ENERGY DEPENDENT TIME DELAYS IN BLAZAR LIGHT CURVES

A FIRST LOOK AT MODELING OF SOURCE-INTRINSIC EFFECT IN THE MEV-TEV RANGE AND CONSTRAINTS ON LORENTZ INVARIANCE VIOLATION WITH H.E.S.S.

Cédric PERENNES

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CONTENTS

Introduction

Testing Lorentz invariance with H.E.S.S.

Markarian 501 flare analysis

Modeling blazar flare

Investigating intrinsic time delays

Conclusions and perspectives
INTRODUCTION

4 fundamental interactions:

- 3 interactions are well described by the **Standard Model** (Particle physics)
- The gravitation is left alone and described by the **General relativity** (Gravitation, Cosmology . . .)

Theorists are trying to **merge these 4 interactions** in a common framework:

**Quantum gravity**
Lorentz Invariance Violation (LIV) appears in some approaches to Quantum Gravity.

This LIV can appear due to a modification of the propagation of photons in vacuum which can be expressed with a simple toy model:

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

This relation leads to energy-dependent velocities for photons:

\[ \nu_n(E) = c \left[ 1 - \frac{n + 1}{2} \left( \frac{E}{E_{QG}} \right)^n \right] \]

2 main cases:
- \( n = 1 \): Linear case
- \( n = 2 \): Quadratic case

Subluminal (+1) or Superluminal (-1)
Energy-dependent velocities for the propagation of photons induce time delays

Considering a LIV sub-luminal effect

(high energy photons slower than low energy photons)
Energy-dependent velocities for the propagation of photons induce time delays.

Considering a LIV sub-luminal effect
(high energy photons slower than low energy photons)
The time delay between 2 photons of different energies coming from an astrophysical source at redshift $z$:

$$\Delta t_n = \pm \frac{n + 1}{2} \frac{E_1^n - E_0^n}{E_Q G} \int_0^z \frac{(1 + z')^n}{H(z')} \, dz'$$

Which source to observe this effect?

Three important criteria to be able to see this effect:

- A variable source in order to measure a time delay
The time delay between 2 photons of different energies coming from an astrophysical source at redshift $z$:

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- **A variable source** in order to measure a time delay
- **A distant source** to maximize the propagation effect
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\Delta t_n = \pm \frac{n + 1}{2} \frac{E_1^n - E_0^n}{E_{\text{QG}}^n} \int_0^z (1 + z')^n \frac{1}{H(z')} \, dz'
\]

Which source to observe this effect?

Three important criteria to be able to see this effect:

- A variable source in order to measure a time delay
- A distant source to maximize the propagation effect
- A source which emits photons with large energy range to maximize the energy difference
Active Galactic Nuclei

Doppler boosting:

\[ t_{\text{obs}} = \frac{t_s}{\delta} \]

\[ \nu_{\text{obs}} = \delta \nu_s \]

\[ F_{\text{obs}} (\nu_{\text{obs}}) = \delta^3 F_s (\nu_s) \]
H.E.S.S. is an **hybrid array** of 5 imaging atmospheric Cherenkov telescopes

- **CT1-4**: 13m telescopes, designed for high energy (100 GeV up to ~50 TeV)
- **CT5**: 28m telescope, designed for low energy (down to ~20 GeV), good instrument to catch transient event such as AGN flares

To look for LIV signatures, we search for **energy-dependent time delays in the arrival time of γ-ray photons** coming from **blazar flares**
H.E.S.S. is an hybrid array of 5 imaging atmospheric Cherenkov telescopes: CT1-4 : 13m telescopes, designed for high energy (100 GeV up to ~50 TeV), CT5 : 28m telescope, good instrument to catch transient event such as AGN flares.

To look for LIV signatures, we search for energy-dependent time delays in the arrival time of γ-ray photons.
To search for LIV signatures, we define a parameter of interest

\[ \tau_n = \frac{\Delta t}{E^n} \quad \longrightarrow \quad \Delta t_{LIV} = \tau_n E^n \]

With \( n = 1 \) or \( 2 \) for linear or quadratic LIV effect
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Real data (H.E.S.S.)

