Energy-dependant time-lags with H.E.S.S.

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Part I - Present results
Part II - New analysis: likelihood

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Workshop «Astrophysique Fondamentale» - Montpellier

Present Results

Dispersion Relation

- Lorentz Invarience Violation effects should appear at E ~ O(E_P = 1.2×10^{19} GeV)
- For E << E_P, a series expansion is expected to be possible, giving:

$$c' = c\left(1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2}\right)$$ at the 2nd order

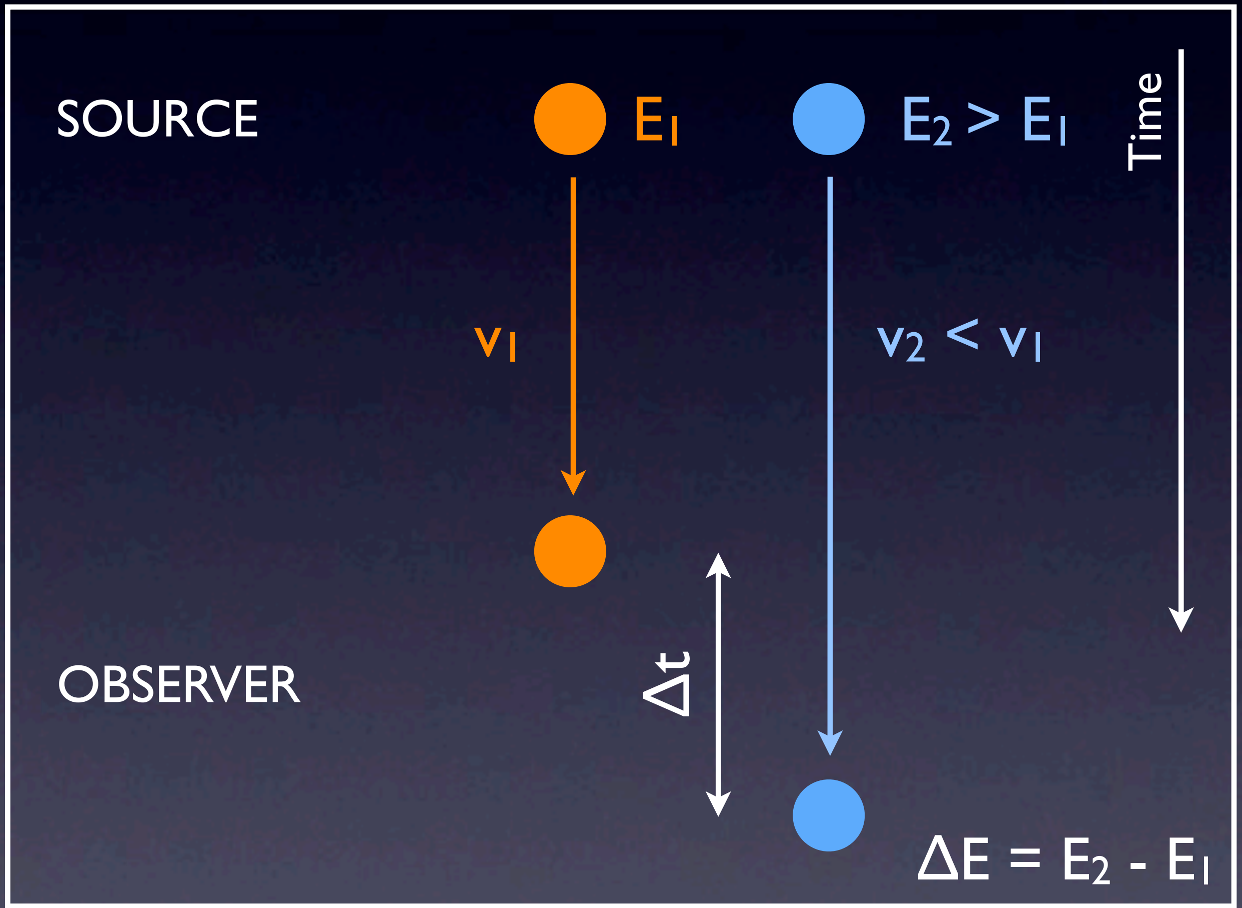
- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays ➔ use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energie E_1 and E_2 emitted at the same time and detected at times t_1 and t_2.
  - At the first order : $$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_P H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$
  - At the second order: $$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2E_P^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}$$

$\Delta t = t_1 - t_2$ $\quad \Delta E = E_1 - E_2$ $\quad \Delta E^2 = E_1^2 - E_2^2$ $\quad \Omega_\Lambda = 0.7$ $\quad \Omega_m = 0.3$

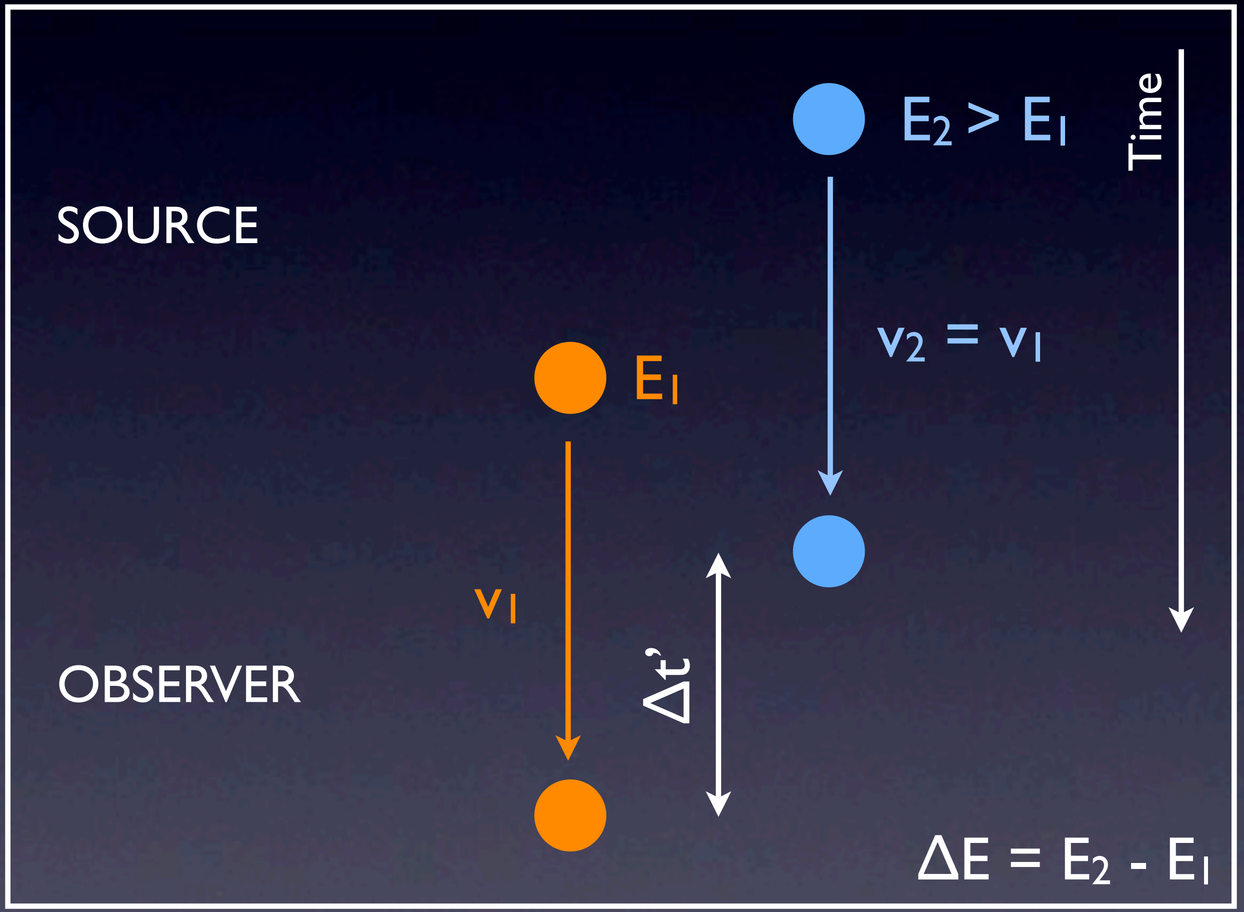
G. Amelino-Camelia et al., Nat. 395, 525 (1998) - U. Jacob & T. Piran, J. of Cosmology and Astropart. Phys. 1, 31 (2008)

QG Effects vs. Source Effects

- BUT : Emission processes or the structure of the source can introduce a time lag too !
- It is necessary to separate the two effects → population studies



Quantum Gravity effect



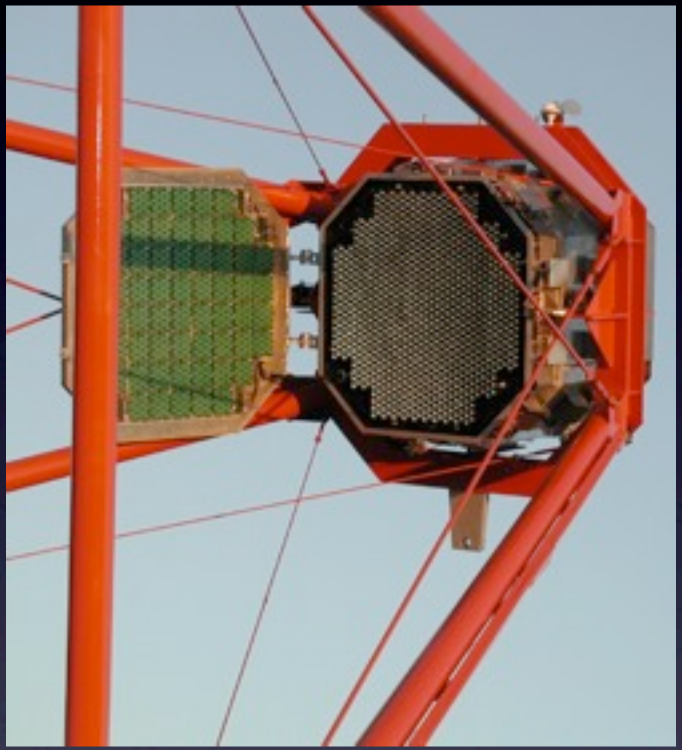
Possible source effect

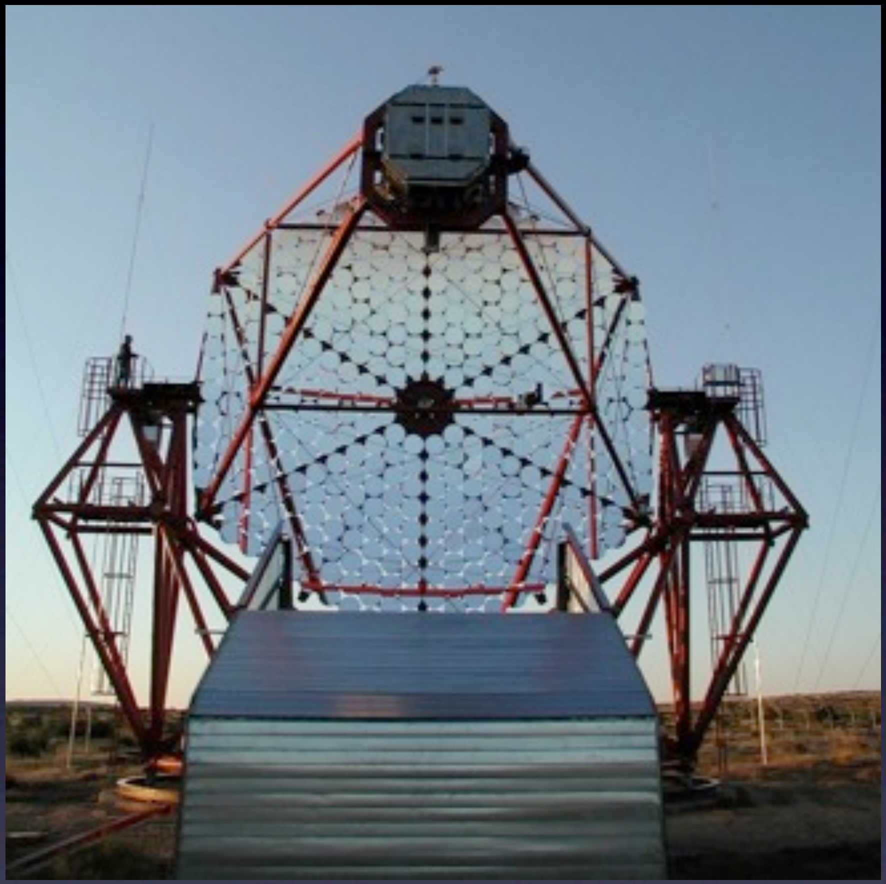
Propagation → LIV Effect

Emission → Source Effect

The High Energy Stereoscopic System
(H.E.S.S.)

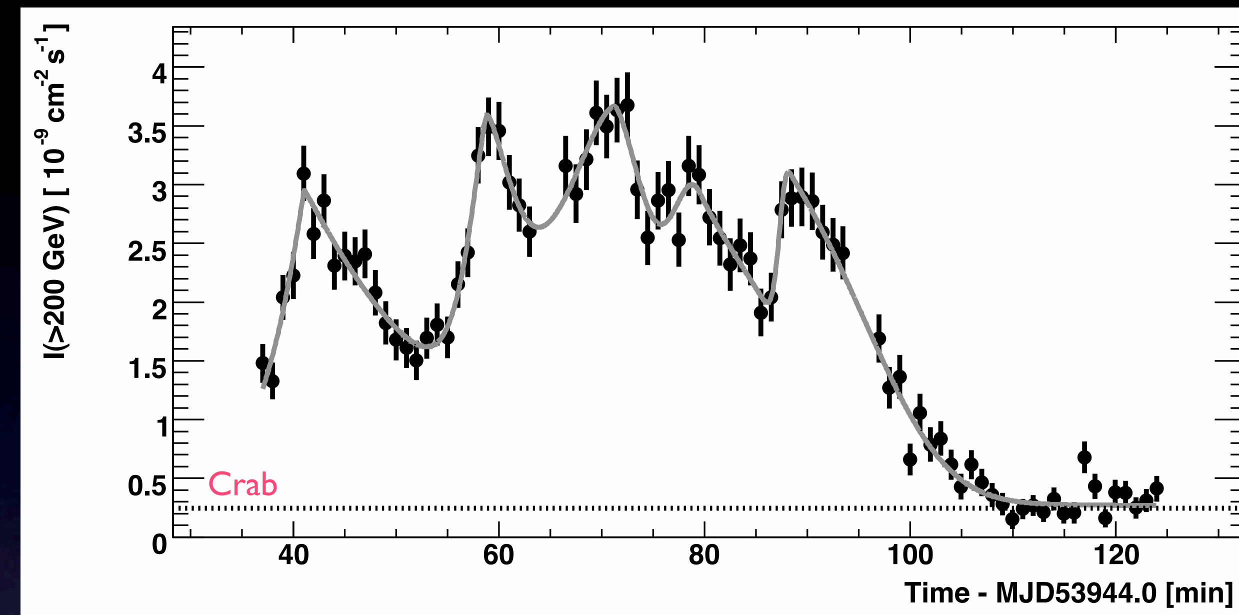
- Located in Namibia
- ~1800 m a.s.l.
- Energy range 0.1-100 TeV
- Point Spread Function ~0.1°
- Energy resolution ~15%

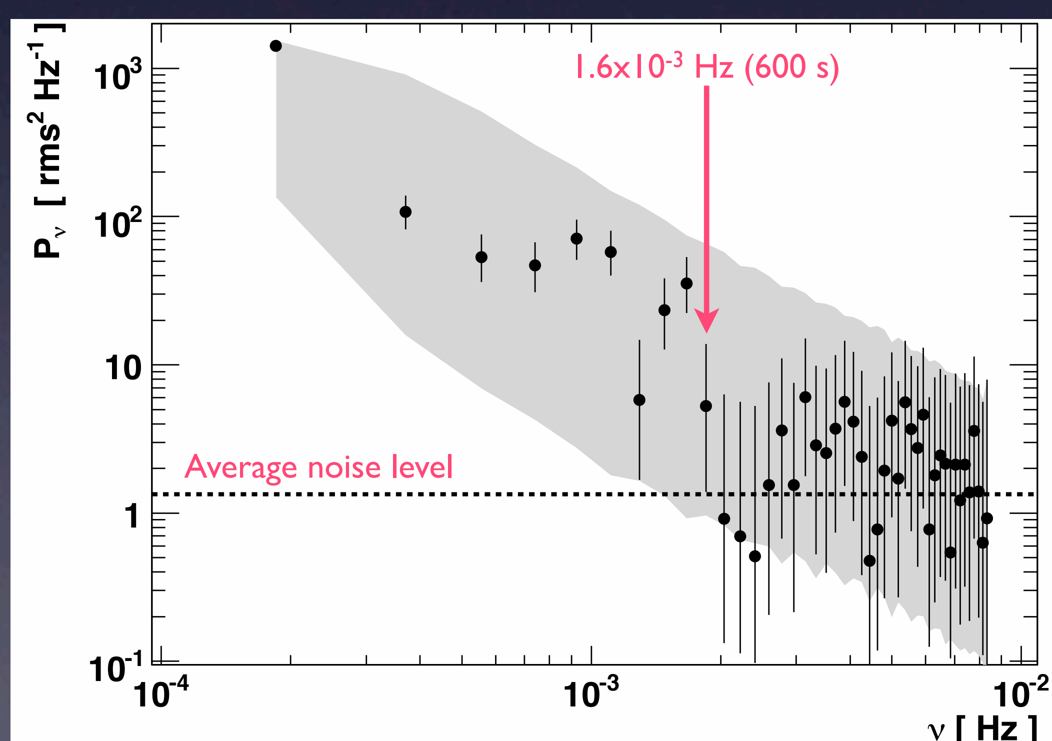


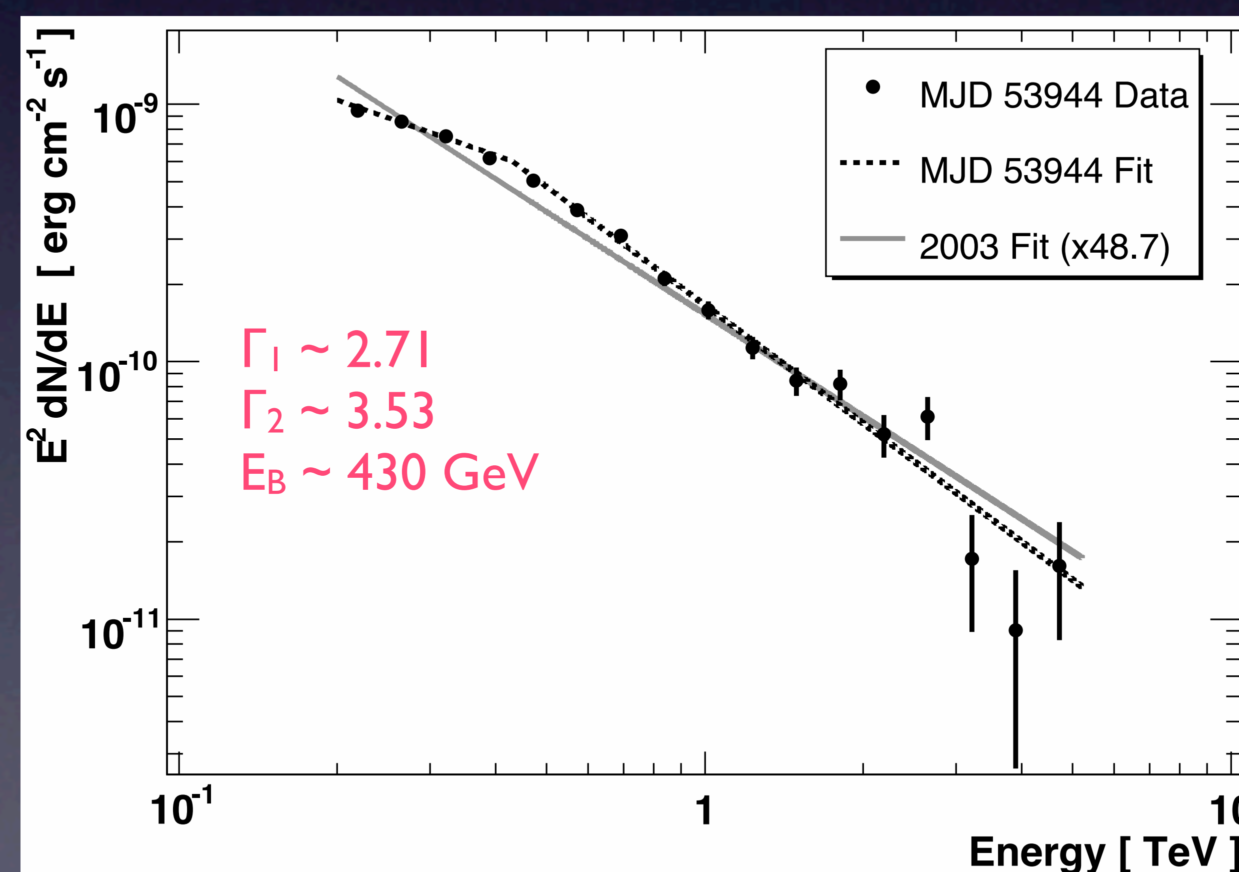


An Exceptional VHE gamma-ray Flare of PKS 2155-304

- Very high flux → ~14 Crab
- High statistics → ~10000 photons
- z = 0.116 (~490 Mpc)
- Broken power-law spectrum
- High variability
  - Fourier Power ~600 s
  - Rise/fall times ~200s



