Gamma-Ray Lightcurve Archivation

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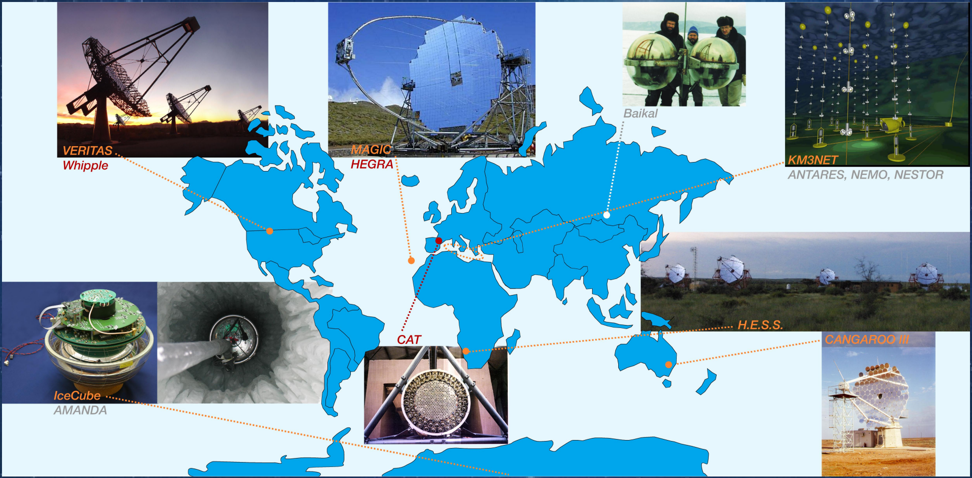
- Motivation
- Gamma-Ray Archive
- Light Curve Analysis
  - High-State Rate: ingredient for Multi-Messenger analyses
  - Comparison to X-rays

Motivation: Multi-Messenger Approach

- **Multi-Wavelength**:
  - different Wavelength bands (simultaneous / non-simultaneous)
  - combination of multi-wavelength information:
    maximize e.m. phenomenology
  - better understanding of astrophysical objects
- **Multi-Messenger**:
  - other messengers + e.m. information: Neutrinos, Gravitational waves
  - complete phenomenology & better understanding
  - increase detection significance of new messengers (e.g. coincidence)
  - can build confidence in new messengers

Multi-Messenger Approach

Focus of this work: Very High Energy (VHE) γ-Ray Data
Scope: multi-messenger studies with time variable signals $\longrightarrow$ light curves
Goal: archivation & combination of VHE γ-Ray data from main experiments



Multi-Messenger studies

Active field

- **AMANDA / IceCube**
  - MPI-K: E. Resconi et al. (X, Gamma / neutrinos)
  - UW Madison: T. Montaruli et al. (radio, optical, X, Gamma / neutrinos)
  - Humboldt: M. Kowalski et al. (Optical / neutrinos)
  - DESY: E. Bernardini et al. (X, Gamma / neutrinos)
- **ANTARES / Km3Net**
  - predictions of neutrinos from H.E.S.S. sources: Kappes et al. 2007
  - ...

Neutrinos and Gamma-Rays

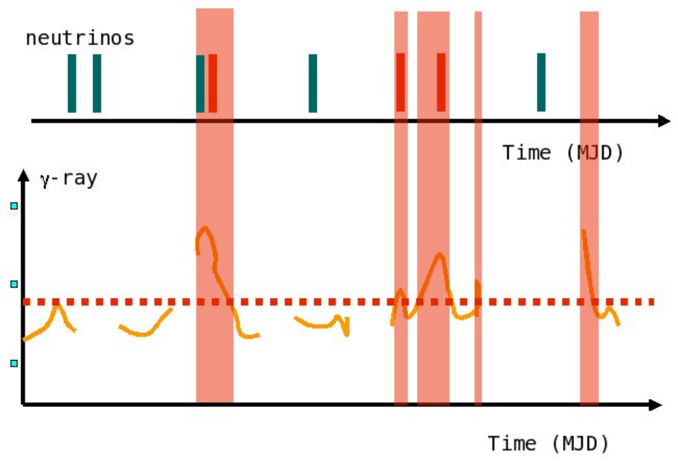
Acceleration of cosmic rays: Hadronic interactions lead to γ-ray & ν emission