Maximum Likelihood method
To search for LIV signatures, we define a parameter of interest

\[ \tau_n = \frac{\Delta t}{E^n} \]

\[ \Delta t_{\text{LIV}} = \tau_n E^n \]

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**TESTING LORENTZ INVARIANCE**

Maximum Likelihood method

Real data (H.E.S.S.)

Mesure on data \( \tau_n^{\text{best}} \)
To search for LIV signatures, we define a parameter of interest

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$N_Y$
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MAXIMUM LIKELIHOOD METHOD

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Maximal probability
MAXIMUM LIKELIHOOD METHOD

The Likelihood function gives the probability of an event to match a model with respect to one or several parameters.

The Likelihood function is built with:

- Time function not delayed by LIV effect to take into account the variability

\[ L(\tau_n) = F\left(t - \tau_n E_i^n\right) \]
The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with:

- **Time function** not delayed by LIV effect to take into account the variability
- **Energy function** to give more strength to high energy events

\[
L (\tau_n) = \Gamma (E_i) F (t - \tau_n E_i^n)
\]
MAXIMUM LIKELIHOOD METHOD

The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with:

- **Time function** not delayed by LIV effect to take into account the variability
- **Energy function** to give more strength to high energy events
- **Instrument response function** to take care of the instrument uncertainties

\[
L(\tau_n) = \frac{\Lambda(E_i) \Gamma(E_i) F(t - \tau_n E^n_i)}{}
\]

Martinez & Errando (2009)
The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with:

- **Time function** not delayed by LIV effect to take into account the variability
- **Energy function** to give more strength to high energy events
- **Instrument response function** to take care of the instrument uncertainties
- **Normalisation factor** to get unbiased estimation of the parameter \( \tau_n \)

\[
L(\tau_n) = \frac{N(\tau_n)}{\Lambda(E_i) \Gamma(E_i) F(t - \tau_n E_i^n)}
\]

*Martinez & Errando (2009)*
The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with:

- **Time function** not delayed by LIV effect to take into account the variability
- **Energy function** to give more strength to high energy events
- **Instrument response function** to take care of the instrument uncertainties
- **Normalisation factor** to get unbiased estimation of the parameter τ<sub>n</sub>
- Multiplied over all high energy events

\[
L(\tau_n) = \prod_i N(\tau_n) \Lambda(E_i) \Gamma(E_i) F(t - \tau_n E_i^n)
\]
MAXIMUM LIKELIHOOD METHOD

To apply the maximum likelihood method, events are split in two samples:

• **Template region:** The low energy part of the events where the LIV effect is neglected in order to estimate \( F(t) \)

• **Likelihood region:** The high energy part of the events used in the likelihood function for the estimation of \( \tau_n \)

Using simulations, we can test the method and evaluate its performances

- Gaussian shape time distribution
- Power law energy distribution
- 500 template events (0.4 - 0.8 TeV)
- 500 likelihood events (0.8 - 4 TeV)
- Energy resolution: 10%
- Acceptance variations neglected
At first, $F(t)$ is the true non-delayed function used for the simulations.

With no injected LIV delay.
At first, $F(t)$ is the true non-delayed function used for the simulations. With no injected LIV delay.

A 1000 realizations of the same data set allows to improve the evaluation of statistical uncertainties.
Then, injecting multiple $\tau_n$ values, the calibration of the method can be deduced.
However, in case of data $F(t)$ has to be deduced from the template region where LIV effect can be non-negligible.

Template: 400-800 GeV

$\tau_{1}^{\text{best}} = 0.82 \times \tau_{1}^{\text{inj}} + 0.98$

$\sigma(\tau = 0) = 13.5 \text{ s.TeV}^{-1}$
To take into account this effect, we implement a template correction in the model used for the likelihood function

\[
L(\tau_n) = \prod_i N(\tau_n) \Lambda(E_i) \Gamma(E_i) F\left(t - \tau_n E_i^n + \frac{E_i^n}{T} \tau_n\right)
\]

which takes into account that the template region can be affected by LIV effect.
To take into account this effect, we implement a template correction in the model used for the likelihood function

\[ L(\tau_n) = \prod_i N(\tau_n) \Lambda(E_i) \Gamma(E_i) F(t - \tau_nE_i^n + \overline{E_T}^n\tau_n) \]

which takes into account that the template region can be affected by LIV effect.

