COM-RP-MPE-DRG-165

Studying the ToF Spectrum as a Function of Energy Part 1: the Forward Peak Region

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1 Introduction

Any kind of analysis with COMPTEL (the "**COMP**licated **TEL**escope") is hampered by the fact that practically every event parameter depends on almost every other event parameter. These interdependencies are hard to disentangle because there are too few data on too many parameters.

A tantalizing, yet still unresolved, problem is to find an accurate description of the ToF (time of flight) distribution. The ToF, the time difference between two coincident interactions in D1 and D2, is one of the prime event parameters for reducing background events in our analyses. Moreover, proper knowledge of the ToF distribution is indispensable if absolute flux values are to be derived. Finally, the ToF distribution reflects to some degree the origin of the measured events and is therefore a powerful tool for studies of the instrumental background.

This report summarizes the results of an unsuccessful attempt to find an accurate analytic description of the ToF distribution as a function of energy. Although this ultimate goal was not reached the findings presented here may provide a useful and solid basis for future attempts to optimize ToF selections and to understand the instrumental background of COMPTEL. All studies presented in this report were performed using `GAMMA-1` data only.

The data base and the fitting procedure used to study the ToF distribution are described in Section 2 of this report. The results and conclusions of this study are summarized in Section 3.

2 Data Base and Fitting Procedure

2.1 Data Base

A large data base is needed to study the ToF distribution as a function of energy with reasonable statistical significance. In NORMAL telescope mode the event class GAMMA-1 can only be assigned to events with ToF_0 (the "in-flight ToF" value measured onboard COMPTEL, without any corrections for PMT gains or cable length or geometry effects) between channels 95 and 150[1]. When studying GAMMA-1 EVP data alone this results in smooth cut-offs of the (corrected) ToF distributions around channels 100 and 155. A comprehensive study of the shape of the ToF distribution over a wider range therefore must also take into account GAMMA-2 data, which contains events outside the GAMMA-1 ToF window. Since the telemetry buffer for GAMMA-2 data is considerably smaller than that for GAMMA-1 data, however, both types of EVP data can only be merged after a correction for the different telescope livetimes (the average GAMMA-1 livetime is around 16 sec, the average GAMMA-2 livetime is only about 10 sec). For studies limited to the forward peak region (roughly between channels 105 and 135), as is the case in this report, it is sufficient to use only GAMMA-1 data.

The GAMMA-1 data base consists of events from OPs 5 - 13.5, 15 - 18, 29 - 32, 210, 214, 223, 226, 229.5, 232.5, 302.3, 304 - 308.6 and 311 - 313 (38 OPs in total). For studies requireing both GAMMA-1 and GAMMA-2 data the following 12 OPs were used: OP 5, 6, 8, 9.5, 16, 18, 31, 305, 306, 308.6, 312 and 313. The data were selected according to the "standard cosmic diffuse background selections" introduced by Ch. Kappadath, UNH:

$$\begin{gathered}
800\ \mathrm{keV} \leq \mathrm{Etot} \leq 30\ \mathrm{MeV} \\
70\ \mathrm{keV} \leq \mathrm{E1} \leq 20\ \mathrm{MeV} \\
730\ \mathrm{keV} \leq \mathrm{E2} \leq 30\ \mathrm{MeV} \\
65\ \mathrm{channels} \leq \mathrm{PSD} \leq 95\ \mathrm{channels} \\
6^\circ \leq \bar{\varphi} \leq 38^\circ \\
\xi \leq 40^\circ
\end{gathered}$$

with ξ being the sum of $\bar{\varphi}$ and the scatter direction zenith angle. In addition only data from times when the OAD parameter

$$\mathtt{GCEL} \geq 120^\circ$$

were considered. The combination of the cut on ξ and the selection on GCEL allows all photons from the Earth's atmosphere to be excluded while the field-of-view of the telescope is independent of time.

All EVP files used in this study contain $\mathrm{ToF}_{\mathrm{II}}$ data, which means that the ToF was corrected by TOFCOR written by Rob van Dijk. This is *not* the highest quality ToF data that could be obtained. Since 1994 there is an even better ToF correction code available (IFCTCF written by Rob van Dijk, see COM-RP-ROL-DRG-62), but this has not yet been implemented as a new standard.

[1]For a comprehensive discussion of ToF please refer to Rob van Dijk's PhD Thesis

2.2 Fitting Procedure

2.2.1 ToF Spectra

In the studies of the forward peak region (using only `GAMMA-1` data) 200 ToF spectra were calculated from this data base, with the energy binning in Etot and E2 determined such that each bin contained about the same number of events. Thus the statistical significance of each fit was about the same. All ToF spectra were corrected for the livetime of the telescope. This was done for three reasons. First, `GAMMA-1` and `GAMMA-2` data can only be combined if both kinds of data are corrected with their respective livetimes. Second, the livetime correction removes any influence of the geophysical parameters on the telescope's efficiency. Finally, last but not least, working with livetime corrected count rate spectra instead of count spectra allows straight forward comparisons when time-variations are studied.

2.2.2 Models

In the analyses of the ToF distribution as a function of energy the forward peak was always represented by a gaussian. The ToF continuum in the forward peak region was described by three different simple analytical functions: a parabola, a gaussian and an exponential. The three energy dependent models are listed below.

Parabolic Model

$$f_p(tof,E) = p_1(E) \cdot \exp\left(-\frac{1}{2}\left(\frac{tof - p_2(E)}{p_3(E)}\right)^2\right) + p_4(E) \cdot (tof - p_5(E))^2 + p_6(E)$$

Gaussian Model

$$f_g(tof,E) = p_1(E) \cdot \exp\left(-\frac{1}{2}\left(\frac{tof - p_2(E)}{p_3(E)}\right)^2\right) + p_4(E) \cdot \exp\left(-\frac{1}{2}\left(\frac{tof - 80}{p_5(E)}\right)^2\right) + p_6(E)$$

Exponential Model

$$f_e(tof,E) = p_1(E) \cdot \exp\left(-\frac{1}{2}\left(\frac{tof - p_2(E)}{p_3(E)}\right)^2\right) + p_4(E) \cdot \exp\left(\frac{97.5}{p_5(E)}\right) \cdot \exp\left(-\frac{tof}{p_5(E)}\right) + p_6(E)$$

In the gaussian model the center of the gaussian describing the continuum background was fixed at ToF=80, the approximate position of the backward peak. Allowing this parameter to be varied in the fits did not improve the results.

2.2.3 Difficulties

The most difficult problem for the fitting procedure was the determination of appropriate *initial values* as a function of energy for the 6 fit parameters of each model. The initial values used in the studies described in the following were obtained from fits to the best fit parameter values of successful test fits. This was crucial for the fits to converge savely and quickly, in particular for the gaussian and the exponential model.

This problem arises from the fact that *the shape of the ToF distribution varies considerably with energy* as is illustrated in Fig. 1, which depicts the ToF distribution for the Etot bins at about 800 keV (top), 3 MeV (center) and 7 MeV (bottom), together with fits of the parabolic model. The general trend (which will be discussed in detail in Section 3 of this report) of the forward peak to decrease in width with increasing energy can clearly be seen, together with a smooth transition of the continuum background. At energies less than about 8 MeV all three models fit the ToF distributions about equally well. Between 8 MeV and 9 MeV the continuum background changes dramatically and the parabola can no longer follow its shape. This is illustrated in Fig. 2, which shows fits of the three models to the ToF distribution around Etot=15 MeV. At even higher energies none of the three models can describe the shape of the ToF distribution.