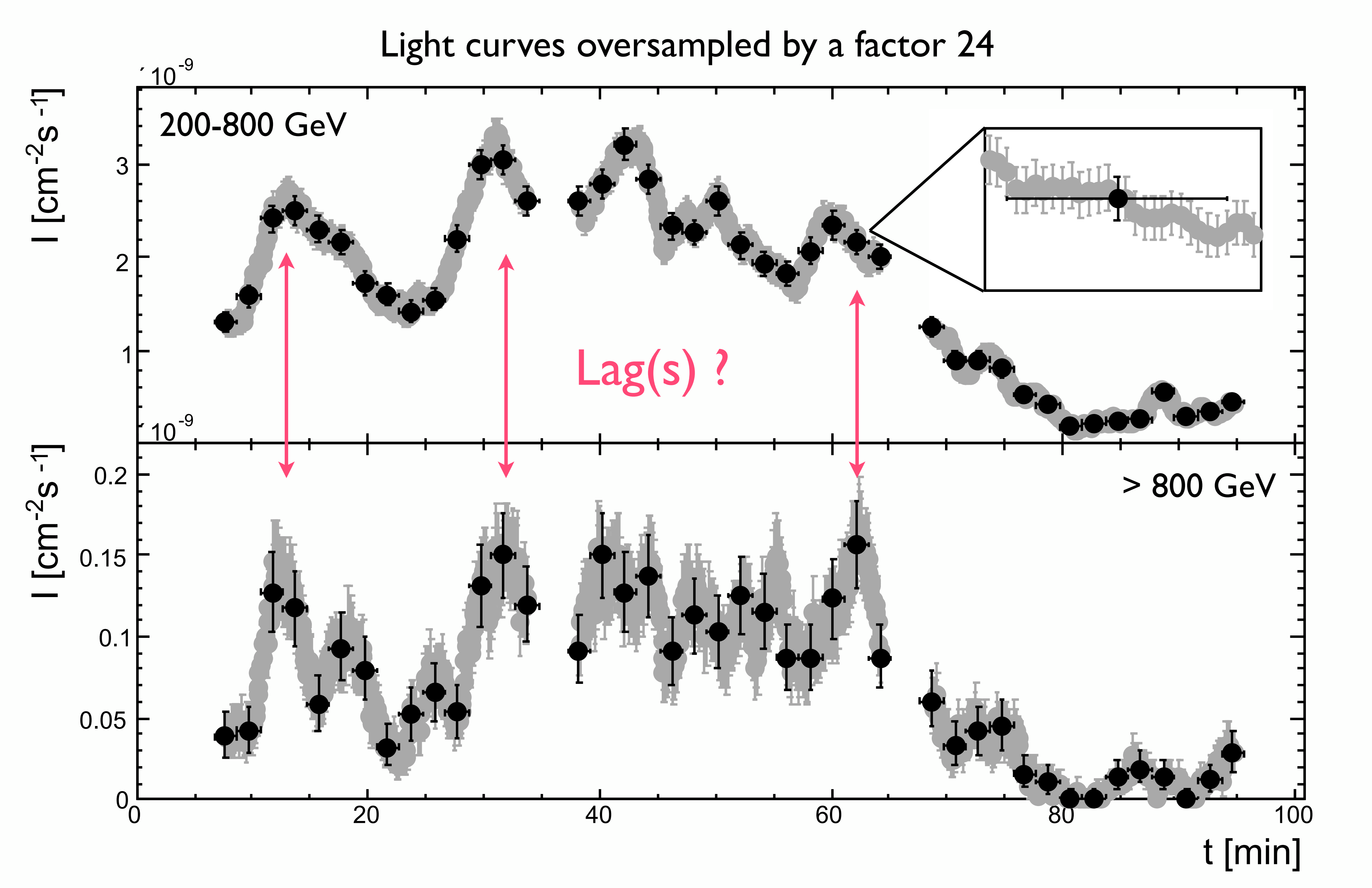




Aharonian et al. (HESS Collaboration), ApJ 664, L71 (2007)

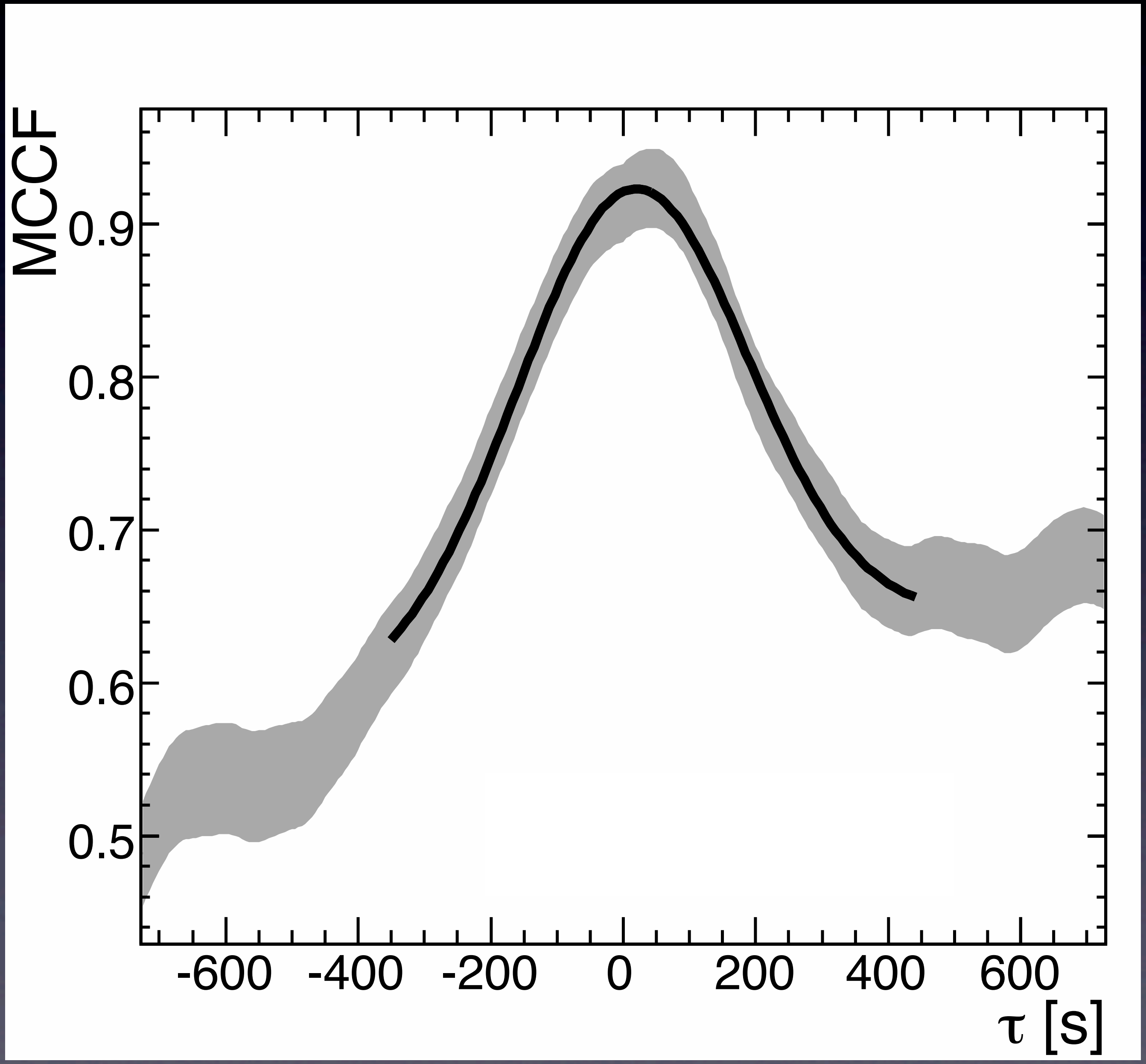
The goal

- Looking for a time delay between light curves in two energy bands



Measuring the time lag

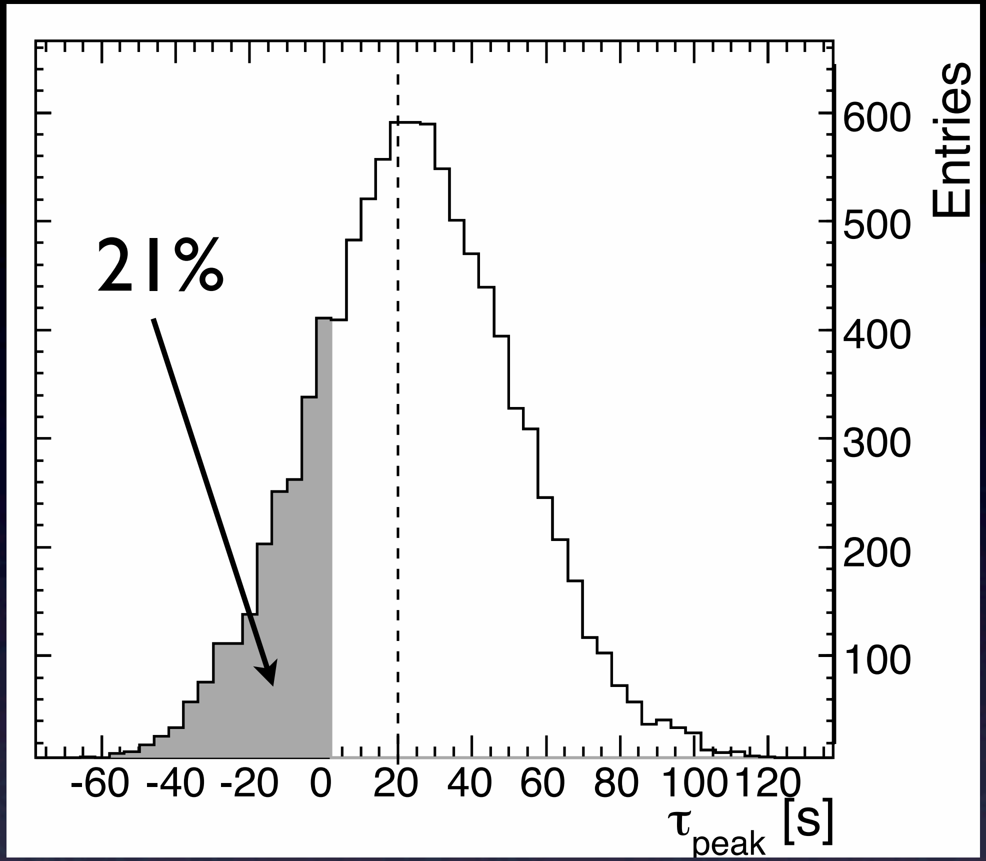
- Use of two different methods:
  - Modified Cross Correlation Function (MCCF)
  - Wavelet Transform
- MCCF :
  - 200 < E < 800 GeV & E > 800 GeV
  - ΔE = 1 TeV
  - Fit with a gaussian + polynomial
  - τ_{peak} = 20 s
- CWT :
  - 210 < E < 250 GeV & E > 600 GeV
  - ΔE = 0.92 TeV
  - Two pairs of extrema identified
  - $\langle\tau\rangle$ = 27 s

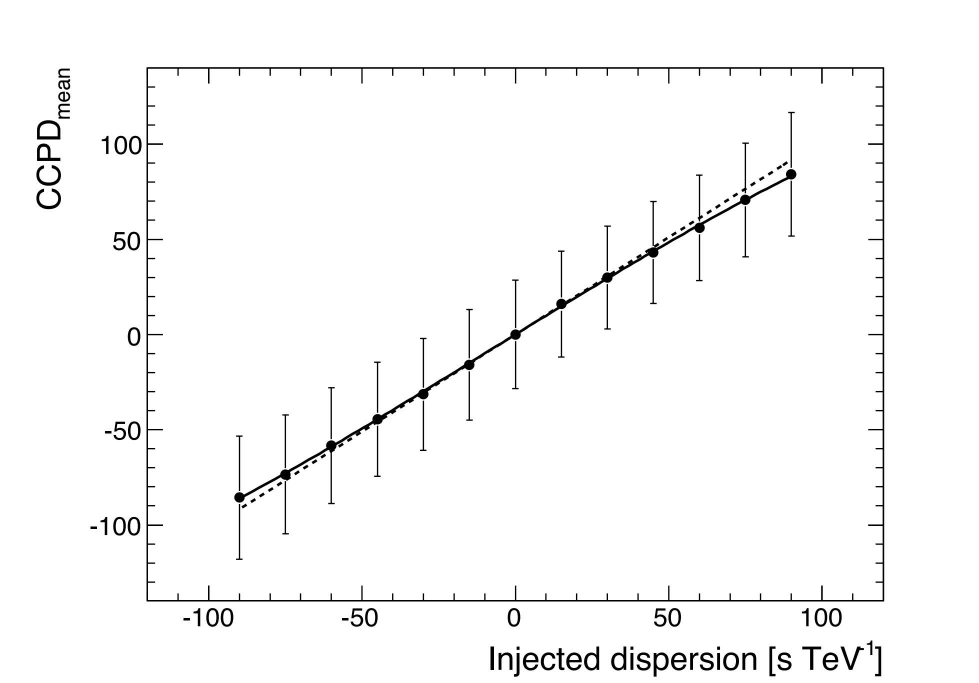


T.-P. Li et al., Chinese J. of Astronomy and Astrophys. 4, 583 (2004) - S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, 1999

Error calibration (MCCF)

- Using a toy Monte Carlo
  - 10000 simulated light curves for each energy band
  - Flux varied within the measurement errors
  - MCCF computed and τ_{peak} measured
- Cross Correlation Peak Distribution
  - Mean = 25 s
  - RMS = 28 s
  - $\tau_{peak} < 0$ for 21% of the simulations
  - $\tau_{peak} = 0$ cannot be excluded
- Response to energy dispersion
  - Injecting a dispersion in the data
  - $|\Delta t/\Delta E| < 90$ s/TeV by steps of 15 s/TeV
- Same kind of procedure for the WT-based method



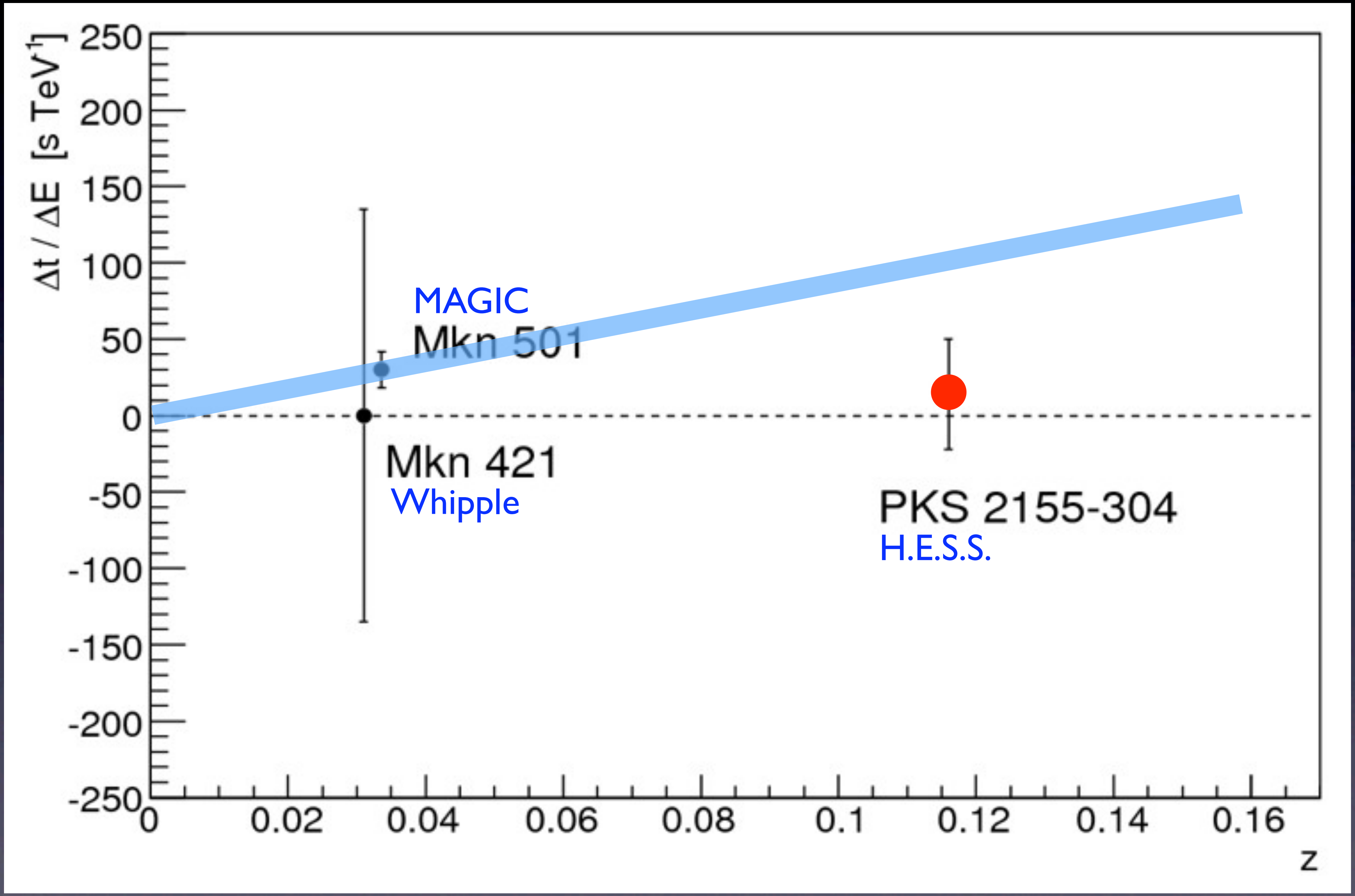


Results

Method	<ΔE> (TeV)	Δt/ΔE 95% CL (s/TeV)	ξ 95% CL	E_{QG} 95% CL (GeV)	$\Delta t/\Delta E^2$ (s/TeV^2)	ζ 95% CL	E_{QG} 95% CL (GeV)
MCCF	1.02	< 73	< 17	$> 7.2 \times 10^{17}$	< 41	$< 7.3 \times 10^{19}$	> 1.4
CWT	0.92	< 100	< 23	$> 5.2 \times 10^{17}$	-	-	-

- Differences between the two methods:
  - mean energy gaps <ΔE>
  - larger Δt measured with CWT
- Best limits obtained with a blazar
- Low sensitivity to the quadratic term

Other Results for AGNs



J. Albert et al. (MAGIC Collaboration) and J. Ellis et al., Phys. Lett. B 668, 253 (2008)
Biller et al. (Whipple Collaboration), Phys. Rev. Lett. 83, 2108 (1999)

Summary

- Analysis of an exceptional flare of PKS 2155-304 ($z = 0.116$) with H.E.S.S.
- Study of fundamental physics with an astrophysical source with unprecedented precision
  Aharonian et al. (HESS Collaboration) PRL, 101, 170402 (2008)
- No significant time-lag detected ($> 3\sigma$) with two different methods
- The most constraining limits on the Quantum Gravity scale found with Blazars, assuming
  no source effect :

$$E_{QG} > 0.7 \times 10^{18}\ \mathrm{GeV}$$
$$\xi < 17$$
at 95% CL

Results: present status

GRBs / AGNs

Source(s)	Expérience	Méthode	Résultat	Référence
GRB 021206	RHESSI	Fit + temps d'arrivée moyen dans un pic	$E_{QG} > 1.8\times10^{17}$ GeV	S. Boggs et al., ApJ 611 (2004) L77
GRB 080916C	Fermi (LAT + GBM)	$t_{Max(E)} - t_0$	$E_{QG} > 1.5\times10^{18}$ GeV	A.A. Abdo et al., Science Express, 02/19/2009
9 GRBs	BATSE/OSSE	Wavelets	$E_{QG} > 6\times10^{15}$ GeV	J. Ellis et al., A&A 402 (2003) 409
15 GRBs	HETE-2	Wavelets	$E_{QG} > 4\times10^{15}$ GeV	J. Bolmont et al., ApJ 676 (2008) 532 + ICRC 07 + COSPAR 08
17 GRBs	INTEGRAL	Likelihood	$E_{QG} > 1.5\times10^{14}$ GeV	Lamon et al., Gen. Rel. Grav. 40 (2008) 1731
35 GRBs	BATSE/HETE-2/ SWIFT	Wavelets	$E_{QG} > 1.4\times10^{16}$ GeV	J. Ellis et al., Astropart. Phys. 25 (2006) 402 + Erratum arXiv:0712.2781
Mkn 421	Whipple	$t_{Max(E < 1\,TeV)} - t_{Max(E > 2\,TeV)}$	$E_{QG} > 0.6\times10^{17}$ GeV	S.D. Biller et al., Phys. Rev. Lett. 83 (1999) 2108
Mkn 501	MAGIC	ECF, Likelihood	$E_{QG} > 3\times10^{17}$ GeV	J. Albert et al., Phys. Lett. B 668 (2008) 253 + Martinez et al., Astropart. Phys. 31 (2009) 226
PKS 2155 -304	HESS	CCF, Wavelets	$E_{QG} > 7\times10^{17}$ GeV	Aharonian et al., Phys. Rev. Lett. 101 (2008) 170402

