H.E.S.S., MAGIC and VERITAS combined studies on Lorentz Invariance Violation from observations of astrophysical sources

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H.E.S.S.

VERITAS

MAGIC
Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes

Lorentz Invariance Violation

- Lorentz Invariance Violation (LIV) appears in some approaches of Quantum Gravity
- We expect energy dependent velocities for photons in vacuum

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

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

-1 subluminal, +1 superluminal

- Delay of two particles emitted at the same time at a source with a redshift z :

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

with

$$\kappa_n^{LIV}(z) \equiv \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz', \qquad (3)$$

- Time delay per energy:

$$\tau_n = \frac{\Delta t_n}{\Delta E_n} = \pm \frac{n+1}{2 H_0 E_{\mathrm{QG}}^n} K_n(z)$$

- To maximize sensibility on LIV effects, we need distant, variable, energetic sources

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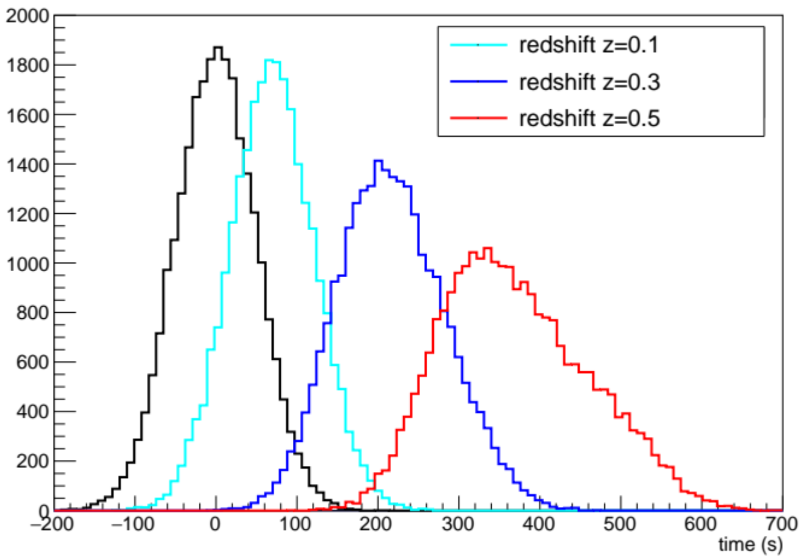
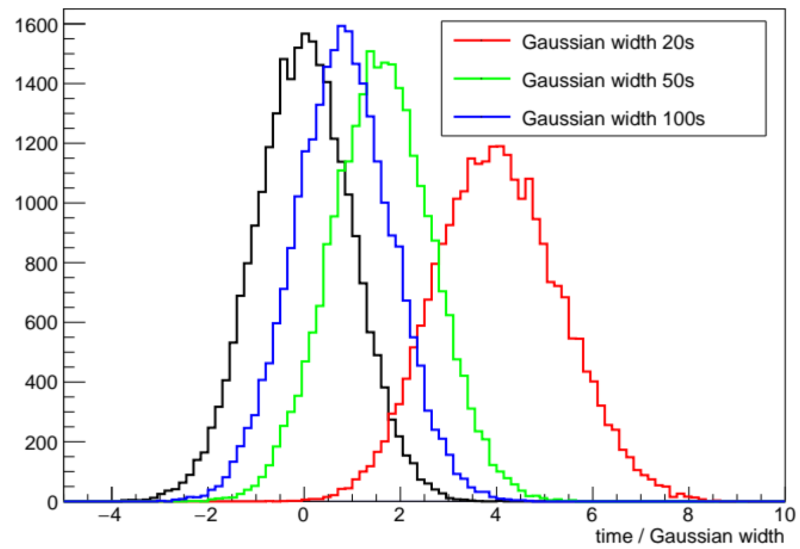
Impact of redshift and variability

- Power Law index 2.5, Energy range 5-10 TeV, light curve width 50 s
- QG Energy : 4.55 10^{18} GeV
- redshift : 0.1. 0.3. 0.5



- redshift directly increased delay observed

- Power Law index 2.5, Energy range 5-10 TeV, redshift 0.113
- QG Energy : 4.55 10^{18} GeV
- light curve width : 20s, 50s, 100s



- Higher variability improve separation between delayed and non delayed light curve → increase the detectability

