Energy-dependant time lags search with Active Galactic Nuclei

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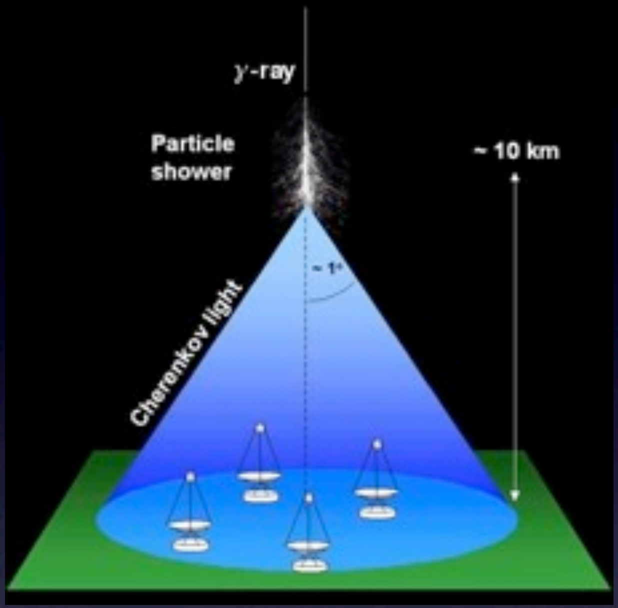
Outlook

- Ground-based gamma-ray astronomy
- Time-of-flights studies with AGNs: present status
- The latest HESS results
  - The method
  - Error calibration and systematics
  - Results
- Conclusions: the future

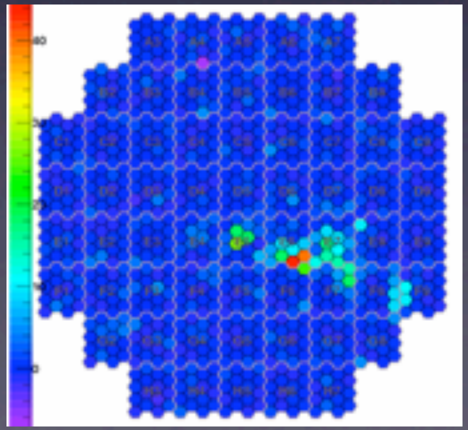
Ground-based gamma-ray astronomy

Ground based gamma-ray astronomy

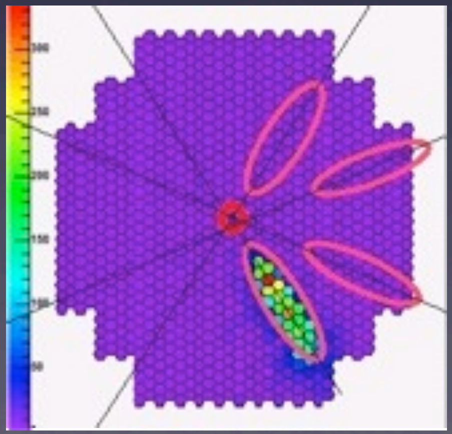
- Production of a shower of particles
- Faint and short flash of Cherenkov light
- Image of the shower on a fast camera in the focal plane
- Analysis of the image:
  - Shape ➔ Type of the particle
  - Intensity ➔ Energy
  - Orientation ➔ Direction
- Stereoscopy: direct measurement of the origin of the γ, multiplicity of the images



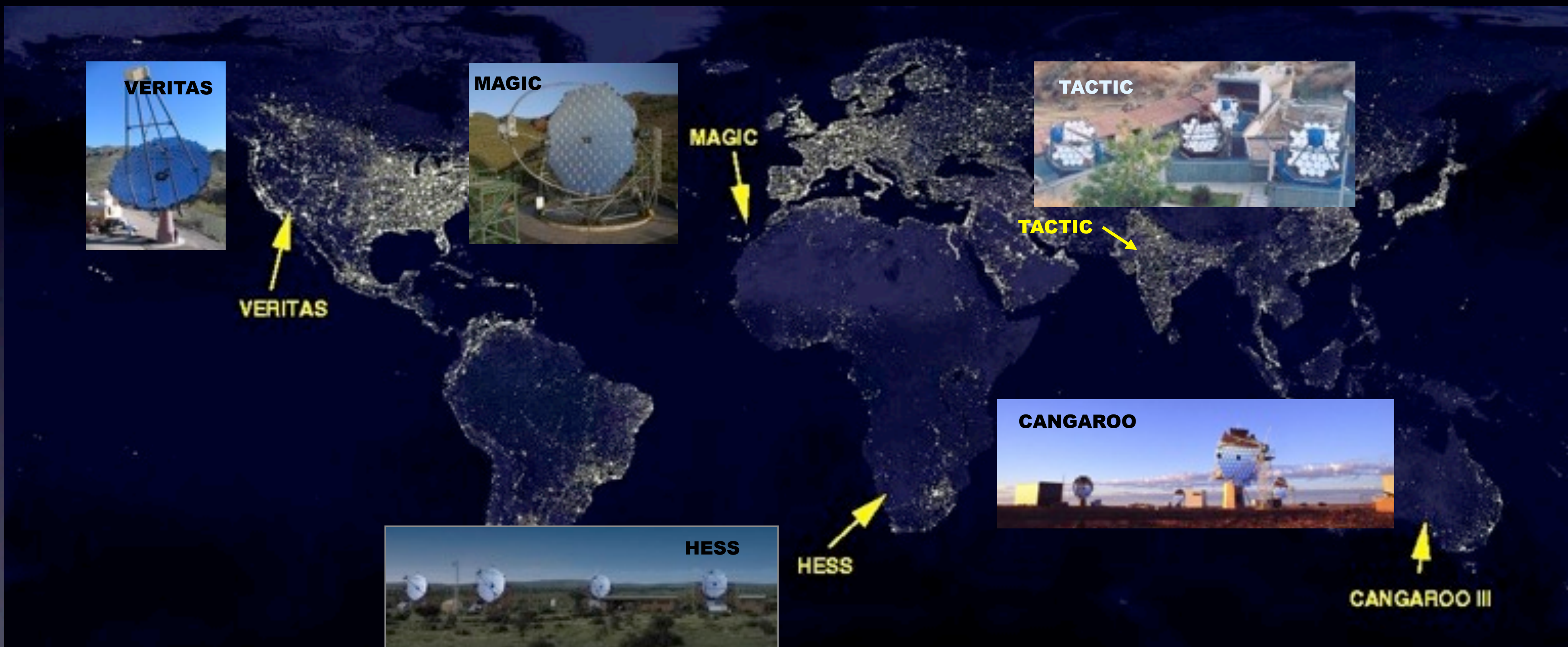
Hadron



Gamma



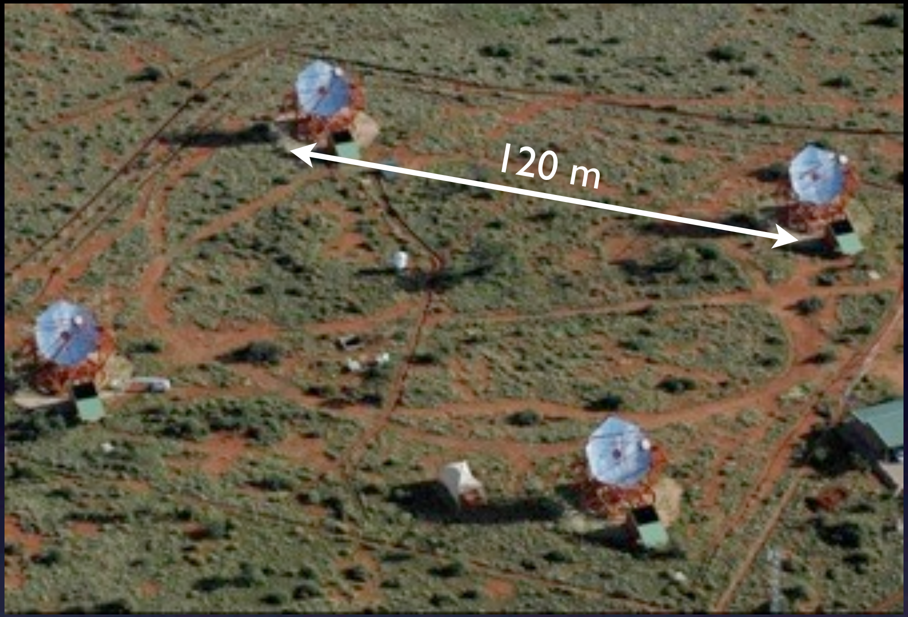
In the world...