Prospects

- AGN and GRB studies are complementary
- Population studies are needed for AGNs
  - More flares observed at TeV energies
  - Necessity of multi-wavelength campaigns and/or fast reactivity
  - HESS-II (+ CTA, ...) will greatly improve the sensitivity to QG effects
- Both CWT and MCCF methods have drawbacks
  - They both use binned data → limited time resolution
  - They need good statistics
  - Necessity to divide the energy range in bands
- A new analysis is being carried-out with a likelihood method
  - Un-binned analysis
  - No energy bands needed

New Analysis: likelihood

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 & 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
- Here we assume a linear effect with a time-lag parameter τ expressed in s/TeV
- The likelihood function is then given by the product

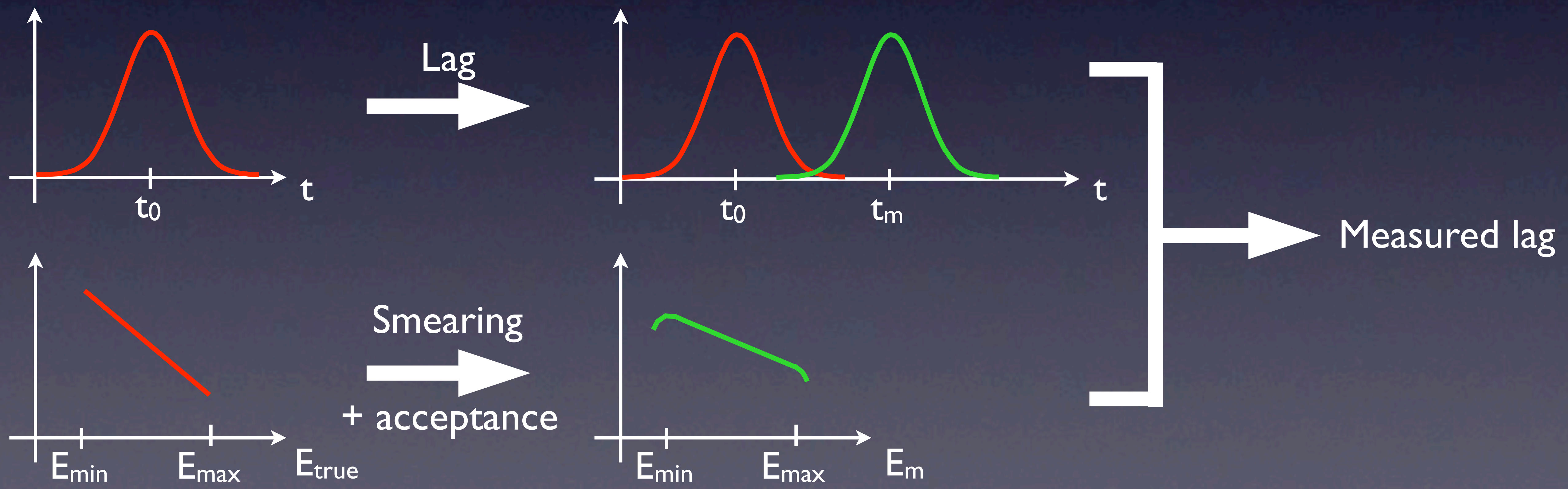
$$L = \prod_i P_i(t,E)$$

  over all photons in the studied sample
- The maximum of the likelihood gives us the time-lag τ in s/TeV

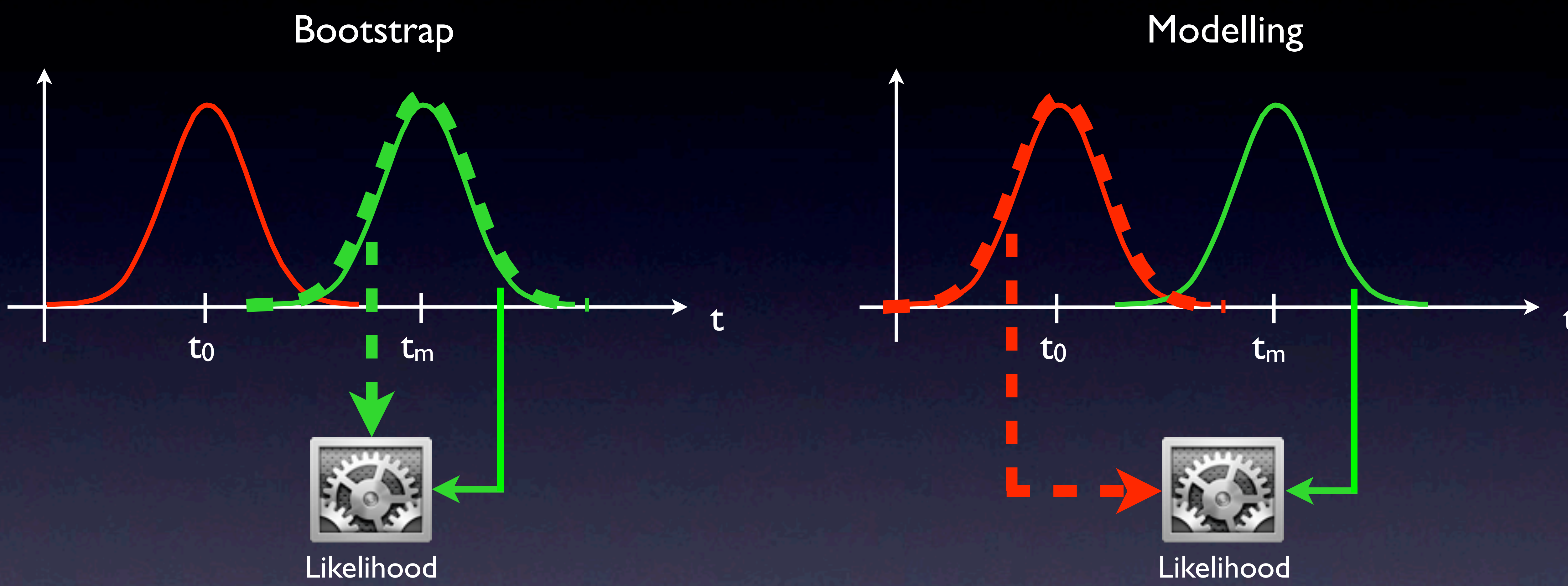
Advantages	Drawbacks
• un-binned • no energy bands needed • can probe the lightcurve locally	• need of a parameterization of the lightcurve • systematics (investigated with Toy MC)

Toy Monte-Carlo: goals

- Check the principle of the likelihood fit
- Two approaches :
  - Bootstrap: the parameterization is done with the shifted light curve
  - Source emission modelling: the parameterization is done with the modelled light curve
- Check the systematics
- Calibrate the error on lag measurement



Bootstrap vs. Modelling



- The likelihood method needs a parameterization of the light curve
  - Bootstrap: the parameterization is done with the shifted light curve
  - Source emission modelling: the parameterization is done with the modelled light curve
- With real data → bootstrap !

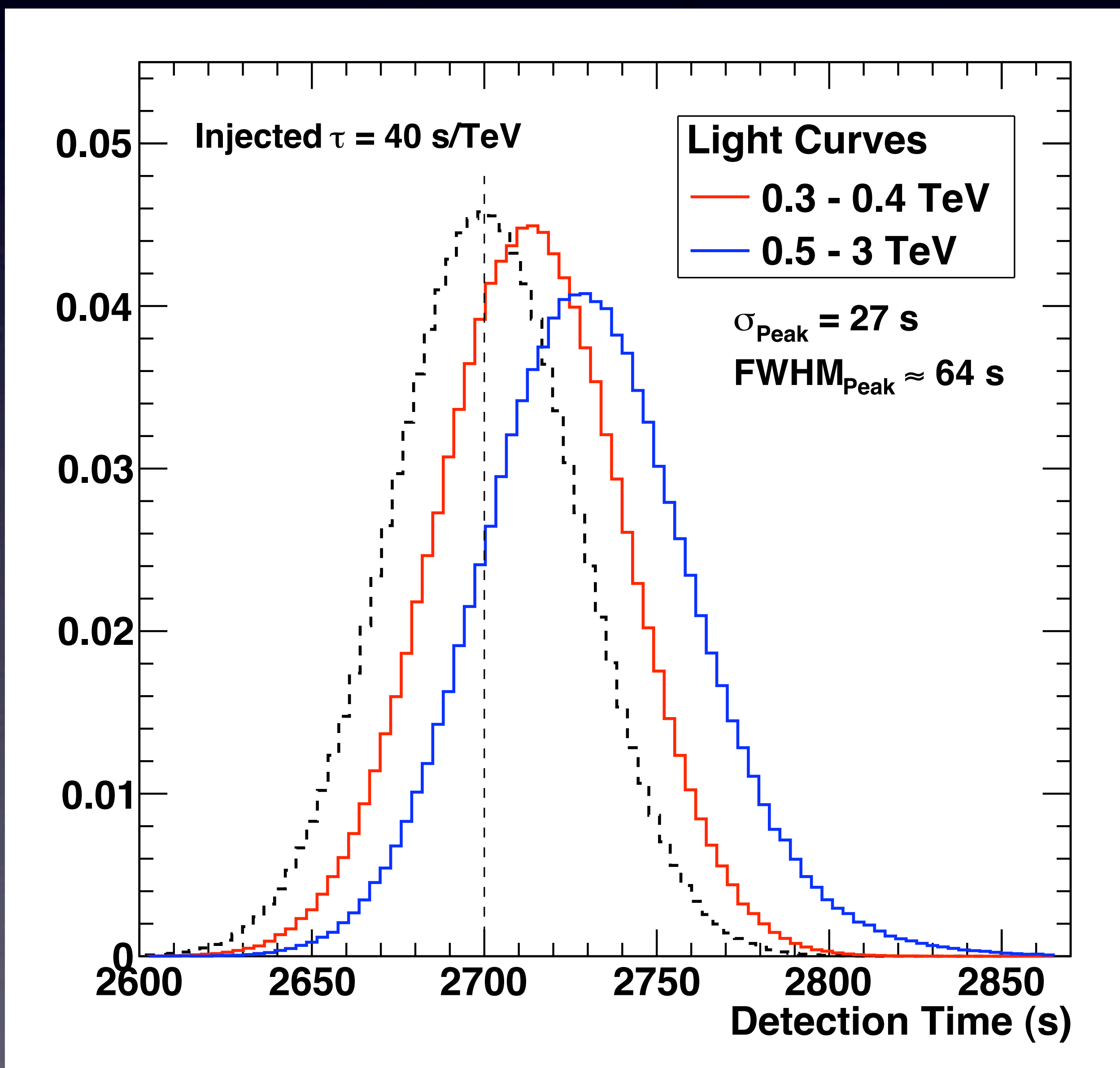
Toy Monte-Carlo: method

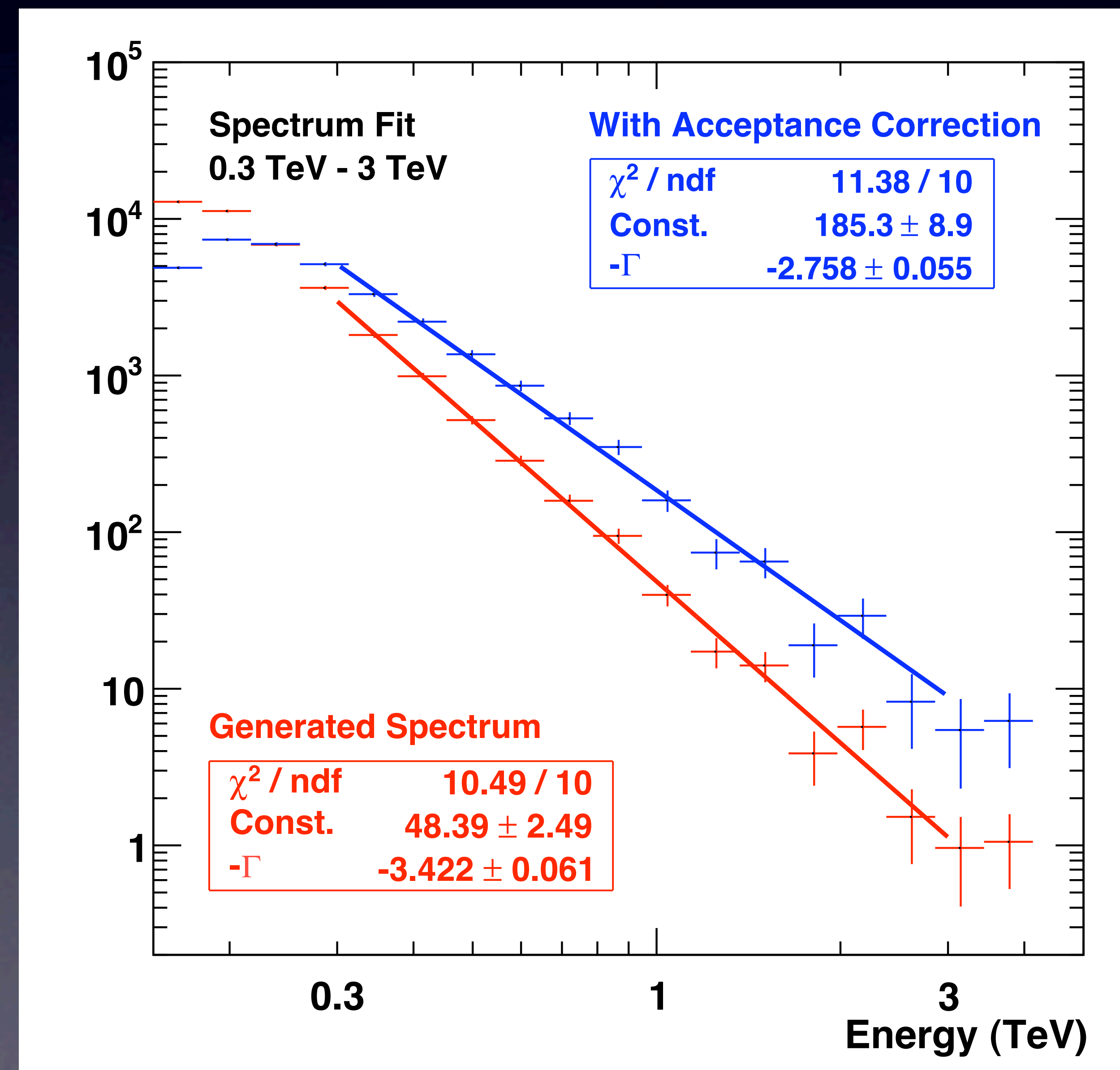
- ROOT macro
- 500 lists (light curves) of 5 000 photons are generated
  - Power law spectrum at the source: $\Gamma = 2.0, 3.4$
  - Smearing on energy: $\sigma(E)/E = 15\ \%$
  - Events weighted taking into account the H.E.S.S. acceptance with CC2, zenith angle = 20°, offset = 0.5°, efficiency = 0.60 (2006)
  - Generation time:
    - gaussian
    - asymmetric gaussian (1 or 2 pulses with different separations)
  - Detection time = Generation time + τ x Energy, with τ = -100, -80, ..., 0, ..., 80, 100 s/TeV
- For each list
  - Histograms for the light curve (bin width = 30 s) and the spectrum
  - Fit of the spectrum
  - Fit of the light curve

    ➔ Two approaches: bootstrap / modelling
  - Computation of the likelihood: minimum of $-2\ \Delta\ln(L)$ ➔ reconstructed τ (in s/TeV)

Toy Monte-Carlo: basics

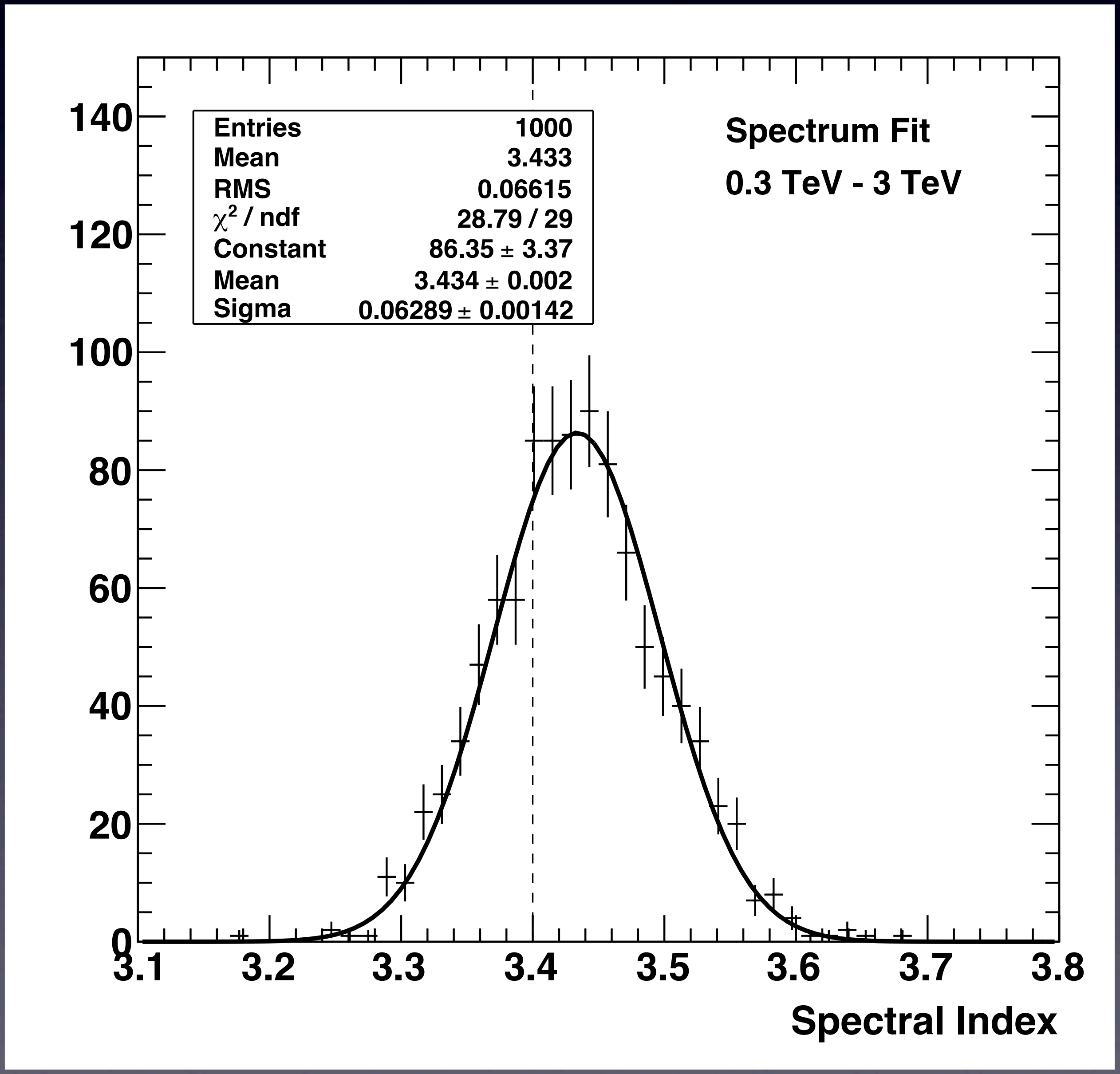
- Example of light curves in different energy bands (normalized)
- Example of spectra with and without acceptance correction