γ-rays can be produced via hadronic or leptonic processes

ν emission is an unambiguous signature for hadronic acceleration

Neutrino Telescopes	Gamma-Ray Telescopes
$>2\pi$ sky coverage	0.02 sr sky coverage
90 % time coverage	max. 12 % time coverage
angular res. $O(1^\circ)$	$O(0.1^\circ)$
low statistics / sensitivity	high statistics / sensitivity
bad spectral resolution	excellent spectral resolution

Multi-Messenger Approach: Offline analysis

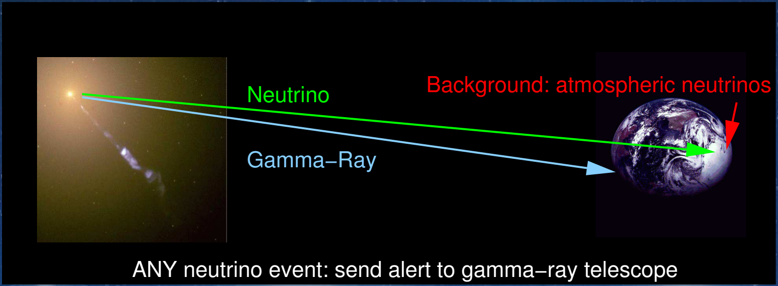


principle: search for $\nu\,\gamma$ correlations from variable objects (e.g. 1ES 1959+650)

need simultaneous data: sparse due to low γ-ray coverage

Example multi-messenger study:
Neutrino Triggered Target of Opportunity

Neutrino triggered Target of Opportunity program: NToO



ν from predefined list of objects:
trigger γ-ray observations within predefined time window

pure background neutrino sample:
random coincidences with flares

signal neutrino content:
enhanced coincidences

Goals

ensure simultaneous ν/γ data

improve detection chance for ν telescopes

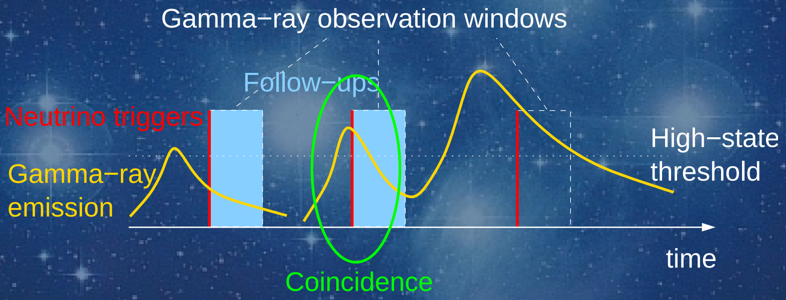
improve phenomenological knowledge of sources

see, e.g. Bernardini et al., Palaiseau 2005, Ackermann et al., ICRC 2007

NToO test run: principle

detection of neutrino by AMANDA-II from given direction
⟶ Trigger is sent to MAGIC

MAGIC carries out follow-up observation if possible



search for deviation from random coincidence with atmospheric neutrino background

NToO test run: details

Implementation of NToO idea: cooperation between AMANDA & MAGIC

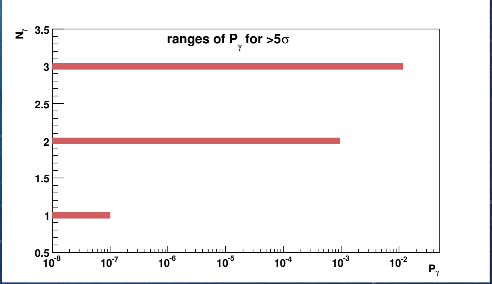
- 2 X-ray binaries: LSI+61 303, GRS 1915+105
- 3 Blazars: 1ES 2344+514, 1ES 1959+650, Mrk 421
- predefinition of γ-observation window: observation of object for 1 hour within a window of 1 day after neutrino trigger was issued
- predefinition of coincidence: γ-ray high-state within obs. window
- predefinition of γ-ray high-state: observed flux above predefined threshold
- Results: Ackermann et al., ICRC 2007, talk by E. Bernardini

