Flux, fluence and upper energy cutoff for GRB 970417a

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1 Introduction

The impact of observing virtually any object with Milagro/Milagrito is that we are looking at the upper energy end of the emmision spectrum for that object. In the case of our observation of an excess from GRB 970417a we are confident that we have observed higher energy gamma-rays that has ever before been seen from a grb, and that at least one grb is bright at teV energies. This memo addresses the question of how we quantified how bright and at what energies and compare these to the BATSE observation of GRB 970417a. We find that the emission at TeV energies is much brighter than that at keV energies and that the TeV observations are not consistent with an extrapolation of the BATSE measured spectrum. We use the scaler data to find that the spectrum at TeV energies must be harder than E-2.86 and must extend up to at least 700 GeV for a 3 sigma upper limit on the scaler counts.

2 Air-shower simulations

We threw simulations at discrete energies from 50 GeV to 100 TeV. We wanted to simulate conditions during GRB 970417a, so these were all from a zenith angle of 22 degrees. Nine tubes were not working during the time of the burst. These tubes were (from DAW) 81, 96, 101, 105, 150, 194, 195, 207, 213. We switched these tubes off for the simulations.

Energy (GeV)	Throws	Throw area	Triggers	Eff. Area (m^2)
50	5000000	200x200	8	0.064
100	1387697	300x300	9	0.58
200	502397	300x300	32	5.73
500	76653	300x300	49	57.53
1000	38888	300x300	146	337.89
2000	29118	300x300	523	1616.5
5000	20000	300x300	1832	8244
10000	8000	300x300	1952	21960
50000	800	2000x2000	25	125000
100000	300	2000x2000	17	226667

Table 1: Milagrito air-shower simulations for a zenith angle of 22 degrees.

3 Scaler simulations

There are sixty scaler channels, four for each patch. Three or four PMTs feed into one scaler channel. The number of scaler counts were incremented by one if one or more of the PMTs in a scaler channel were hit. Four noisy scaler channels were excluded from the analysis of the data on GRB 970417a. In addition to the dead tubes listed above, the tubes corresponding to these four noisy channels were switched off. We found that the

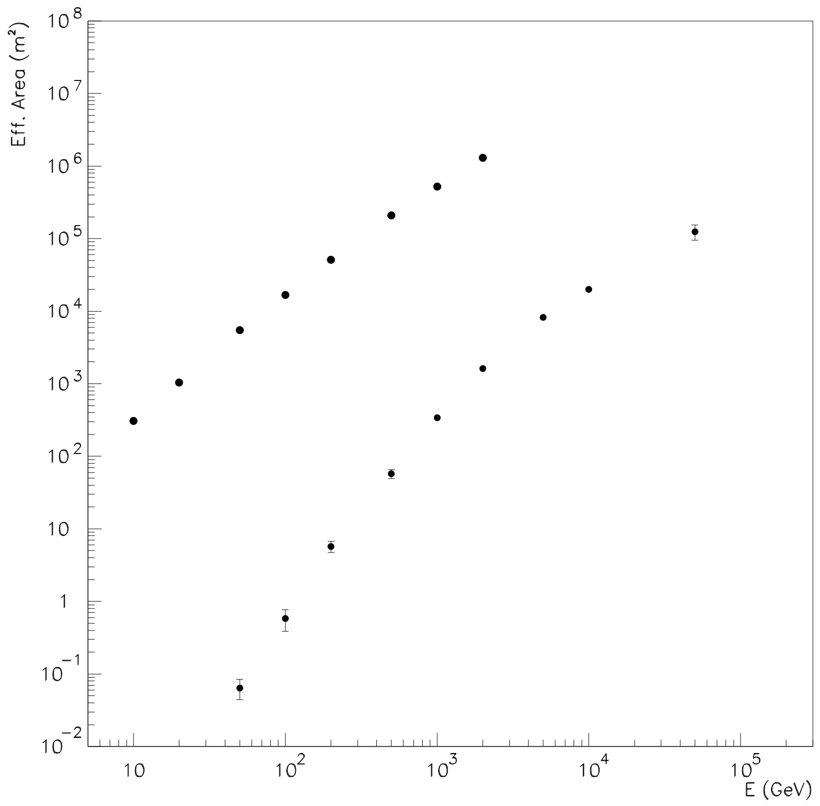

Figure 1: Effective area versus energy for air-shower and scaler simulations

throw area needed to be much larger than for the air-shower simulations. For example, the effective area for the scalers to 20 GeV gamma-rays increased from 421.7 m^2 to 1044.2 m^2, when the throw area was increased from $300m \times 300m$ to $2000m \times 2000m$. The effective area is (throw area)*(scaler cnts)/throws. The error in this number is not SQRT(scaler cnts), but is more likely dominated by fluctutions in the number of showers which triggered at least one tube. The number of showers with at least one hit PMT has been included in table 2.