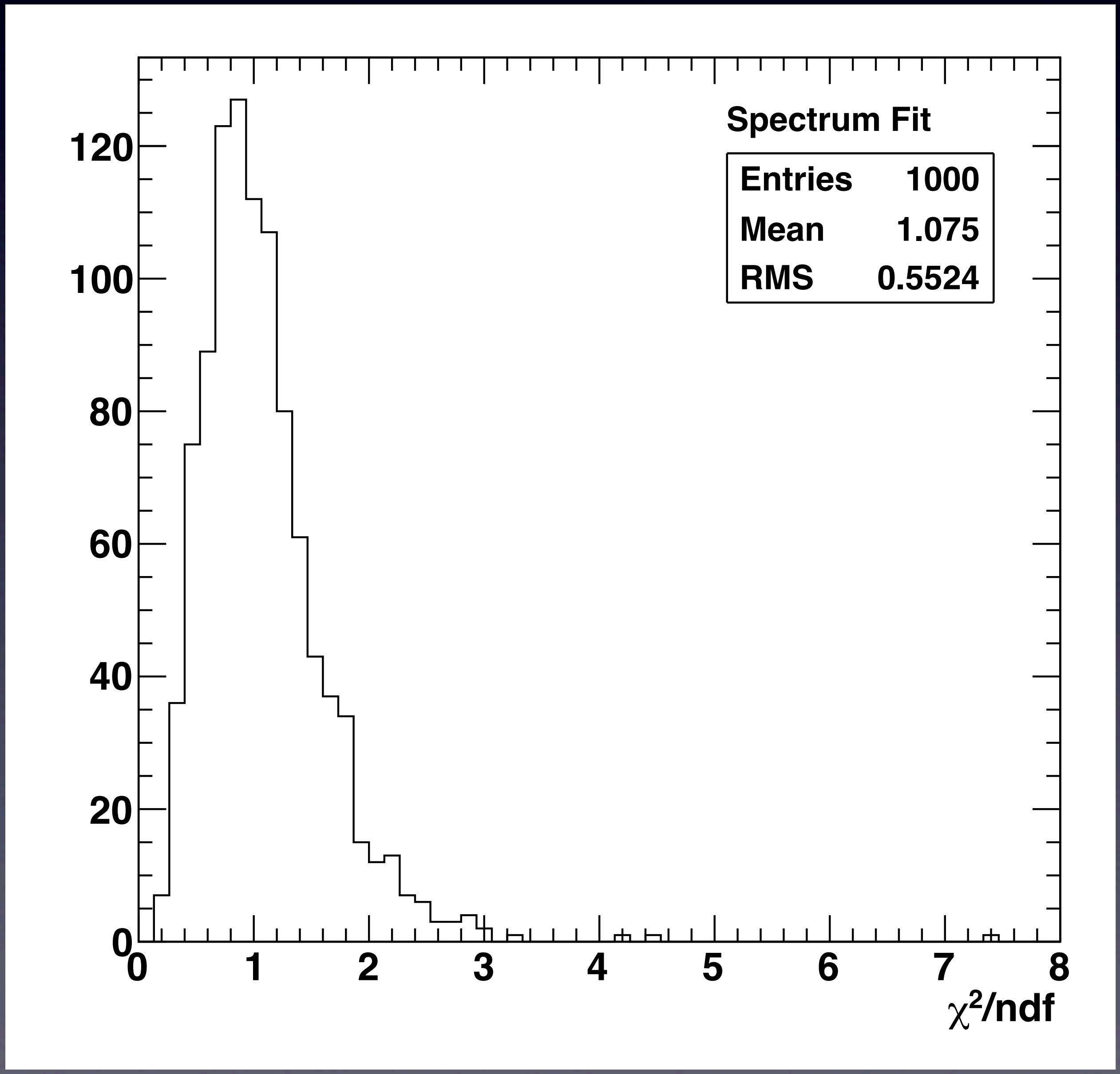




Toy Monte-Carlo: basics

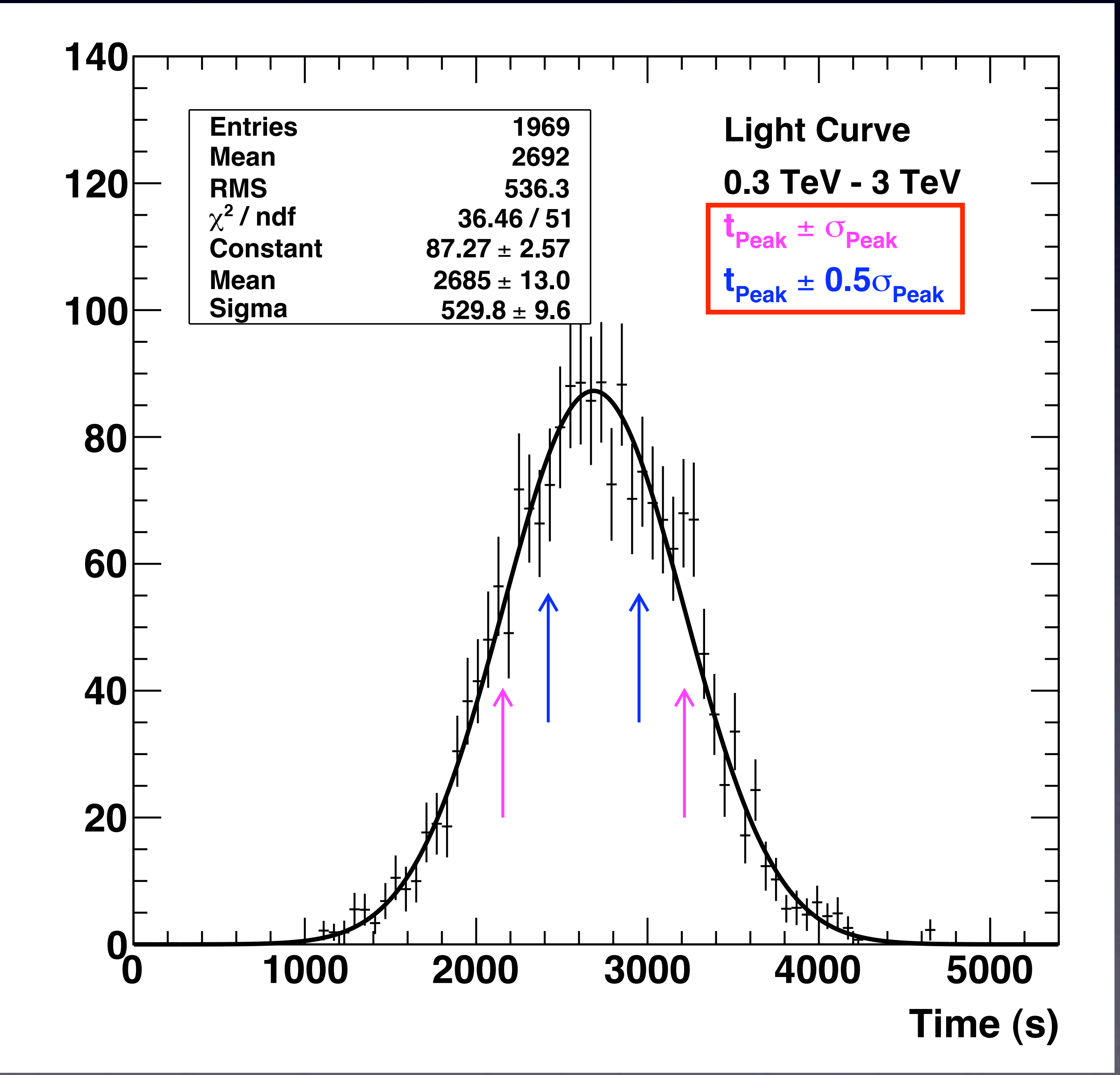
- Distribution of fitted spectral indices
- Distribution of χ^2/ndf

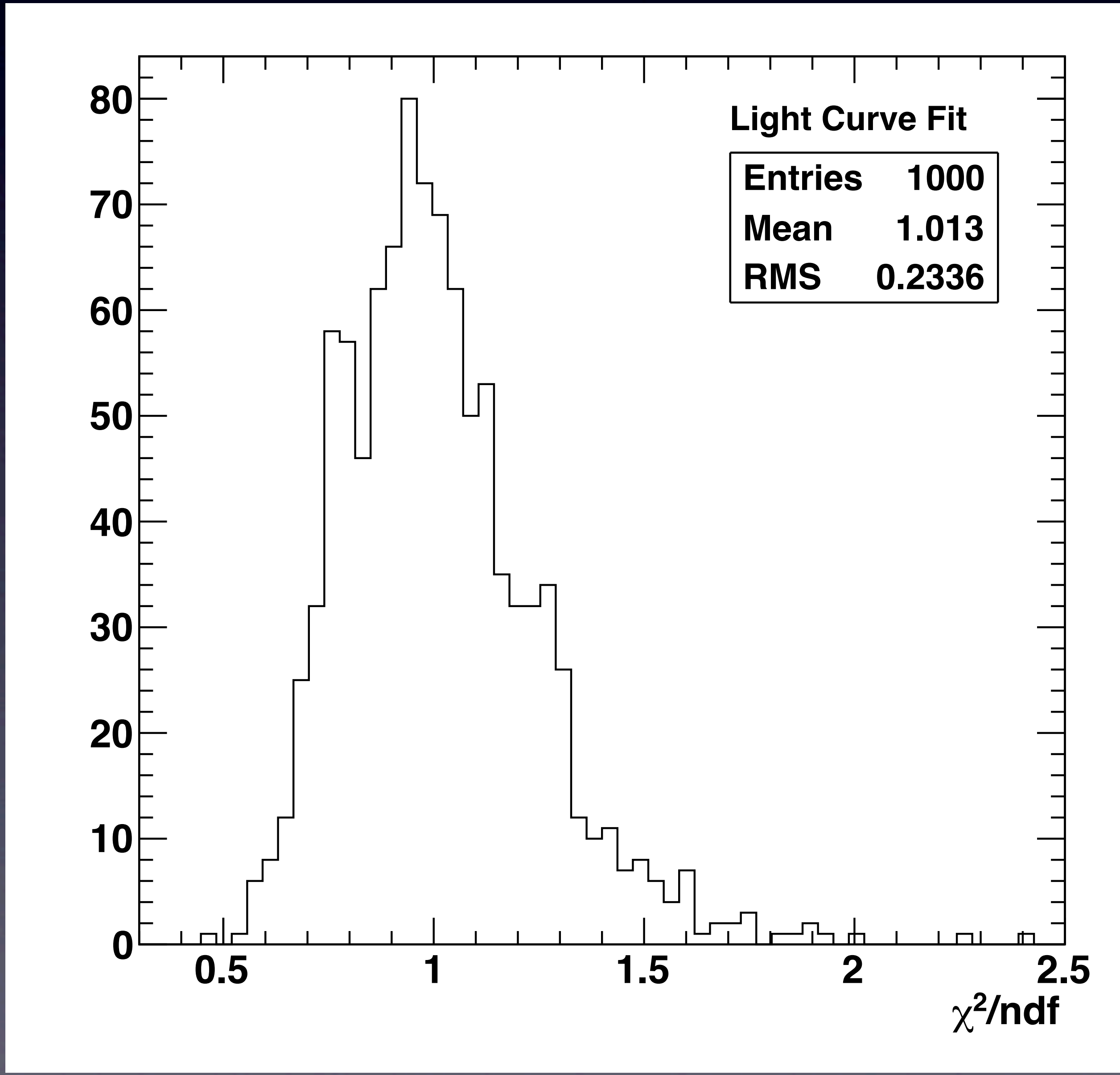




Toy Monte-Carlo: basics

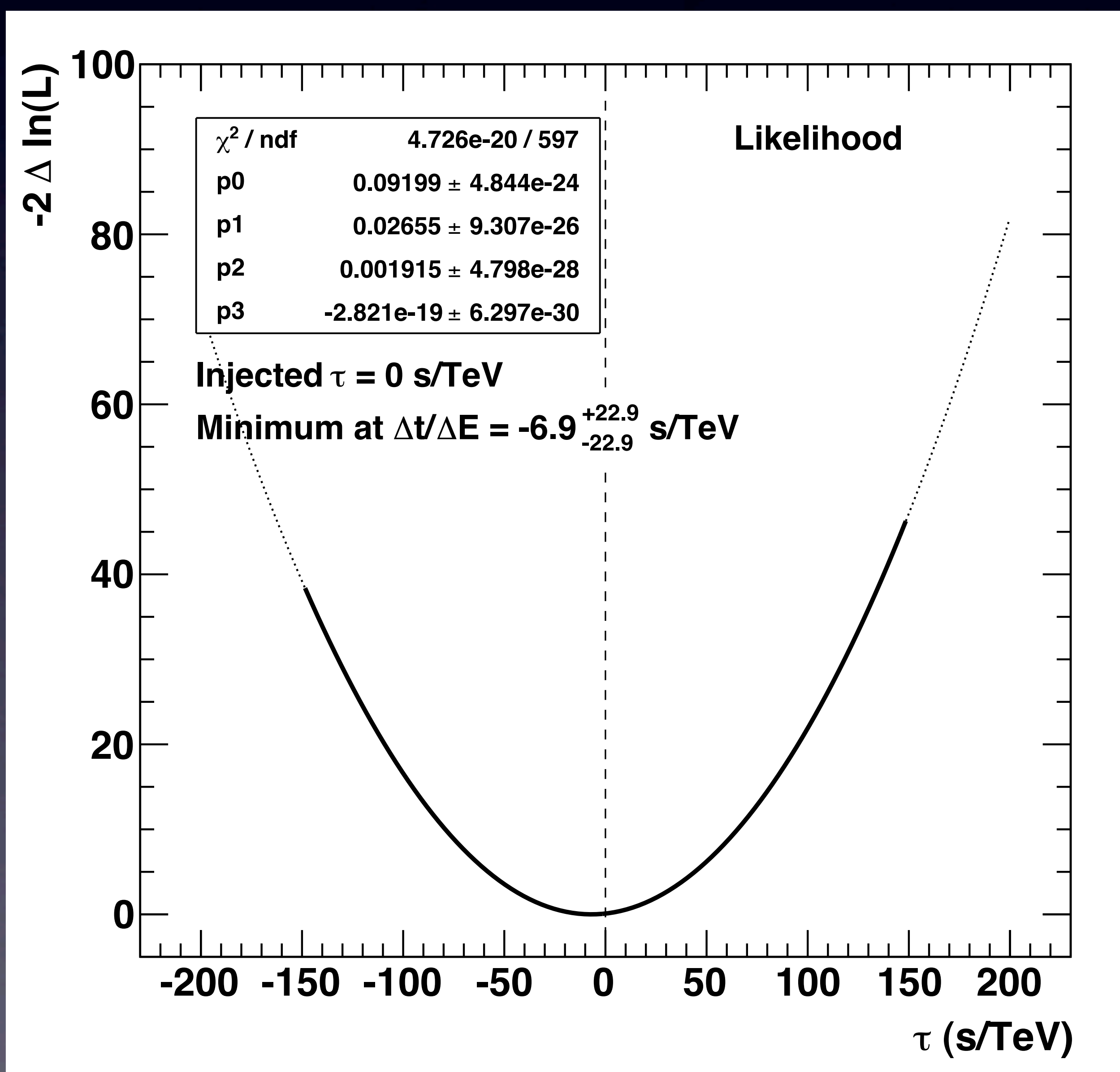
- Light curve in the energy range 0.3 - 3 TeV (~ 2000 photons measured)
- The arrows show the intervals used for likelihood calculation : $t_{max} \pm k\sigma$ with $k \in \{0.5, 1\}$
- Distribution of χ^2/ndf

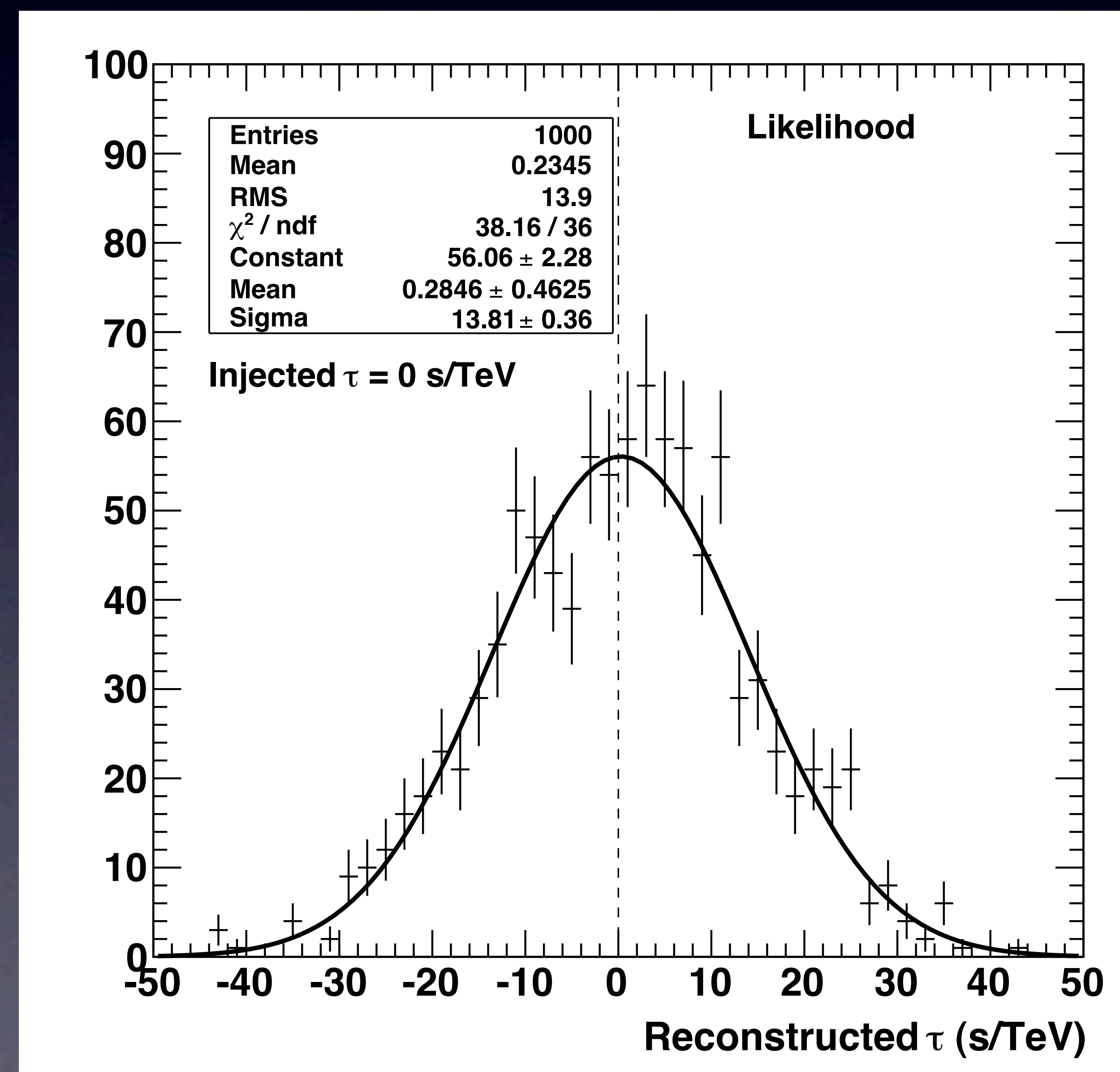




Toy Monte-Carlo: basics

- Likelihood curve minimum → reconstructed τ
- Distribution of Likelihood minimum positions → calibrated error σ_τ