VERITAS
MAGIC
MAGIC
TACTIC
TACTIC
VERITAS
CANGAROO
HESS
HESS
CANGAROO III

H.E.S.S.

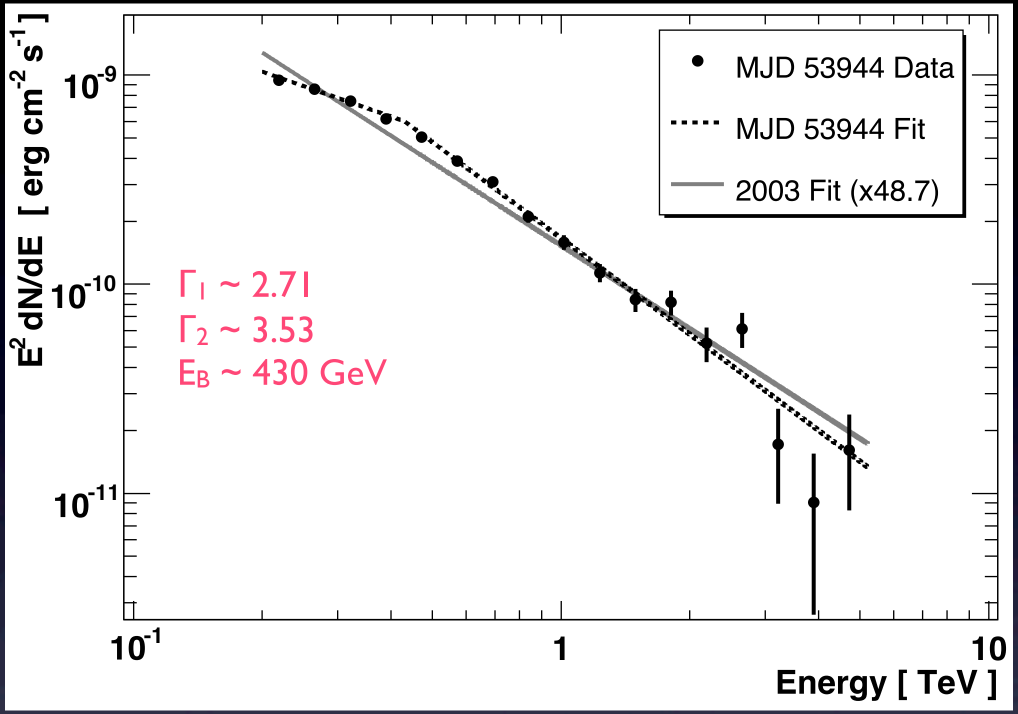
- High Energy Stereoscopic System
- ~180 poeple, 12 countries
- 4 telescopes located in Namibia
- 12 m diameter, 15 m focal length
- Field of view ~5°
- Angular resolution < 0.1°
- Energy resolution ~15%
- Energy range from ~100 GeV to ~100 TeV
- More than 60 sources discovered

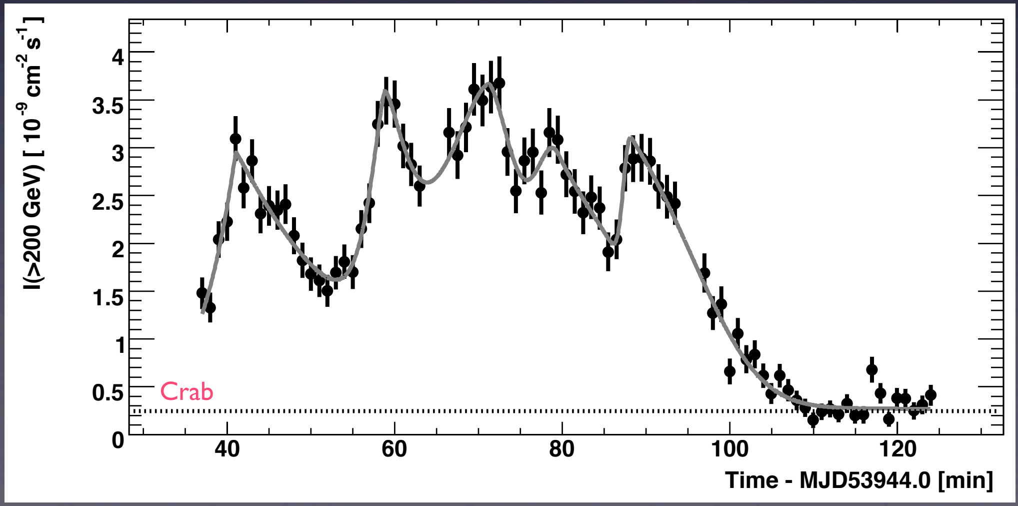


Present status

HESS - PKS 2155-304

- z = 0.116 (~490 Mpc)
- Flare in july 2006
- High flux ➔ ~14 Crab
- High statistics ➔ ~10000 photons after cuts
- Light curves with 1 minute bins
- Broken power-law spectrum
- High variability:
  - Minute time-scale variability
  - Rise and fall-times of ~200s



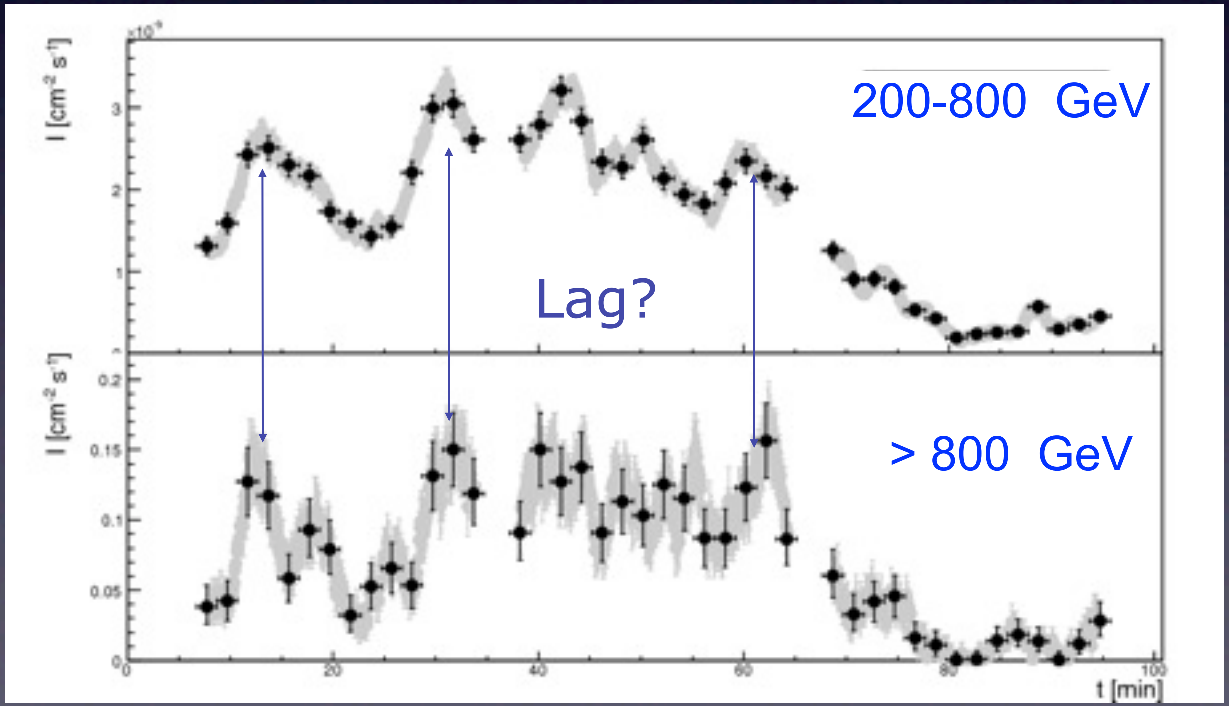


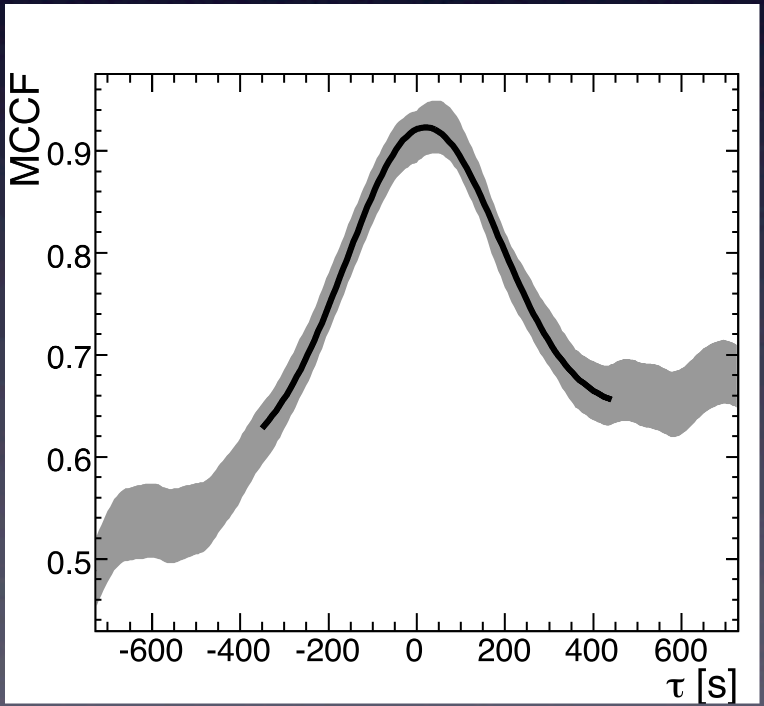
Aharonian et al. (HESS Collaboration), ApJ 664, L71 (2007)

