The Multi Messenger Approach and The MAGIC/IceCube Target of Opportunity Program

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Venice, TeV III, 2007

- Multi messenger approach
  - principles
  - ongoing efforts
- Neutrino Triggered Target of Opportunity program
- Gamma-Ray data archive & lightcurve analysis

Motivation: Multi-Messenger Approach

- **Multi-Wavelength**:
  - different Wavelength bands (simultaneous / non-simulataneaous)
  - 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 studies

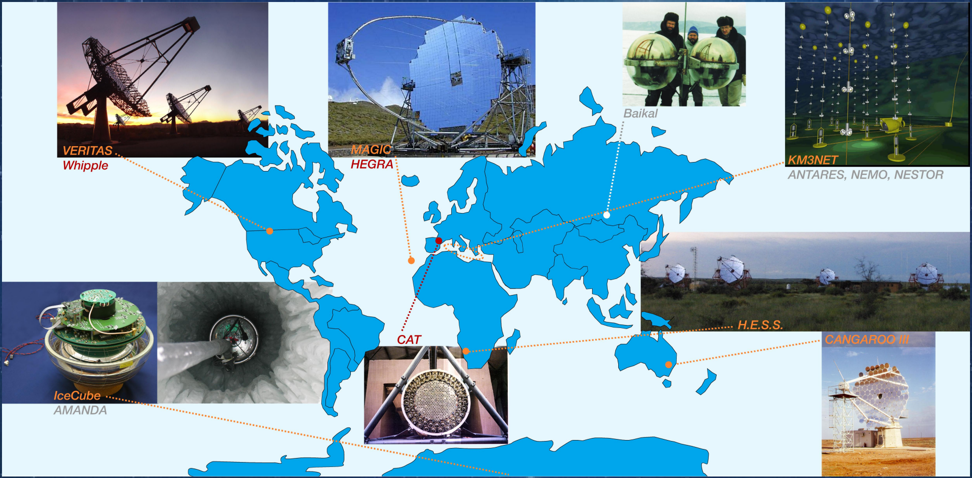
Several ongoing Multi-Messenger studies including neutrinos

Can include Radio, Optical, X-rays, gamma-rays + neutrinos

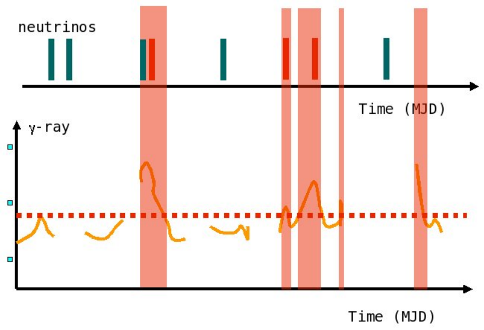
- AMANDA / IceCube
  - MPI-K: E. Resconi et al.
  - UW Madison: T. Monaruli et al.
  - DESY: E. Bernardini et al.
  - Humboldt Uni: M. Kowalski et al.
- ANTARES / Km3NeT
  - Predictions based on galactic H.E.S.S. sources: Kappes, Hinton, Stegmann & Aharonian, astro-ph/0607286
  - ...

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**
Need: archivation & combination of VHE γ-Ray data from main experiments



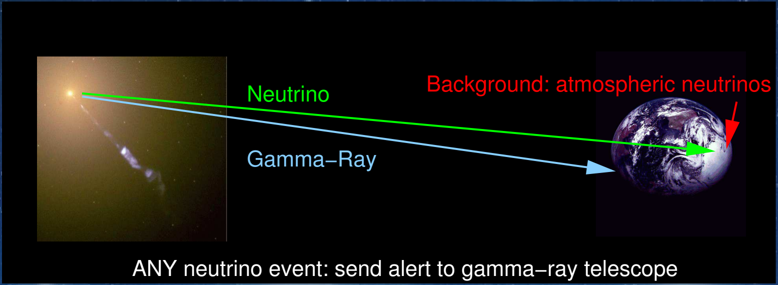
Multi-Messenger Approach: Offline



- search for $\nu\,\gamma$ correlations from variable objects (e.g. 1ES 1959+650)
- need simultaneous data: sparse due to low γ-ray coverage
- need good knowledge of e.m. phenomenology: estimation of random coincidences

Only possible if simultaneous data is available
Online approach: take simulataneous data