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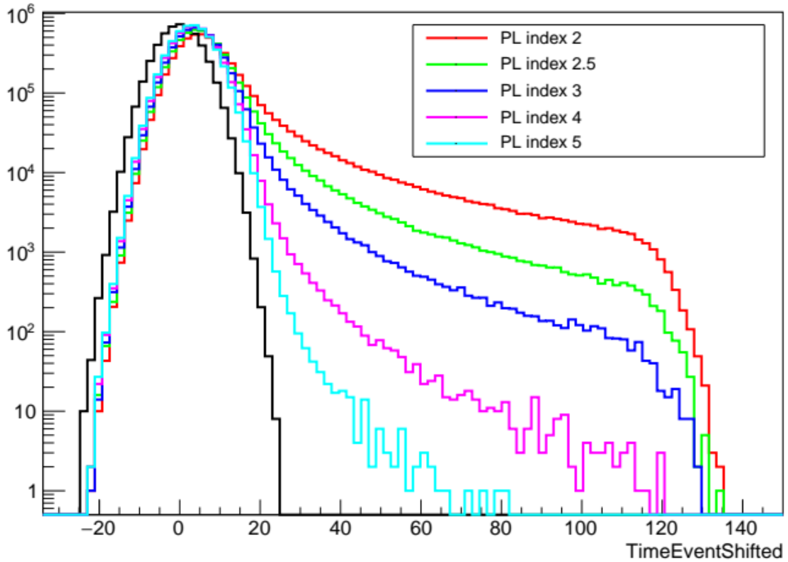
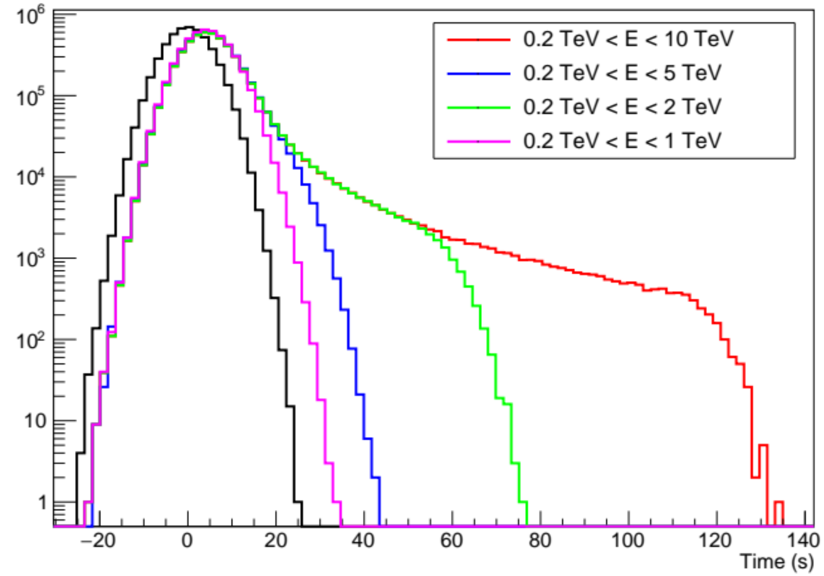
Impact of energy

- redshift 0.113, Energy range 0.2-10 TeV, light curve width 10 s
- QG Energy : 4.55 10^{18} GeV
- Power Law index : 2, 2.5, 3, 4, 5

- redshift 0.113, Power Law index 2.5, light curve width 10 s
- QG Energy : 4.55 10^{18} GeV
- Energy range : 0.2-1, 2, 5, 10 TeV

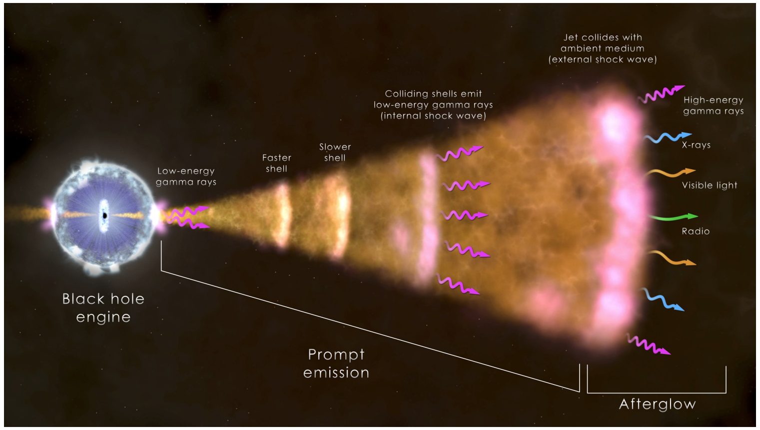


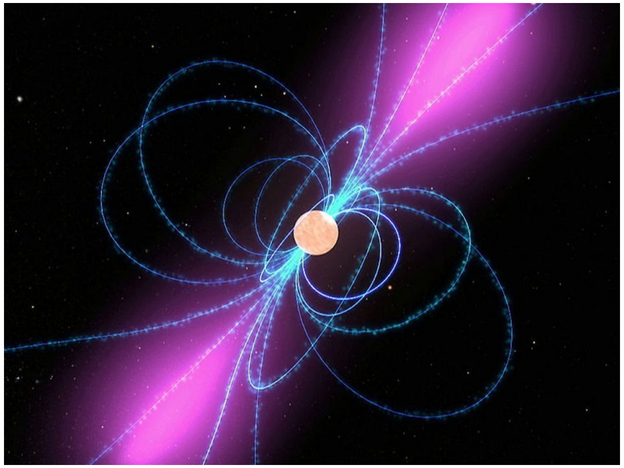


improve availability of highly shifted photons → increase the detectability

Astrophysical sources

- distant, variable, energetic, important statistics
- No source can combine all this characteristics
- Flaring Active Galactic nuclei → distant sources, important energy range
- pulsar → “local“ sources but high variability
- GRB → important variability (short GRB) and distance





Goal of the H.E.S.S. + MAGIC + VERITAS LIV consortium

- Combination of all available data from the three leading Ground Cherenkov experiment
- Improvement of current Quantum Gravity limit by improvement of the statistic
- Joined analysis of different type of sources (AGNs, pulsar, GRB) with different intrisic characteristics
  - Different redshift and sources type → important to disentangle between LIV and intrisic variability of sources
  - Prepare the CTA era (combination of different arrays with different IRFs)