NToO: possible interpretation scheme

$$P = \sum_{i=n_{\rm obs}}^{+\infty} \frac{(n_{\rm bck})^i}{i!} \mathrm{e}^{-\mathbf{n}_{\rm bck}} \sum_{j=n_\gamma}^{i} \frac{i!}{j!(i-j)!} p_\gamma^j (1-p_\gamma)^{i-j},$$

$n_{\rm obs}$	observed neutrino events
$n_{\rm bck}$	expected atmospheric neutrino events
n_γ	observed ν / γ coincidences
p_γ	Probability of a γ-ray high-state

Ranges of p_γ for which an observation of n_γ coincidences would yield a Significant detection, $P > 5\,\sigma$

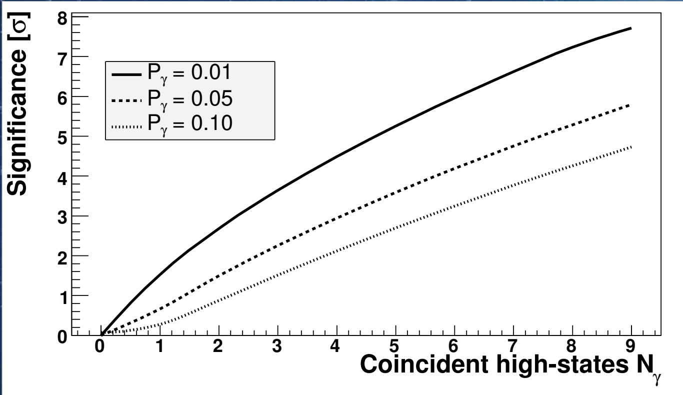


NToO: possible interpretation scheme

Example neutrino observation: $n_{\rm obs} = 10$, $n_{\rm bck} = 10$

In itself this neutrino observation is not really significant...

Adding information from coincident observations:



Need information on γ-ray variability: p_γ

Very little known so far

VHE lightcurve archive:

- central open archive
- definition of common lightcurve format
- lightcurve combination

Gamma-Ray Data Archive

- Collect all available (public) data from VHE experiments
- Current focus: Active Galactic Nuclei
- Extension to other objects...
- Issues:
  - no common lightcurve format ⟶ definition of SLF lightcurve format
  - normalization difficult: different flux units, partly unknown calibration
  - old data are not available in electronic form
  - ...
- input / collaboration from different sides (e.g. MPI-K)
- open archive but... use with care!

  `http://www-zeuthen.desy.de/multi-messenger/GammaRayData/`

Gamma-Ray Data Archive – Screenshot

http://www-zeuthen.desy.de/multi-messenger/GammaRayData/

Objects

1ES1959+650 Mrk421 Mrk501 PKS2155-304

1ES 1959+650:

publications	available data							
	1999	2000	2001	2002	2003	2004	2005	2006
7TA 99 HEGRA 00/01 Whipple 02 VERITAS 02 VERITAS 06 MAGIC 05 CAT		HEGRA CTS * HEGRA CT1	HEGRA CTS * HEGRA CT1	HEGRA CTS * HEGRA CT1 Whipple	Whipple ?	MAGIC Whipple ?	VERITAS MAGIC ?	VERITAS MAGIC ?
slf format:		HEGRA_CTS HEGRA_CT1	HEGRA_CTS HEGRA_CT1	HEGRA_CTS HEGRA_CT1 Whipple		MAGIC	VERITAS	VERITAS

1ES1959_combined_v1.slf

Mrk421

publications	available data														
	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
publ. link	Whipple	Whipple	Whipple	Whipple	HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 Whipple CAT	HEGRA CTS HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 CAT MILAGRO	HEGRA CTS HEGRA CT1 MILAGRO STACEE	Whipple MILAGRO	Whipple MILAGRO	Whipple MAGIC H.E.S.S. MILAGRO	VERITAS MAGIC	VERITAS
slf format:	Whipple	Whipple	Whipple	Whipple	HEGRA CT1 CAT	HEGRA_CTS HEGRA CT1 CAT	HEGRA_CTS HEGRA CT1 Whipple CAT	HEGRA_CTS HEGRA CT1 CAT	HEGRA_CTS HEGRA CT1 CAT	HEGRA_CTS HEGRA_CT1	Whipple	Whipple	HESS MAGIC	MAGIC VERITAS	VERITAS