Without correction

Linear LIV effect

\[ \tau_1^{\text{best}} = 0.82 \times \tau_1^{\text{inj}} + 0.98 \]
\[ \sigma(\tau = 0) = 13.5 \text{ s.TeV}^{-1} \]

With correction

Linear LIV effect

\[ \tau_1^{\text{best}} = 0.99 \times \tau_1^{\text{inj}} + 1.04 \]
\[ \sigma(\tau = 0) = 15.0 \text{ s.TeV}^{-1} \]
A flare from Markarian 501 ($z = 0.034$) in 2014 was observed by H.E.S.S.

The source is detected with a high significance ($> 60\sigma$) but with a large zenith angle ($>60^\circ$) involving a high energy threshold for this data set at 1.3 TeV.

The data show 1435 events between 1.3 and 20 TeV.

The two regions for the maximum likelihood are chosen between:

- **1.3 - 3.25 TeV** for the template region (773 events)
- **3.25 - 20 TeV** for the likelihood region (662 events)
For the time function $F(t)$, a double Gaussian function is preferred over a single Gaussian to parameterize the light curve in the template energy range.

\[
\frac{\chi^2}{ndf} = \frac{38.1}{13}
\]

\[
\frac{\chi^2}{ndf} = \frac{15.9}{10}
\]
The energy function $\Gamma(E)$ is obtained by fitting the energy spectrum in the likelihood energy range.

A simple power law function represents fairly the energy spectrum and allows a simple computation of the Likelihood function.

Index $\alpha_{SP} = 3.1 \pm 0.1$
The likelihood function provides the best estimations of $\tau_n$.

No significant time delay is found for both linear and quadratic LIV effect.
To improve the estimation of statistical uncertainties, simulations are done which reproduce the flare data.

From a 1000 realizations of the flare data set with no LIV delay, the dispersion of the reconstructed $\tau_n$ is used to deduce the statistical uncertainties.
Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics

<table>
<thead>
<tr>
<th>Source of systematic errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood calibration</td>
</tr>
<tr>
<td>F(t) and $\Gamma(E)$ determination</td>
</tr>
<tr>
<td>Analysis selection cut</td>
</tr>
<tr>
<td>Energy bias</td>
</tr>
<tr>
<td>Background contribution</td>
</tr>
</tbody>
</table>
Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics.

**Maximum likelihood calibration**

From a 1000 realization reproducing Mrk 501 flare, injecting different $\tau_n$ values.

\[ \tau_{1,\text{best}} = 0.89 \times \tau_{1,\text{inj}} + 0.50 \]
\[ \sigma(\tau = 0) = 21.5 \text{ s.TeV}^{-1} \]

\[ \tau_{2,\text{best}} = 0.98 \times \tau_{2,\text{inj}} + 0.42 \]
\[ \sigma(\tau = 0) = 1.8 \text{ s.TeV}^{-2} \]
**MARKARIAN 501 – SYSTEMATIC STUDIES**

Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics.

<table>
<thead>
<tr>
<th>Source of systematic errors</th>
<th>Linear effect</th>
<th>Quadratic effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood calibration</td>
<td>+5.5</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>−2.8</td>
<td>−0.5</td>
</tr>
<tr>
<td>F(t) and ( \Gamma(E) ) determination</td>
<td>+4.6</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>−3.5</td>
<td>−0.2</td>
</tr>
<tr>
<td>Analysis selection cut</td>
<td>+10.6</td>
<td>+0.7</td>
</tr>
<tr>
<td></td>
<td>−8.2</td>
<td>−0.6</td>
</tr>
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<td>+2.3</td>
<td>+0.1</td>
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<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>−0.1</td>
<td>−0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+13</td>
<td>+0.9</td>
</tr>
<tr>
<td></td>
<td>−11</td>
<td>−1.0</td>
</tr>
</tbody>
</table>
MARKARIAN 501 – RESULTS