HESS former results with PKS2155-304

- Cross Correlation Function
- Wavelets
  - Localization of local extrema
  - Pairs with HE and LE extrema

$M^l_{QG} > 0.7 \times 10^{18}$ GeV (CCF)
$M^l_{QG} > 0.5 \times 10^{18}$ GeV (Wavelets)

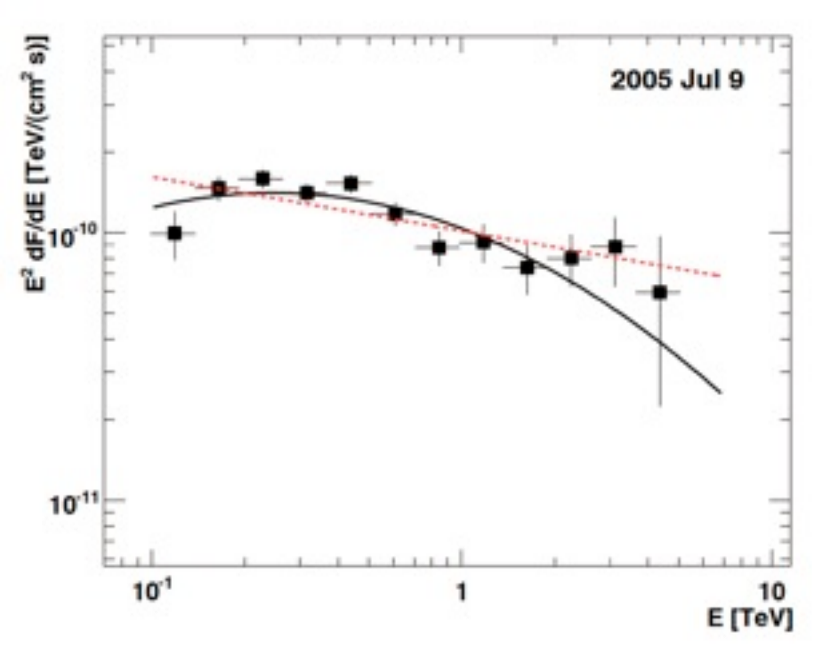


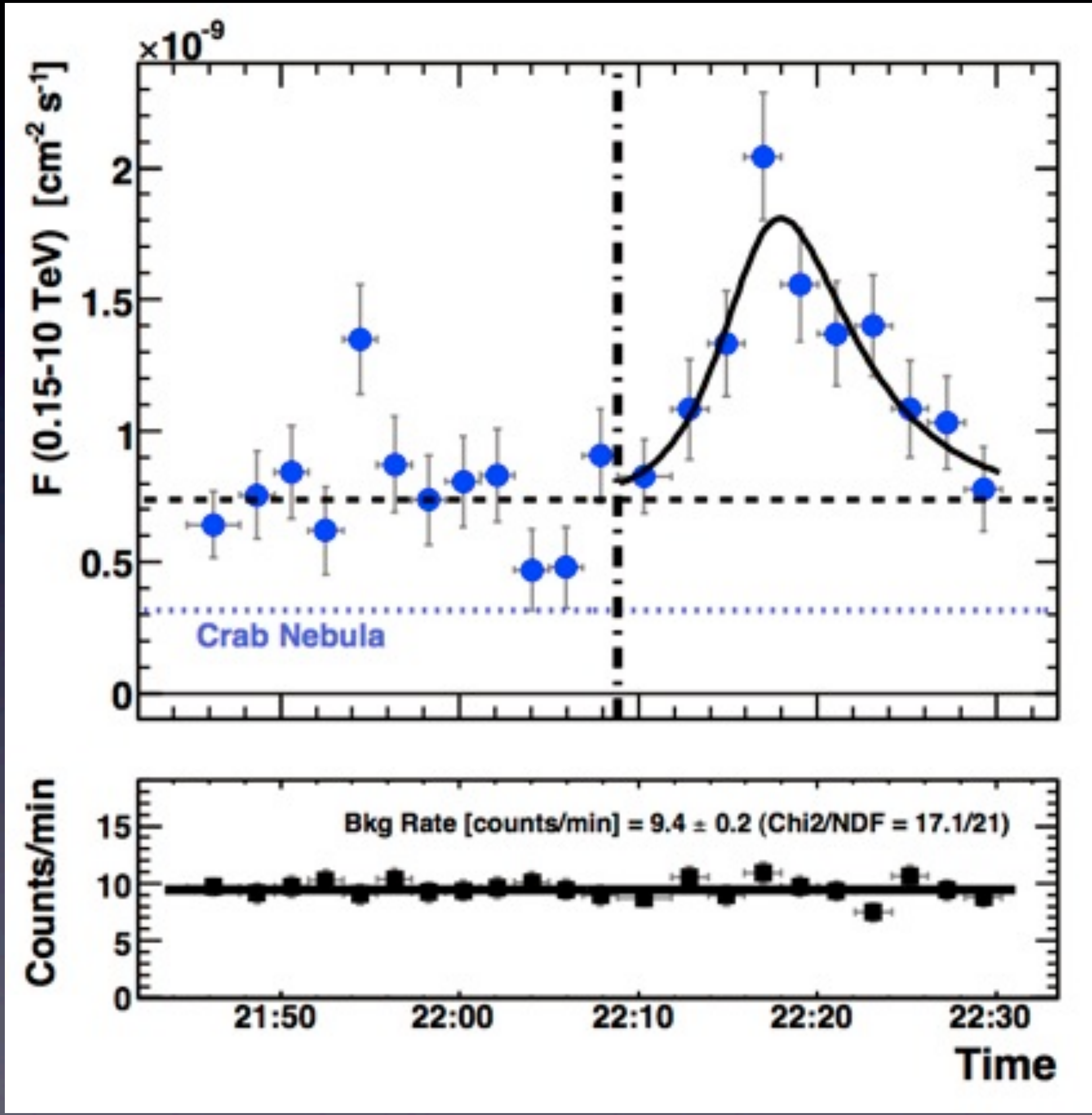


MJD 53944.02

MAGIC - Mkn 501

- z = 0.034 (~135 Mpc)
- Flare of 2005 July 9
- High flux ➔ ~5 crab
- LC with 2 minutes bins
- Hard spectral index of ~2.2





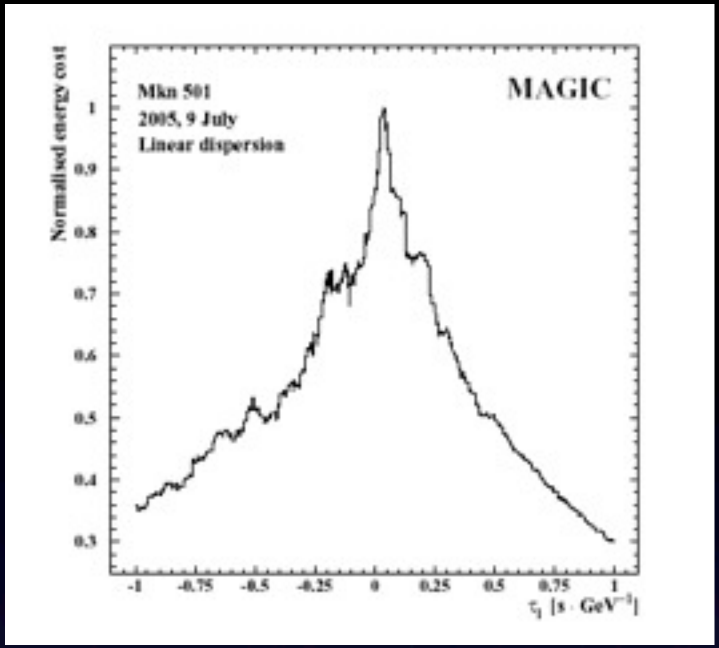
Albert et al. (MAGIC Collaboration), ApJ 669, 862 (2007)