LIV consortium goals

- Common software in order to simulate, analyse and combine results → good progress, already functionnal code
- From now, work on simulations in order to validate the methods
- List of sources (only individually published sources will be studied):
  - Markarian 501 (MAGIC) 2005
  - PG 1553+113 (H.E.S.S.) 2012
  - PKS 2155-304 (H.E.S.S.) 2006
  - Crab pulsar (MAGIC, VERITAS)
  - Vela pulsar (H.E.S.S.)
  - GRB 190114C ? (MAGIC)
- All class of sources are represented
- Different characteristics:
  - PKS 2155-304 : important stat, redshift 0.116, no background
  - PG 1553+113 : redshift 0.5, background
  - Vela : pulsar, local, period 89 ms

Likelihood method (negligible background)

Telescopes IRFs — Spectrum — Light curve

$$R_{\mathrm{Sig}}(E,t|\tau_n) = \int_{E_{true}=0}^{\infty} D(E,E_{true})A_{\mathrm{eff}}(E_{true},t)\Lambda_{\mathrm{Sig}}(E_{true})F_{\mathrm{Sig}}(t-\tau_n\cdot E_{true}^{n})dE_{true}$$

Normalization

$$N_{\mathrm{Sig}}(\tau_n) = \int_{t=t_{min}}^{t_{max}}\int_{E=E_{cut}}^{E_{max}} R_{\mathrm{Sig}}(E,t|\tau_n)dEdt$$

- IRFs vary for each source and for each instrument
- Light curve for $\tau_n = 0$ derived with selection of low energetic events
- Likelihood is computed for each event (unbinned likelihood) and combined :

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\mathrm{Sig}(E,t|\tau_n)}}{N_{\mathrm{Sig}(\tau_n)}}$$

- For pulsars, the formula is similar but the time is replaced by the phase

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Likelihood method with background

- Two types of background :
  - Hadronic background : residual hadronic events that are not rejected the by gamma-ray like selection
  - Gamma background : baseline flux of the source before and after the flare
- This two backgrounds are both constant versus time...
- ...but have different energy distributions (index 2.7 for Hadronic, depends of the source for gamma background)

$$R_{\mathrm{bck}}(E,t) = \int_{E_{true}=0}^{\infty} D(E, E_{true}) A_{\mathrm{eff}}(E_{true}, t) \Lambda_{\mathrm{bck}}(E_{true}) F_{\mathrm{bck}}(t) dE_{true}$$

$$N_{\mathrm{bck}} = \int_{t=t_{min}}^{t_{max}} \int_{E=E_{cut}}^{E_{max}} R_{bck}(E,t) dE dt \qquad F_{\mathrm{bck}}(t) = \mathrm{cst}$$

- Then combination for all events is :

$$\mathcal{L}(\tau_n) = \prod^{N} (1 - w_s) \left(w_\gamma \frac{R_{\mathrm{bck},\gamma}(E,t)}{N_{\mathrm{bck}}} + (1 - w_\gamma) \frac{R_{\mathrm{bck,hadron}}(E,t)}{N_{\mathrm{bck}}} \right) + w_s \frac{R_{\mathrm{sig},\gamma}(E,t|\tau_n)}{N_{\mathrm{sig}(\tau_n)}}$$

Combination sources

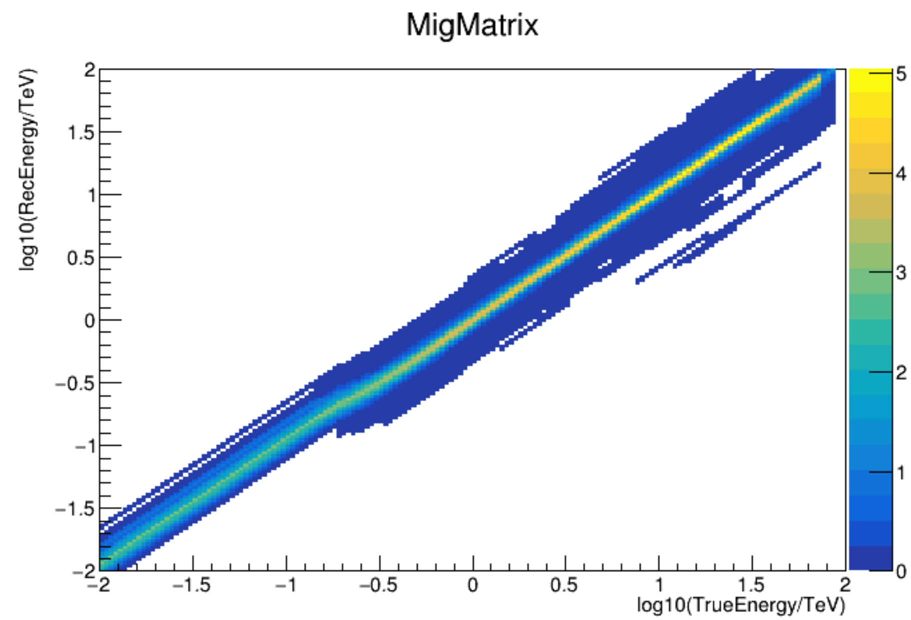
- To work on the same variable for combination of source, should fit the redshift corrected lag
- Likelihood can be combined between all the sources, and minimize using the full dataset of all sources