Mrk421, combined lightcurve: Mrk421_combined_v2.slf

Current status of conversion/plotting :

The SLF format: Smarties Lightcurve Format

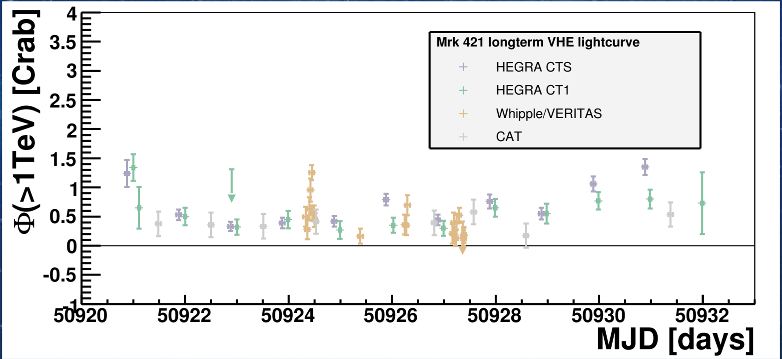
1. MJD of start of observations
2. MJD of end of observations
3. Measured flux
4. Statistical error of measured flux
5. Systematic error of measured flux
6. Spectral index
7. Spectral index statistical error
8. Spectral index systematic error
9. Energy threshold
10. Energy Cutoff
11. Experiment
12. Duration of observation
13. Additional entry 1
14. ...

simple ascii-table

extendable (e.g. spectra with exponential cutoff)

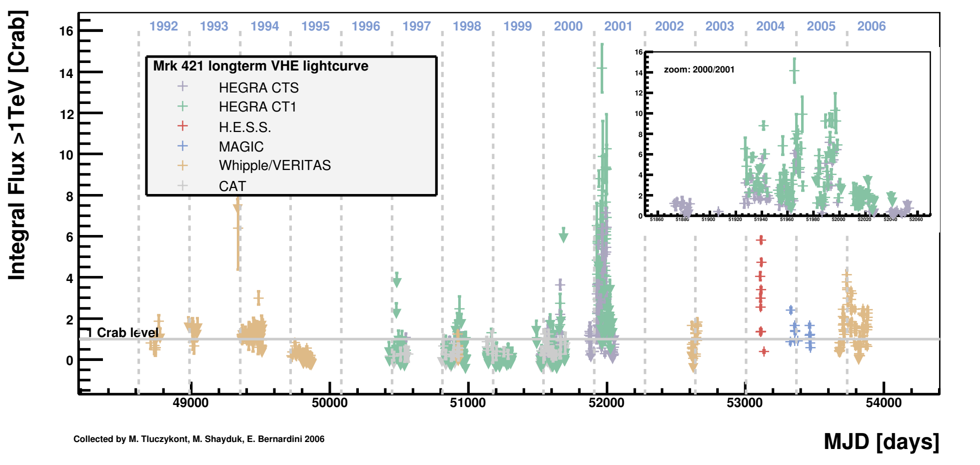
Light-Curve Combination

- **Ingredients:**
  - Common lightcurve format (SLF), threshold (1 TeV), Flux unit (Crab)
  - Spectral shapes as measured by experiments: power-law including possible cutoff
- $F(E > 1\,\mathrm{TeV}) = \left(\frac{E_{thr}}{1\mathrm{TeV}}\right)^{-\Gamma+1} \frac{\Phi(>E_{thr})}{\Phi_{Crab}(E>1\mathrm{TeV})}$