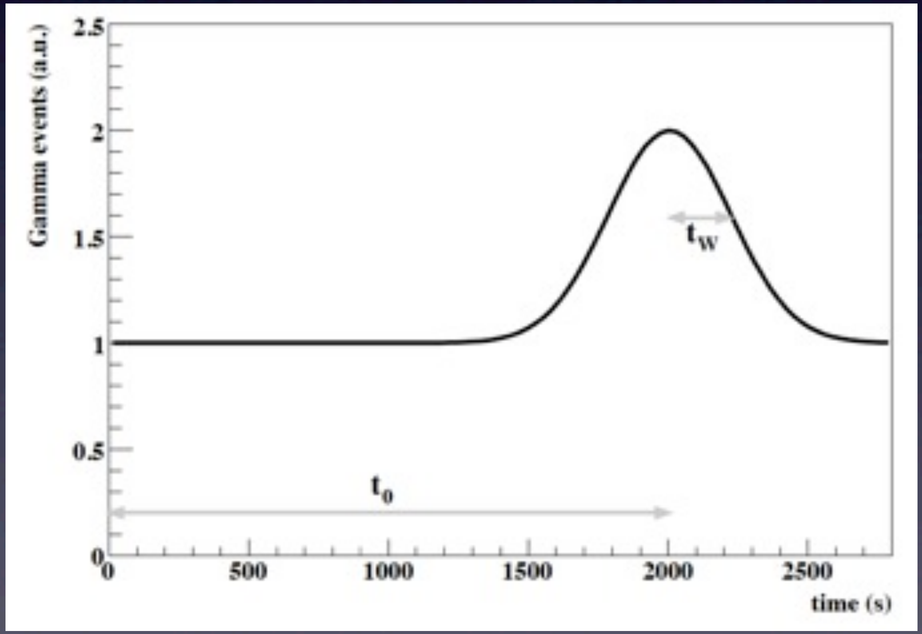
MAGIC present results

- Two different techinques
  - Energy Cost Function
  - Likelihood
- Idea behind ECF
  - Apparent duration of the pulse increased by the dispersion
  - The energy per unit of time decreases with distance from the source
  - dispersion can be extracted by maximizing the energy emitted by the source
- Likelihood fit
- Best limit:

$$ECF_L = \sum_{T_1<t<T_2} E(i)$$

$M^l_{QG} > 0.3\times10^{18}$ GeV





Albert et al. (MAGIC Collaboration) and Ellis et al., Phys. Lett. B 668, 253 (2008)
Martinez and Errando, Astropart. Phys. 31, 226 (2009)

The latest HESS results

Formalism in use

- We use the following formalism for linear and quadratic effects:

$$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_{\mathrm{P}} H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2E_{\mathrm{P}}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

- Intrinsic source effects are neglicted
- Constraints are put either on ξ and ζ or on $M^{l}_{QG} = E_P/\xi$ and $M^{q}_{QG} = E_P/\zeta^{1/2}$

The Method

- Study of the correlation between the arrival time and the energy of the photons
- Method used by Lamon *et al.* for INTEGRAL and by Martinez and Errando for MAGIC
- We use the following form for the probability density function:

$$P(t,E) = N \int_0^\infty A(E_S)\,\Gamma(E_S)\,G(E-E_S,\sigma(E_S))\,F_S(t-\tau E_S)\,dE_S$$

where $\Gamma(E_S)$ is the emitted spectrum, $G(E-E_S, \sigma(E_S))$ is the smearing function in energy, $A(E_S)$ is the acceptance of H.E.S.S. and F_S is the emission time distribution at the source

- Here we assume linear and quadratic effects with a time-lag parameter τ expressed in s/TeV (s/TeV^2)
- The likelihood function is then given by the product