Combining statistical and systematic uncertainties:

\[ \tau_{1}^{\text{best}} = -8.2 \pm (\pm22)_{\text{stat}} \pm (\pm13)_{\text{syst}} \text{s} \cdot \text{TeV}^{-1} \]
\[ \tau_{2}^{\text{best}} = -0.6 \pm (\pm1.6)_{\text{stat}} \pm (\pm0.9)_{\text{syst}} \text{s} \cdot \text{TeV}^{-2} \]

Which allows to derive 95% confidence level lower limits on \( E_{QG,n} \) for subluminal and superluminal LIV effect

\[ E_{QG,1}^{95\%} = \begin{cases} 3.63 \times 10^{17} \text{ GeV}, & \text{subluminal case} \\ 2.89 \times 10^{17} \text{ GeV}, & \text{superluminal case} \end{cases} \]
\[ E_{QG,2}^{95\%} = \begin{cases} 8.79 \times 10^{10} \text{ GeV}, & \text{subluminal case} \\ 7.66 \times 10^{10} \text{ GeV}, & \text{superluminal case} \end{cases} \]

\[ E_{QG,1}^{95\%} \sim 0.03E_{P} \]
\[ E_{QG,2}^{95\%} \ll E_{P} \]

Paper will be submitted soon
MARKARIAN 501 – RESULTS

The 95% lower limits on the Quantum Gravity energy scale obtained with Mrk 501 can be compared to the results obtained with other AGN flares.

Linear LIV effect

Quadratic LIV effect
**BLAZAR MODELING**

*Why modeling the source?*

*High energy photon*

*Low energy photon*

What happens if there is a *source-intrinsic time delay*?
Why modeling the source?

High energy photon

Low energy photon

What happens if there is a source-intrinsic time delay?
Why modeling the source?

High energy photon

Low energy photon

What happens if there is a source-intrinsic time delay?

Modeling is crucial in order to understand time delays and get more robust constraints for Quantum Gravity models.
MODELING BLAZAR FLARE

A "Blob" is responsible of high energy emissions

We consider only electrons as the main emitters:

Leptonic models
MODELING BLAZAR FLARE

A "Blob" is responsible of high energy emissions

We consider only electrons as the main emitters:

**Leptonic models**

2 main processes responsible of photons emissions:

- **Synchrotron process**
- **Inverse Compton process**

**Synchrotron Self Compton (SSC)**
MODELING BLAZAR FLARE

A "Blob" is responsible of high energy emissions.

We consider only electrons as the main emitters:

**Leptonic models**

2 main processes responsible of photons emissions:

- **Synchrotron** process
- **Inverse Compton** process

---

**Markarian 421 SED**

- Optical/UV data
- Swift/XRT
- RXTE
- Swift/BAT
- Fermi-LAT
- MAGIC

**Synchrotron bump**

**Inverse Compton bump**

Radio data

Zech et al. (2017)
A time-dependent blazar flare model was developed describing the evolution of electrons responsible for the high energy emissions:

Starting point: A general transfer equation which describes the evolution of electrons in plasma *(The Origin of Cosmic Rays, V.L. Ginzburg, 1964)*:

\[
\frac{\partial N_e(t, E)}{\partial t} + \frac{\partial}{\partial E} \left( b(t, E) N_e(t, E) \right) - \frac{1}{2} \frac{\partial^2}{\partial E^2} \left( d(t, E) N_e(t, E) \right) = Q(t, E) - p(t, E) N_e(t, E)
\]

- Systematical energy variation (acceleration, SSC, adiabatic expansion . . .)
- Fluctuation of systematical variation (second order terms)
- Injection of particles
- Loss of particles
ELECTRONS EVOLUTION

A simplified differential equation is used to provide a minimal time dependent model, with an analytic solution (under some assumptions):

$$\frac{\partial N_e(t, \gamma)}{\partial \gamma} = \left\{ \frac{\partial}{\partial \gamma} \left[ C_{cool}(t) \gamma^2 - (C_{acc}(t) - C_{adiab}(t)) \gamma \right] N_e(t, \gamma) \right\}$$