4 Fluence

Using the effective area versus energy data for the air-showers, we can integrate to find the implied fluence for an excess of 18 photons as a function of assumed differential energy

Energy (GeV)	Throws	Throw area	scaler cnts.	Trigs	Eff. Area (m^2)
10	3400000	1500x1500	464	130	307.1
20	5696390	2000x2000	1487	398	1044.2
50	5000000	3000x3000	3025	813	5445
100	800431	3000x3000	1488	376	16730.9
200	502397	3000x3000	2856	697	51162.7
500	107682	3000x3000	2501	540	209032.1
1000	58890	3000x3000	3429		524044.8
2000	23047	3000x3000	3330		1300386.2
5000	15000	3000x3000	5915		3549000

Table 2: Milagrito scaler simulations for a zenith angle of 22 degrees.

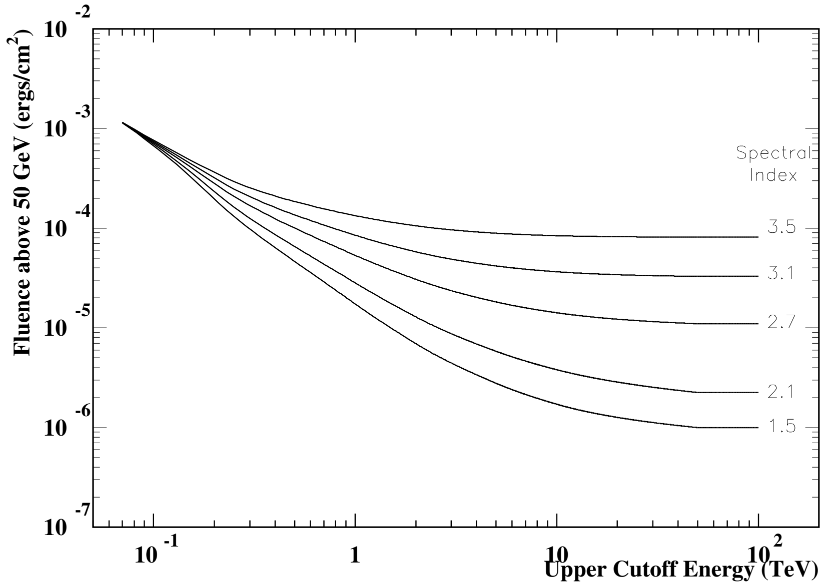

Figure 2: Fluence (>50GeV) as a function of upper cutoff energy for 5 assumed differential spectral indices

spectrum and high energy cutoff.

$$fluence = \int E \times \frac{dN}{dE}$$

We integrate from 50 GeV to the upper cutoff energy and plot the results as a function of upper cutoff energy for a range on assumed input spectra in figure 2.

4.1 Comparison with BATSE

The best spectral fit to the BATSE data is a single power law (not Band function) with a differential spectral index of -2.7 ± 0.2. In the energy range from 20 keV to 300 keV the fluence measured by BATSE was 1.673×10^{-6}. A standard quantity to compare power output at different energies is $E^2 dN/dE$

$$E^2 dN/dE = 2.72 \times 10^{-5} \times E^{-0.7}/(keV)$$

Obviously to compare this to our data we have to assume an input spectrum and cutoff energy. For example consider an $E^{-2.1}$ spectrum and a cutoff at 600 GeV, the implied fluence from 50 GeV to 600 GeV is 5.175×10^{-5} (from figure 2. The fluence at TeV energies is then