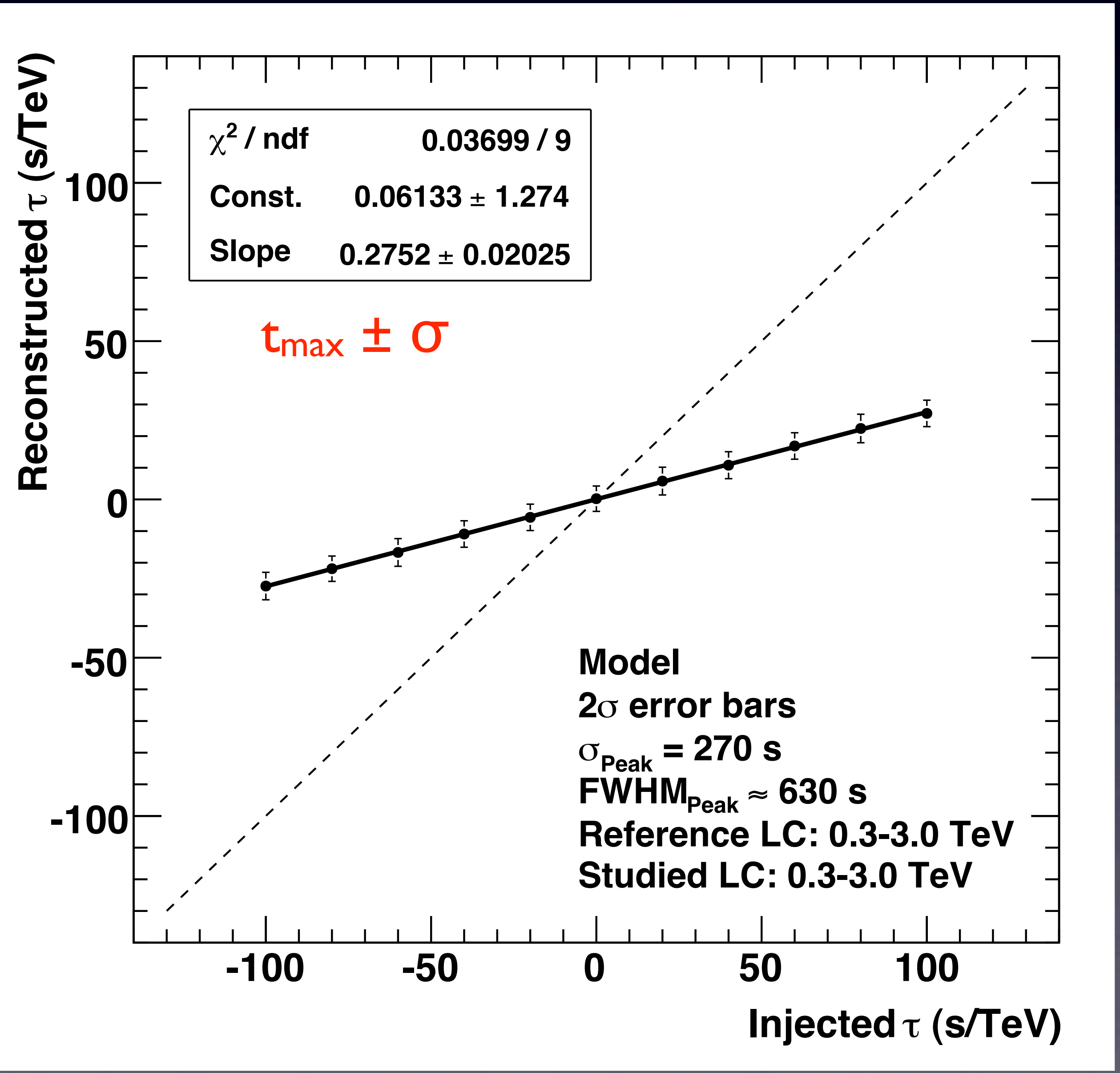


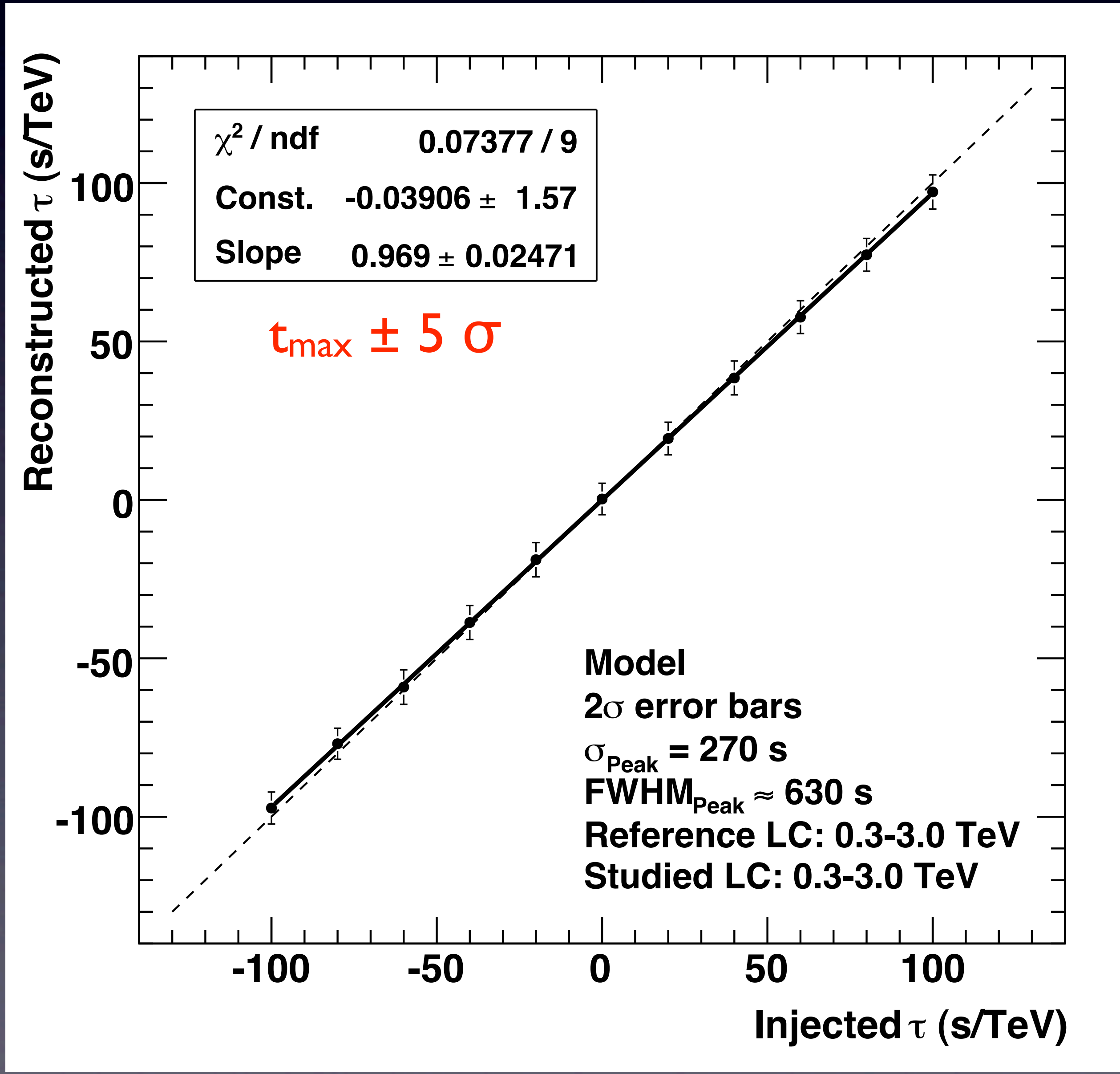
Modelling

Modelling

- The modelled light curve (no lag) is injected in the likelihood
  - → $t_{max} \pm \sigma$
  - → $t_{max} \pm 0.5\ \sigma$

It is necessary to use a wide interval

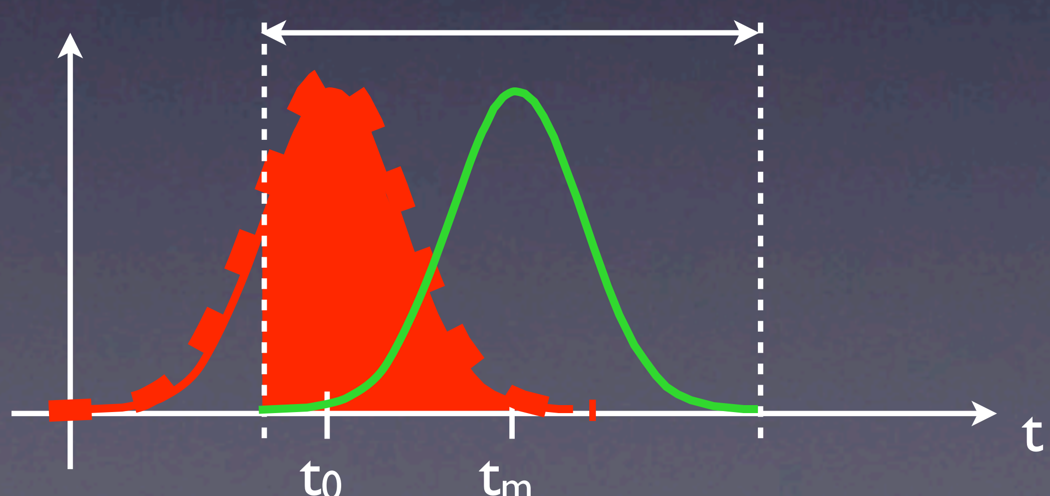


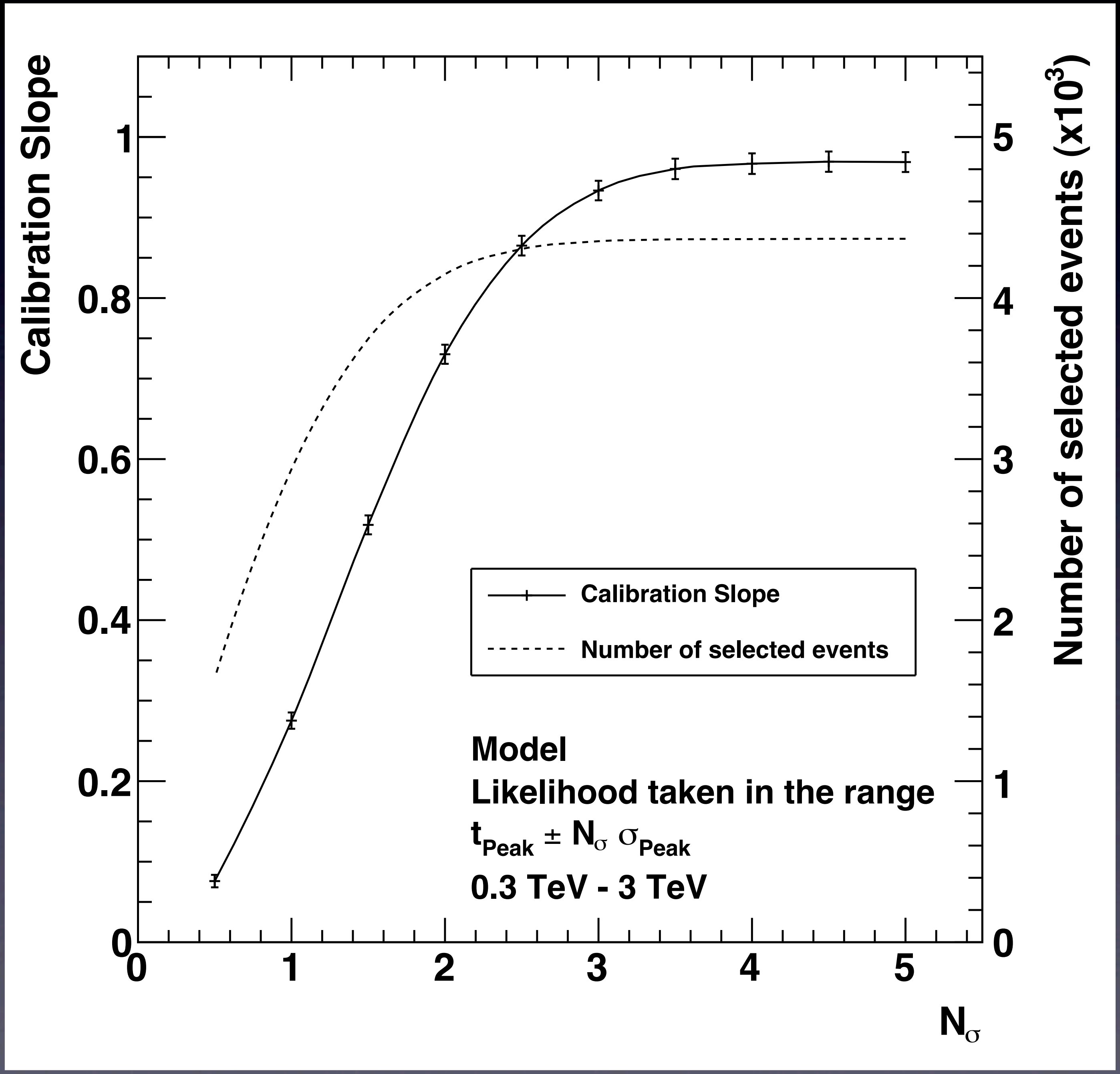


Modelling

- The calibration slope depends on the time interval taken for the likelihood calculation
  - Centered on t_{Peak}
  - Different width $2N_\sigma\ \sigma_{Peak}$ with N_σ = 0.5, 1, 1.5, .., 5 and σ_{Peak} = 270 s

It is necessary to use a wide interval





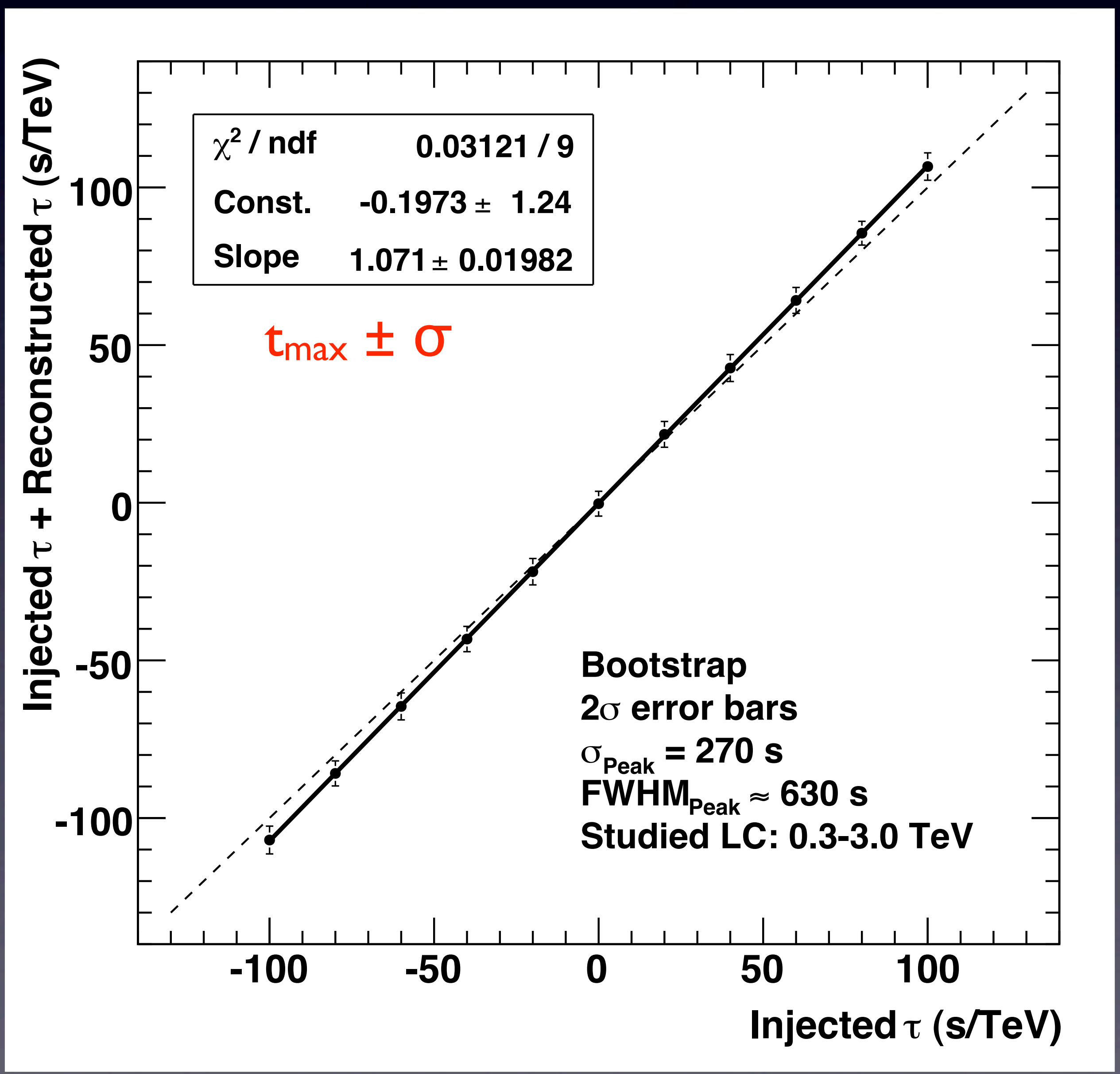
Bootstrap

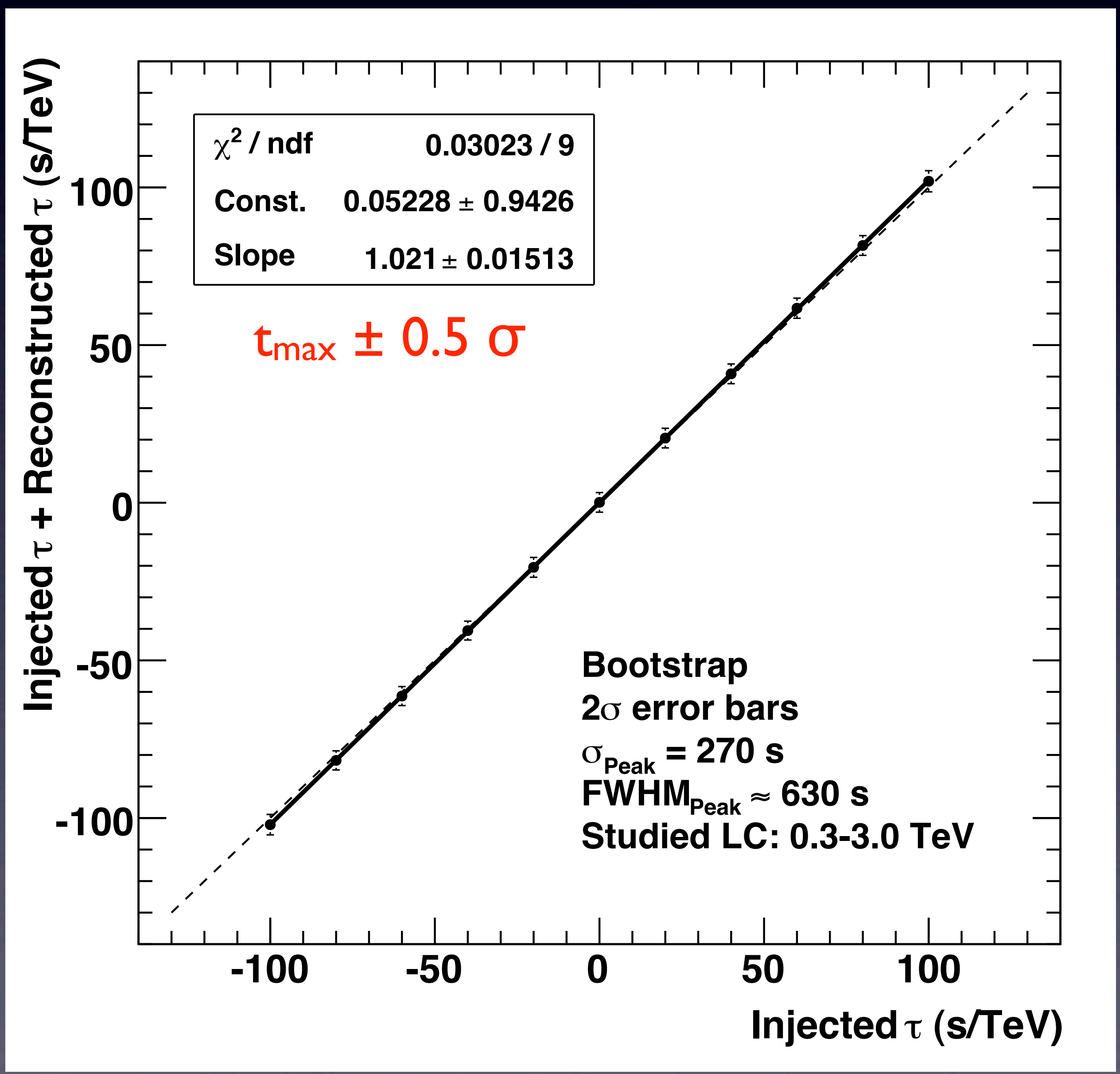
- Gaussian spike
- Asymmetric gaussian spike
- 2 asymmetric gaussian spikes

Bootstrap

- (reconstructed τ + injected τ) vs. injected τ, with 2σ error bars
  - → $t_{max} \pm \sigma$
  - → $t_{max} \pm 0.5\ \sigma$