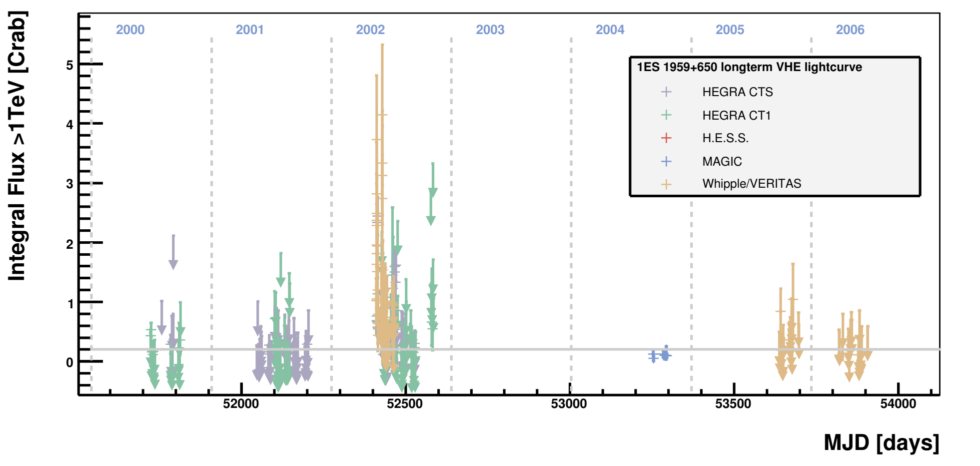


Long-Term Lightcurve of Mrk 421

15 years · more than 1500 h of observations



1ES 1959 Long-Term Lightcurve



Lightcurve Analysis:

- flux-state distributions
- relative high-state rates
- comparison to ASM X-ray data

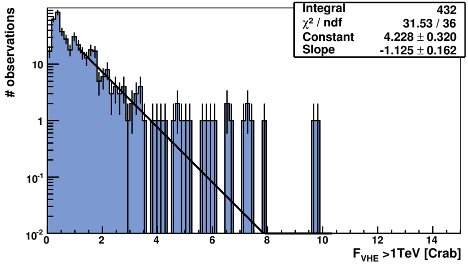
Mrk 421 Flux-State Distributions: Long-Term VHE Data

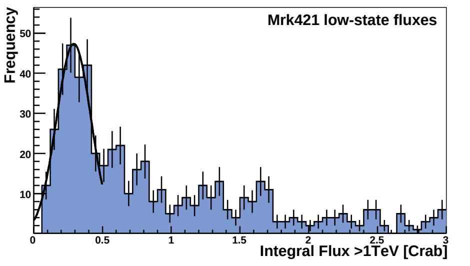
Flux distribution

- selected observations (no U.L.)
- bias at high flux states: high-state trigger

Zoom into low fluxes

- observation of low state ?
- … but at low flux states: sensitivity threshold bias



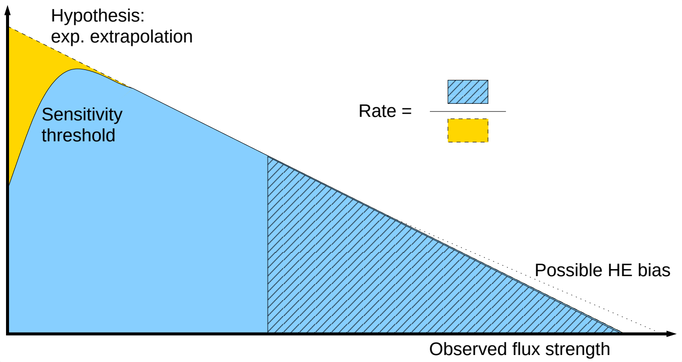


Stochastic flux state distribution with: $\frac{dN}{d\Phi} = a \cdot e^{b\Phi}$

Estimation of high-state rates

- **Motivation**: important ingredient in multi-messenger analyses (ν Correlation)
- **Hypothesis**: the distribution of flux states on the observed time scale is stochastic, exponential: $\frac{dN}{d\Phi} = a \cdot e^{b\Phi}$
- **High-State Rate**: $R_{HS}(F_{thr}) = \frac{T(F>F_{thr})}{T_{tot}} = \frac{\int_{F_{thr}}^{\infty} e^{b\Phi} dx}{\int_{F_0}^{\infty} e^{b\Phi} dx} = \frac{e^{bF_{thr}}}{e^{bF_0}}$
- **Caveats / open questions**:
  - biases at low and high fluxes
  - flux state distributions are not exactly stochastic
  - influence of different time-scales, i.e. sub-structures of lightcurves ?