In the studies presented in this report which used only `GAMMA-1` data the fit range for the parabolic model was ToF=106 to ToF=144 at all energies. The lower limit results from the fact that the `GAMMA-1` ToF spectra start to break down at lower ToF values; the upper limit is imposed by the parabola describing the ToF continuum background which increases with increasing ToF values. The fit range for the gaussian and exponential model could be extended to higher ToF channels since these fit functions asymptotically approach a constant value with increasing values of ToF. The fit range for the exponential model was ToF=106 to ToF=148 below 7 MeV and ToF=104 to ToF=148 at higher energies. For the gaussian model the fit range was ToF=106 to ToF=148 below 9.5 MeV and ToF=104 to ToF=148 at higher energies. For these two models the fit range is entirely determined by the break-down of the `GAMMA-1` ToF distribution at low and high ToF values.

The parabolic model proved to be most robust against fluctuations in the ToF continuum close the lower boundary of the fit range. This is illustrated in Fig. 3, which depicts fits to the ToF distribution at Etot around 1800 keV with the parabolic model (top), the gaussian model with all parameters free (center), and the gaussian model with the width of the forward peak fixed at the initial value for the parabolic model (bottom). For this particular energy bin the area in the forward peak derived from the gaussian fit with all parameters free would be much too large. The same is true for the exponential model. In general the exponential model "fails" (note that according to the χ^2_ν values of the fit there is no reason for complaints) wherever the gaussian model "fails" and vice versa. The parabolic model hardly ever shows this behaviour.

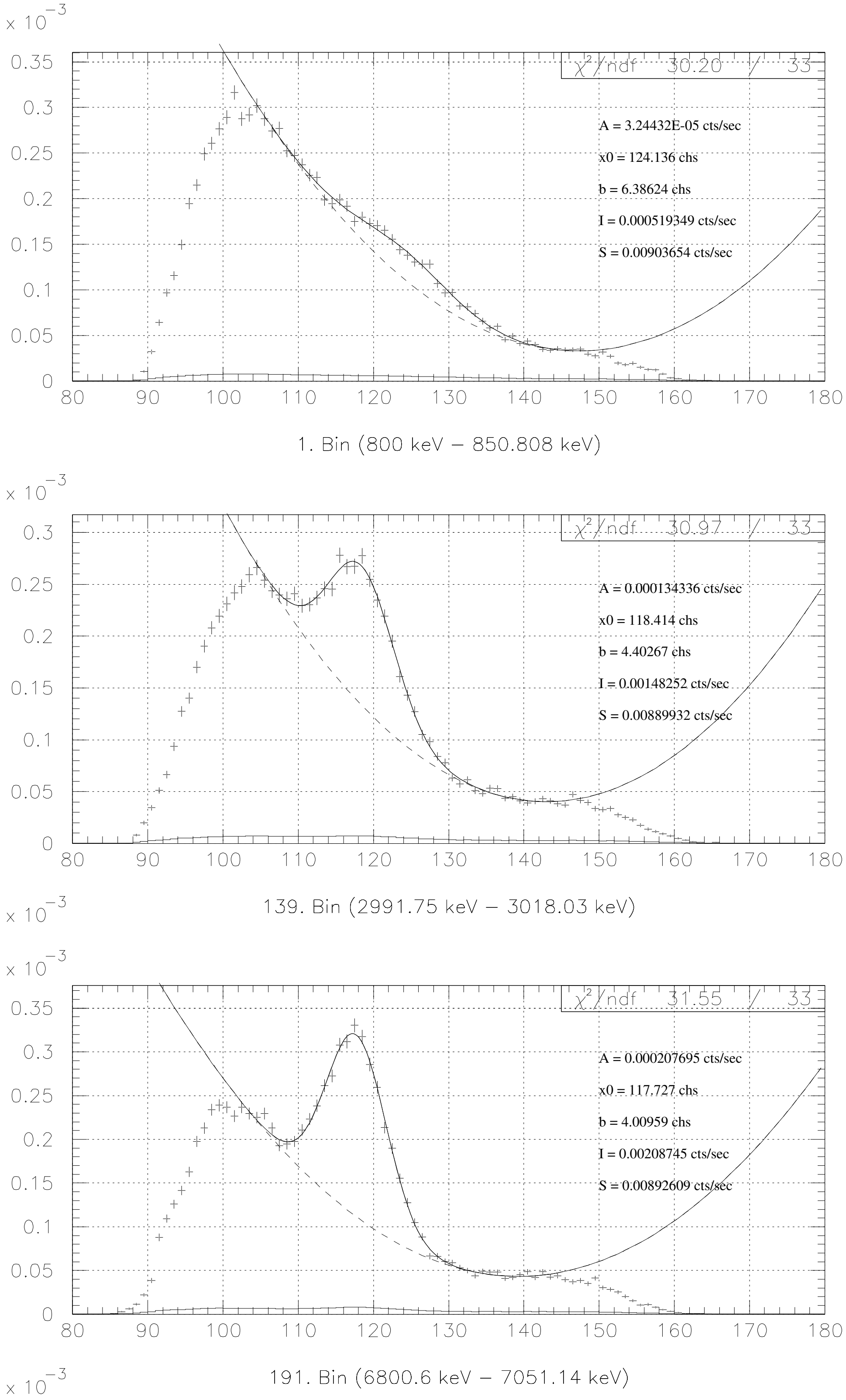

Figure 1: *Illustration of the energy dependence of the ToF distribution. Also shown are fits with the parabolic model.*

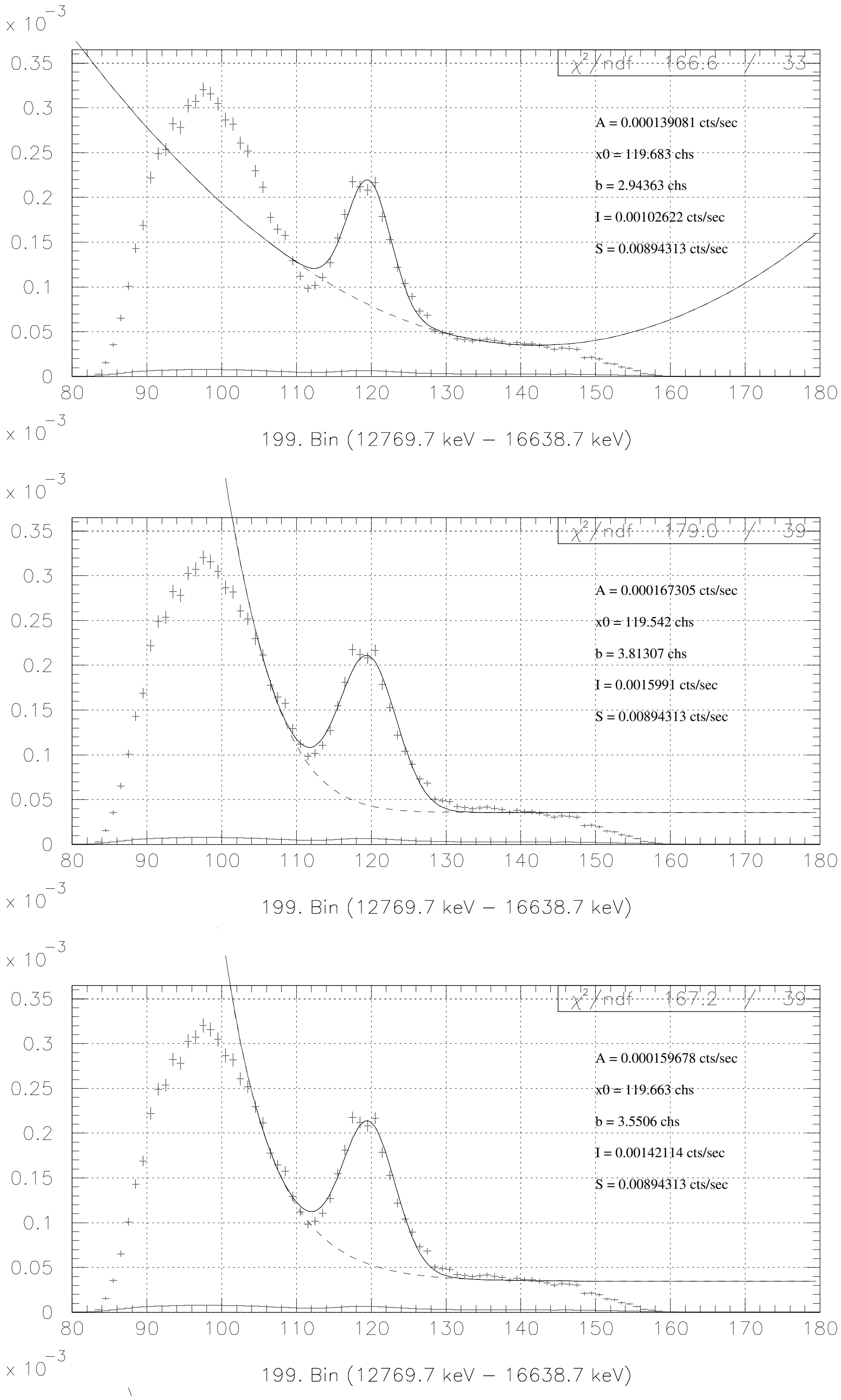

Figure 2: *Fits of the three models to the ToF distribution for Etot around 15 MeV.*