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

$\longrightarrow$ ensure simultaneous ν/γ data

$\longrightarrow$ improve detection chance for ν telescopes

$\longrightarrow$ improve phenomenological knowledge of sources

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
- test run active from September 27 to November 27, 2006
- results first shown at ICRC 2007: Ackermann et al., talk by E. Bernardini

NToO testrun: results

Successfully tested technical feasability & procedures

No coincidences observed during NToO testrun in 2006

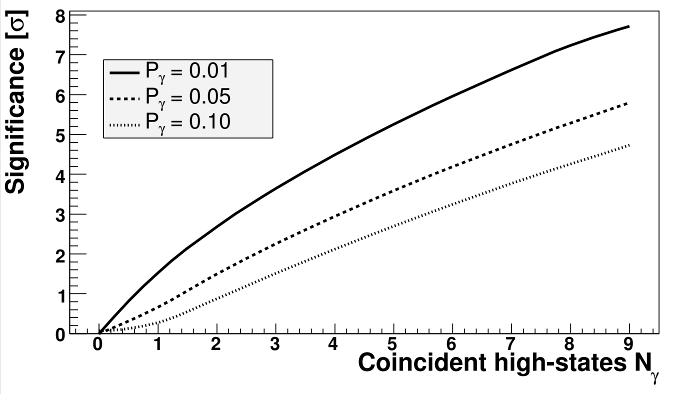
		LSI+61 303	GRS 1915+105	1ES 2344+514	1ES 1959+650	Mrk 421
expected background	n_{bck}	0.86	1.26	0.99	0.92	1.51
observed νs	n_{obs}	0	1	1	0	3
	Follow ups	0	0	1	0	1
observed coincidences	n_{γ}	–	–	0	–	0
High state flux threshold	F_{thr} [C.U.]	0.2	0.2	0.5	1.0	4.0
High state probability	p_{γ}	–	–	–	< 0.15	< 0.05
Significance	P_{ν}	1.0	0.7	0.6	1.0	0.2

NToO: possible interpretation scheme

Example (0-significance) neutrino observation: $n_{obs} = 10$, $n_{bck} = 10$

Chance probability in case of coincidence with gamma-ray high states:

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



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 $\longrightarrow$ definition of SLF lightcurve format
  - normalization difficult: different flux units, partly unknown calibration
  - old data are not available in electronic form
  - ...
- 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

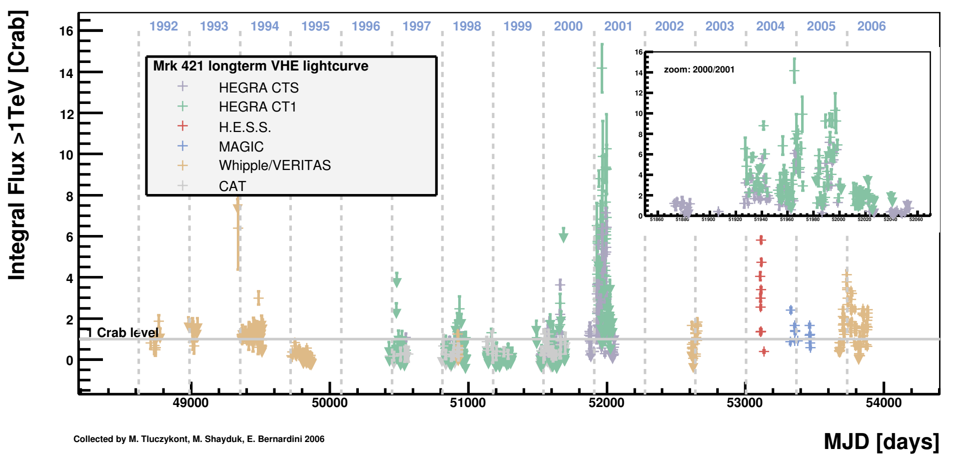
publications	available data														
	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
publ. link	Whipple	Whipple	Whipple	Whipple	HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 Whipple CAT	HEGRA CTS HEGRA CT1 CAT	HEGRA CTS HEGRA CT1 CAT MILAGRO	HEGRA CTS HEGRA 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