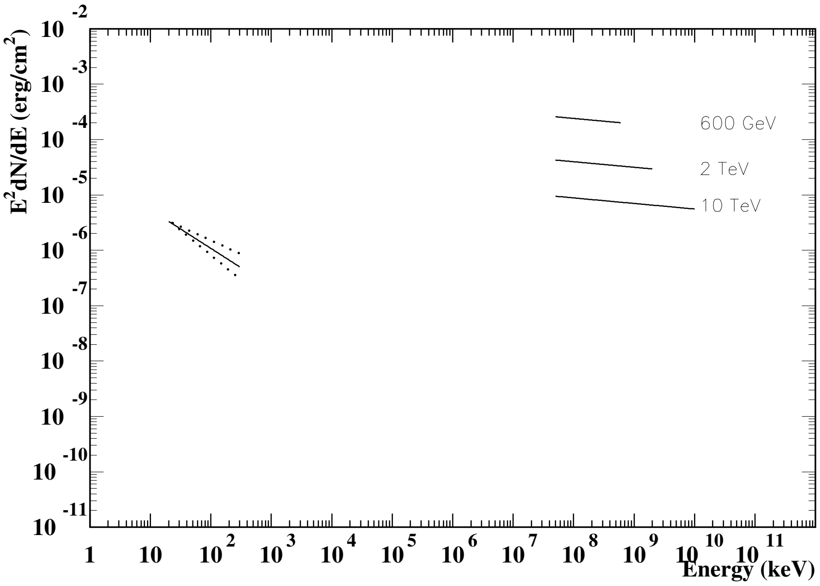

Figure 3: Spectral energy distribution showing BATSE data form 20 keV to 300 keV, and the implied fluence of the Milagrito observation for an assumed $E^{-2.1}$ spectrum with upper energy cutoffs at 600 GeV, 2 TeV and 10 TeV respectively

$$E^2 dN/dE = 3.818 \times 10^{-4} \times E^{-0.1}/(GeV)$$

for an $E^{-2.1}$ spectrum and a cutoff at 2 TeV, the implied fluence from 50 GeV to 2 TeV is 1.28×10^{-5}. The fluence at TeV energies is then

$$E^2 dN/dE = 6.3 \times 10^{-5} \times E^{-0.1}/(GeV)$$

for an $E^{-2.1}$ spectrum and a cutoff at 10 TeV, the implied fluence from 50 GeV to 10 TeV is 3.7849×10^{-6}. The fluence at TeV energies is then

$$E^2 dN/dE = 1.4 \times 10^{-5} \times E^{-0.1}/(GeV)$$

To give you a feel for how our measuremnet compares to BATSE these data are plotted in figure 3. The dotted line around the BATSE line corresponds to an E-2.5 and E-2.9 spectrum (the measured BATSE spectrum is E-2.7(+-0.2). The upper energy cutoff corresponds to a limit on redshift. If we wish to have a higher upper energy cutoff and lower fluence, then we require that the GRB be relatively close. For a cutoff at 600 GeV the opacity of the universe is one at a redshift of 0.1, for cutoffs above 2 TeV the opacity becomes one at 0.5 (from James Bullock's thesis). The curve for redshift vs. energy for an opacity (for IR absorption) of one is appoximately flate between 2 TeV and 10 TeV.

5 Limits on Spectra and Cutoff Energy

5.1 Introduction

Shortly after the discovery of a possible excess in GRB 6188, the possibility that the excess could be due to a very large flux of lower energy (<100 GeV) gamma-rays was raised. Since the scalers are more sensitive than the air-shower data at low energies it seemed feasible that the scalers could be used to put a lower limit on the maximum photon energy.

The Milagrito pond was divided into 15 patches with either 12 or 16 pmts per patch. There were 4 scaler channels per patch, each consisting of 3 or 4 pmt channels or'd together. Each of the low threshold scaler channels is read once per second. A scaler count in any given channel is obtained when one or more of the 4 pmts fire. So if the pond was hit by a very large event and all tubes fired, the increase in scaler counts would be 60.

Distributions of scaler count rates are broader than $\sqrt{N}$ statistics due to correlations in hits. One shower can produce several scaler counts. In order to establish the significance of a scaler excess or to determine the sensitivity of the scalers we need to find the width of these distributions.

5.2 Data Analysis

We first needed to decide which data we would include in this analysis. Figure 4 shows the scaler read duration as a function of time. The read duration of the scaler channels is not exactly one second, but depends on the cpu load on mgroems. The widely scattered points that can be seen on the top panel occur during periods of greater cpu activity on mgroems. The bottom panel shows the data we used in this analysis (the grb occured at 50016 seconds).