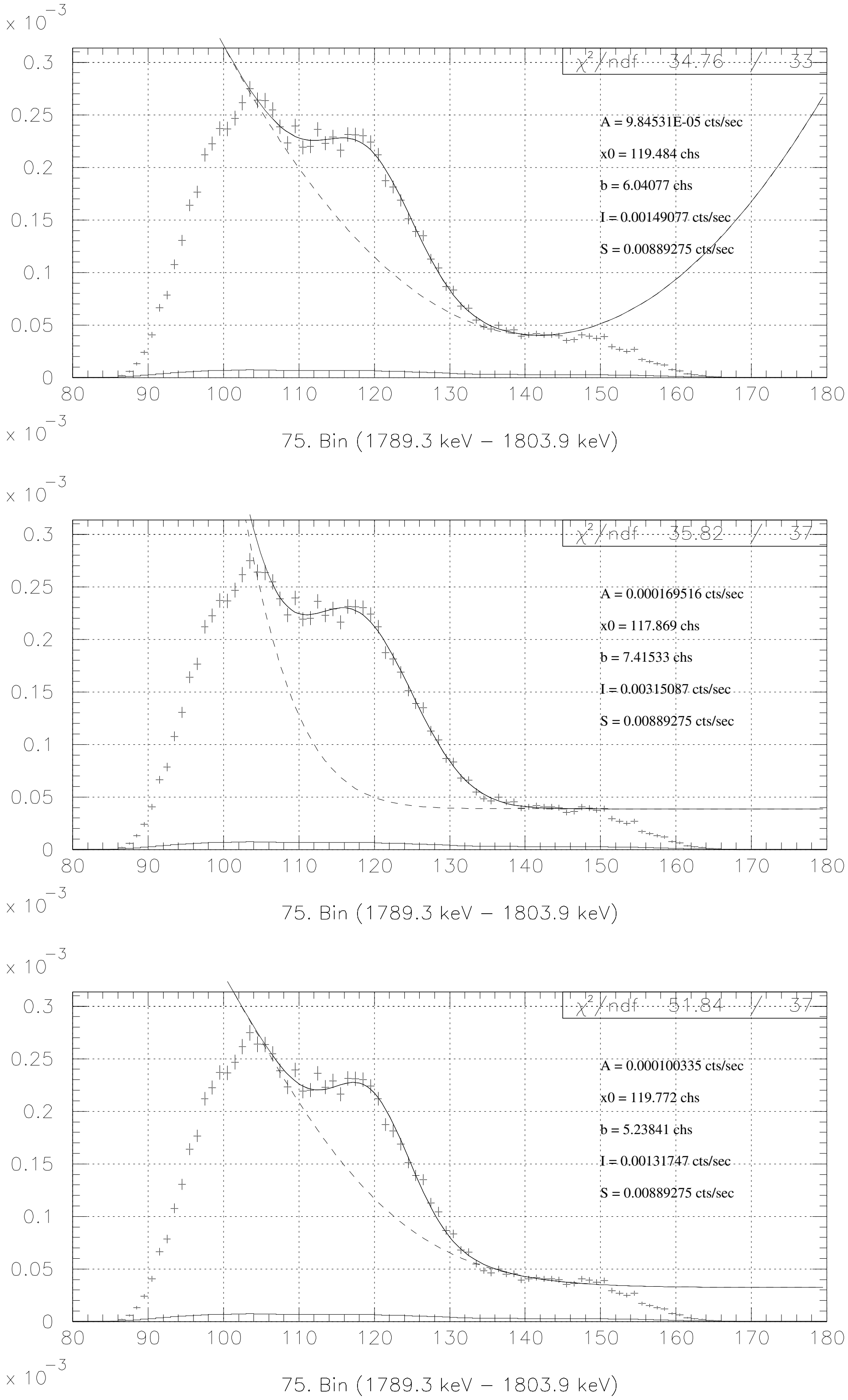

Figure 3: *Illustration of the robustness of the parabolic model and lack of robustness of the gaussian model.*

3 Results and Conclusions

3.1 Best Fit Parameter Values

The best fit parameter values for the forward peak and the ToF continuum background obtained from the study of the `GAMMA-1` data ToF distribution in the forward peak region as a function of Etot are depicted in Fig. 4 and Fig. 5, respectively. The results for the parabolic, the gaussian and the exponential model are plotted in red, green and blue, respectively.

In Fig. 4, showing the forward peak results, "Height" corresponds to the parameter p_1 for all three models. Similarly, "Center" and "Width" correspond to the model parameters p_2 and p_3, respectively. The results for the continuum background are summarized in Fig. 5. Here "Factor" corresponds to the parameter p_4, and "Position" and "Constant" correspond to the model parameters p_5 and p_6, respectively. In Fig. 5 the values of "Factor" and "Position" for the different models were scaled so that they fitted well in one plot.

All parameter values are plotted at the position of the energy-weighted centers of the energy bins for which they were derived. The scatter of the data points indicates the size of the statistical error. Sometimes "outliers" can be seen. These originate from fits that "failed", as illustrated in Fig. 3. The parabolic model is the most robust, the gaussian model is most likely to "fail". It has to be noted that the scatter in the data points decreases drastically at energies above about 2 MeV.

From Figs. 4 and 5 it is obvious that the curves describing the values of the 6 fit parameters as a function of Etot are very similar for all three models. There are, nowever, also systematic differences between the three models. The "Height" and the "Width" of the forward peak are largest for the exponential model and smallest for the parabolic model. For these two parameters the gaussian model always yields "average" values. With regard to the "Centre" of the forward peak the parabolic and the gaussian models are very similar, the only difference being the robustness of the two models. The exponential model persistently yields smaller values for the forward peak position. The values for the parameter "Constant" representing the event rate due to so-called chance coincidences behave inversely to those for "Height" and "Width" in the sense that the parabolic model now yields the largest and the exponential the lowest values. Again, the values from the gaussian model are between those from the other two models. As will be pointed out later in more detail, there seems to be a correlation between the values for the parameters "Height", "Width" and "Constant". The parameters "Factor" and "Position", which describe the prompt ToF continuum background, cannot be compared easily since they represent different analytical functions. Nevertheless, the three curves for the parameter "Factor" match almost perfectly after a suitable rescaling of the values, in particular, above 2 MeV. The different behaviour of the parameter "Position" at the highest energies reflects the capability of the different models to describe, or fail to describe, the shape of the ToF continuum background.

The parameter "Height", the amplitude of the forward peak, tracks the energy spectrum of the forward peak well (see Fig. 7), as will be discussed in detail in Sec. 3.3.1.