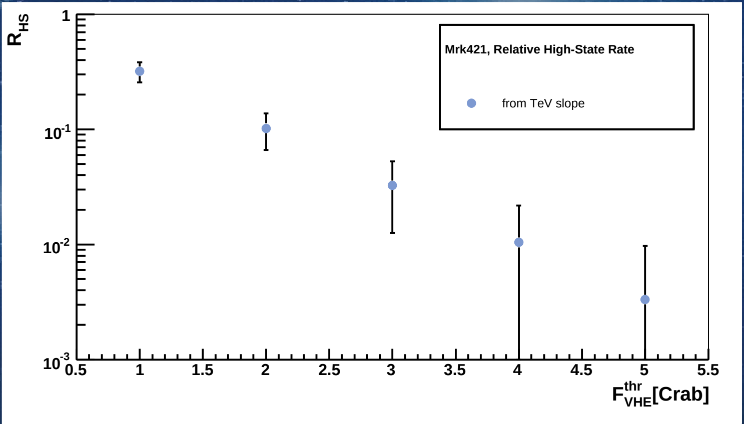
Estimation of high-state rates



Hypothesis: estrapolation of exponential down to 0.
bias at high fluxes: overestimation of high-state rate
unbiased procedure: use same detector for rate estimation & coincidence measurement
optimal: use this detector for random observations (monitoring)
... Cherenkov telescope network

Estimation of Relative High-State Rate

High-State Rate: $R_{HS}(F_{thr}) = \frac{T(F>F_{thr})}{T_{tot}} = \frac{\int_{F_{thr}}^{\infty} e^{b\Phi} dx}{\int_{F_0}^{\infty} e^{b\Phi} dx} = \frac{e^{bF_{thr}}}{e^{bF_0}}$

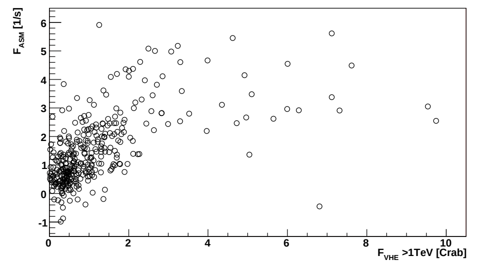


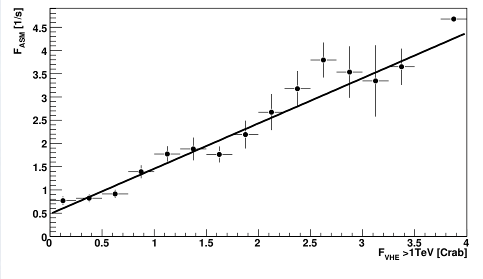
Comparison to X-rays:

- correlation
- flux state distributions

VHE to X-Ray Correlation

- observations are **not 100% simultaneous**
- high VHE flux states: observational bias due to external- and self-triggering
- on average: linear correlation up to 4 Crab-level





Comparison to ASM X-Ray Data

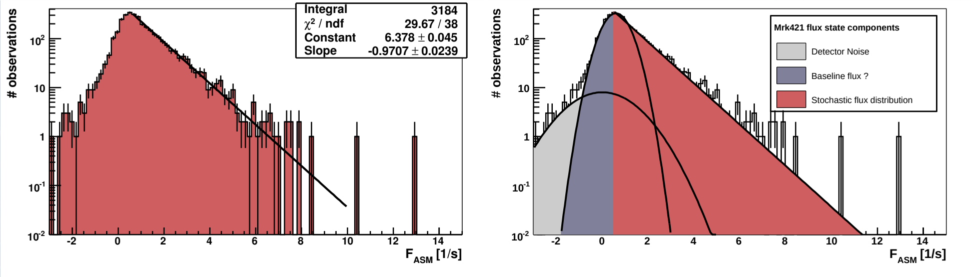
Flux-State Distributions from Contemporaneous data

ASM X-ray data

- `http://xte.mit.edu/ASM_lc.html`
- only partly simultaneous !