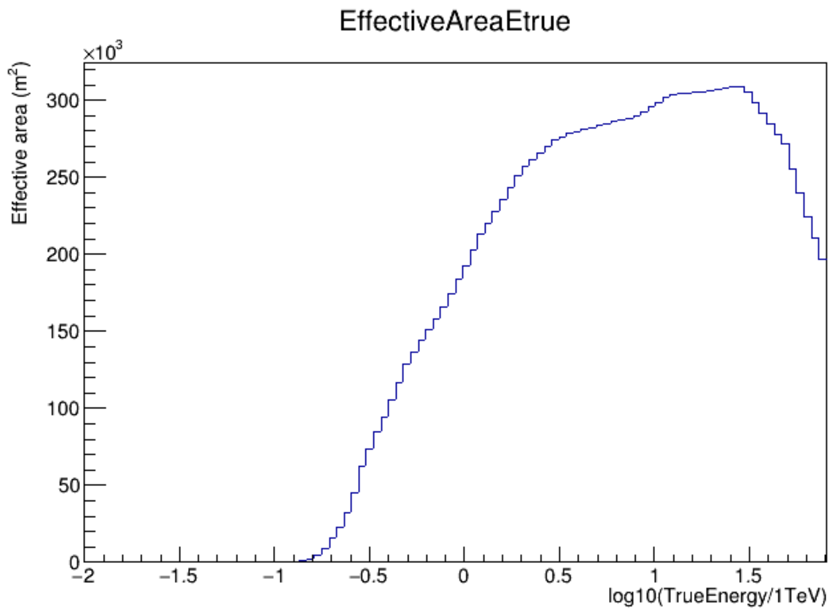
$$\tau_n = \lambda_n K(z)$$

$$L_{comb}(\lambda) = \sum_{i=1}^{N_{source}} L_i(\lambda)$$

Intrumental Response Function

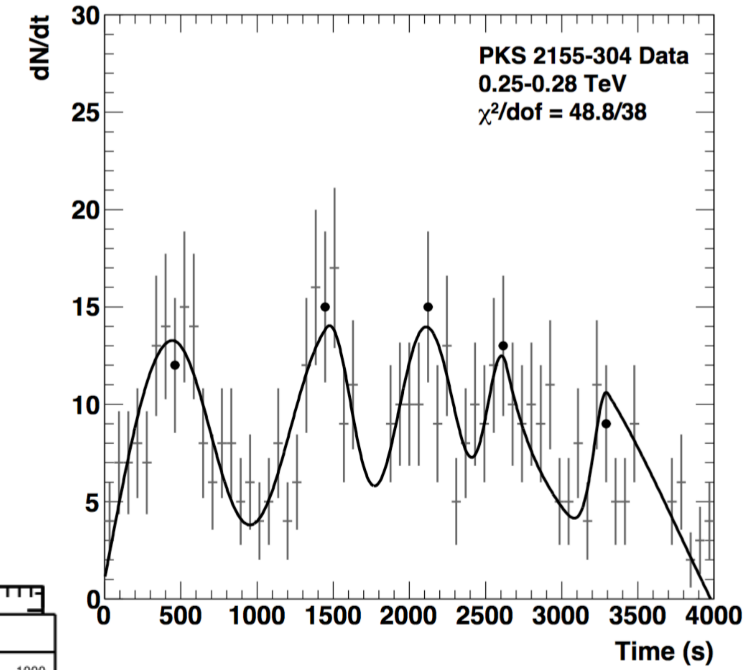
- Taking into account the IRFs imply a triple and a simple integral for each events → time consuming
- For most of the previous studies, approximation were done to simplify this calculation
- We developed a method to fully take into account IRFs without any simplification
- pdf and normalization are precomputed and stored in tables for each sources
- During the likelihood minimization, pdf and normalization values are obtained by trilinear and linear interpolation from tables