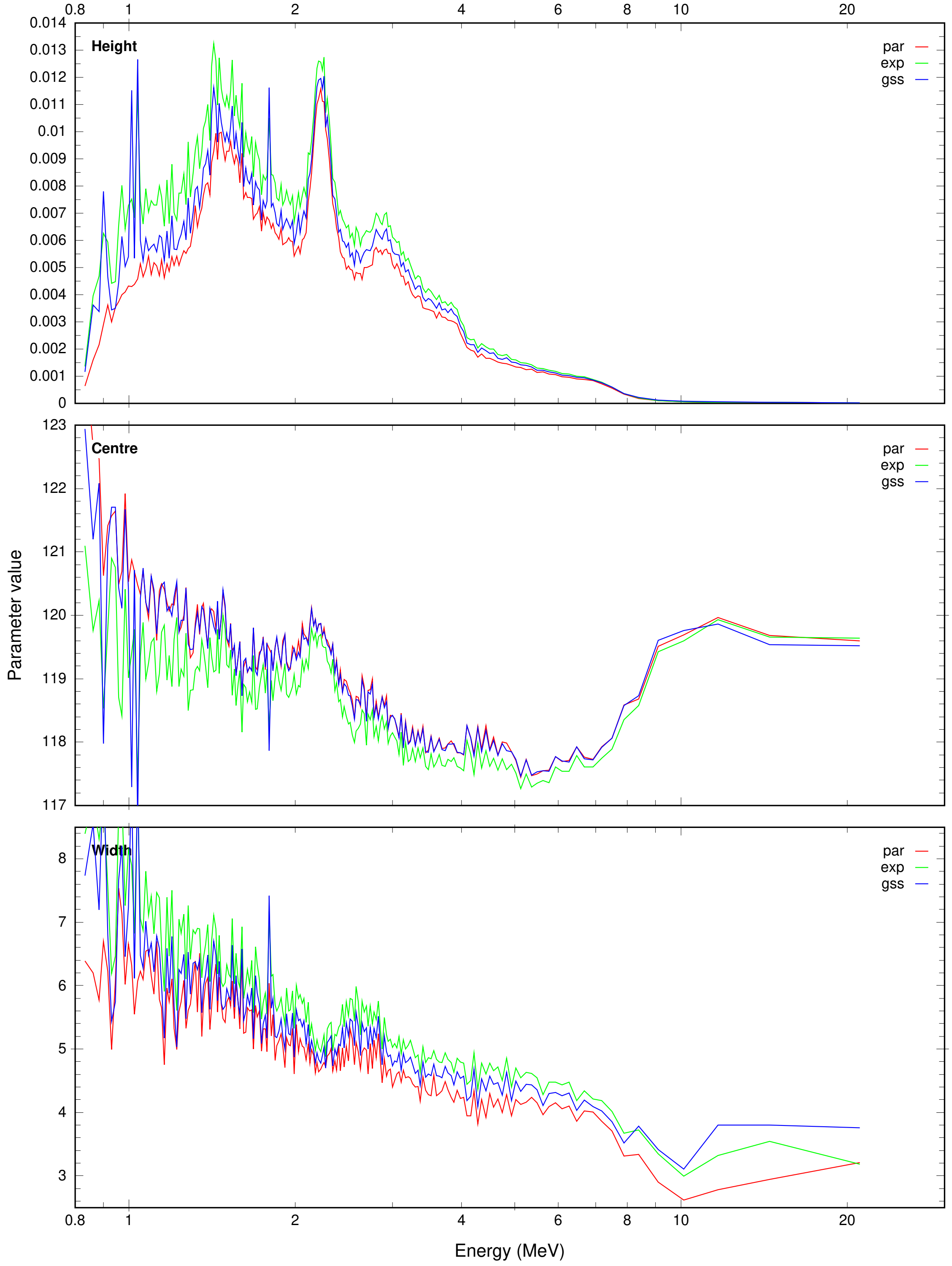

Figure 4: *The best fit values of the parameters describing the forward peak. "Height" corresponds to the parameter p_1 for all three models. Similarly, "Center" and "Width" correspond to the model parameters p_2 and p_3, respectively.*

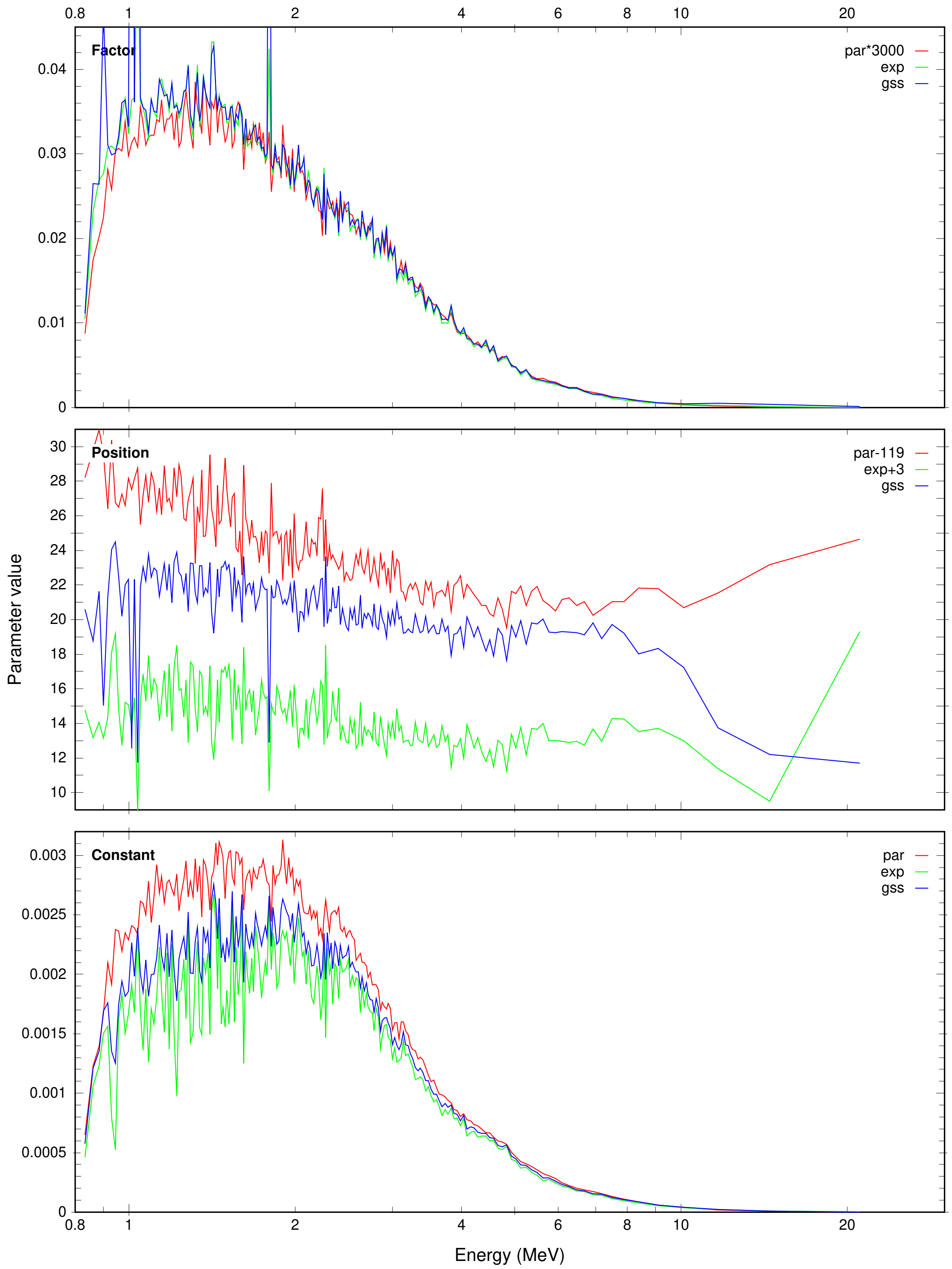

Figure 5: *The best fit values of the parameters describing the ToF continuum background. Here "Factor" corresponds to the parameter p_4, and "Position" and "Constant" correspond to the model parameters p_5 and p_6, respectively. In Fig. 5 the values of "Factor" and "Position" for the different models were scaled so that they fitted well in one plot.*