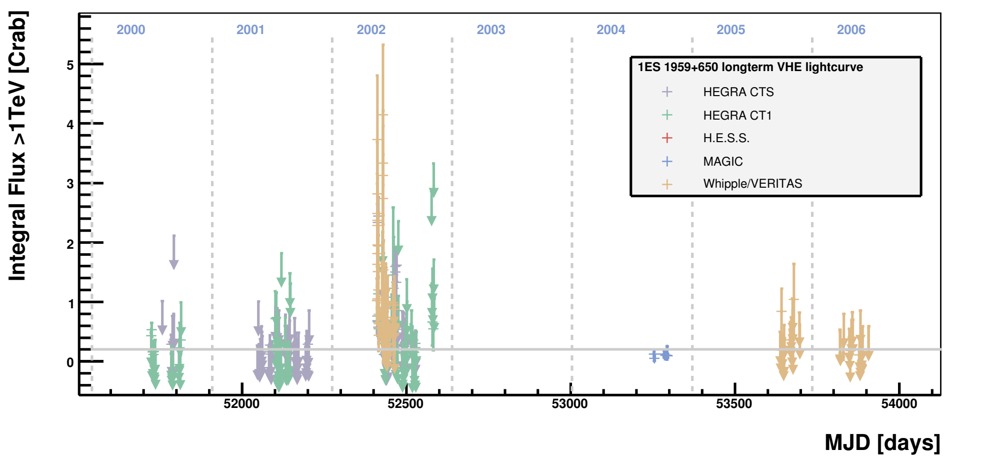
Current status of conversion/plotting :

Long-Term Lightcurve of Mrk 421

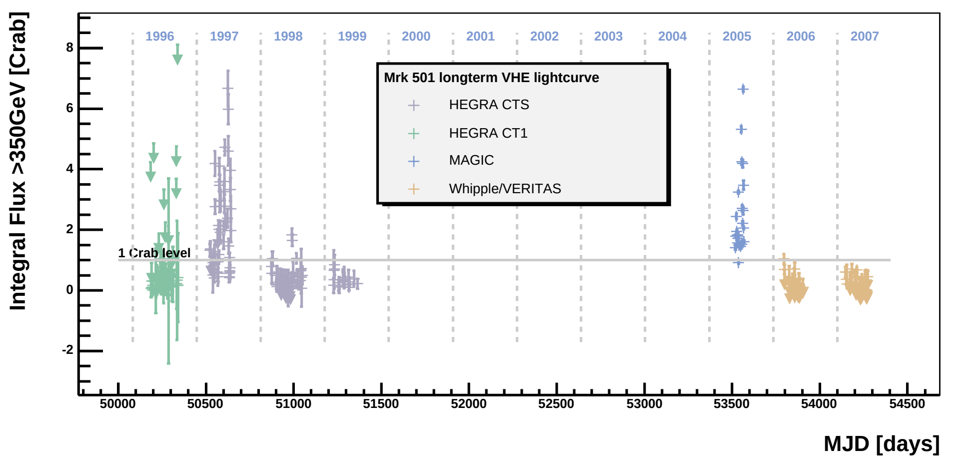
15 years · more than 1500 h of observations



1ES 1959 Long-Term Lightcurve



Mrk 501 Long-Term Lightcurve



Lightcurve Analysis:

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

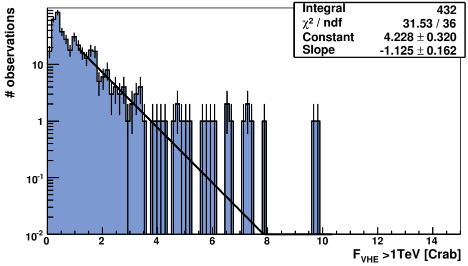
Mrk 421 Flux-State Distributions: Long-Term VHE Data