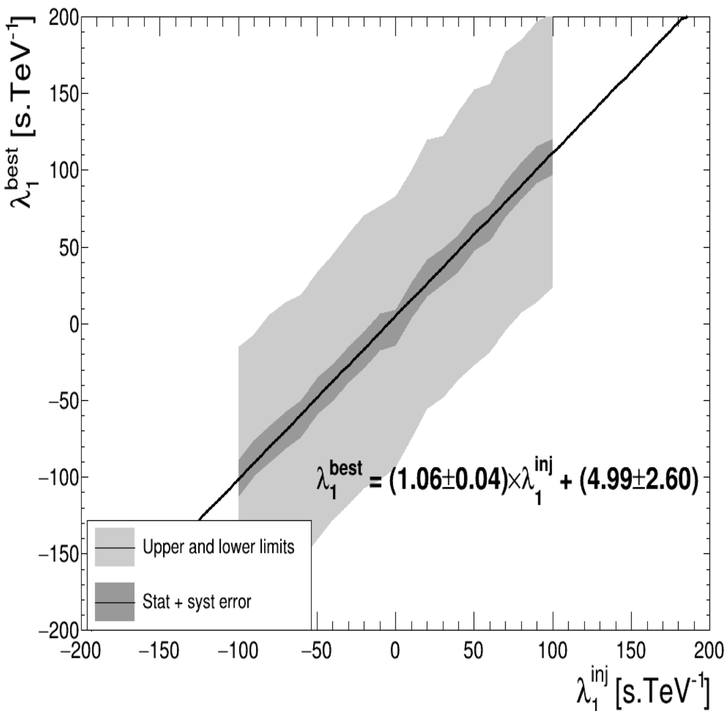


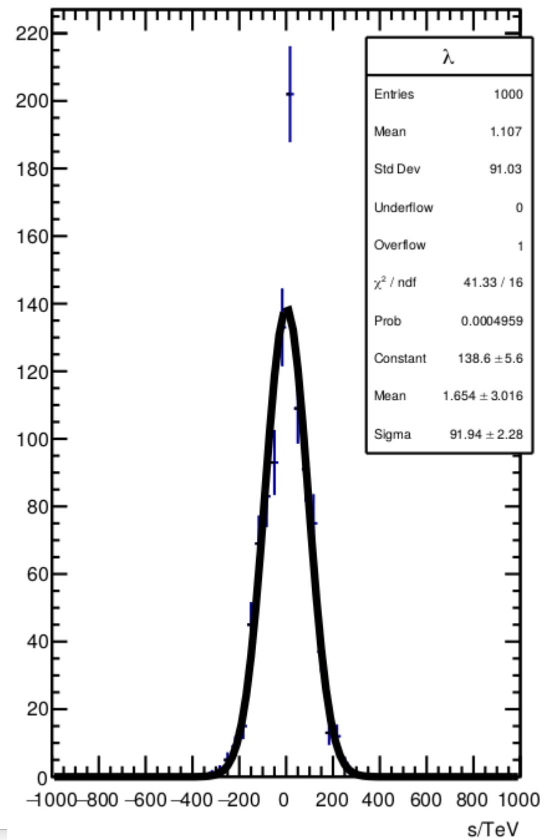


PKS 2155-304 (preliminary) results

- Good example of source with negligible background
- redshift 0.116, PL index 3.46
- Light curve derived from low energetic events, well described by sum of 5 asymmetric Gaussian







E_{QG} 0.95 Limit:

2.3e+18 GeV

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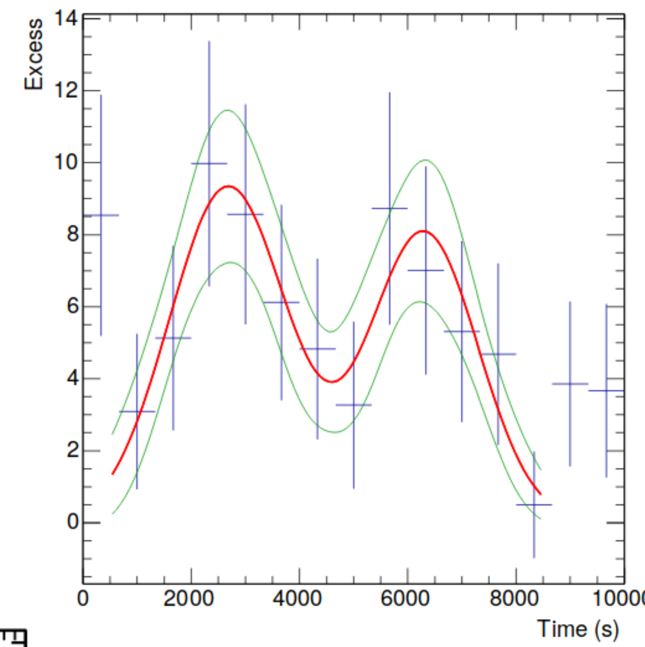
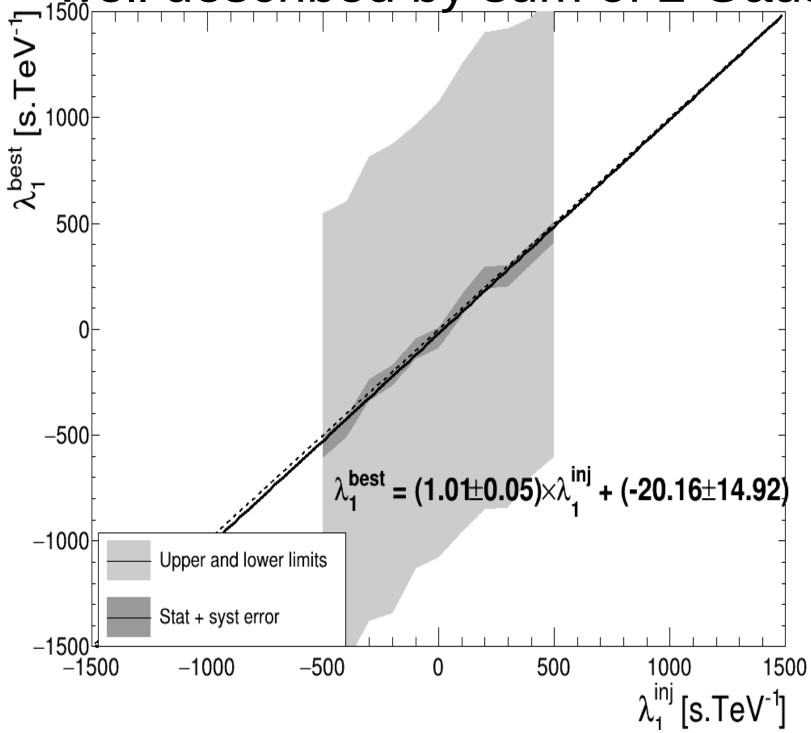
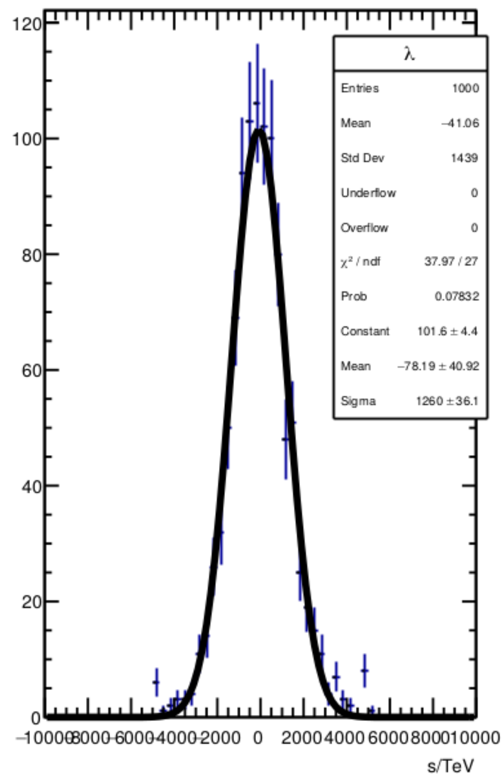
PG 1553+113 (preliminary) results