At the moment the parameters "Center" and "Position" are of much more interest. The position of the forward peak changes significantly with energy. To some degree this reflects inadequacies of the `TOFCOR` routine, but most of the variation reflects the variation of the continuum ToF background and of the background in the forward peak. The ToF correction factors used in `TOFCOR` were derived by fitting the ToF forward peak in Earth-viewing where the forward peak dominates the instrumental background. For sky-viewing data, as it was used in this study, the situation is very different, except for energies where strong instrumental lines dominate, such as the 2.2 MeV line or, to a lesser extent, the "1.4 MeV line", or where the instrumental background is of the same magnitude as the celestial signal, as is the case above about 9 MeV. At these energies the position of the forward peak is very close to the nominal value of 120 channels. At all other energies the instrumental background dominates and results in a systematic shift of the forward peak. The fact that all three models consistently show this shift indicates that it is not an artifact of the models - it has a physical origin. The forward peak not only consists of celestial photons (which peak at ToF $\approx$ 120 channels), but also of instrumental background. The ToF distribution of this background depends on the physical process that produces this background, and on the location of those parts of the telescope that emit this background. The 2.2 MeV line is produced within the D1 detector, therefore the 2.2 MeV line photons have a ToF distribution that is narrowly peaked around channel 120. The ToF distribution of the ^{24}Na cascade is different. It peaks slightly below ToF=120 (see `COM-RP-MPE-DRG-162` by M. Varendorff and G. Weidenspointner) because it is a 2-photon process with simultaneous emission of a β-particle and because it originates from the Al-structure around D1. The ToF forward peak as it is seen in the data is the superposition of many different ToF distributions, only one of which results from celestial photons.

The energy dependence of the width of the forward peak is only indirectly influenced by the instrumental background. The width of the forward peak is determined by the D1 and D2 energy deposits (or more precisely: by the D1 and D2 analogue sums, see `COM-RP-ROL-DRG-62` by Rob tof Dijk): the larger the D1 or D2 energy deposit (analogue sum) the narrower is the forward peak. This is nicely illustrated by the dip in the measured forward peak width at 2.2 MeV. The 2.2 MeV photons are produced isotropically within the D1 detector. Thus they have to scatter on the average by a large angle to hit the D2 detector, which results in large D1 energy deposits and therefore a narrow forward peak. It is interesting to note (although it should be no surprise) that the robustness of the fits increases with decreasing line width. This is clear from Fig. 1: the narrower the forward peak the better defined is the ToF continuum background. It seems that at forward peak widths less than about 5.5 channels all three models are insensitive to statistical fluctuations in the ToF continuum background. As will be shown later, the width of the forward peak is the fit parameter that determines the fit! It also seems that improving the ToF in the standard `GAMMA-1` data by implementing $\mathrm{ToF_{III}}$ (the ToF returned by `IFCTCF`) would extend the energy range that allows good ToF fits to lower energies.

3.2 Statistical Significance of the Fits

A comparison of the values of χ^2_ν for fits of different exponential and gaussian models with the values from the fit with the parabolic model is given in Fig. 6. "Exponential/Gaussian" refers to fits of the respective models with all parameters varied freely. "Exponential-par/Gaussian-par" and "Exponential-Fix/Gaussian-Fix" refers to fits of the exponential/gaussian model with the width of the forward peak fixed at the initial value of the parabolic model or the initial value of the exponential/gaussian model.

As can be seen from Fig. 6, in general all models fit the data about equally well (or equally bad). There are small systematic differences between the different models that reflect systematic changes in the shape of the ToF continuum background. Below 3.5 MeV the parabolic and the gaussian model are practically identical from a statistical point of view. At these lowest energies the exponential model is slightly worse, especially around 1.3 MeV and 2.7 MeV, the position of the ^{24}Na cascade lines. From 3.5 MeV to about 8 MeV the parabolic and the exponential models are statistically identical, with the gaussian model being slightly better. Between 8 MeV and 10 MeV the shape of the ToF distribution changes dramatically, as will be discussed later in more detail. This change is clearly seen in the increase of the χ^2_ν values for all models. Above 10 MeV none of the models can properly describe the shape of the ToF distribution.

In conclusion the χ^2_ν values of all the different models are practically independent of the energy below about 8 MeV, above this energy all models "fail". No model can be preferred to any other model on a statistical basis.

3.3 Forward Peak and ToF Continuum Background Energy Spectra

3.3.1 Time-Averaged Spectra

Using the best fit parameter values depicted in Figs. 4 and 5 the energy spectrum of the forward peak and of the ToF continuum background were calculated for the ToF range from 107 channels to 130 channels. The two energy spectra are depicted in Fig. 7 and Fig. 8 for the Etot ranges from 800 keV to 8 MeV and from 5 MeV to 22 MeV, respectively (note that the energy-weighted center of the last energy bin from 16.6 MeV to 30 MeV is at about 21 MeV). The curve for the parabolic model with all parameters free is labeled "Parabola". Because of the scatter in the results for the gaussian and the exponential model with all parameters free these results are not shown. Instead, the results shown were derived by fixing the width of the forward peak at the initial value of the parabolic model (labelled "-par") or by fixing the width at the initial value of the respective model (labelled "-Fix"), which corresponds to a fit with a robust exponential or gaussian model.

As was to be expected from the curves for the best fit parameter values, the shapes of the energy spectra of the forward peak and the ToF continuum background are very similar for all models, with the forward peak spectrum being dramatically different from the spectrum of the ToF continuum background. Up to about 9 MeV the forward peak spectrum is