The initial electron spectrum follows a power law function with a high energy cut-off:

$$N_e(0, \gamma) = K_0 \gamma^{-n} \left[ 1 - \left( \frac{\gamma}{\gamma_{c,0}} \right)^{n+2} \right]$$
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Electrons cooling effect: energy losses via SSC emissions

$$C_{cool}(t) = \frac{4\sigma_T c}{3m_e c} U_B(t) \left( 1 + \frac{1}{\eta} \right)$$

$$U_B = \frac{B(t)^2}{8\pi}$$

$$\eta = \frac{U_B(t)}{U_{rad}(t)}$$

Has to be large

Synchrotron dominated

$$B(t) = B_0 \left( \frac{t_0}{t} \right)^{m_b}$$
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\]

Electron acceleration: Energy gain from acceleration processes (generic one)

\[
C_{acc} = A_0 \left( \frac{t_0}{t} \right)^{m_a}
\]

Acceleration term allows to initiate the flare
ELECTRONS EVOLUTION

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\[
\frac{\partial N_e(t, \gamma)}{\partial \gamma} = \frac{\partial}{\partial \gamma} \left\{ \left[ C_{cool}(t) \gamma^2 - (C_{acc}(t) - C_{adiab}(t)) \gamma \right] N_e(t, \gamma) \right\}
\]

Adiabatic expansion: Energy losses from the evolution of the emission zone radius

\[
R(t) = R_0 \left( \frac{t_0}{t} \right)^{-m_r}
\]

\[
C_{adiab} = \frac{m_r}{t}
\]

\[
V_{exp} \approx \frac{c}{\sqrt{3}}
\]

\[
t_0 = \frac{R_0}{V_{exp}}
\]

Speed of sound in relativistic plasma

ELECTRONS EVOLUTION

A simplified differential equation is used to provide a minimal time dependent model, with an analytic solution (under some assumptions):

$$\frac{\partial N_e(t, \gamma)}{\partial \gamma} = \frac{\partial}{\partial \gamma} \left\{ \left[ C_{cool}(t) \ \gamma^2 - (C_{acc}(t) - C_{adiab}(t)) \ \gamma \right] N_e(t, \gamma) \right\}$$

Adiabatic expansion: Energy losses from the evolution of the emission zone radius

$$R(t) = R_0 \left( \frac{t_0}{t} \right)^{-m_r}$$

$$C_{adiab} = \frac{m_r}{t}$$

$$V_{exp} \approx \frac{c}{\sqrt{3}}$$

At first, adiabatic expansion is not considered to simplify the scenario.
A simplified differential equation is used to provide a minimal time dependent model, with an analytic solution (under some assumptions):

At first, adiabatic expansion is not considered to simplify the scenario.
Two different cases were identified which depend on the time $t_{\text{max}}$ when the electrons highest energy $\gamma_c(t)$ is reached and starts to decrease with time.

**Case 1**
The time $t_{\text{max}}$ happens after all the light curves peak.

**Case 2**
The time $t_{\text{max}}$ happens before all the light curves peak.

The difference between the 2 cases is related to the process which initiates the flux decrease for the highest energy light curves.
INVESTIGATING INTRINSIC TIME DELAY

The light curves at different energies show the presence of time delays.

**Case 1**

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<tr>
<td>41.6 - 75.2 GeV</td>
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<tr>
<td>1.4 - 2.6 TeV</td>
<td>$1.2 \times 10^{-14}$ cm$^2$.s$^{-1}$</td>
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<tr>
<td>2.6 - 4.7 TeV</td>
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**Case 2**

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The light curves at different energies show the presence of time delays

Case 1

Case 2
The time delay is computed using time difference between the maximum of the light curve at 1 MeV to the maximum of the light curve at energy $E$. 

**Case 1**  Perennes et al. ICRC 2017

**Case 2**  

Paper in preparation
The time delay is computed using time difference between the maximum of the light curve at 1 MeV to the maximum of the light curve at energy $E$. 

---

**Case 1**

Perennes et al. ICRC 2017

*Paper in preparation*

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**Case 2**
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The time delay is computed using time difference between the maximum of the light curve at 1 MeV to the maximum of the light curve at energy $E$.  