- Good example of source with non negligible background ($w_s = 0.56$)
- redshift 0.5, PL index 4.8
- Light curve derived from low energetic events, well described by sum of 2 Gaussian





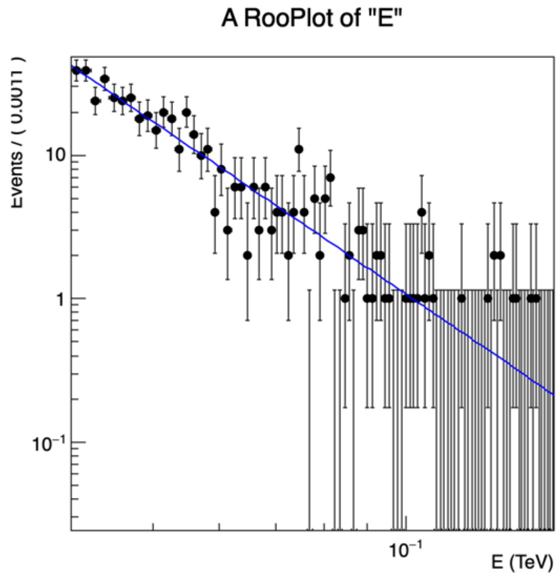


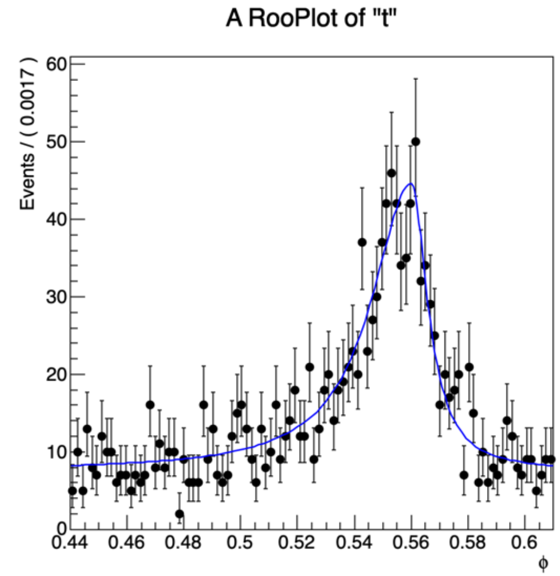
E_{QG} 0.95 limit:

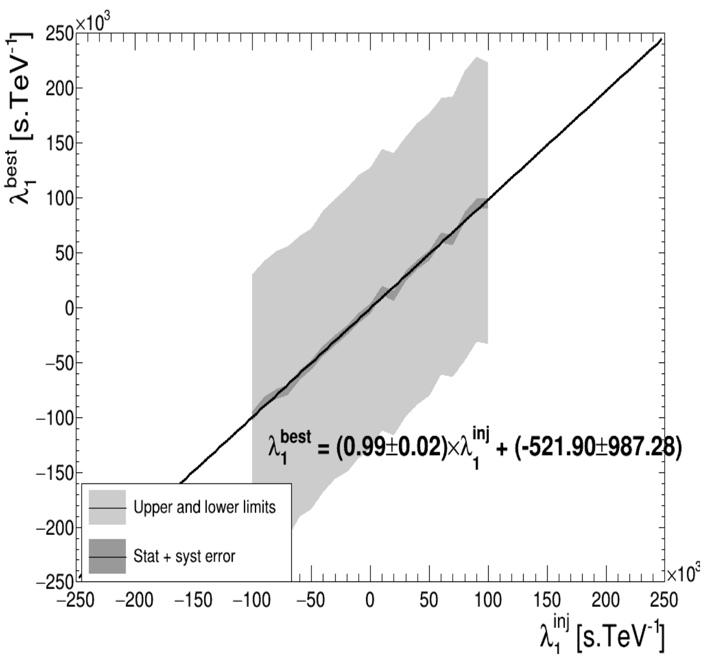
1.8e+17 GeV

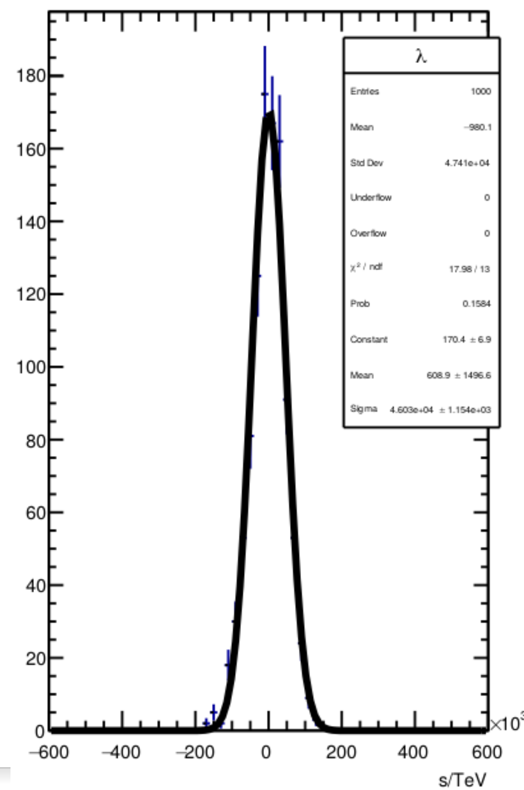
Vela pulsar (preliminary) results

- 40 GeV < E < 150 GeV
- pulsation 89 ms
- phasogram well described by asymmetric Lorentzian