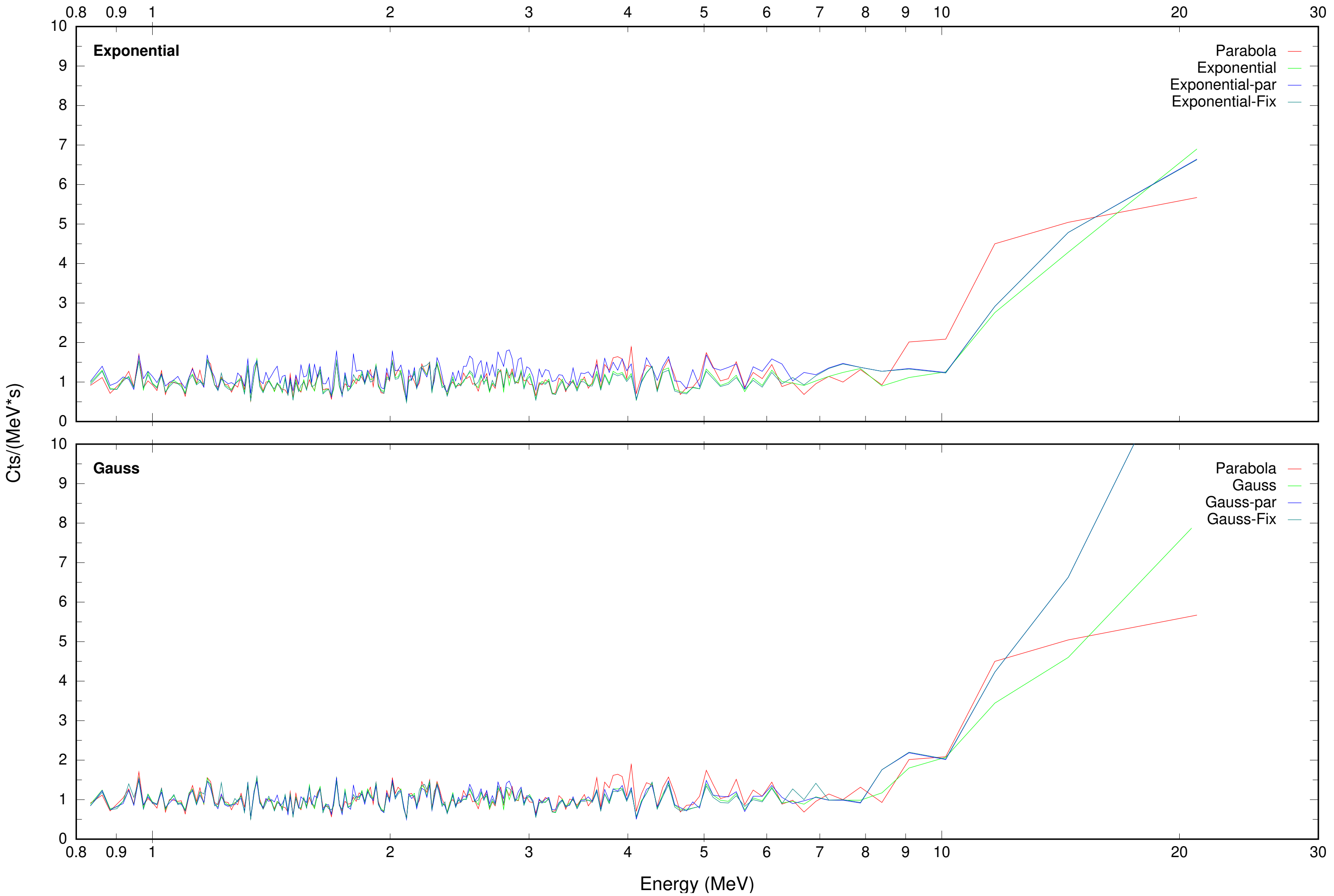

Figure 6: A comparison of the values of χ^2_ν for fits of different exponential and gaussian models with the values from the fit with the parabolic model.

basically a nuclear spectrum consisting of the superposition of some strong characteristic structures due to individual isotopes such as ^{2}H, ^{24}Na or ^{40}K and an underlying nuclear continuum which breaks down rather abruptly between 7 MeV and 9 MeV. Above 9 MeV the forward peak spectrum is smooth. In comparison, the energy spectrum of the ToF continuum background is very smooth. There are no line features and the significance of the little extended structure is low. There is no abrupt breakdown at 8 MeV, the ToF continuum is smooth over the whole energy range under study. From this it has to be concluded that the signal of all the instrumental background lines in the forward peak ToF flight range used in astrophysical studies is contained in the forward peak (which ideally should contain only celestial photons)!

As also was to be expected from the results for the best fit parameter values, there are systematic differences between the different models. The parabolic model ("Parabola") systematically yields the lowest forward peak count rate and consequently the largest ToF continuum count rate. From all models the exponential model ("Exponential-Fix") results in the highest forward peak and lowest ToF continuum background count rates. The gaussian model ("Gauss-Fix") returns rates close to the model "Exponential-Fix" at the lowest energies below 1 MeV. At higher energies the robust gaussian model returns count rates about half way between the parabolic model and the robust exponential model. This systematic can be understood if the curvature of the three models is considered. The curvature of the parabolic model is the smallest, and this model is the least suited to increase the curvature. On the other hand the curvature of the exponential is largest, and the curvature can be increased most easily. A large curvature of the function describing the ToF continuum background results in a large number of counts assigned to the forward peak. This effect is illustrated in Fig. 3, center and bottom, where the curvature of the ToF continuum background is small and large, respectively. The different curvatures of the different models are also reponsible for the systematic differences in the forward peak widths (see Fig. 4 bottom). In the parabolic model the parabola with its small curvature is picking up part of the wings of the forward peak and thus the width of the forward peak is small. If the ToF continuum background is described by an exponential then the wings of the forward have to be taken up by the gaussian - and the width of the forward peak is large.

It is very interesting to fix the width of the forward peak in the fits with the gaussian model (see "Gauss-par") and the exponential model (see "Exponential-par") at the parabolic initial value. This results in a significant decrease of the difference between these two models and the parabolic model. In fact, the width of the forward peak determines to a large degree the forward peak and ToF continuum background rate derived with the different models. If the "true" forward peak width were known, it wouldn't matter too much which model were used in the fit.

The systematic difference in the forward peak and ToF continuum background intensities was to be expected considering the systematic differences in the best fit parameter values described in Sec. 3.1. At first sight the systematic difference in the intensities seems to decrease with increasing energy. This is not exactly the case: the systematic difference decreases with decreasing forward peak width (which in turn decreases with increasing

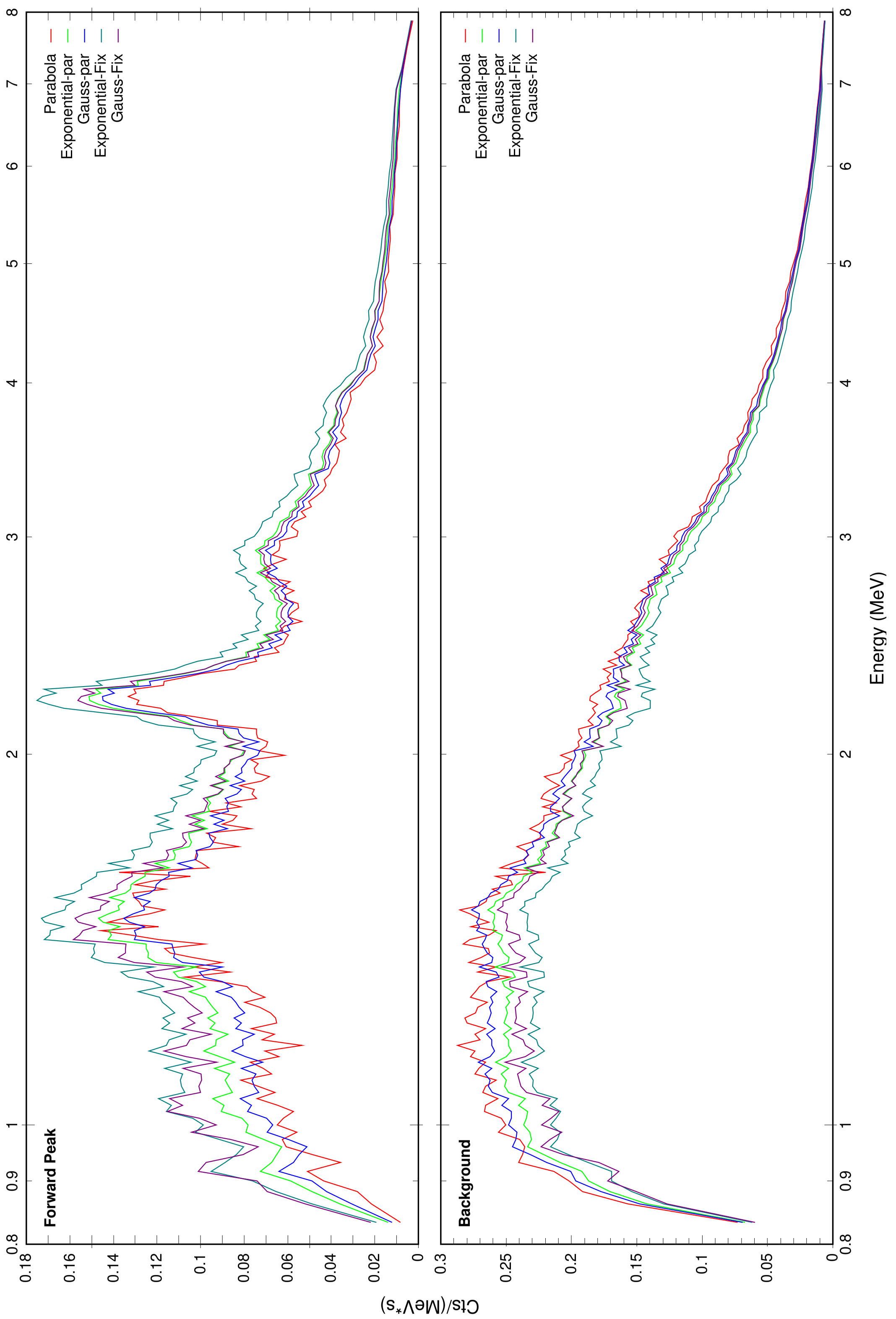

Figure 7: *The forward peak and the ToF continuum background signal from 0.8 MeV to 8 MeV.*