It is better to use a narrow interval





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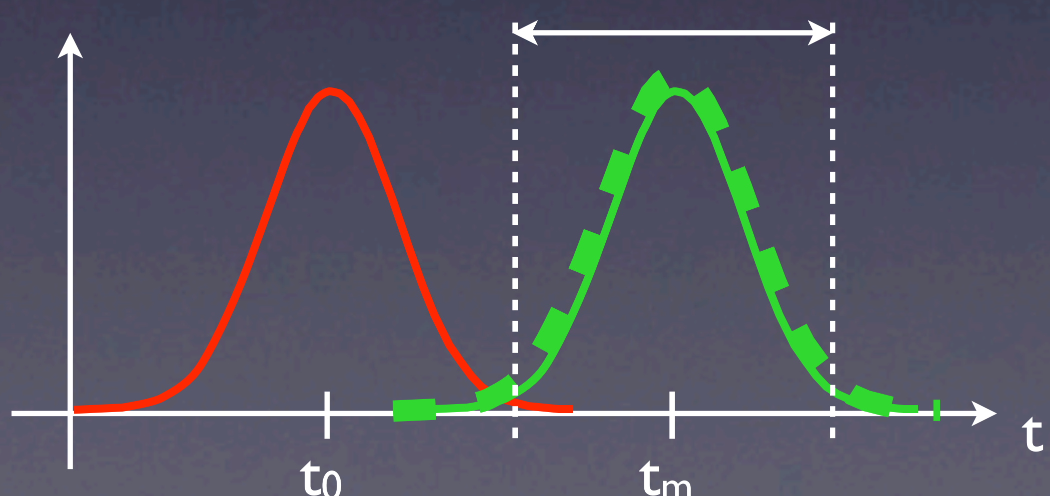
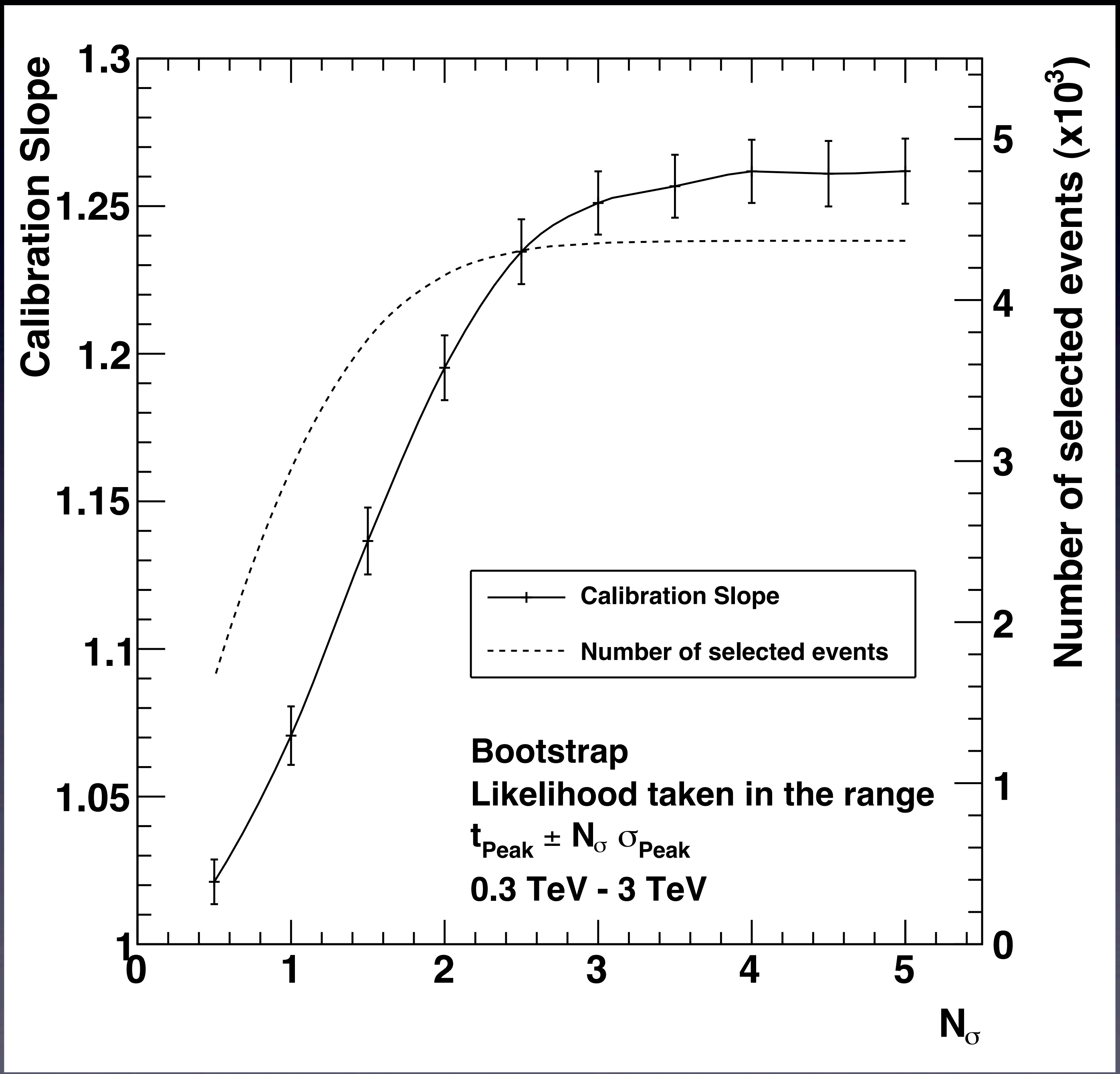
It is better to use a narrow interval

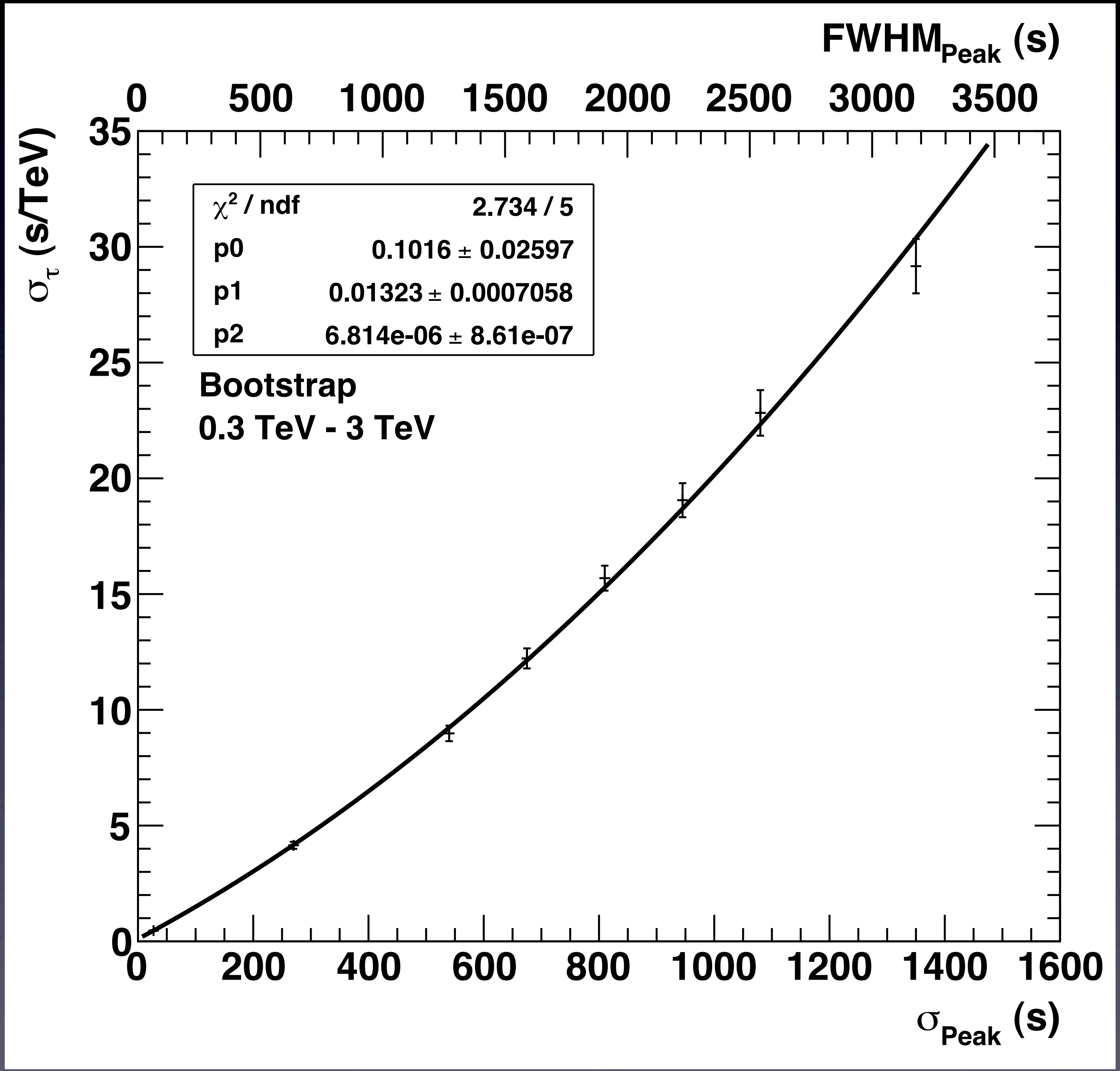




Bootstrap

- σ_{Peak} : width of the simulated pulse
- σ_{τ} : width of the distribution of likelihood minima

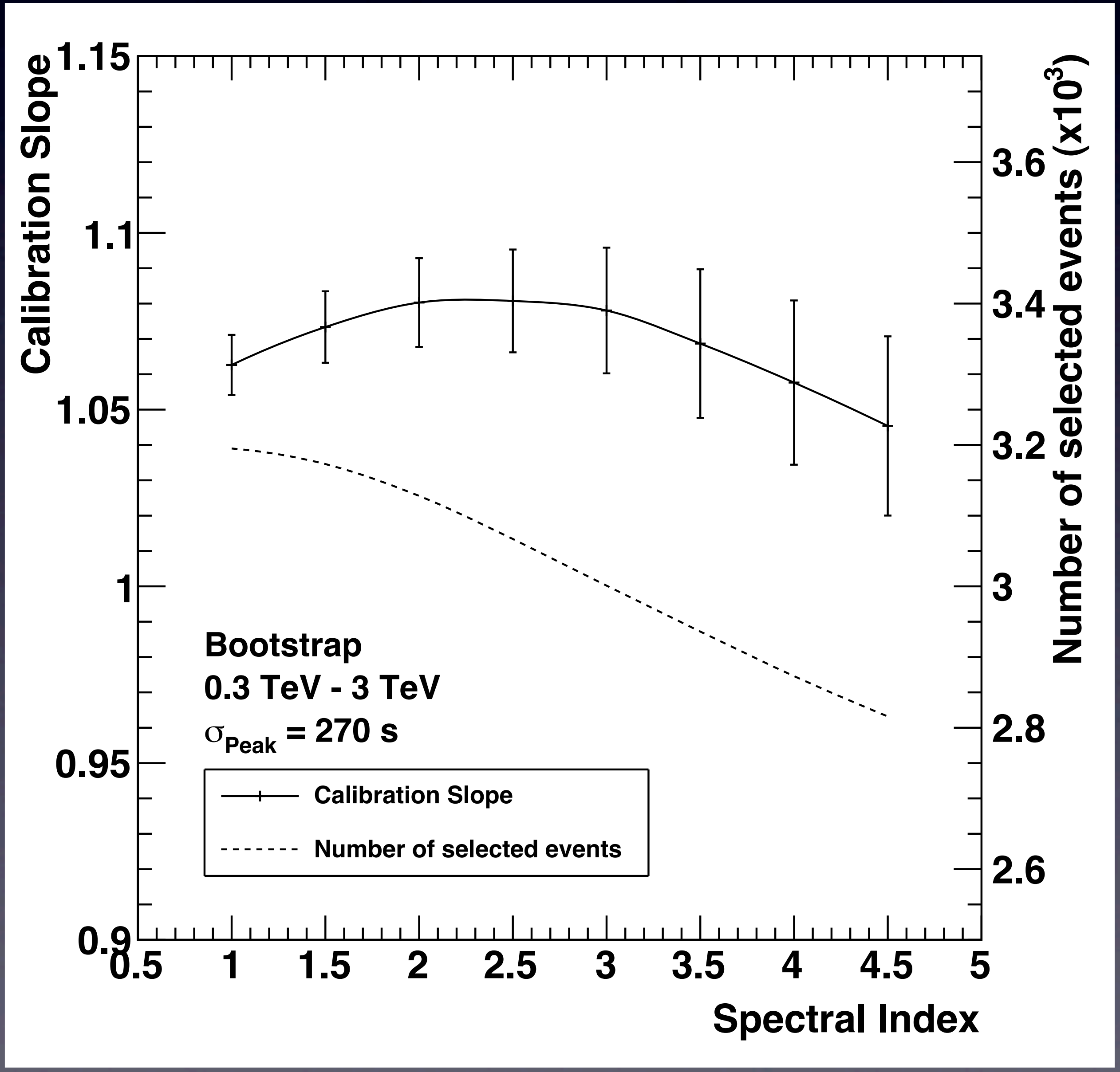
Will be used for statistical error calculation with data

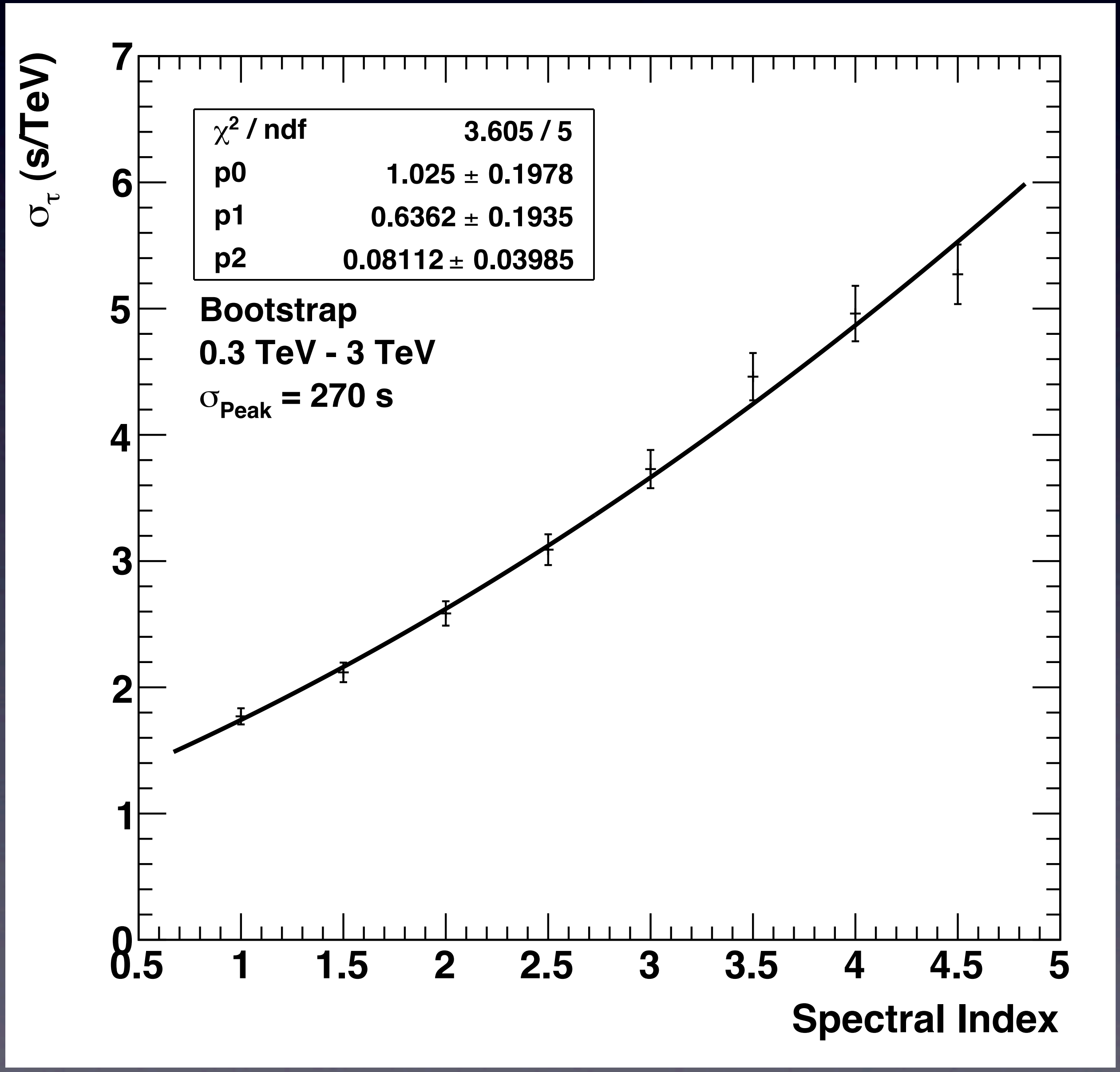


Bootstrap

- Variation of the calibration slope and of σ_τ with the spectral index

The harder the spectrum, the better

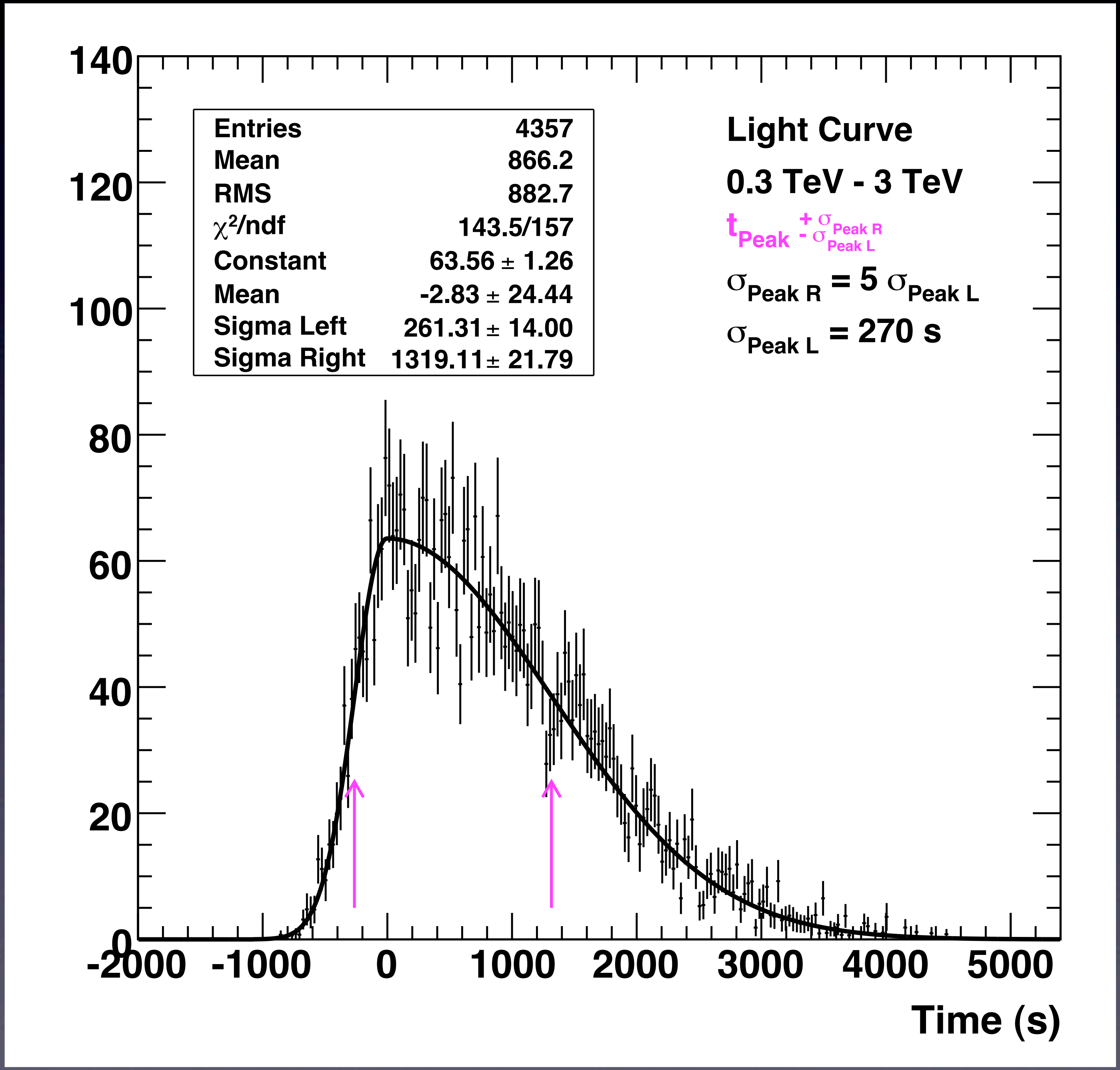




Bootstrap: Asymetric Gauss

$$\begin{cases} y = A\, e^{-\frac{(x-\mu)^2}{2\sigma_L^2}}, & \text{if } x < \mu \\ y = A\, e^{-\frac{(x-\mu)^2}{2\sigma_R^2}}, & \text{otherwise} \end{cases}$$