**Case 1**  
Perennes et al. ICRC 2017  
Paper in preparation  

**Case 2**
The time delay is computed using time difference between the maximum of the light curve at 1 MeV to the maximum of the light curve at energy E.
The MeV-GeV time delays are explained by the combined action of the magnetic field decrease and the energy depend cooling effect.

Above GeV energies, we identify two distinct regimes depending on the process driving the delay:

**Acceleration driven regime (Case 1)**
The increasing time delay comes from a long-lasting acceleration where electrons need time to be accelerated.

**Cooling driven regime (Case 2)**
The decreasing time delay comes from a strong radiative cooling affecting high energy electrons.

The influence of the model parameters is investigated by varying individually each of them.
A small $B_0$ allows the acceleration to last long and leads to an acceleration driven regime.

At the transition, a constant delay is produced at GeV energy leading to no delay in this range.

A large $B_0$ induces a strong radiative cooling leading to a cooling driven driven regime.

\[ B(t) = B_0 \left( \frac{t_0}{t} \right)^{m_b} \]
INVESTIGATING INTRINSIC TIME DELAY

\[ C_{acc}(t) = A_0 \left( \frac{t_0}{t} \right)^{m_a} \]

A small \( A_0 \) provides a weak acceleration which lasts long due to small radiative cooling leading to an acceleration driven regime.

At the transition, a constant delay is produced at GeV energy leading to no delay in this range.

A large \( A_0 \) induces a strong acceleration leading to a cooling driven driven regime.

\( \text{Paper in preparation} \)
From the variations of all the model parameters, the two regimes are found when the parameter influences the electron evolution.

The transition from one regime to the other is related to the relative strength between acceleration and radiative cooling.

Between the two regimes, a transition area is found producing no delay at GeV-TeV energies.

Until now, adiabatic expansion was removed from the scenario to simplify the interpretation about the time delay origin.

We propose now to study the addition of adiabatic expansion.
The adiabatic expansion brings an additional source of energy loss for electrons leading to a shorter flare as well as a dilution of the electron density due to $R(t)$.

### Acceleration driven case

### Cooling driven case
CONRAINTS FROM TIME DELAY INFORMATION

The time delay information can provide some constraints on either blazar modeling or time delay studies such as the search of LIV signatures.

Several characteristics of intrinsic delays can be used:

- The temporal evolution of time delay
- The energy evolution of time delay at GeV-TeV energies
- The presence of one of the time delay regimes

In addition, the redshift dependency of LIV delays can be used with multiple sources in order to minimize the impact of intrinsic effect.
CONSTRAINS FROM TIME DELAY INFORMATION

The temporal evolution of the time delay can reveal the presence of intrinsic delays

It is a consequence of the electrons acceleration and radiative cooling

From an acceleration driven case
In opposition, the LIV delay is not expected to produce such a signature as it affects all photons during their propagation.

From simulated LIV delayed light curves.
The energy evolution of the time delay at GeV-TeV energies can be used to try disentangle intrinsic delay from another source of delay

\[ \Delta t = \xi \left( E^\alpha - E_0^\alpha \right) \]

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**Constrains from time delay information**

**Acceleration driven case**

\[ \chi^2 / \text{ndf} = 0.8013 / 6 \]

\[ \text{Prob} = 0.992 \]

\[ \xi = 175 \pm 23.1 \]

\[ \alpha = 0.7244 \pm 0.1432 \]

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**Cooling driven case**

\[ \chi^2 / \text{ndf} = 0.4435 / 6 \]

\[ \text{Prob} = 0.9985 \]

\[ \xi = -29.07 \pm 8.384 \]

\[ \alpha = 0.5709 \pm 0.2405 \]
The energy evolution of the time delay can be used to try disentangle intrinsic delay from another source of delay

\[ \Delta t = \xi \left( E^\alpha - E_0^\alpha \right) \]

From all the parameter space investigated with the model presenting significative time delays above GeV energies, we found:

\[ \alpha \in [0.4; 0.8] \]

LIV delays are generally expressed with an energy dependence \( n = 1 \) or \( 2 \)

How accurate are these descriptions?