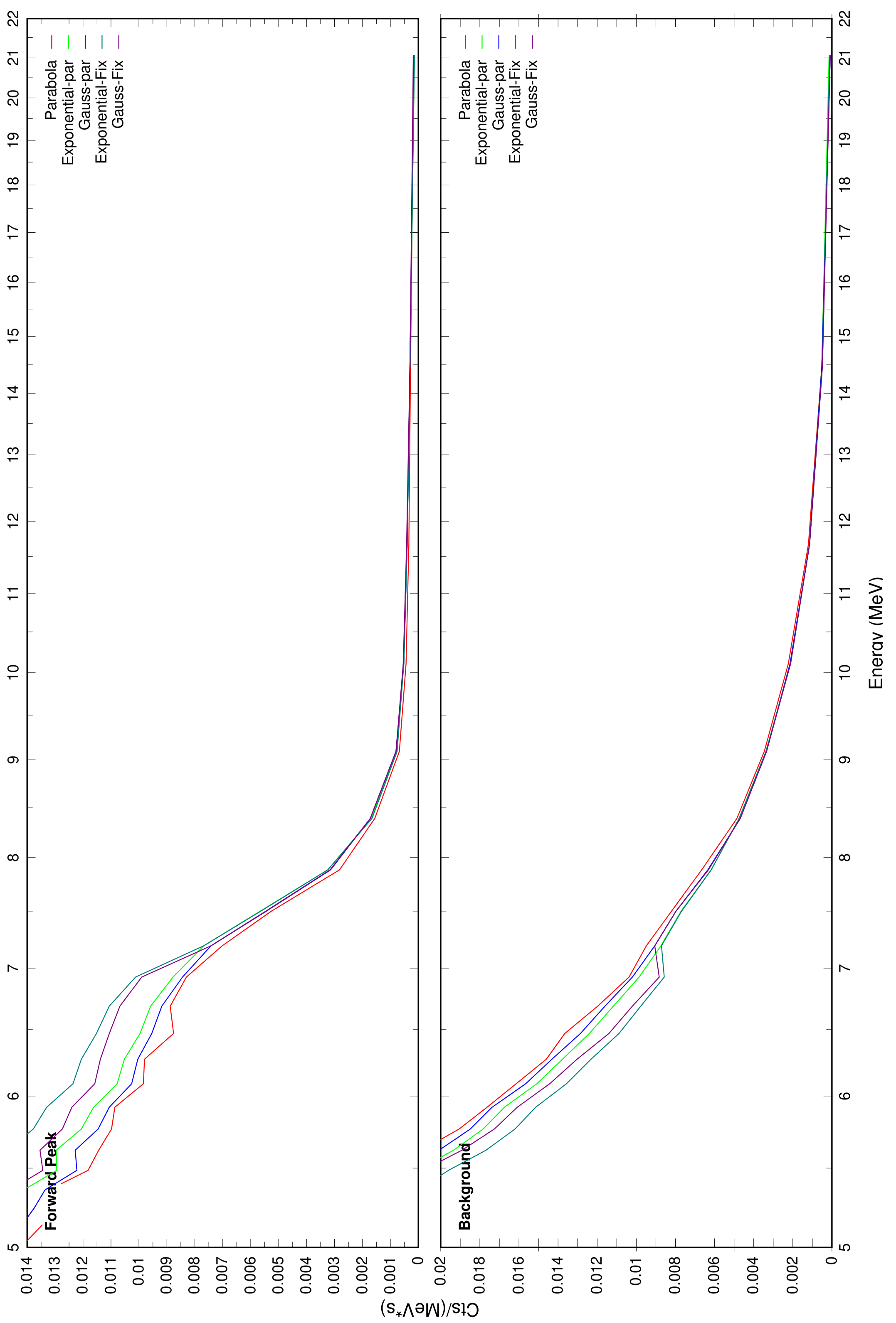

Figure 8: *The forward peak and the ToF continuum background signal from 5 MeV to 30 MeV.*

energy). Comparing the two extremes "Parabola" and "Exponential-Fix" the systematic difference is about a factor of 2 at 1 MeV and decreases to about 25% above 2.2 MeV. Fixing the forward peak width decreases the difference between all three models to about 50% at 1 MeV and less than 20% above 2.2 MeV.

This uncertainty alone introduces a systematic uncertainty of about 25% for all COMPTEL flux measurements. Further systematic uncertainties that have to be taken into account for flux measurements are those of the calibration measurements, which again are on the order of 20%.

3.3.2 Variations in Time

As described above, the signal from instrumental lines originating from within or around the D1 detector is apparently confined exclusively in the forward peak. Therefore fits of the ToF distribution are an ideal tool not only for identifying the characteristic features of these lines, but also for studying their time variability.

To study the time variability of the ^{24}Na cascade signal 75 ToF spectra were calculated for the following time periods: OP 5 - 9.5 (TJD 8449 - 8518), OP 210 - 232.5 (TJD 9040 - 9237), OP 302 - 308.6 (TJD 9237 - 9322) and OP 311 - 313 (TJD 9334 - 9355). The first time period represents the "early mission" when the altitude of the COMPTEL orbit was about 450 km at solar maximum. The "pre-reboost" conditions with a low orbit altitude of about 350 km are represented by the second time interval. The third time period contains the "reboost", when the orbit was elliptical between 350 km and 450 km. The "after reboost" conditions are represented by the last time interval, with the orbit again being circular at an altitude of about 450 km, but now approaching solar minimum.

The E2 spectra of the forward peak, of the ToF continuum background and of the total event rate in the forward peak region (ToF=107 to ToF=130) in the four time periods are depicted in Fig. 9. The activation of the ^{24}Na cascade in relative units according to the activation model described in `COM-RP-MPE-DRG-155` by M. Varendorff is given as a function of time from launch (t=0) to TJD 9492 (t=1100) in Fig. 10. The four different time periods can easily be identified, as the activation during SAA (South Atlantic Anomaly) passages increases with increasing altitude.

Considering the statistical uncertainty of the fits the ToF continuum background has the same shape in all four time periods. However, the average event rate in the four time intervals is different. As was to be expected, it is lowest during "pre-reboost" since the cosmic ray flux incident on COMPTEL decreases with altitude. It is higher in the "early mission" because the orbit was higher. The highest ToF continuum background rates occurred during "reboost" and "after reboost", when the altitude was high again but with less solar activity than after launch.

The differences between the four time periods are more pronounced in the forward peak. The ^{24}Na cascade produces the line-like excess around 2.7 MeV and part of the excess at 1.3 MeV (the additional component is currently under study). The differences between "early mission" and "pre-reboost" in the forward peak continuum are very small, except that the 2.7 MeV feature is stronger immediately after the launch, in agreement