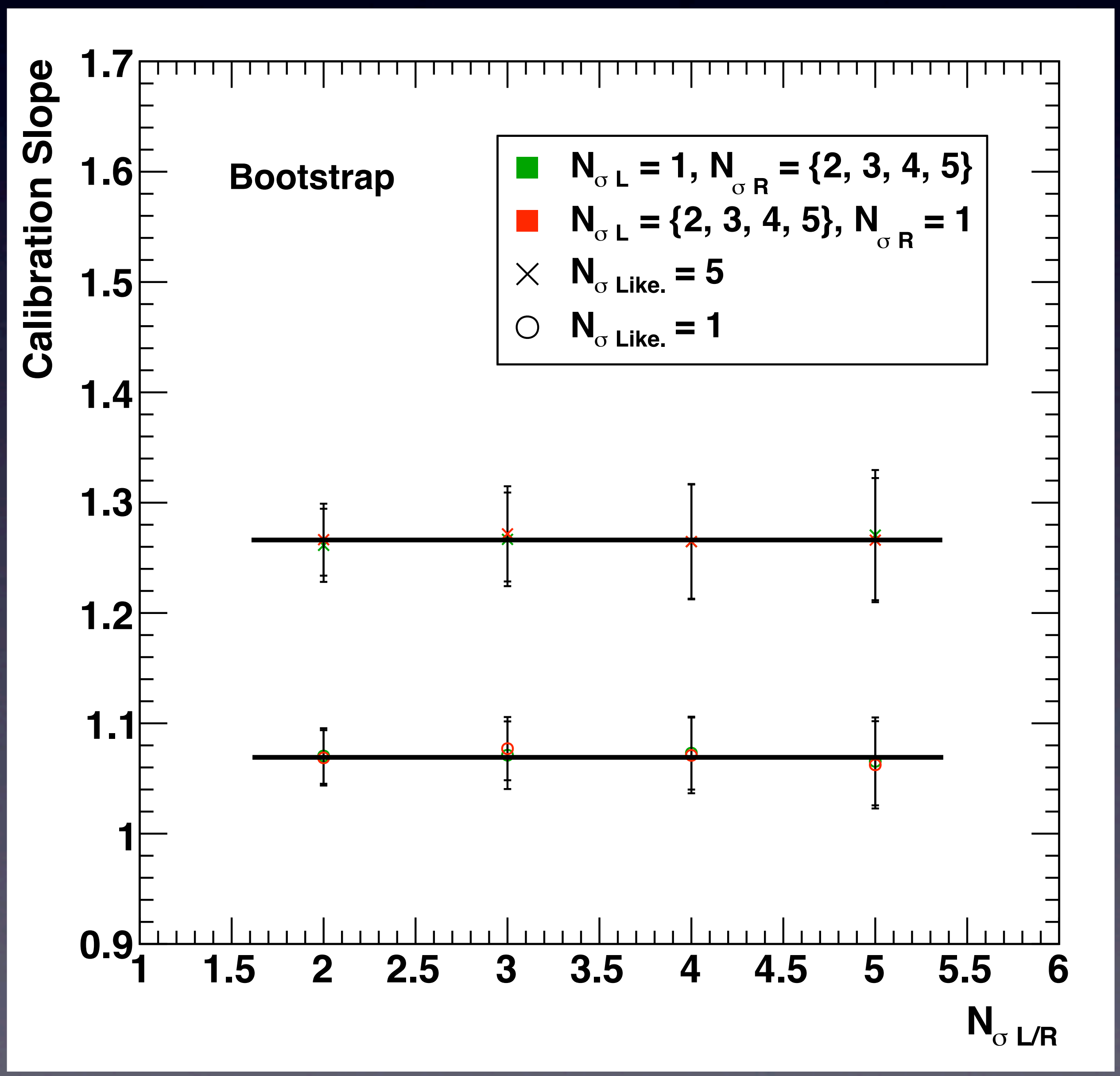
- Width defined on the left and on the right by $N_{\sigma L/R}\ \sigma_{Peak}$ with σ_{Peak} = 270 s and
  - $N_{\sigma L}$ = 1 and $N_{\sigma R}$ = 2, 3, 4, 5
  - $N_{\sigma L}$ = 2, 3, 4, 5 and $N_{\sigma R}$ = 1

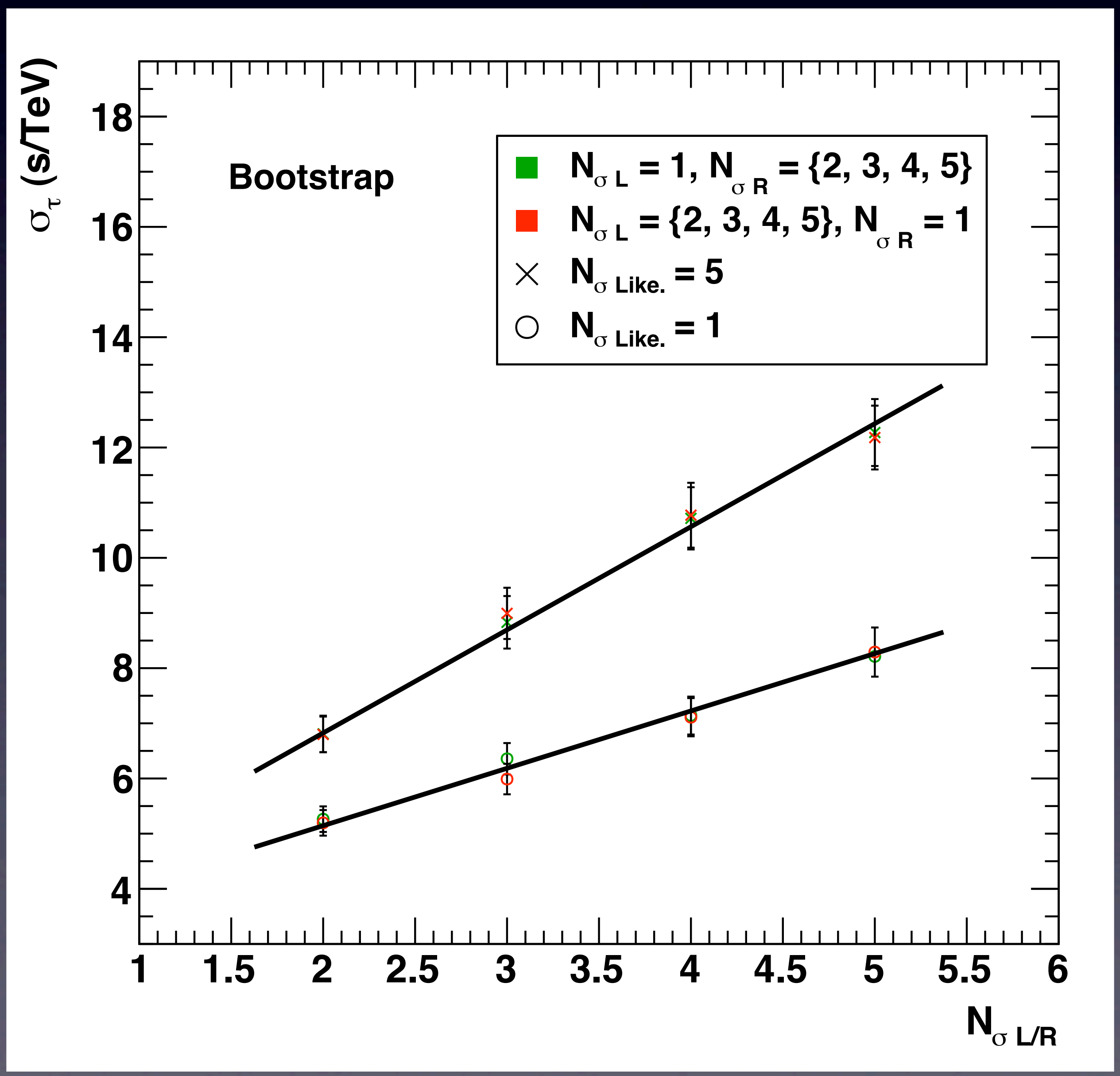


Bootstrap: Asymetric Gauss

- The asymmetry has no effect on the calibration slope
- The asymmetry has an effect on σ_τ

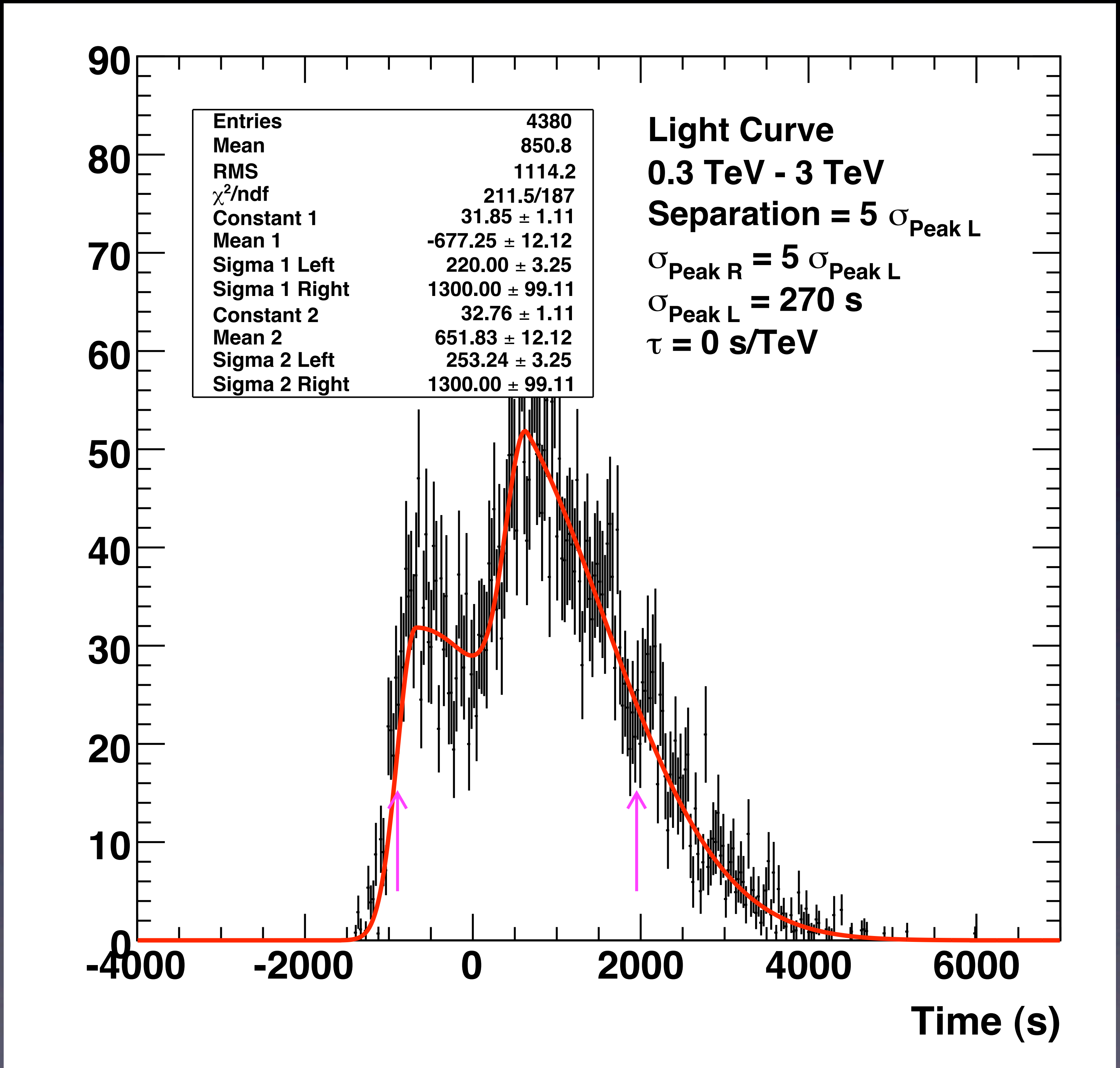
The asymmetry has no effect on the precision





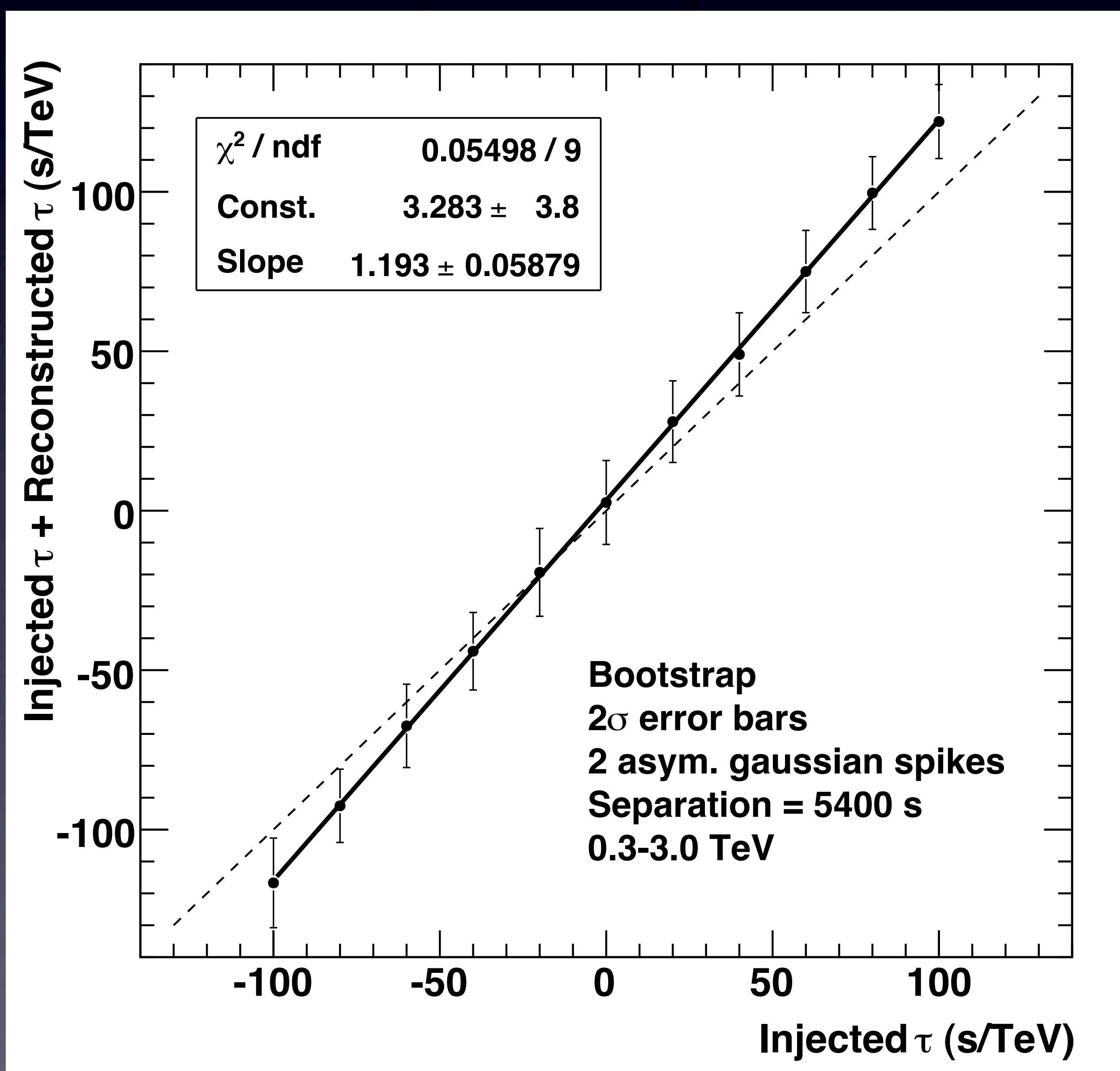
Bootstrap: 2 asymetric pulses

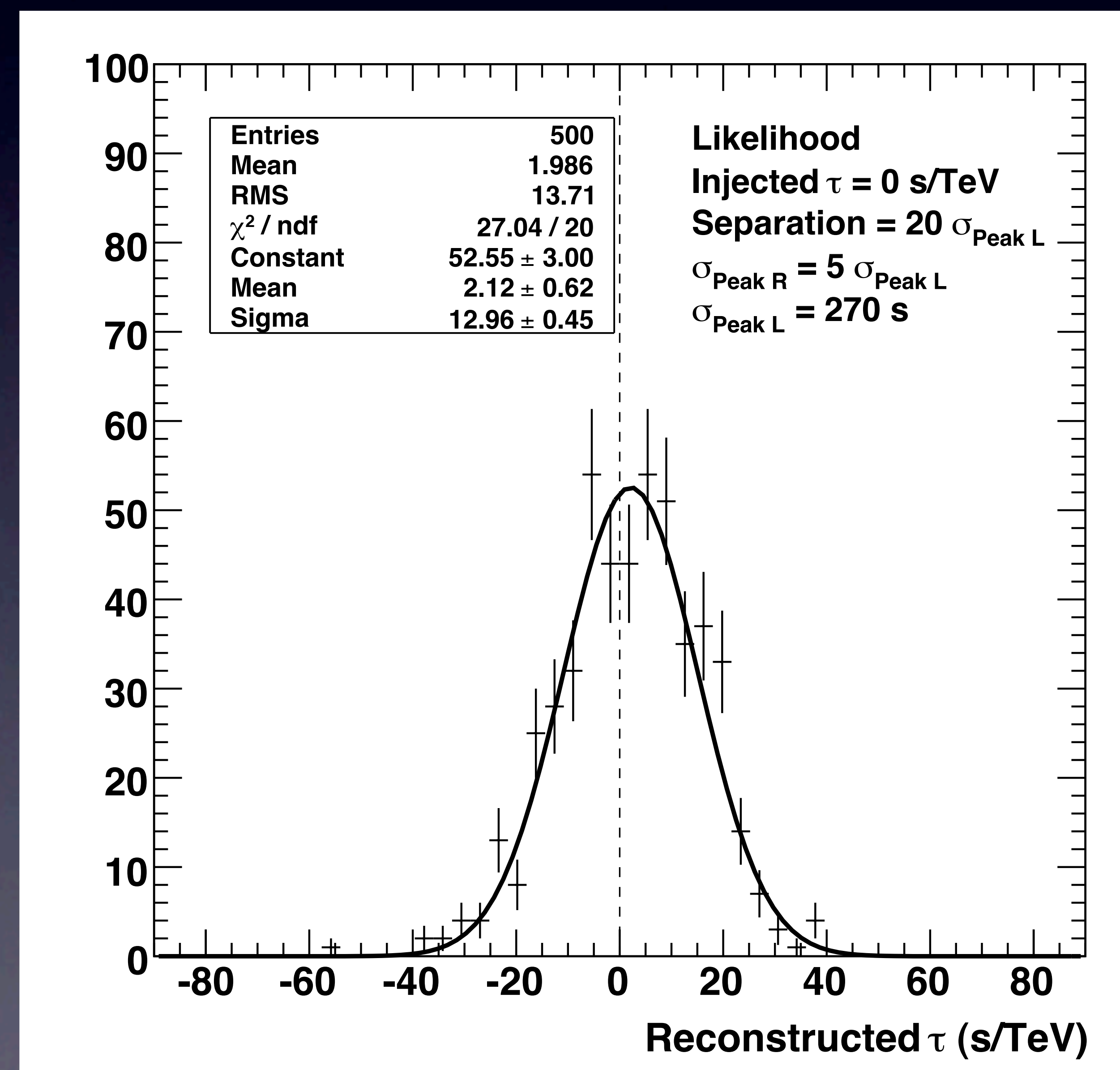
- Two pulses
  - Asymetric gaussian
  - Varying inter-pulse distance: L = {5, 10, 20} x 270 s
- The likelihood is computed in the range $[t_{max1} - \sigma_{L1}, t_{max2} + \sigma_{R2}]$



Bootstrap: 2 asymetric pulses

- Separation 20 x 270 s:
  - $\sigma_\tau \approx 13$ s/TeV ➔ like a gaussian with $\sigma \approx 700$ s
  - Slight positive shift of the calibration line