E_{QG} 0.95 limits:

4.7e+15 GeV

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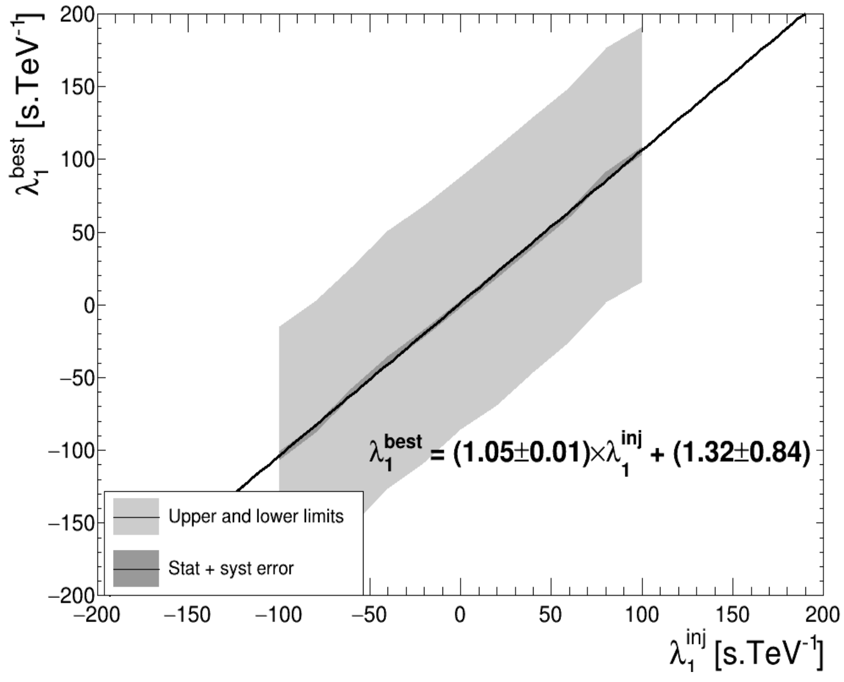
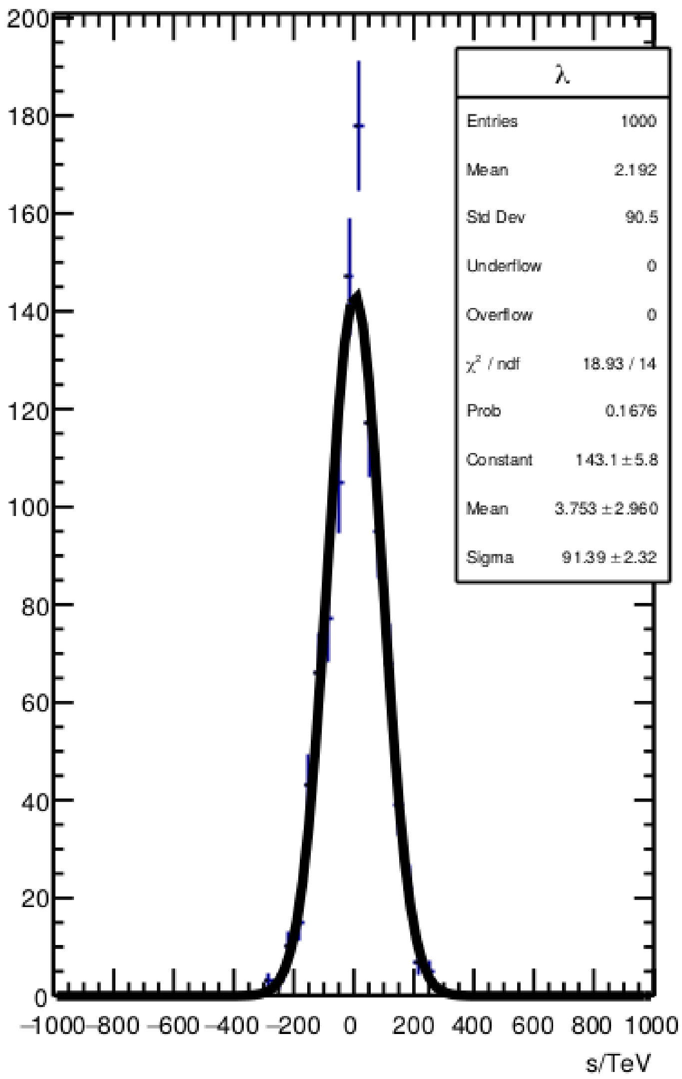
Combination of sources (preliminary) results

PKS 2155 + Vela + PG1553





E_{QG} 0.95 Limit: 2.3e+18 GeV

Good reconstruction, PKS 2155 is dominant (as expected), E_{QG} limit almost unchanged compared to PKS 2155 only