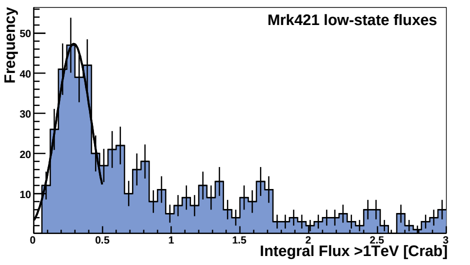
Flux distribution

- 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





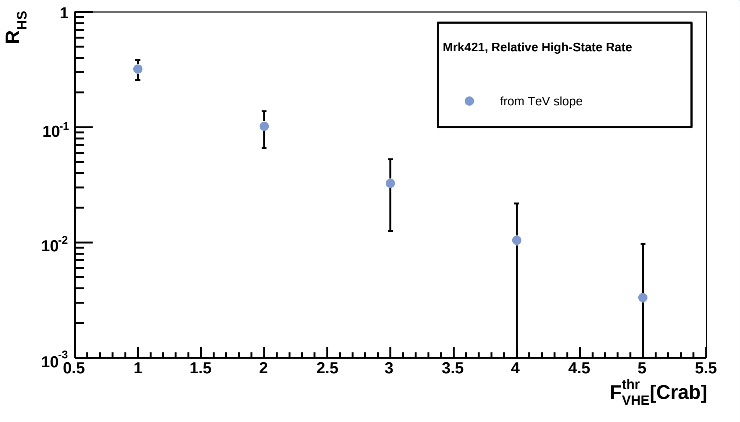
Stochastic flux state distribution: $\frac{dN}{d\Phi} = a \cdot e^{b\Phi}$

Estimation of Relative High-State Rate

Motivation: important ingredient in multi-messenger analyses (ν Correlation)

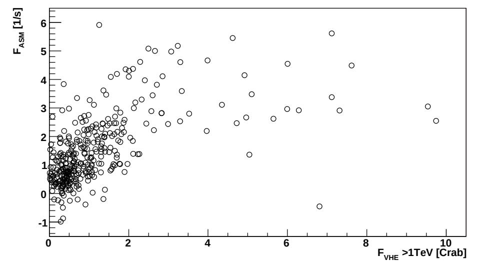
Hypothesis: stochastic flux-state distribution $\frac{dN}{d\Phi} = a \cdot e^{b\Phi}$

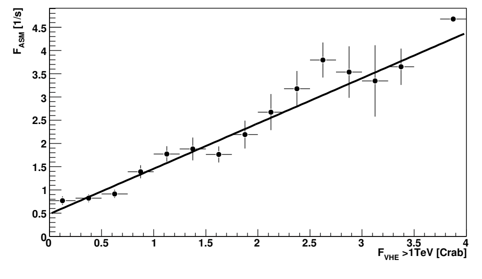
High-State Rate: $R_{HS}(F_{thr}) = \frac{T(F>F_{thr})}{T_{tot}} = \frac{\int_{F_{thr}}^{\infty} e^{b\Phi} dx}{\int_{F_0}^{\infty} e^{b\Phi} dx} = \frac{e^{bF_{thr}}}{e^{bF_0}}$



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

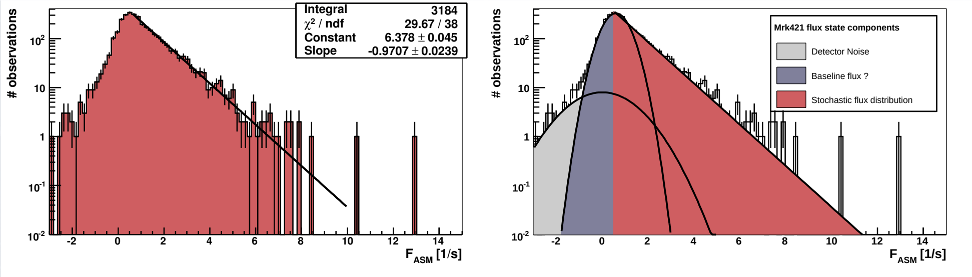
Flux-State Distributions from Contemporaneous data

ASM X-ray data

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

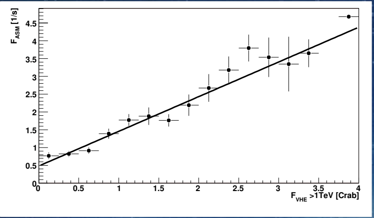
Component Interpretation

- 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

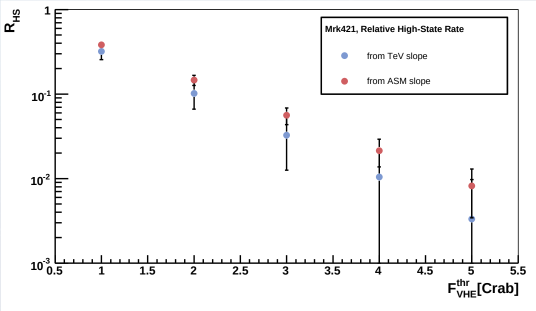


15-year-VHE lightcurve + ASM archive data:

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

expected and found

comparable R_{HS}:



Summary & Outlook

- Neutrino triggered Target of Opportunity program
  - successfully tested technical feasability, procedures etc.
  - no coincidences observed
  - work towards furthe application of the concept
- 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
  - collecting data: archive growing ...