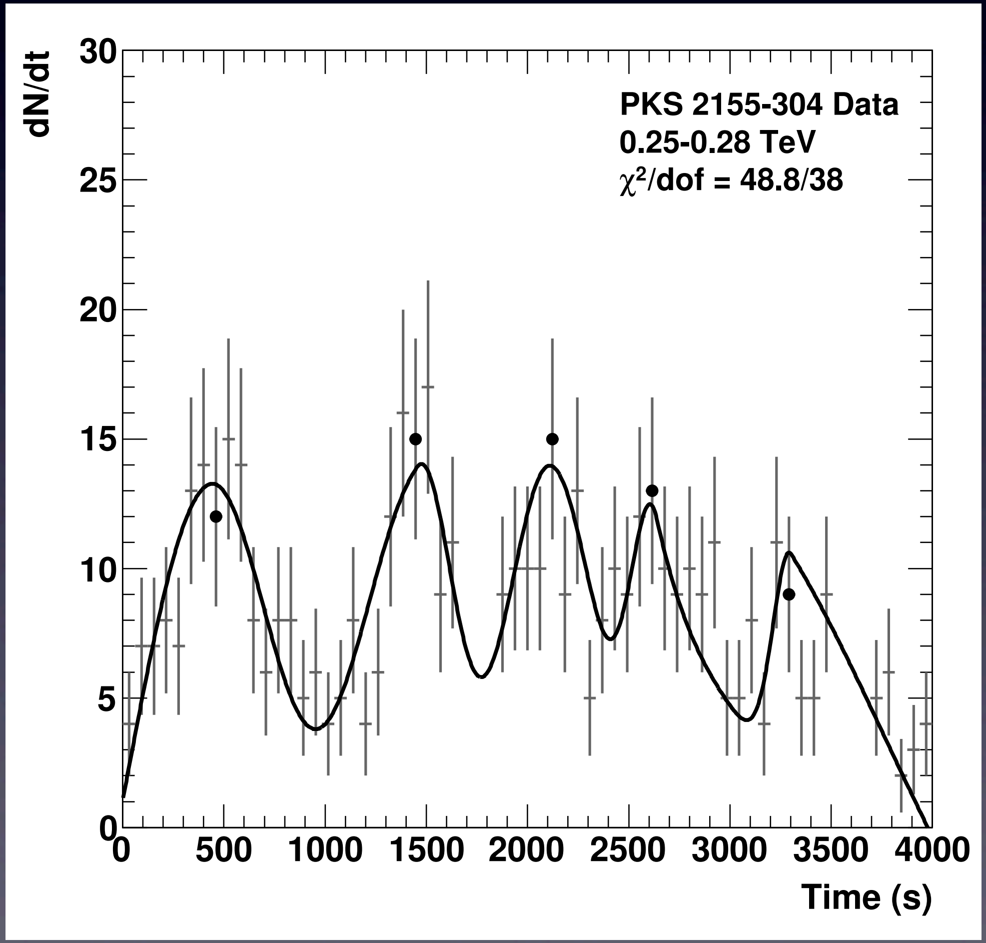
$$L = \prod_i P_i(t,E)$$

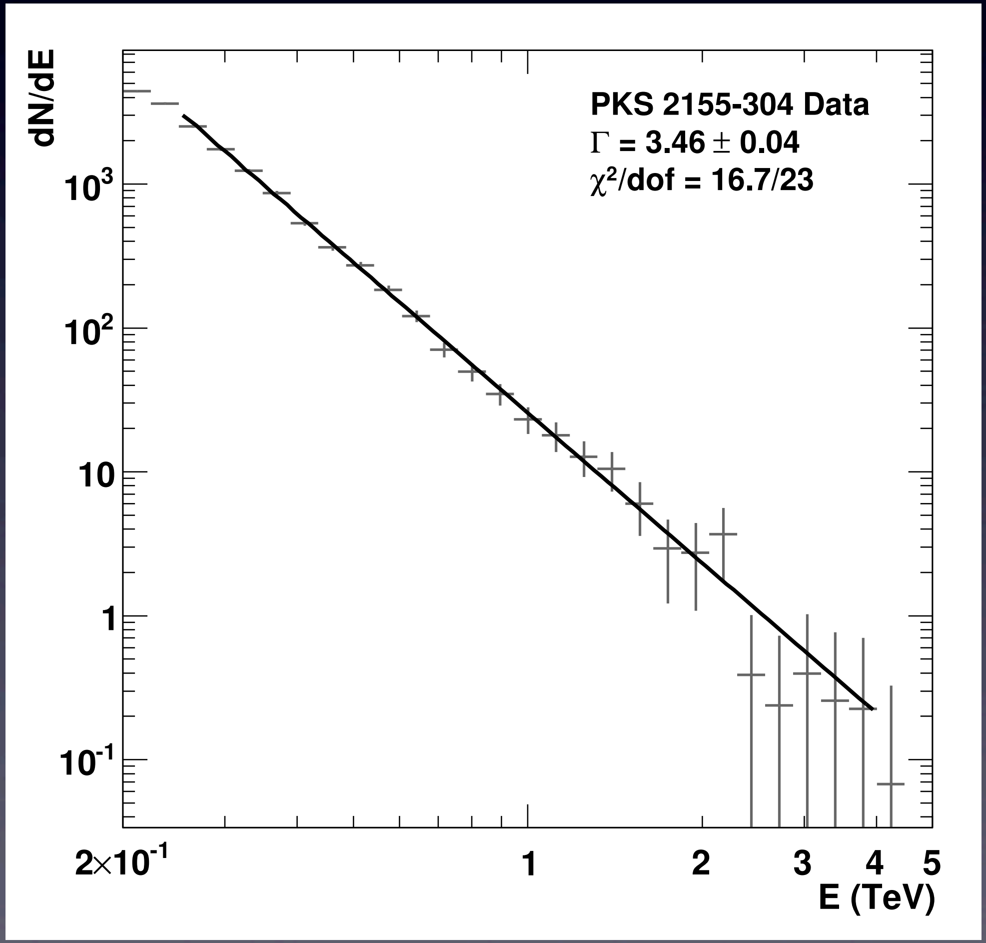
over all photons in the studied sample

- The maximum of the likelihood gives the time-lag τ_l (τ_q) in s/TeV (s/TeV^2)

Application on PKS 2155 data

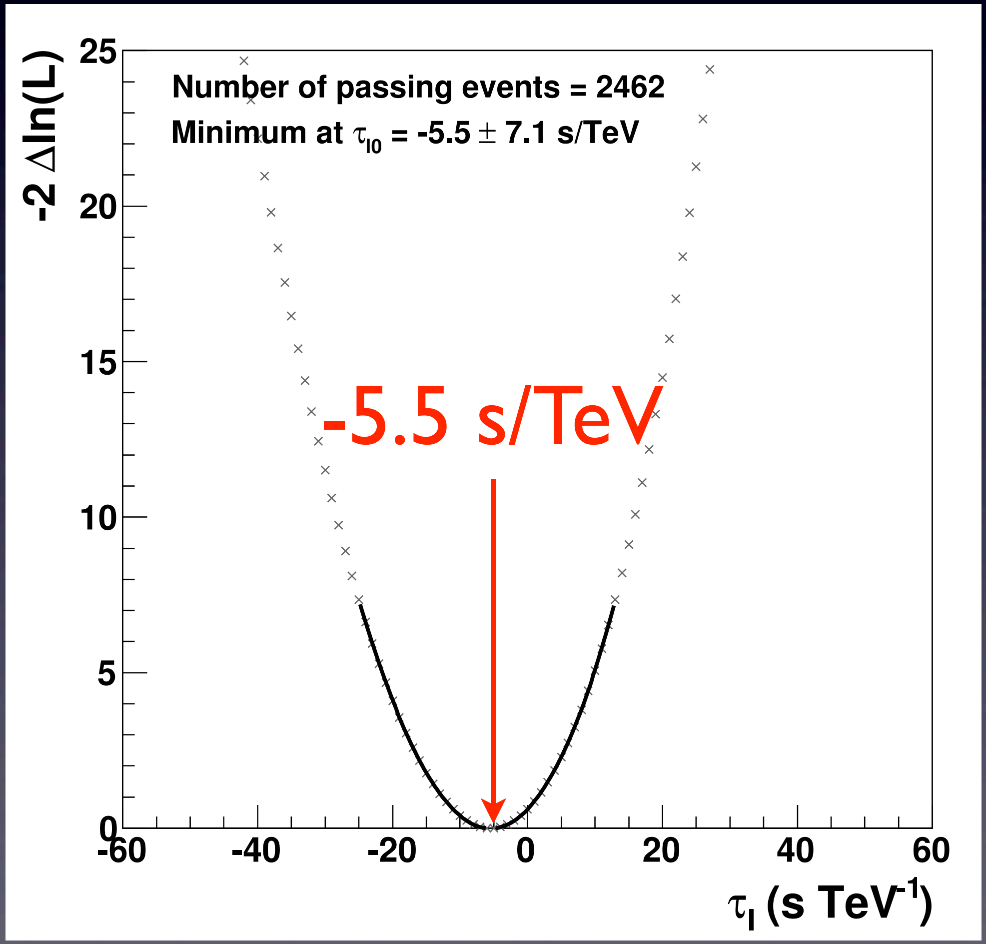
- The light curve and spectrum have to be parameterized
- «Template» light curve at low energies (0.25-0.28 TeV), binning of 61s