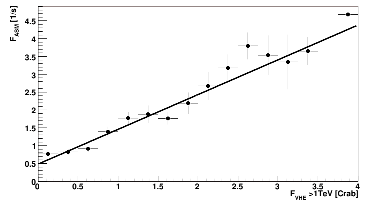
Component Interpretation

- Noise: Gaussian
- Signal: Gaussian + Exponential



Stochastic flux state distribution: $\frac{dN}{d\Phi} = a \cdot e^{b\Phi}$

Comparison to ASM Data: High-State Rate

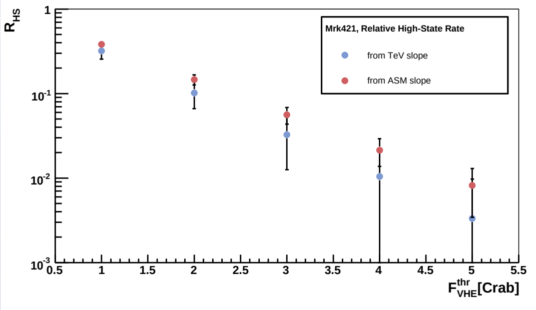


15-year-VHE lightcurve + ASM archive data:

- ASM data: same stochastic behaviour
- only partly simultaneous data
- clear correlation seen

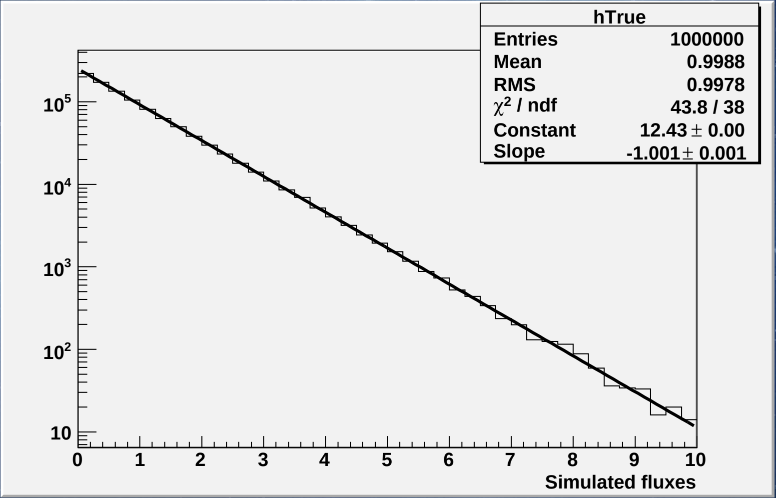
expected and found

comparable R_{HS}:



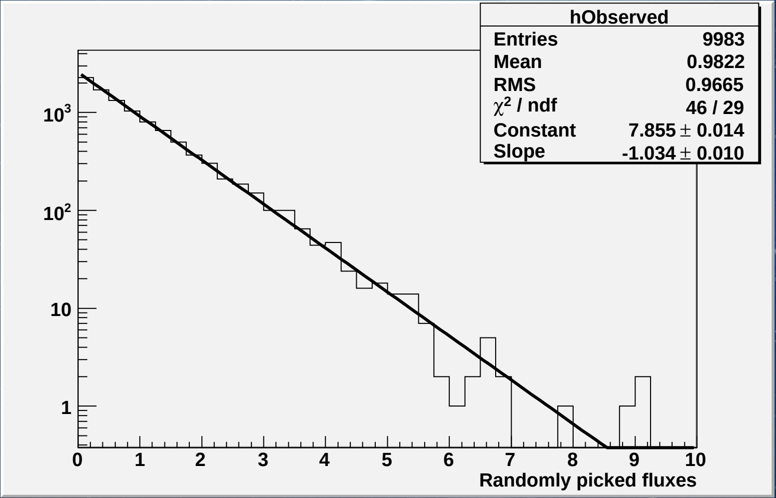
Lightcurve simulation: proof of principle

simulation of exponential flux-state distribution (arb. units)



Lightcurve simulation: proof of principle

Picking randomly observations with a total coverage of 1 %



Lightcurve simulation: plans

- full simulation of different flux state distributions
  - different time scales of variability
  - different shapes of distribution
- estimation of errors on high-state rate estimation

Summary & Outlook

- **Very High Energy Data Archive**:

  http://www-zeuthen.desy.de/multi-messenger/GammaRayData/

- archivation of lightcurves: AGN ++
- combination of data: long-term lightcurves
- analysis:
  - estimation of high state rates
  - correlation studies
- collecting data: archive growing ...
- **Future:** Random γ-ray observations