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

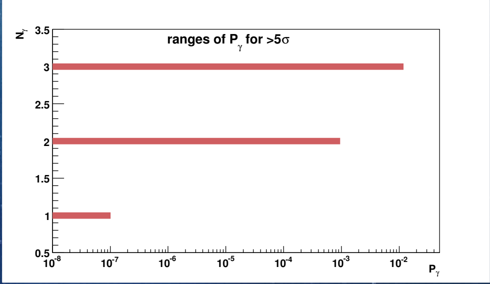
Neutrino Telescopes	Gamma-Ray Telescopes
$>2\pi$ sky coverage	0.02 sr sky coverage
90 % time coverage	max. 12 % time coverage
angular res. $O(1^\circ)$	$O(0.1^\circ)$
low statistics / sensitivity	high statistics / sensitivity
bad spectral resolution	excellent spectral resolution

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, $P > 5\,\sigma$



The SLF format: Smarties Lightcurve Format

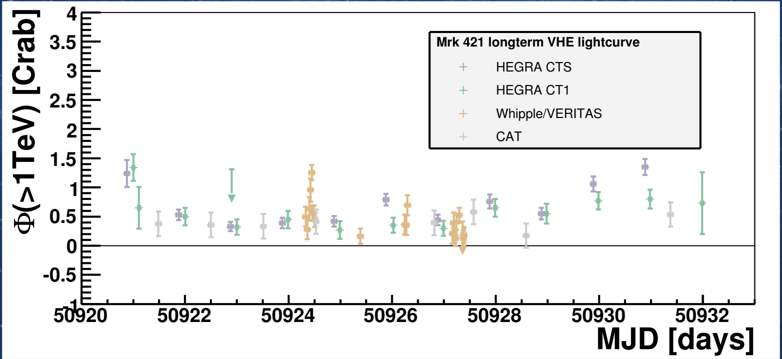
1. MJD of start of observations
2. MJD of end of observations
3. Measured flux
4. Statistical error of measured flux
5. Systematic error of measured flux
6. Spectral index
7. Spectral index statistical error
8. Spectral index systematic error
9. Energy threshold
10. Energy Cutoff
11. Experiment
12. Duration 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
- $F(E > 1\,\mathrm{TeV}) = \left(\frac{E_{thr}}{1\,\mathrm{TeV}}\right)^{-\Gamma+1} \frac{\Phi(>E_{thr})}{\Phi_{Crab}(E>1\,\mathrm{TeV})}$

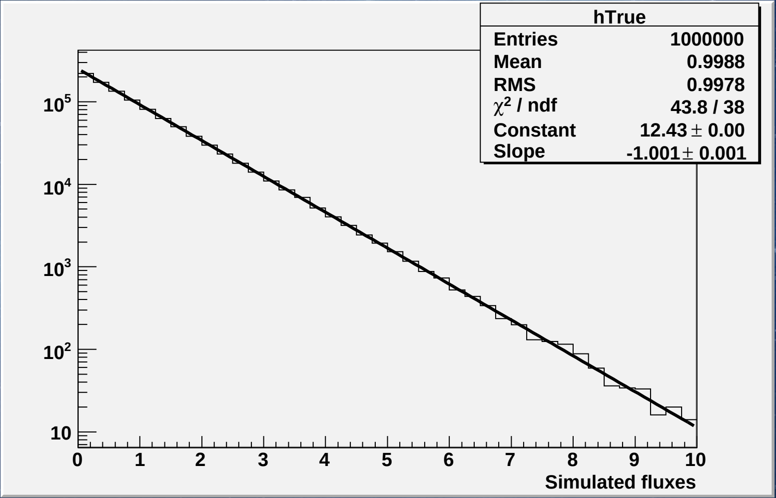


Plans

- variability simulation
- propper treatment of upper limits

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 %