Systematic uncertainties

- Some parameters used to compute the Likelihood are simply fixed to a certain value… but they are measured and have an intrisic uncertainty
  - Template of the light curve
  - Energy distribution of signal
  - Proportion of signal, gamma and hadronic background
  - redshift
- All this parameters are added as nuisance parameters inside the Likelihood in order to take into account their uncertainty :

$$\mathcal{L} = \mathcal{L}_{LIV}(\tau_n, \vec{\theta}) \prod \mathcal{L}_i(\theta_i)$$

- The unidimensionnal Likelihood became N+1 dimensionnal Likelihood, at the end uncertainty of parameters is propagated to tau

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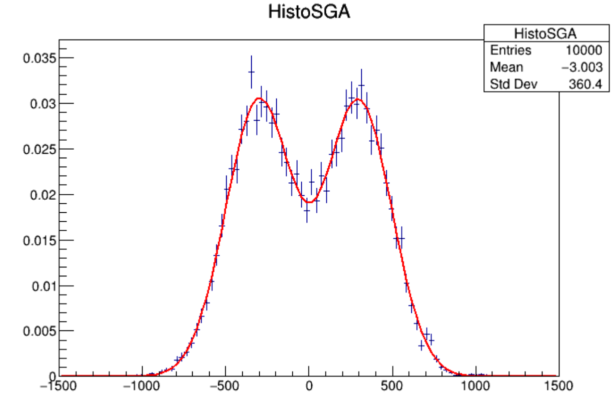
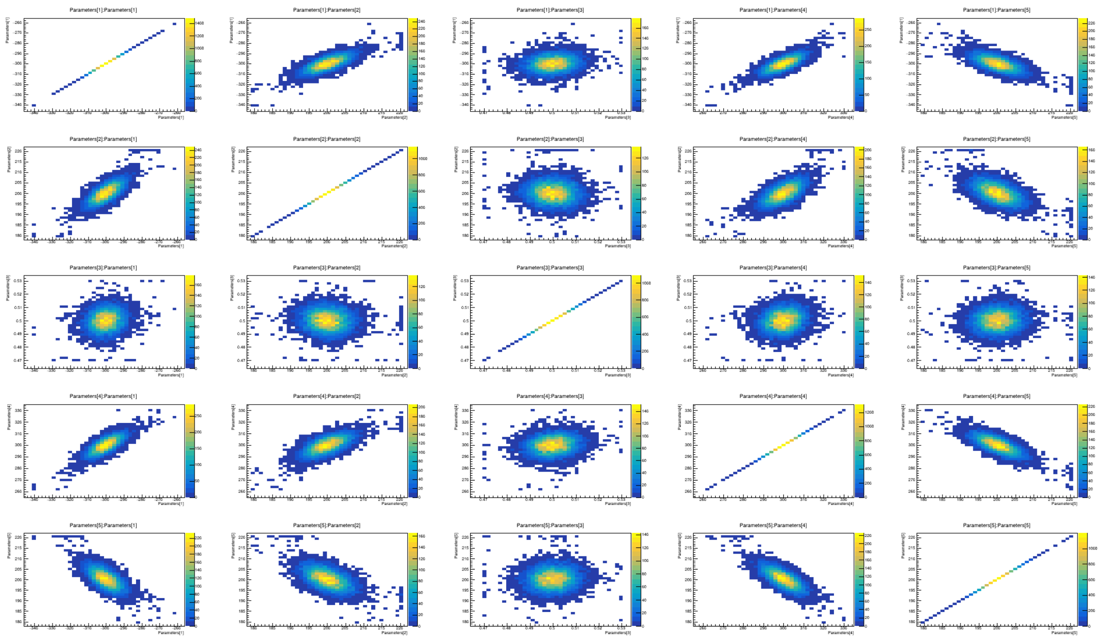
Correlations

- Previous formula suppose no correlation between nuisance parameter
- For the template parameters it is not true
- nuisance parameter Likelihood can be obtained from inverted covariance matrix
- Or it can be directly the likelihood of the light curve model compared to template data
- Second solution found to be more stable (but also more time consuming)



Toy MC simulation



COV matrix

Systematical uncertainties

- Nuisance parameters :
  - Statistics of the time templates → Likelihood obtained by fitting the template
  - Impact of background proportion on time templates → Background added to template and Likelihood obtained by fitting it
  - Spectral index → Likelihood obtained from fit of spectral index in papers
  - Background and signal proportion → Likelihood obtained from the normalisation uncertainty of flux

- Check the convergence of the fit with a large number of sources (imply many nuisance parameters) → stable so far but time consuming

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PG1553+113 systematics (preliminary)

- Most important systematics found to be the template statistics
- Total systematics 392 s/TeV
- To be compared with 330 s/TeV found on previous study, likely underestimation of systematics on previous studies

uncertainties	1 sigma	syst uncertainty
stat only	687 s/TeV	0 s/TeV
stat + stat template	772 s/TeV	352 s/TeV
stat + stat template with background	785 s/TeV	380 s/TeV
stat + PL index	691 s/TeV	74 s/TeV
stat + Signal proportion	708.5 s/TeV	171 s/TeV
stat + hadron proportion	691 s/TeV	74 s/TeV
All	791 s/TeV	392 s/TeV

Conclusions

- We developed a generic tool to combine IACTs time delay measurements
- Tools already in a good shape, can already handle various sources (pulsar, AGN)
- IRFs are fully implemented without any simplification, tools already ready to support various experiments data
- Systematical uncertainties on-going, need to reproduce the work done for PG1553+113 for every sources
- Already done combination of 3 H.E.S.S. sources with different nature and redshift
- First paper about the technique is on-going