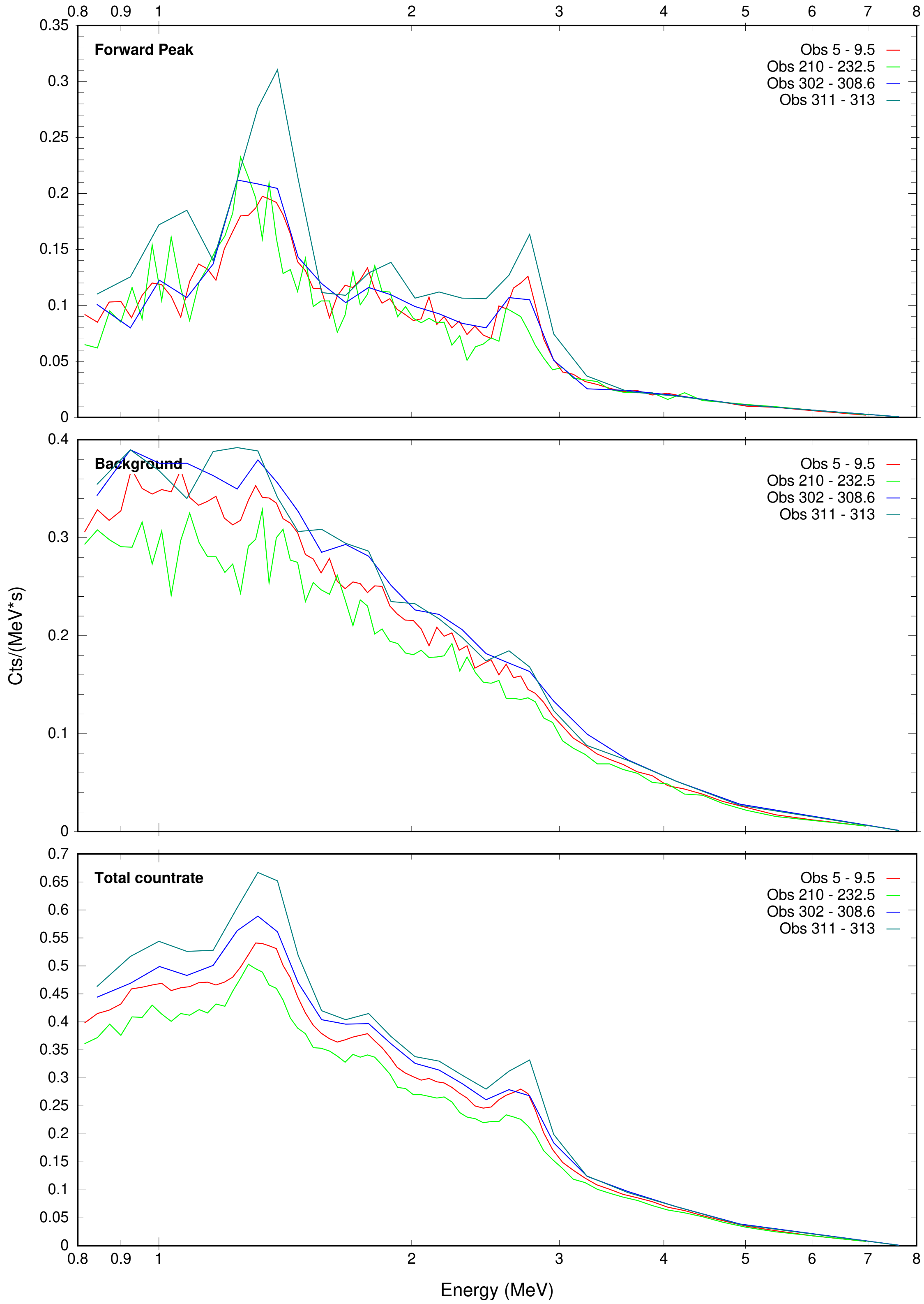

Figure 9: *The time variation of the the E2 spectrum.*

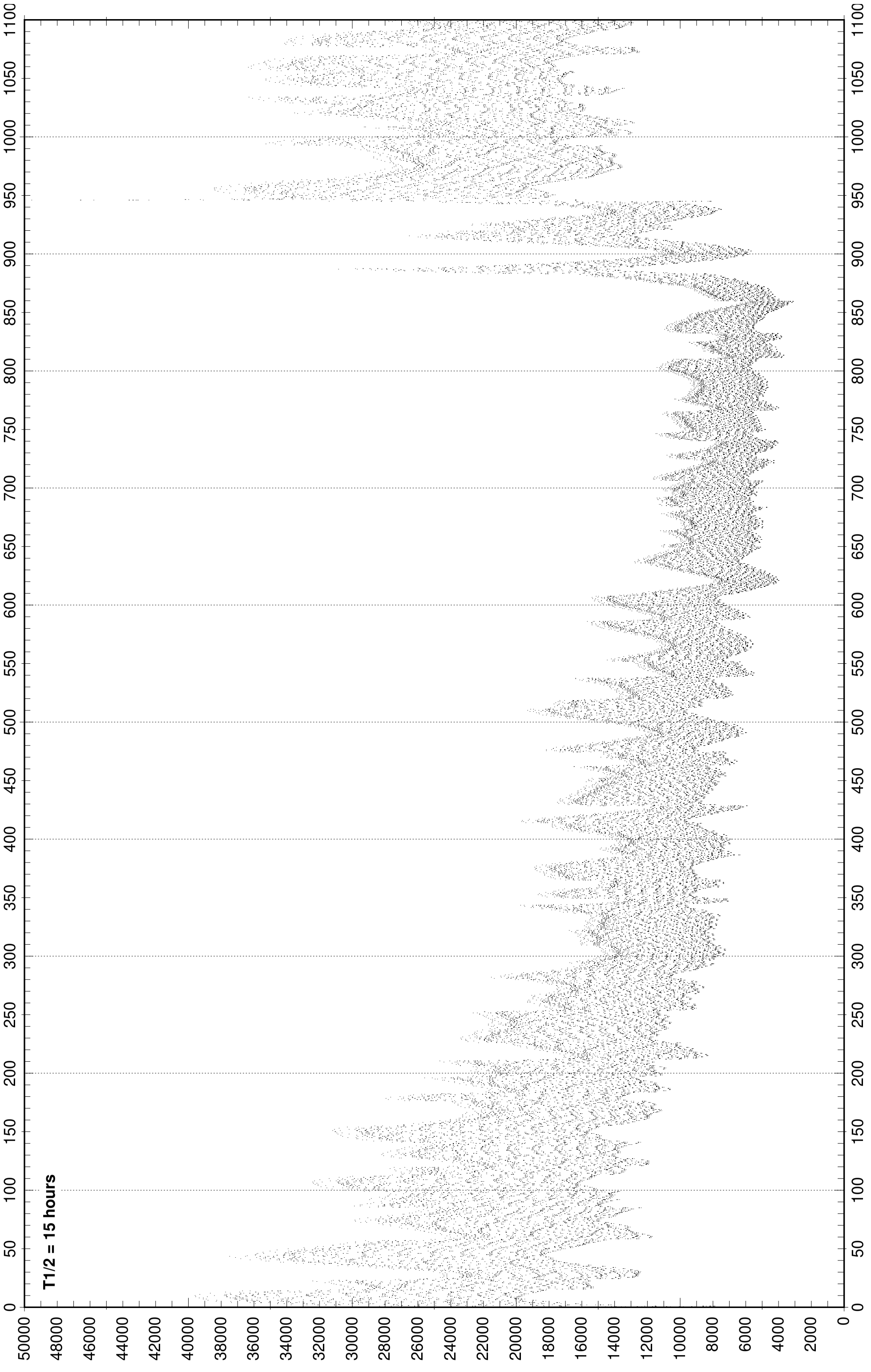

Figure 10: *The activation of the* ^{24}*Na cascade from lauch (t=0) to TJD 9492 (t=1100) in relative units.*

with the activation model depicted in Fig. 10. Unfortunately, the strong scatter around 1.3 MeV does not allow a comparison there. During “reboost” the continuum increased, and the ^{24}Na cascade lines seem to be somewhat stronger than during “pre-reboost”. The continuum is highest “after reboost”, as is the intensity of the ^{24}Na cascade lines. It seems that the 1.3 MeV feature increased more strongly than the 2.7 MeV feature, which might be due to the additional component at 1.3 MeV. The statistics, however, don't allow any firm conclusions. It is also interesting to note that there are pratically no changes in the forward peak spectrum above about 4 MeV, in contrast to the ToF continuum background.

The time variation in the total count rate spectrum again indicates that the 1.3 MeV feature increased more strongly in time than the 2.7 MeV feature. The continuum shows the expected variation with altitude. In addition, from comparing “early mission”, “pre-reboost” and “after reboost” it seems that the solar cycle has about the same (if not a stronger) effect on the total count rate as altitude has.