The top panel in Figure 5 shows the scaler rate as a function of time for each scaler channel. One can clearly see evidence of a noisy channel at the top of this plot. It is necessary to exclude noisy channels from the analysis. To identify noisy channels (those with large fluctuations) we calculated $d = rms/sqrt{<}\, rate >$ for each channel. For a

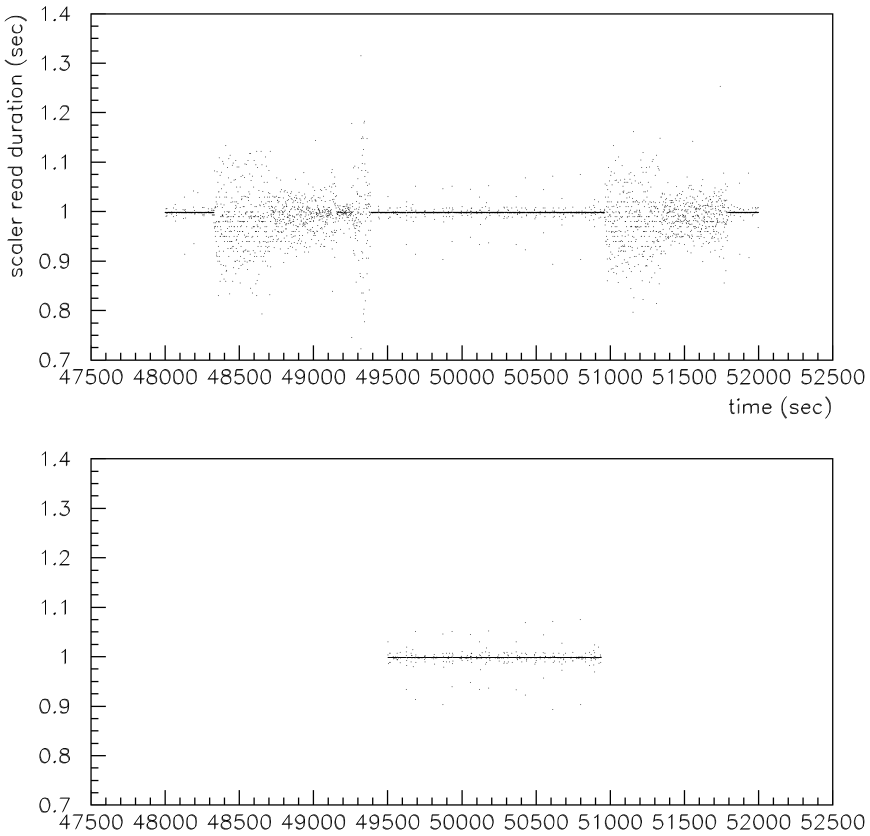

Figure 4: Scaler read duration as a function of time

Poisson distribution the standard deviation $= \sqrt{< rate >}$, thus if the scaler counts obey $\sqrt(N)$ statistics we would expect the distribution of this parameter for the scaler channels to be centered on one. Scaler channels which are noisy will have d >> 1. The bottom left panel of Figure 5 shows the distribution of d for the 60 scaler channels. You can clearly see that 4 channels are significantly more noisy than the rest. We excluded these channels (42,62,11,15) from the analysis. The rest of the scaler channels are shown in the bottom right panel, the center of this distribution is at 1.4. Thus the rms of 1 second distributions is 1.4 times wider than for one would expect for $\sqrt{N}$ statistics. This we believe is due to correlations between scaler hits.

The remaining channels were summed and binned in 1 second intervals. The $rate/\sqrt{< rate >}$ for these bins as a function of time are shown on the bottom panel of Figure 6. The histogram of the scaler counts for these one second intervals is shown on the top of Figure 6. The width of this distribution is $7299/\sqrt{4.420 \times 10^6} = 3.48$ times broader than one would