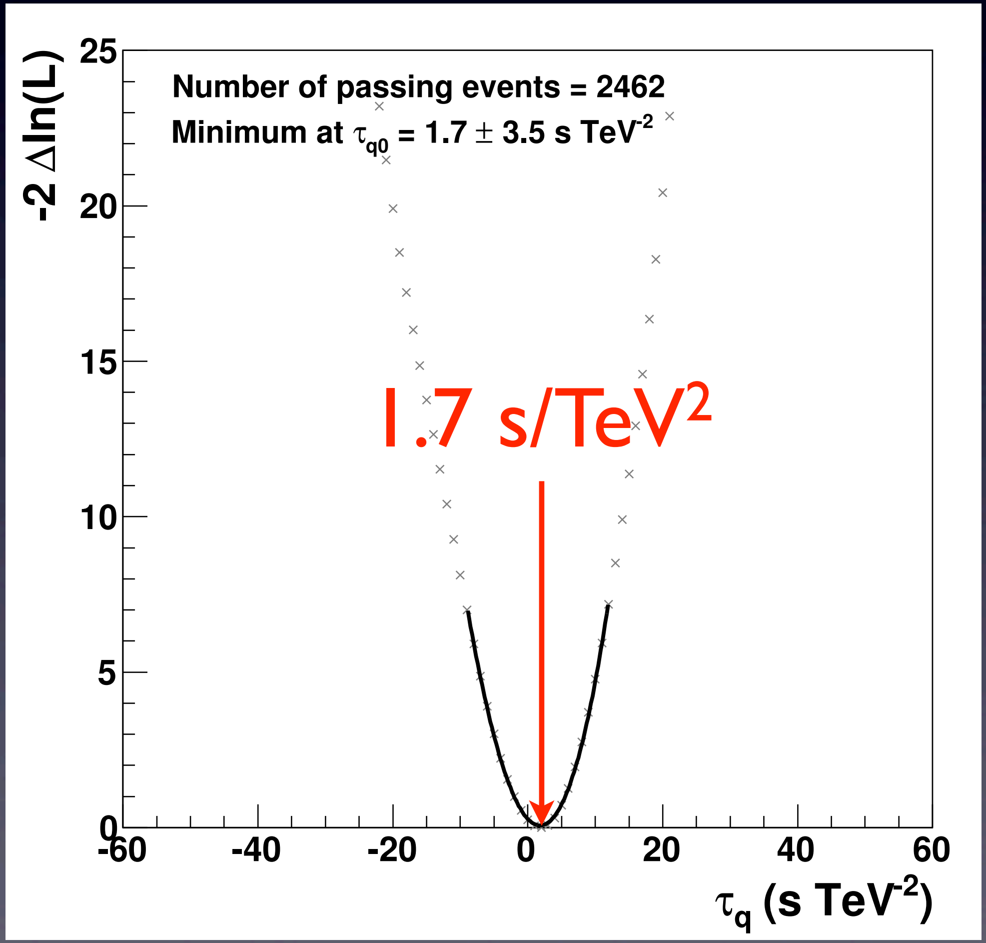




Application on PKS 2155 data

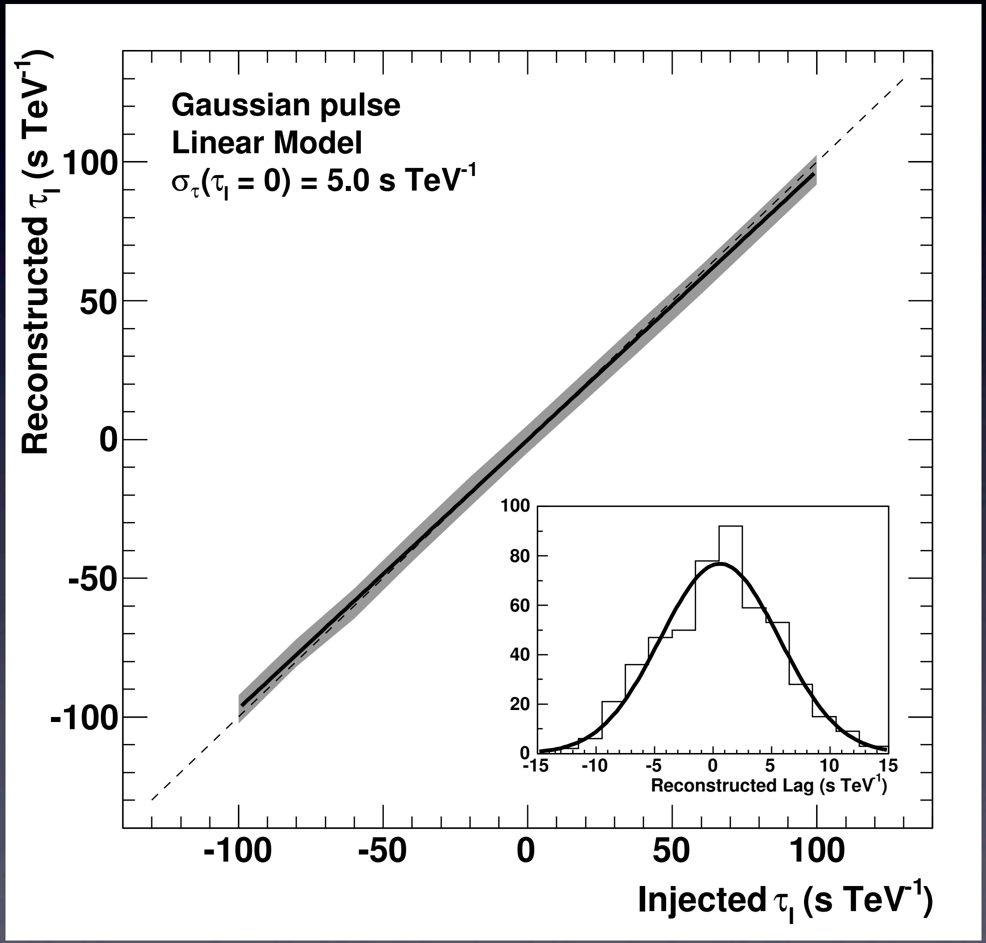
- Maximization of likelihood for the linear and quadratic cases
- Errors are obtained for $-2\Delta\ln(L) = 1$





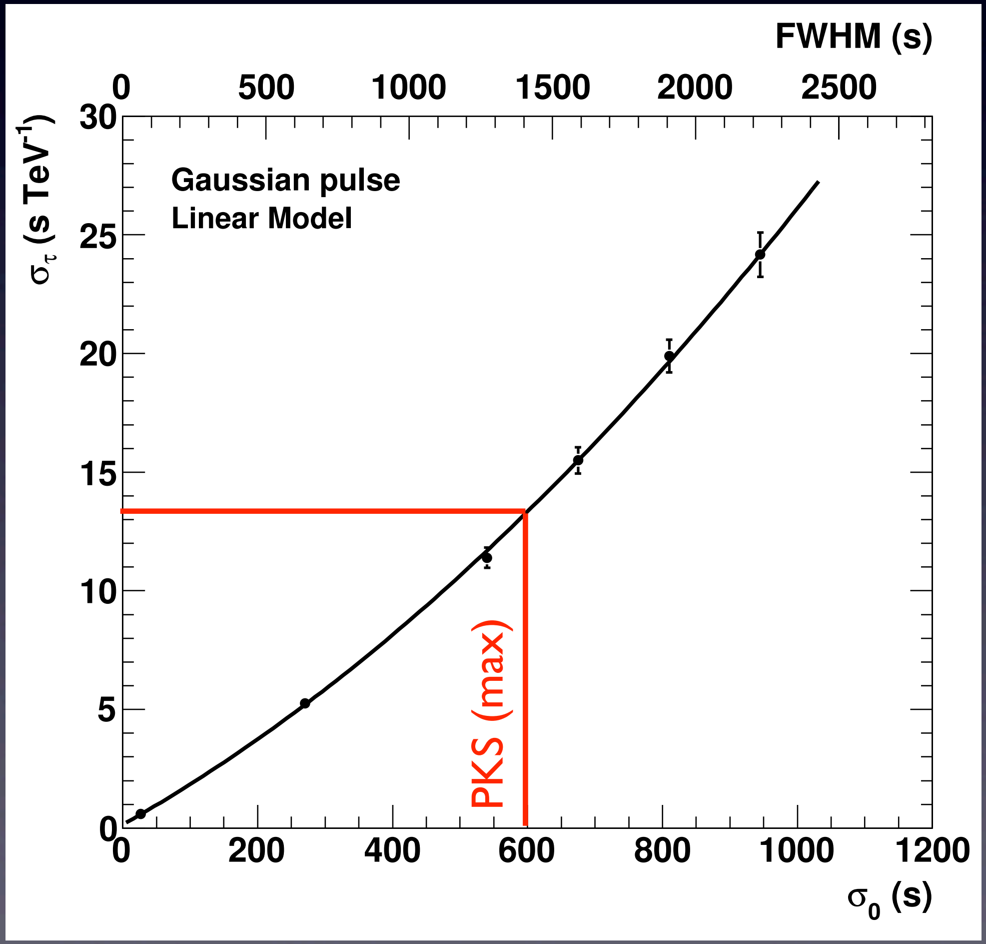
Error Calibration and Systematics

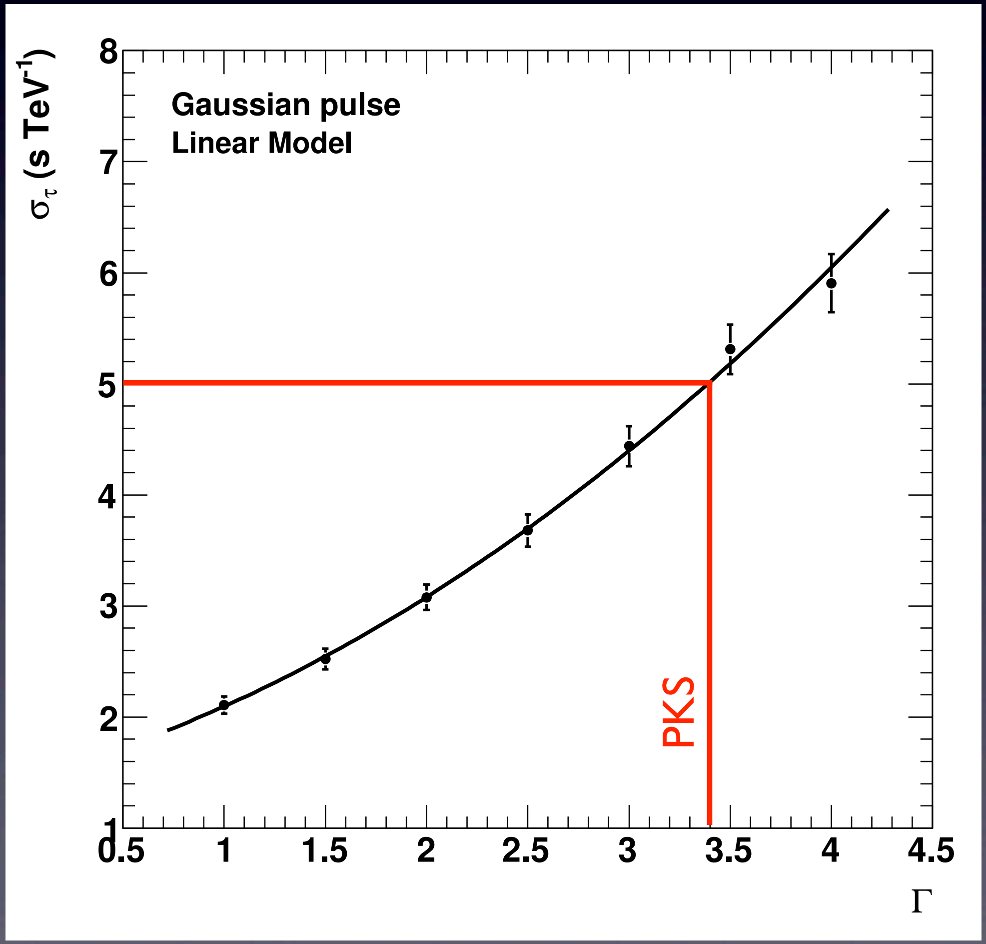
- A toy Monte Carlo was used to evaluate systematics and to calibrate the errors
- Generation of a set of photons
  - Same statistics as in data
  - Energy distribution according to the measured spectrum of PKS
  - Time distribution following a gaussian distribution or following the measured LC of PKS
  - Time lag injected in the range -100 s/TeV (s/TeV^2) to 100 s/TeV (s/TeV^2)
  - Lag reconstructed with the likelihood fit
- Important parameters:
  - The slope of the calibration curve
  - The width of the distribution of reconstructed lags σ_τ