We need more theoretical insight on the energy dependency of the LIV delays in order to try disentangle them from intrinsic effect
The presence of one regime gives information about the relative strength between acceleration and radiative cooling.

Mrk 501 flare in 2005 observed by MAGIC

An increasing delay was reported with respect to the energy.

This corresponds to an acceleration driven regime.

The modeling of the source requires a long-lasting acceleration to reproduce this flare.

Albert et al. (2007)
CONSTRANTS FROM TIME DELAY INFORMATION

The presence of one of the regime gives information about the relative strength between acceleration and radiative cooling.

PKS 2155-304 flare in 2006 observed by H.E.S.S.

A Cross-correlation function reported no significant time delay.

This delay could correspond to the transition zone between the two regimes.

Thus strong constraints on the flare modeling can be made in order to produce no delay.

Aharonian et al. (2008)
SUMMARY

I have developed a time dependent blazar flare model focused on γ-ray emission to study intrinsic time delays.

Using the model, I have found the presence of intrinsic delays and determined their origins and specific characteristics which can provide new constraints using the time delays information.

I have presented the maximum likelihood method used to search for LIV signatures and I have implemented a template correction for high energy threshold data set.

I have analyzed the flare of Markarian 501 observed by H.E.S.S. and found no significant delay allowing to derive lower limits on the Quantum Gravity energy scale.
CONCLUSIONS (1/2)

The linear lower limits obtained on $E_{\text{QG}, 1}$ from the 2014 flare of Mrk 501 are similar compared to the limits from the 2005 flare of Mrk 501 observed by MAGIC.

The quadratic lower limits provide the best constraint on $E_{\text{QG}, 2}$ using an AGN flare.

In addition, the implementation of the template correction in the maximum likelihood method will improve the analysis of future flares presenting a high energy threshold.
CONCLUSIONS (2/2)

The intrinsic delays produced with our minimal model are found to be quite important, within the sensitivity of current instruments for some cases and would be detected by CTA.

These delays present some specific characteristics that can already be used for blazar modeling or the search for fundamental physics such as LIV.

However, some theoretical progress on energy dependency of LIV delays may be necessary to use the energy dependency information from intrinsic delays.

This work combining modeling and the search of LIV signatures provides a new insight for LIV searches which should be more focused on time delays in a general way.
PERSPECTIVE

From the modeling results on time delays, new investigations emerge within H.E.S.S. to search for any energy dependent time delays from all the data available.

The time dependent blazar flare model provides the simplest scenario to generate a flare but only allows to investigate a limited parameter space. However, the model can be extended including for instance external inverse Compton emission.

A more general and flexible model can also be investigated using the general transfer equation (Ginzburg, 1964) but requires a numerical resolution of the equation.

Also, a joint effort on LIV studies from the H.E.S.S., MAGIC and VERITAS Collaboration tries to combine all available data (AGN, Pulsars, GRB?) to improve current limits on $E_{QG,n}$ with population studies.

The limits deduced from the Mrk 501 flare will be included for this combination study as well as for future flares with the goal to prepare the science for CTA.
Thanks for your attention
LIV appears in some approaches to quantum gravity

**String Theory**
Tentative to describe the 4 fundamental forces in a unified description

One type of particle: Strings. All known particles are vibrational mode of strings

The particle of gravity (graviton) can only be represented by relativistic strings

In some String Theory models **LIV can emerge from the interaction between high energy photons and compactified extra-dimension (D-branes)**
LIV appears in some approaches to quantum gravity

**Loop Quantum Gravity**

Tentative to quantize gravity as the other fundamental interactions

A new formalism is used based on loop instead of field

The space time becomes discrete and lead to an energy-dependent birefringence effect for the propagation of high energy photon in vacuum.
**BACK-UP**

**Significance Map**

  - 00h 45m 16s
  - 00h 50m 45s
  - 00h 55m 50s

- **Declination (J2000)**
  - 38° 38'
  - 39° 00'
  - 40° 30'