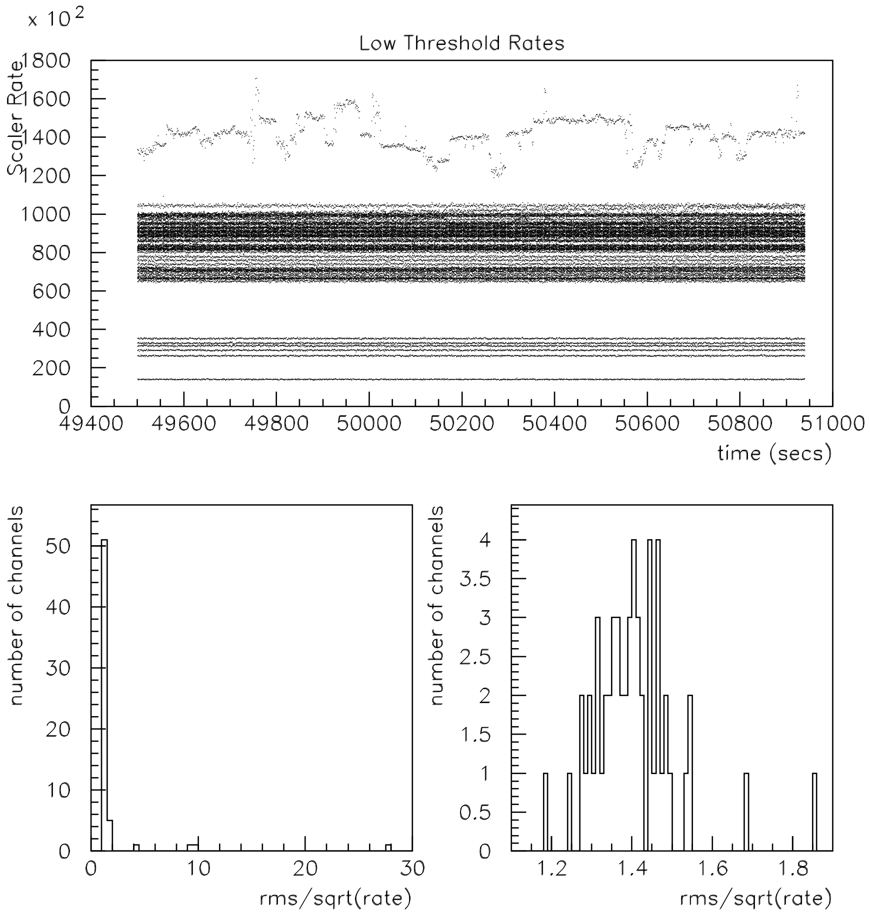

Figure 5: The top panel shows, for each scaler channel, its rate as a function of time. The histogram in the bottom right panel is the distribution of $rms/\sqrt{< rate >}$ for the 60 scaler channels. The graph in the bottom left panel shows the same distribution with the 4 hot channels removed.

expect from $\sqrt{N}$ statistics.

We are more interested in intervals of T90 (8sec). Figure 7 shows the same data binned in 8 second bins. The solid line in the plot on the bottom panel of this figure indicates the T90 interval for GRB 970417a. We do not see the burst in the scaler data, there is a small deficit. The rms deviation is $2.336 \times 10^4/\sqrt{3.536 \times 10^7} = 3.93$ times larger than one would expect from $\sqrt{N}$ statistics. Thus for a given rate to be 3 sigma from the rest of this distribution the rate must be $3*4*\sqrt{N}$ above the average rate. We then decided on a level at which we would consider a scaler excess to be significant - we chose a 3 sigma excess - which corresponds to an increase of $4*3*\sqrt{N} = 12\ \sqrt{N}$, We then used simulations to determine what photon flux is required for this excess. We then ask the question: What