Error Calibration and Systematics (2)

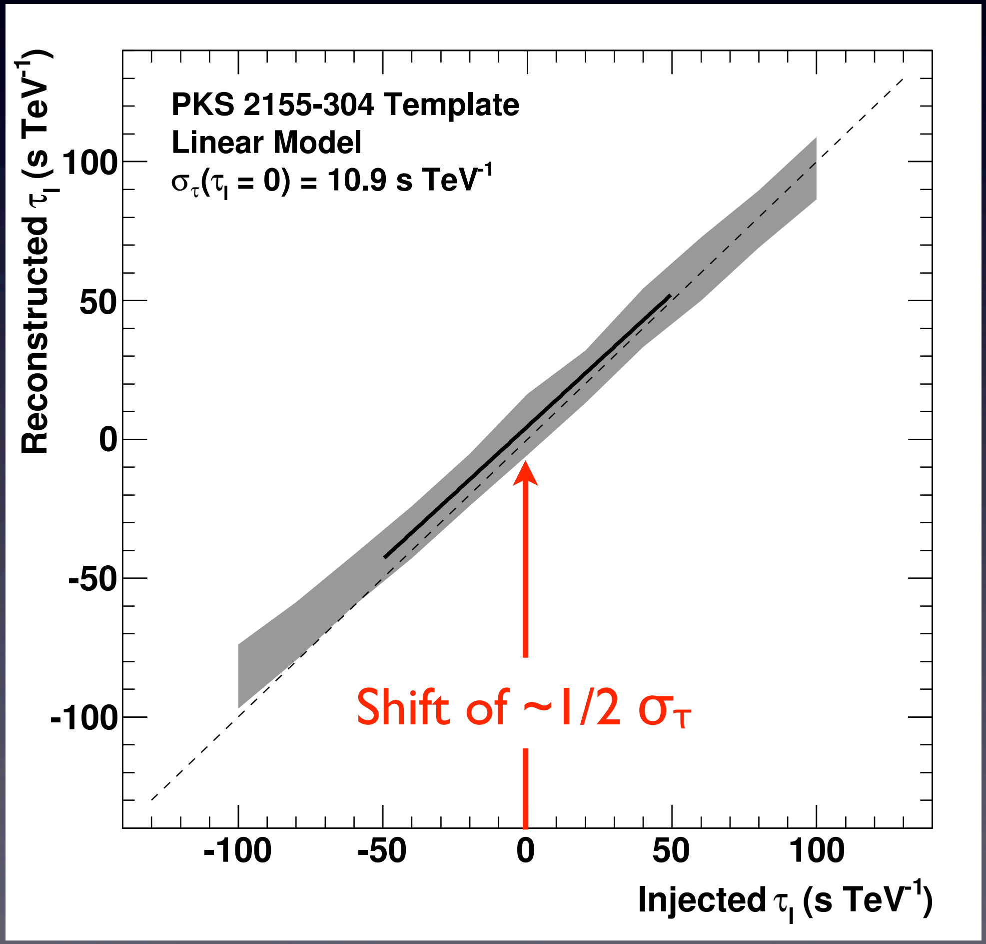
- Pulse shape: width and symmetry/asymmetry of the pulse
- Variation of the error with the spectral index

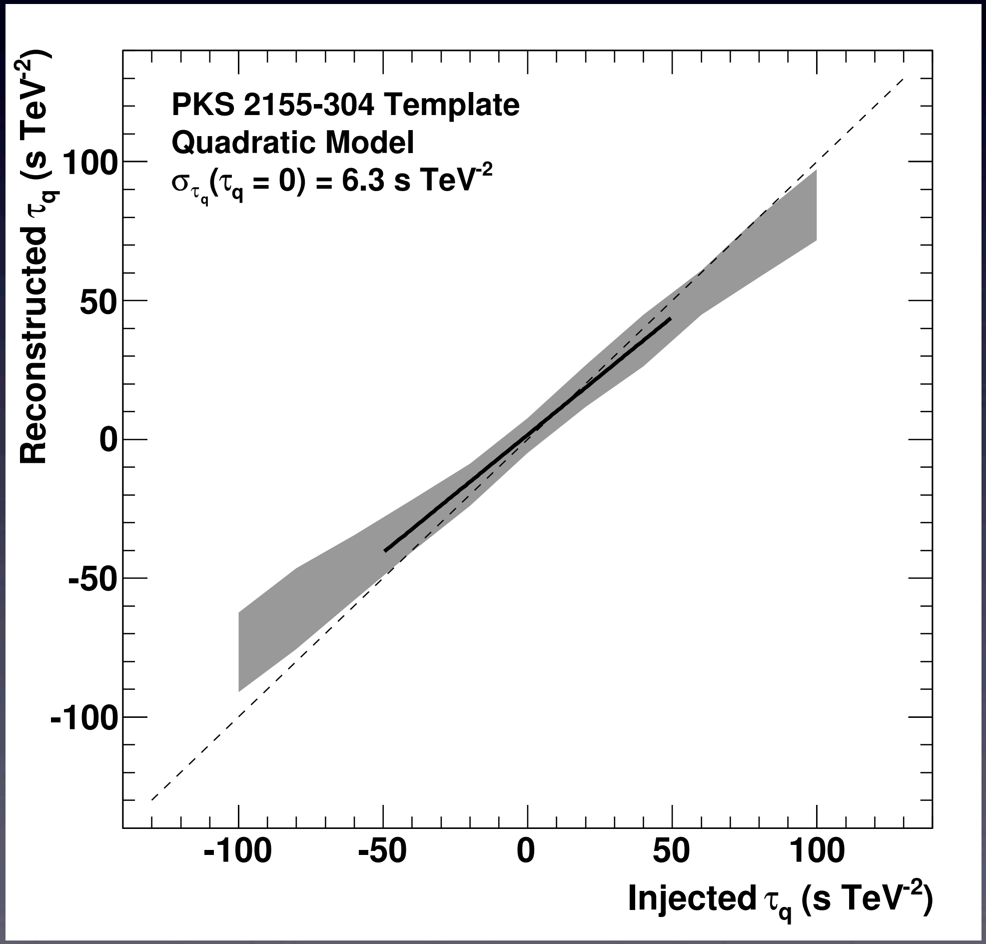




Error Calibration and Systematics (3)

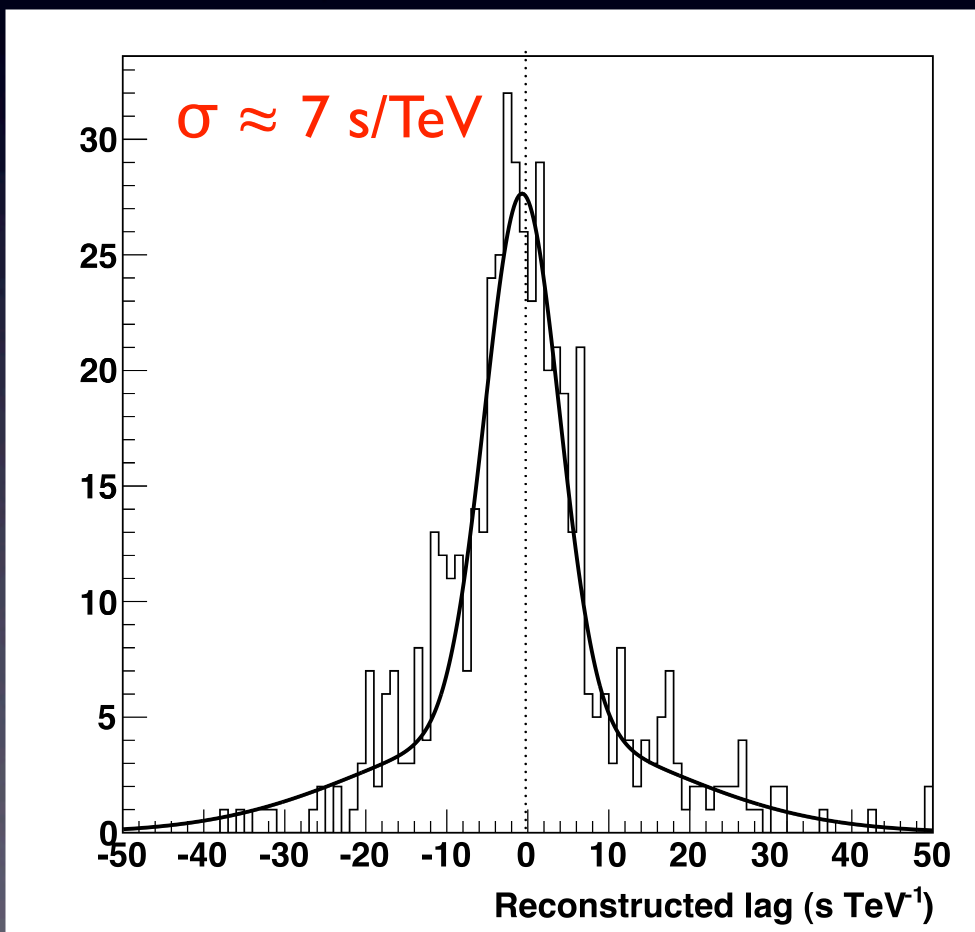
- The time distribution of photons is generated from the measured light curve at low energies
  ➔ Statistical error

