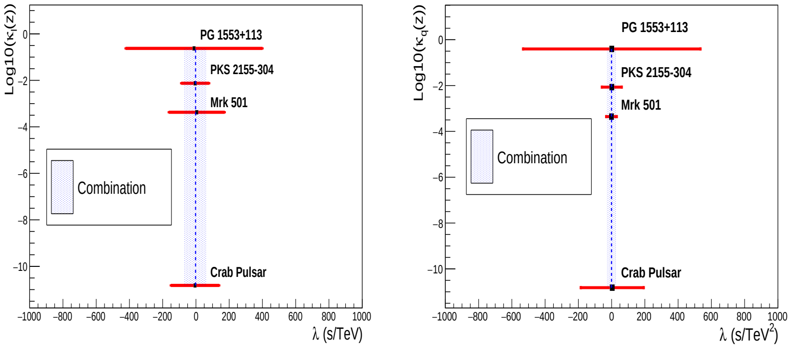
$$\frac{\Delta t_n}{E_h^n - E_l^n} \simeq s_\pm \frac{n+1}{2\,H_0} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m\,(1+z')^3 + \Omega_\Lambda}}\, dz' = s_\pm \frac{n+1}{2\,H_0} \frac{1}{E_{QG}^n} \kappa(z),$$

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

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

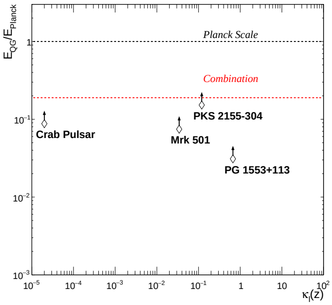
- Distribution of best fit value of the parameter λ.
- Distribution of 1-sided 95% CLs.
- Upper limits on E_{QG}.

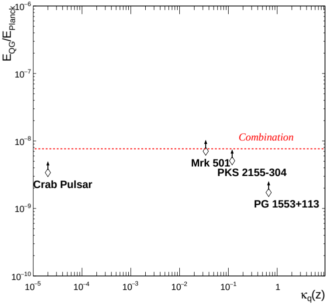

counts
Linear
χ2 / ndf 20.12 / 19
Constant 108.6 ± 4.2
Mean −2.041 ± 2.109
Sigma 64.63 ± 1.39
λ (s/TeV)
counts
Quadratic
χ2 / ndf 24.32 / 18
Constant 131.3 ± 5.6
Mean −0.4084 ± 0.8642
Sigma 26.68 ± 0.74
λ (s/TeV2)


Log10(κl(z))
PG 1553+113
PKS 2155-304
Mrk 501
Crab Pulsar
Combination
λ (s/TeV)
Log10(κq(z))
PG 1553+113
PKS 2155-304
Mrk 501
Crab Pulsar
Combination
λ (s/TeV²)

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



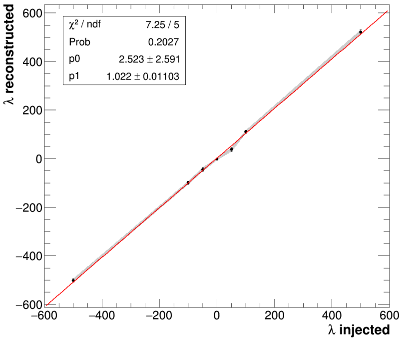


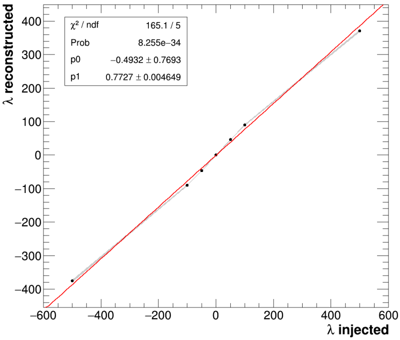
Source	$E_{QG\_linear}(10^{18}GeV)$	$E_{QG\_Quadratic}(10^{10}GeV)$	Redshift
PKS 2155	1.86	6.20	0.116
Mrk 501	0.91	8.57	0.034
PG 1553	0.38	2.08	0.5
Crab	1.07	4.14	2kpc
Combination	2.31	9.34	-

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.

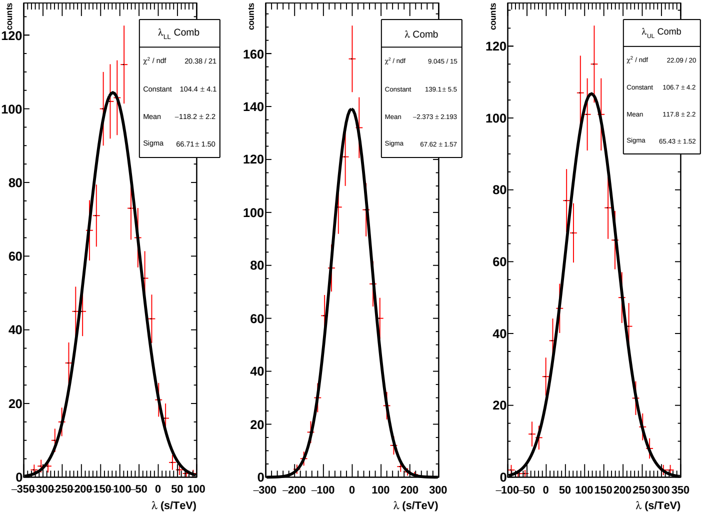
Rolke, Lopez & Conrad (2009) arXiv:040359

Systematic uncertainties	**Typical range per source (%)**
Selection cuts	5 - 10
Background contribution	1 - 5
Acceptance factors	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 $\rightarrow$ dominate systematic effects

Combination plots - Linear case



Combination plots - Quadratic case