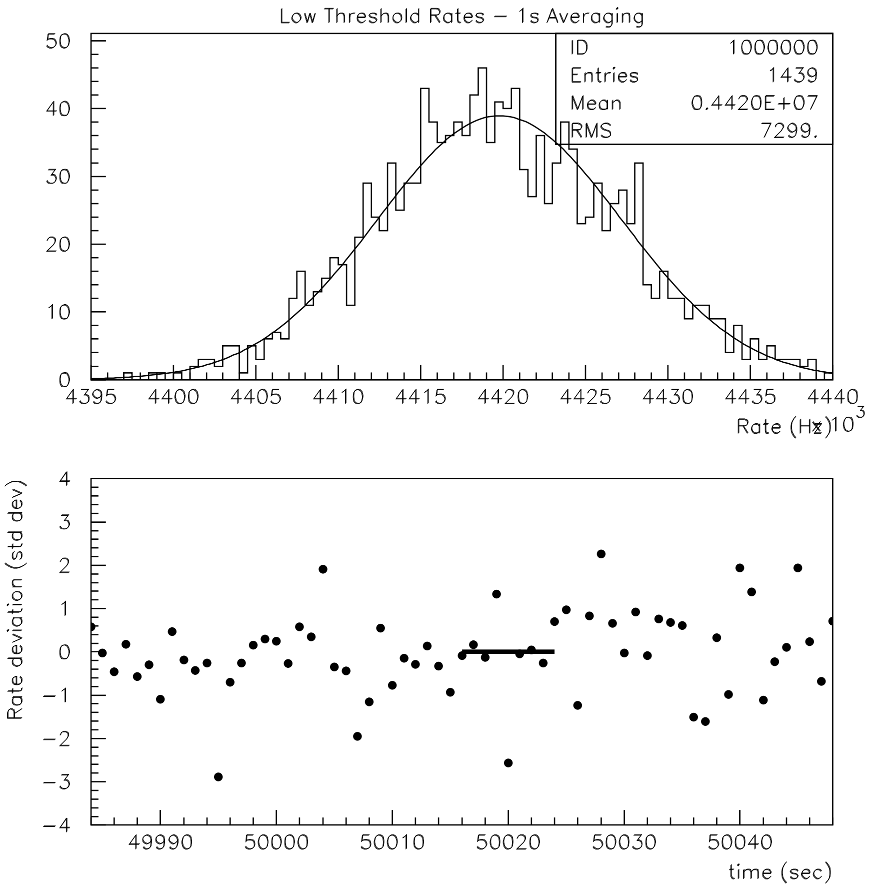

Figure 6: The bottom panel shows the summed scaler rates per second (in units of standard deviations) as a function of time for the 56 scaler channels used in the analysis. The top panel shows the distribution of these rates. The width of this distribution is 3.48 times broader than one would expect from $\sqrt{N}$ statistics

(if any) combinations of assumed spectrum and cutoff energy will the observation of the 18 air-shower events imply that or higher photon flux? This combination of spectrum and cutoff energy is therefore excluded by the non-detection of a significant excess in the scalers.

to summarize, 4 scaler channels were found to be noisy and were excluded from the analysis. The sum of the remaining 56 scaler channels showed no excess during T90 above the average rate for the surrounding 1500 seconds. The background fluctuations in the low threshold scalers when binned in 8 second intervals was found top be about 4 times wider than $\sqrt{< rate >}$.