**Model Combined [Mkn 501]**

- **Mkn 501 1.8 live hours (1.6 acc. corrected)**
- **ON=1930 OFF=364 (α=8.95)**
- **1889.3 γ, σ=83.3 S/B=46.5 (Single OFF: σ=48.0)**
- **17.28 ± 0.40 γ/mn**

**N_{ON}** | **N_{OFF}** | **N_{excess}** | **S/B** | **Average Zenith angle**
---|---|---|---|---
Run 1 | 424 | 82 | 415 | 45.5 | 64.2
Run 2 | 543 | 87 | 533 | 55.1 | 63.8
Run 3 | 531 | 101 | 520 | 46.3 | 62.2
Run 4 | 432 | 94 | 422 | 40.4 | 63.5
Total | 1930 | 364 | 1890 | 46.5 | 63.4
For the time function $F(t)$, a double Gaussian function is preferred over a single Gaussian to parameterize the light curve in the template energy range.

$X^2/ndf = 15.9/10$

First peak:
$A_1 = (80.6 \pm 5.6) \times 10^{-12}\text{ cm}^2\text{ s}^{-1}$
$\mu_1 = (2361 \pm 185)\text{ s}$
$\sigma_1 = (2153 \pm 302)\text{ s}$

Second peak:
$A_2 = (61.5 \pm 11.1) \times 10^{-12}\text{ cm}^2\text{ s}^{-1}$
$\mu_2 = (6564 \pm 220)\text{ s}$
$\sigma_2 = (676 \pm 283)\text{ s}$
Actually, the template and likelihood energy ranges were chosen for the maximum likelihood method to ensure a robust estimation of $F(t)$.

Such a behavior indicates a possible intrinsic effect close to the energy threshold of the data analysis.
A time delay was observed in the light curves from a flare of Markarian 501 in 2006 (Albert et al., 2007).

Bednarek & Wagner (2008) proposed a model to explain this delay with an increase of the Doppler factor of the emitting zone

$$\delta \propto A \times t$$

The Doppler boosting effect increasing with time produces high energy at later time.

Some published models show intrinsic time delays.
Some published models show some intrinsic time delays

A model from Sokolov et al. (2004) describes the emission with a complex jet structure and considering shocks accelerating particles and photon internal travel time in the jet.

Time delays arise from the spatial distribution of particle in the jet

In addition, variation of the viewing angle leads to a modification of the photon travel time for an observer and so time delays
Time dependent model based on a differential equation to describe the evolution of electrons

They attempt to model a flare from Mrk 421 at X-ray energies

From the Fourier transform of the time delay they obtain an temporal evolution of the time delay which match the data
Inversion Compton energy losses in the differential equation

\[
\frac{\partial N_e(t, \gamma)}{\partial t} + \frac{\partial}{\partial \gamma} \left[ \left( \eta^{-1} + \int_{0}^{\infty} \gamma'^2 N_e(t, \gamma') d\gamma' \right) C_{cool}(t)\gamma^2 N_e(t, \gamma) \right] = 0
\]
Motivations: Combine all available data for the search of LIV signatures in order to improve current limits on LIV

Work: Develop a joined analysis which will allow to use many sources and different kinds of sources

This is another way to try to separate source and propagation effects
Simulation were done to evaluate the performances of such a combination.

Source used for the combination:

- Mrk 501 flare in 2005 from MAGIC
- PKS 2155-304 "Big flare" in 2006 from H.E.S.S.
- PG 1553+113 flare in 2012 from H.E.S.S.
- Crab Pulsar with 194 hours of data from of VERITAS

Simulations include:

- 990 simulations of each data set
- True energy and time generated from public data only
- Application of the IRFs to obtain measured values
The LIV parameter is scaled for all sources as

\[ \Lambda = \frac{\Delta t_n}{\Delta E_n \kappa_n(z)} = \frac{1}{E_{QG} H_0} \]

\[ \Lambda = \tau \kappa(z) \]
Combinaison results on the $E_{\text{QG}}$ lower limits

1: PKS 2155-304 simu
2: PG 1553+113 simu
3: Mrk 501 (MAGIC) simu
4: Crab Pulsar (VERITAS) simu
5: Mrk 501 (H.E.S.S.)