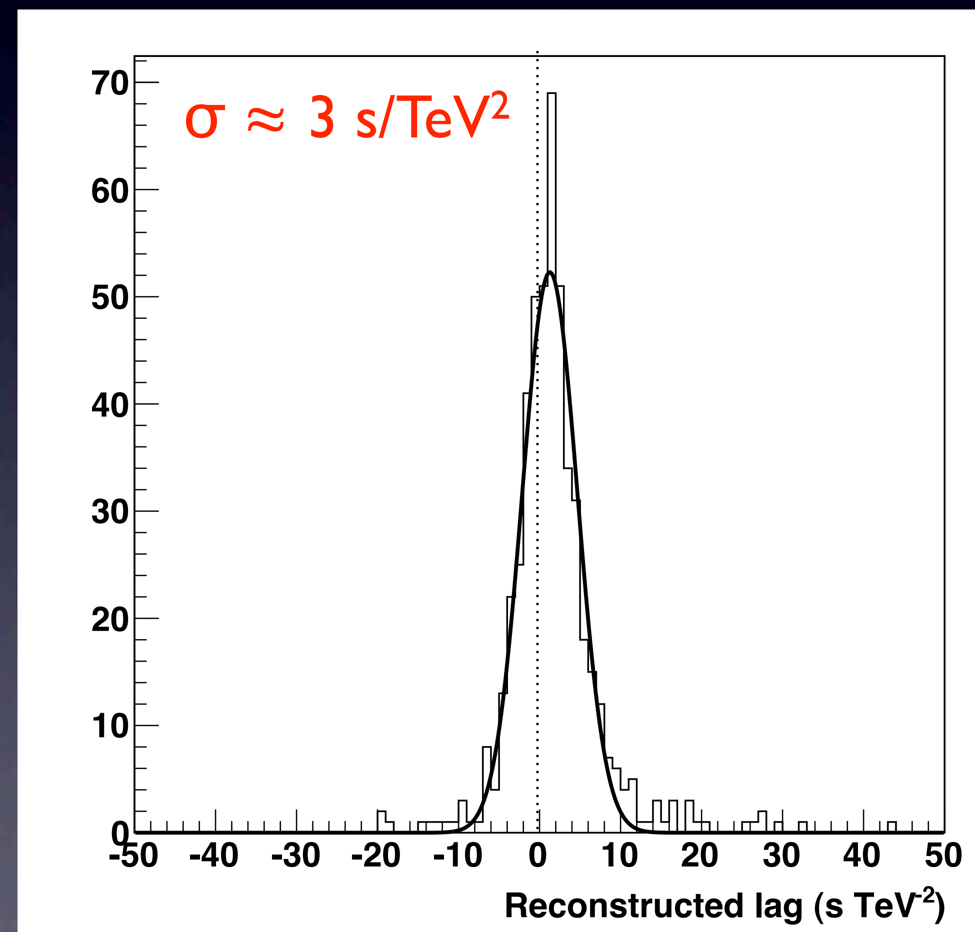




Error Calibration and Systematics (4)

- Variation of the fitted parameters of the F_S function following to gaussian distributions according to the diagonalized covariance matrix
- 500 realizations
- Results are very stable even when the parameterization shape changes





Summary of systematic studies

	Change in estimated τ_l (s/TeV)	Change in estimated τ_q (s/TeV^2)
Selection cuts	< 5	
Background contrinution	< 1	
Acceptance factors	< 1	
Energy resolution	< 1	
Energy calibration	< 2	
Spectral index	< 1	
Calibration systematics (constant, shift)	< 5	< 1
$F_S(t)$ parameterization	≈ 7	≈3
Total	< 10.3	< 6.6

Results

- Considering the results from data and taking into account systematics:

$$\tau'_{0l} = -5.5 \pm 10.9_{(stat)} \pm 10.3_{(sys)} \text{ s/TeV}$$
$$\tau'_{0q} = 1.7 \pm 6.3_{(stat)} \pm 6.6_{(sys)} \text{ s/TeV}^2$$

- The corresponding limits are

$$M^l_{QG} > 2.1\text{x}10^{18} \text{ GeV } (\xi < 5.7)$$
$$M^q_{QG} > 0.6\text{x}10^{11} \text{ GeV } (\zeta < 3.6\text{x}10^{16})$$

- The best limits obtained with an AGN so far

Paper submitted to ApJ

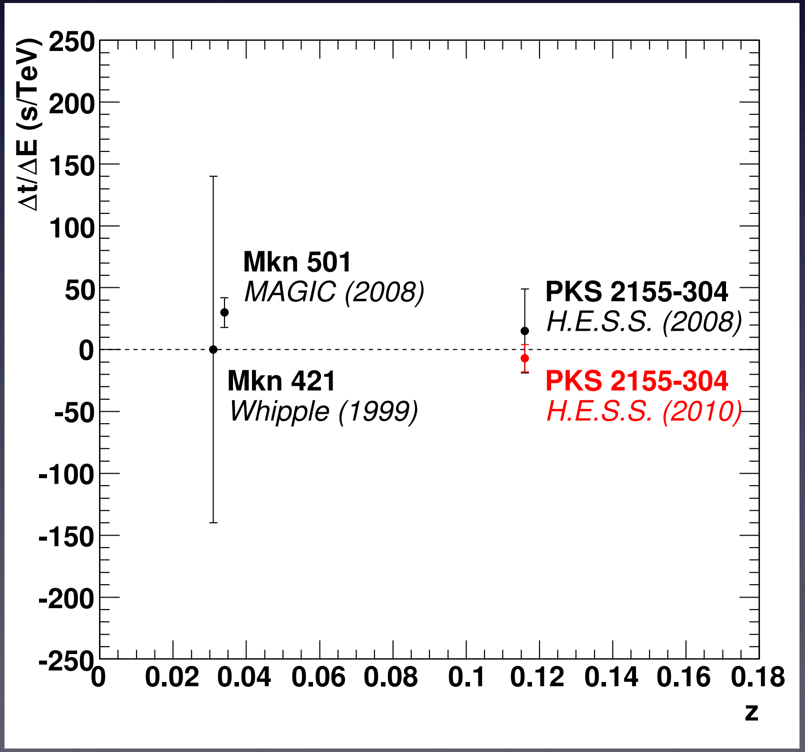
Conclusions

Past results with AGNs

Mkn 501	MAGIC	ECF, Likelihood	$E^{l}_{QG} > 3\times10^{17}$ GeV	J. Albert et al., Phys. Lett. B 668 (2008) 253 + Martinez & Erando, Astropart. Phys. 31, 226 (2009)
PKS 2155 -304	HESS	CCF, Wavelets	$E^{l}_{QG} > 7\times10^{17}$ GeV	Aharonian et al., Phys. Rev. Lett. 101 (2008) 170402

- The last HESS result is
  - A factor of ~3 higher than the previous HESS result
  - A factor of ~10 higher than MAGIC result for the linear correction
  - A factor of ~2 higher than the MAGIC result for the quadratic correction
- Essentially due to higher statistics and greater distance
- Latest result with HESS:

$$M^{l}_{QG} > 2.1\times10^{18}\ \text{GeV}$$
$$M^{q}_{QG} > 0.6\times10^{11}\ \text{GeV}$$



The future

- We need more sources observed on a wider energy range and with high variabilities !
  - HESS-2 will help with a threshold decreased to ~30 GeV
  - CTA will be even better with a factor ~10 increase in sensitivity and a threshold ~10 GeV (cf. talk by M. Raue)