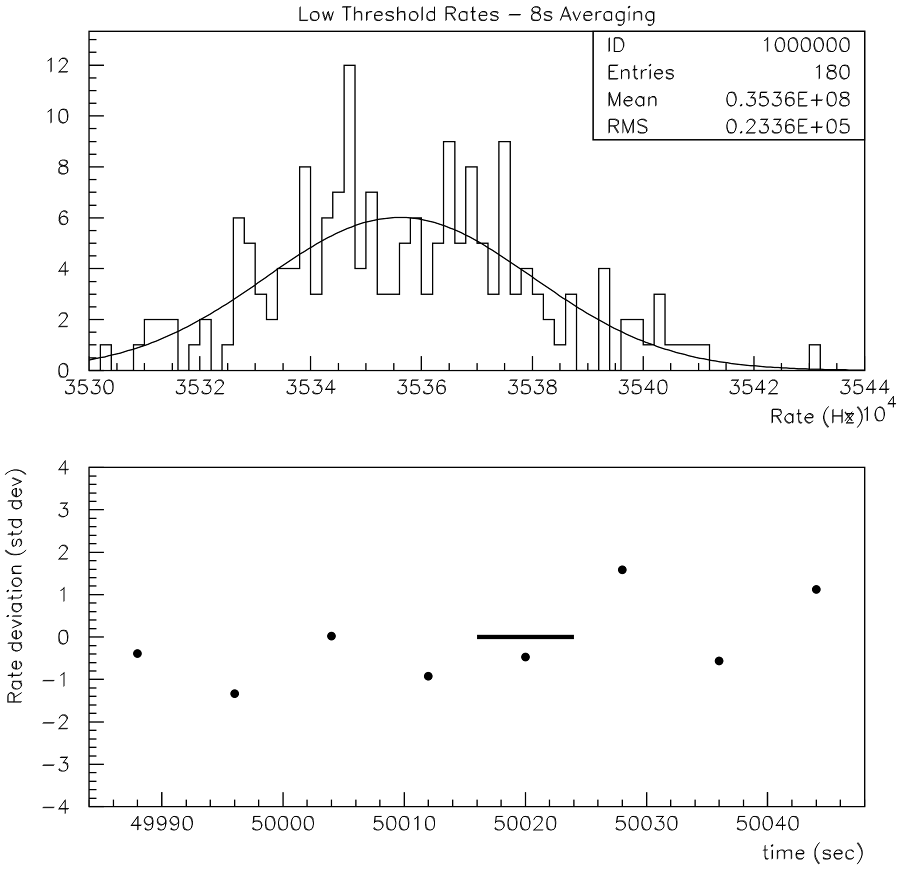

Figure 7: The bottom panel shows the summed scaler rates per 8 second bin (in units of standard deviations) as a function of time for the 56 scaler channels used in the analysis. The horizontal line indicates the t90 interval for GRB 970417a.The top panel shows the distribution of these rates. The width of this distribution is 3.93 times broader than one would expect from $\sqrt{N}$ statistics

5.3 Deriving Limits on max. energy and spectra

Using the effective area vs energy data in table 2, for an assumed differential power law spectrum and upper energy cutoff on can obtain the flux as a function of energy implied by the observation of an 18 event excess. One can then combine this information with the data in table 2 to find how many excess scaler counts would arise. We did not observe an excess in the scaler data, we can therefore exclude all combinations of spectral index and upper cutoff energy which would have given rise to an observable excess in the scaler data. We required a 3 sigma excess before we would consider a detection significant. The distribution of scaler rates, for 8 second bins, around the time of the burst was a factor of

4 wider than expected from sqrt(N) statistics.

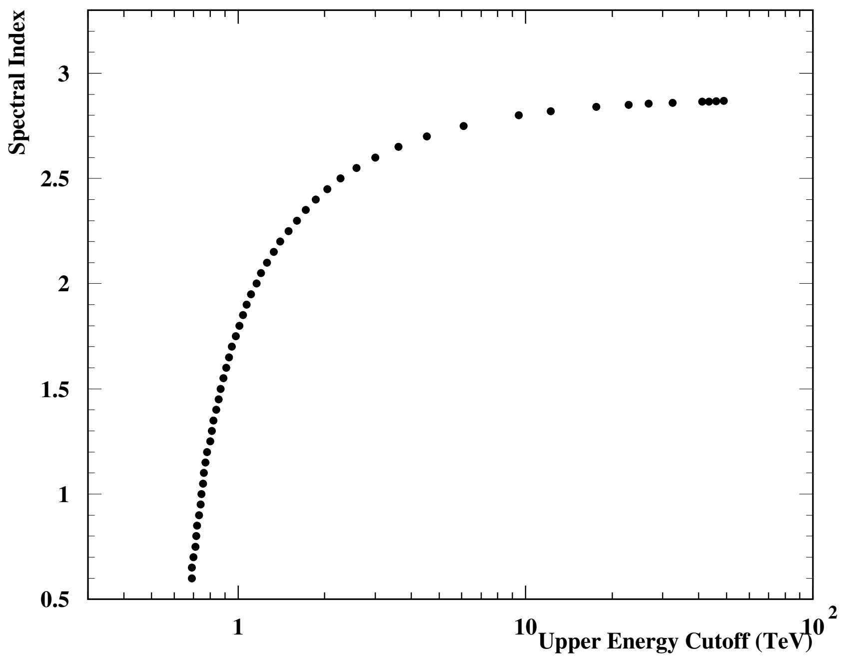

Figure 8: Spectral index vs cutoff energy which give rise to a 3 sigma excess in the scaler data. The region above and to the left of this line is excluded at the 3 sigma level by the non-detection of an excess in the scaler data. This implies that the spectrum of GRB 970417a at TeV energies must have been harder than E-2.8 and must have extended up to at least 700 GeV

The background in the scaler data was $4.4MHz = 3.5 \times 10^7$ (see section 5.2 above) scaler counts for the period around the burst time. For a 3 sigma detection we require 70993 (4*sqrt(bkg)) excess scaler counts. Figure 8 shows some values of spectral index and upper energy cutoff at which one would observe a 3 sigma excess in the scaler data. The region above and to the left of this line is therefore excluded at the 3 sigma level by the non-detection of an excess in the scalers. These data imply that the energies of the events observed by Milagrito from GRB 970417a extended up to at least 700 GeV and that the spectrum must have been harder than E-2.86.