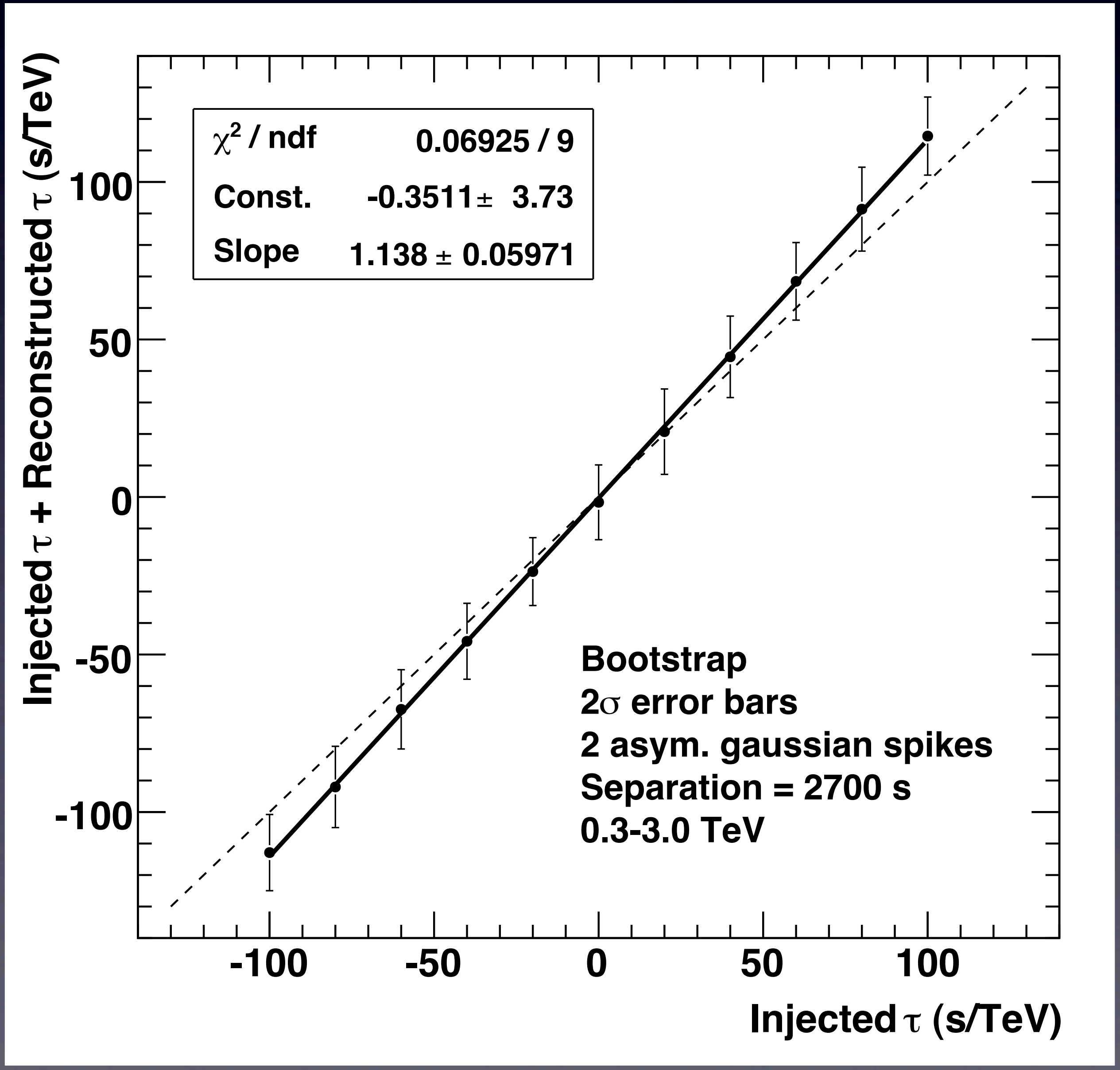


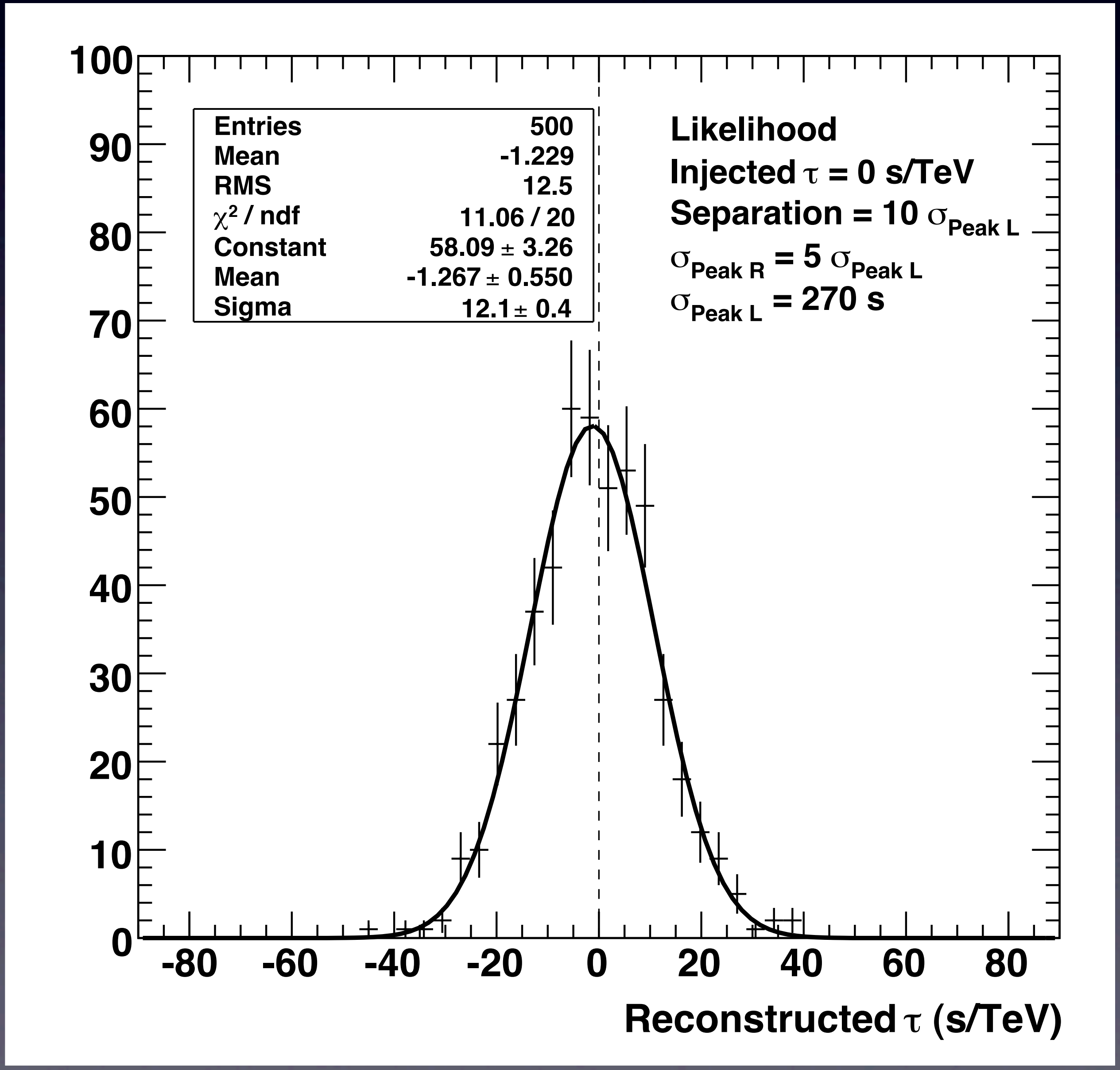


Bootstrap: 2 asymetric pulses

- Separation 10 x 270 s:
  - $\sigma_\tau \approx$ 12 s/TeV ➔ like a gaussian with $\sigma \approx$ 650 s
  - Slight negative shift of the calibration line

σ_τ seems to be governed by the width of individual pulses

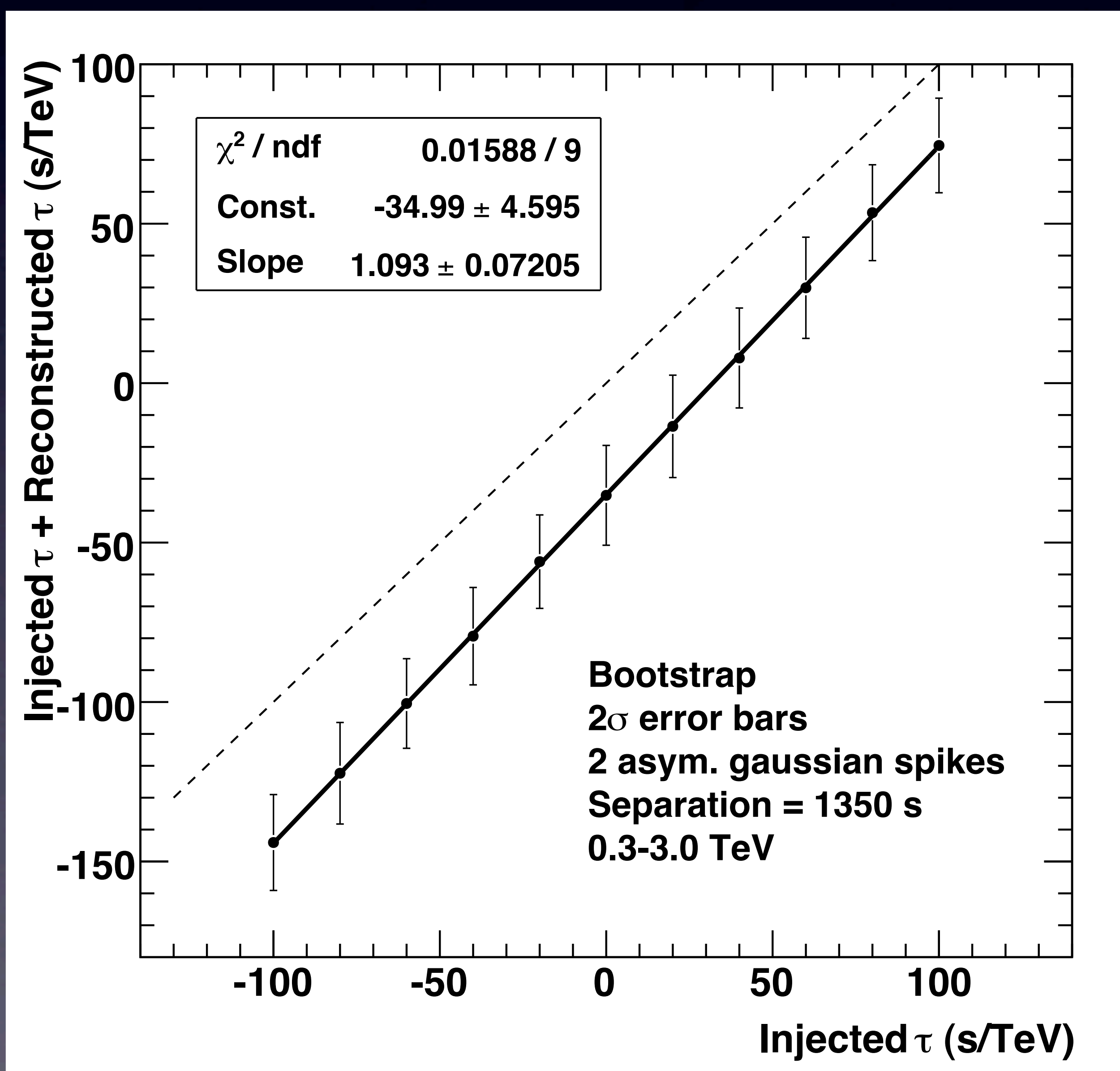


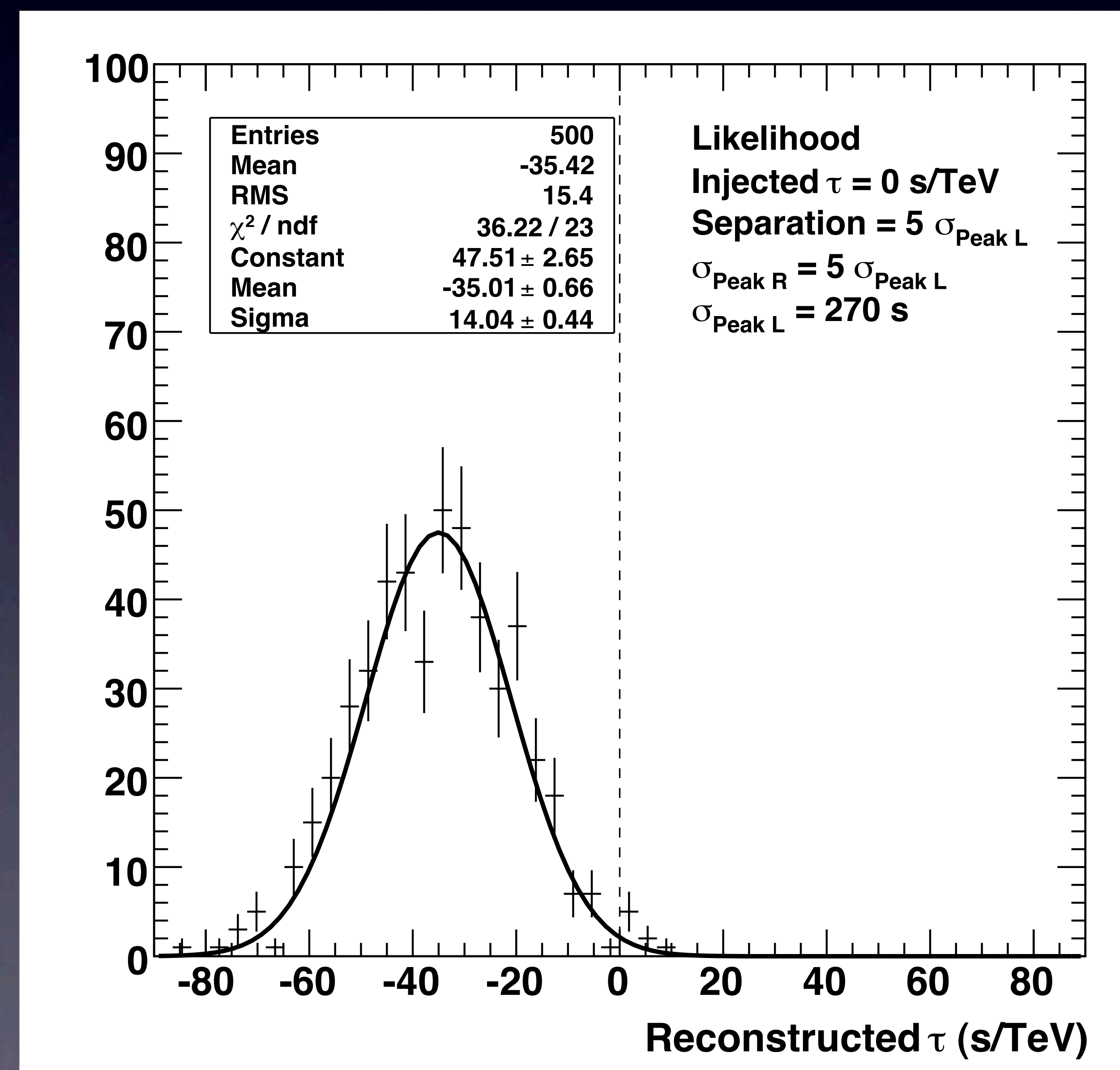


Bootstrap: 2 asymetric pulses

- Separation 5 x 270 s:
  - $\sigma_\tau \approx 14$ s/TeV ➔ like a gaussian with $\sigma \approx 750$ s
  - Large negative shift of the calibration line

To be understood !





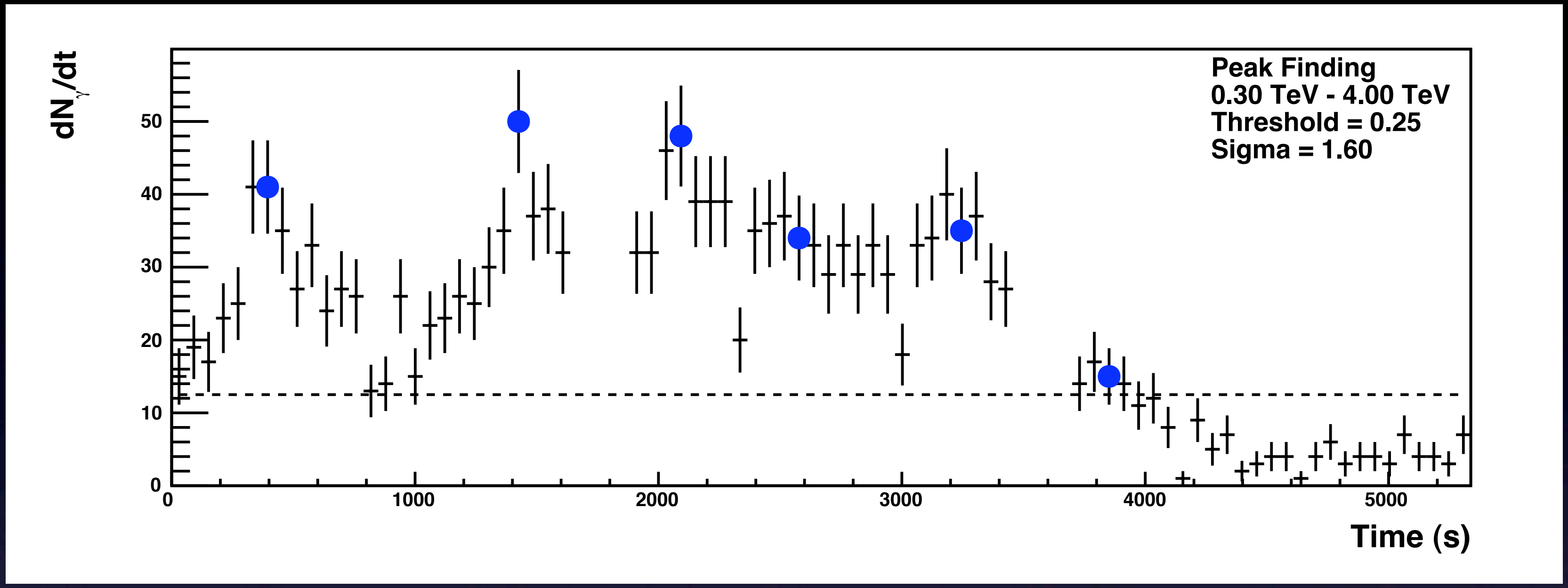
Conclusions

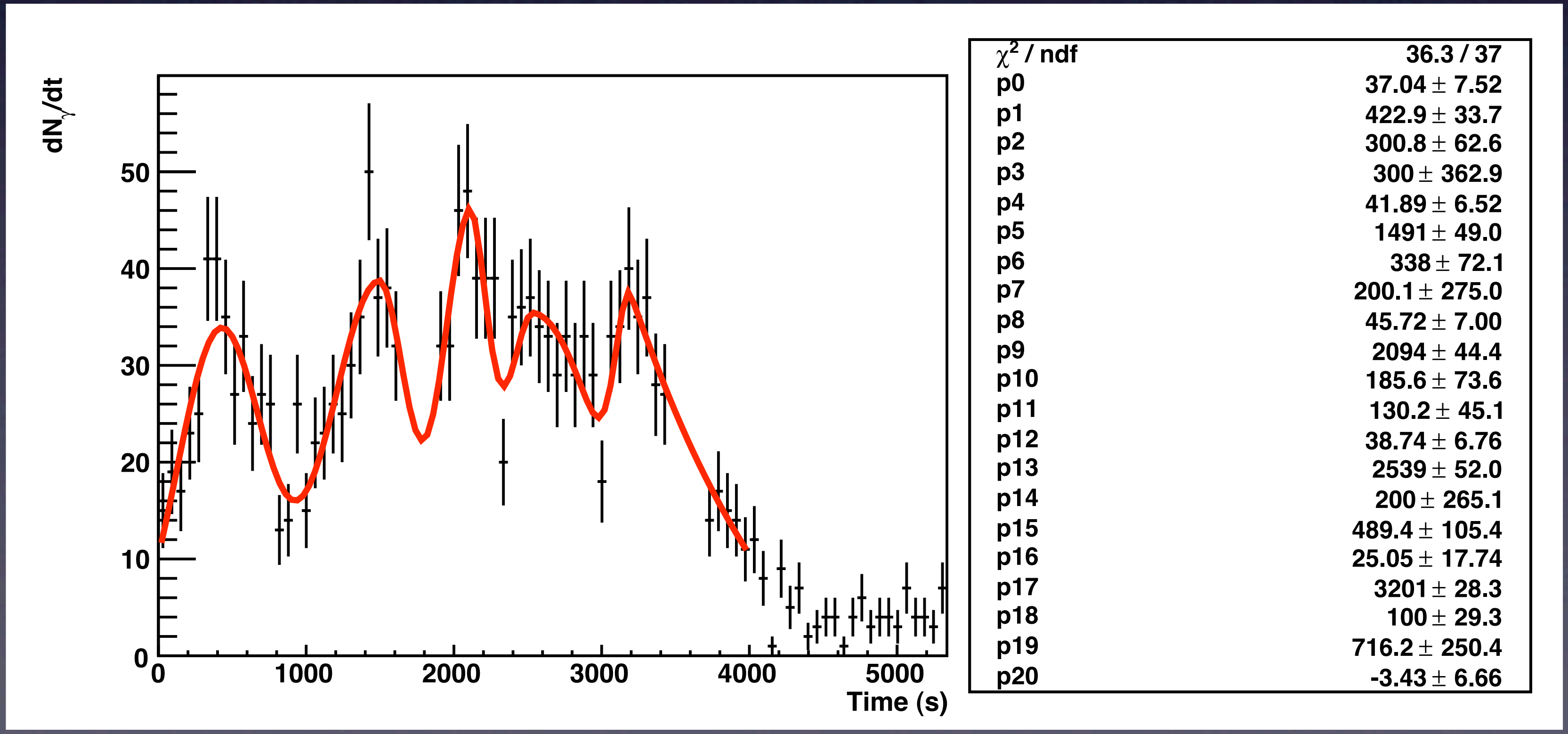
- Modelling
  - The interval in which the likelihood is calculated have to be chosen wide enough to contain both shifted and un-shifted light curves
  - The method works extremely well
  - This approach can be used to test models: interesting for LIV and source intrinsic effects
- Bootstrap
  - Precise determination of constraints if $\tau = 0$
  - It is not possible to detect a lag with measured light curve
  - If a lag is detected, it may not be due to the LIV
  - With complex light curves, probably better to study individual pulses ➔ to be investigated !

A glance on PKS 2155

Fit - Big Flare

- 3 runs, 8148 total events
- Choice of parameters:
  - Light curve : binning
  - Peak finding :
    - threshold
    - width
  - Fit : initial conditions
- Necessity to avoid sharp discontinuities





Conclusions

- Study of an exceptional flare of PKS 2155-304
- Search for an energy-dependant time-lag
- The most constraining limits on the Quantum Gravity scale found with Blazars, assuming no source effect using a wavelet analysis and CCF: $E_{QG} > 0.7 \times 10^{18}$ GeV
- The development of a new analysis based on likelihood fit is on-going
  - Higher precision
  - Higher limit on E_{QG}
  - Toy MC developped to calibrate the statistical errors and evaluate the systematics
  - Two modes:
    - Modelling: usefull to work with emission processes at the source (intrinsic lags)
    - Bootstrap: it is not possible to detect a lag with measured light curve, but precise measurement around $\tau = 0$ s/TeV