

Vertexing Time Reconstruction for Heavy Photon Search



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The Heavy Photon Search is an experiment aimed at discovering a hidden-sector, heavy photon. Key to the experiment is the ability to run a silicon vertex tracker in the high-background environment downstream of an electron beam. We plan to accomplish this using the continuous duty cycle of the CEBAF accelerator at Jefferson Lab, combined with time reconstruction of hits in the silicon microstrips to discard hits with times too far removed from the trigger time. This time reconstruction requires that we be able to extract hit times with a resolution of a few nanoseconds; Monte Carlo studies show that this performance is achievable.

APV25 Readout

The tracker will be made up of six measurement layers, each containing two closely spaced planes of silicon microstrip sensors to measure both X and Y coordinates for momentum measurement and track identification. We will read out the microstrips using the APV25 chip developed for the CMS tracker at the LHC. The APV25 preamplifier and shaper produce a CR-RC shaping curve with a shaping time T_p which, for our experiment, will be set at 35 ns. The approximate functional form of this curve, for hit time of t_0 and peak height (proportional to the charge generated in the silicon) of A , is:

$$v_{out}(t) = A \frac{t - t_0}{T_p} e^{-(t-t_0)/T_p}$$

If there are multiple hits, the output is the sum of the shaping curves for the individual hits.

The APV25 samples the shaper output once per clock cycle (24 ns for HPS), and in “multi-peak” mode, outputs 3 consecutive samples per trigger request. HPS will read out 6 samples for each trigger. The trigger timing can be controlled to select the series of 6 samples that gives us the most information for a fit; currently we believe that it is best to take 2 samples before the signal hit and 4 samples after.

In general, we want to fit a set of samples y_i and errors σ_i , taken at times t_i , with the sum of pulses with shaping curve $f(t)$, each of height A_j and hit time t_j .

$$\chi^2 = \sum_i \left(\frac{y_i - \sum_j A_j f(t_i - t_j)}{\sigma_i} \right)^2$$

Background Pileup

With our high background rate, it is expected that the “signal” hit corresponding to the track to be fitted will often overlap with “background” hits. Overlapping hits sum to make a fictitious “pileup” hit, whose apparent height and hit time are weighted sums of the signal and background values.

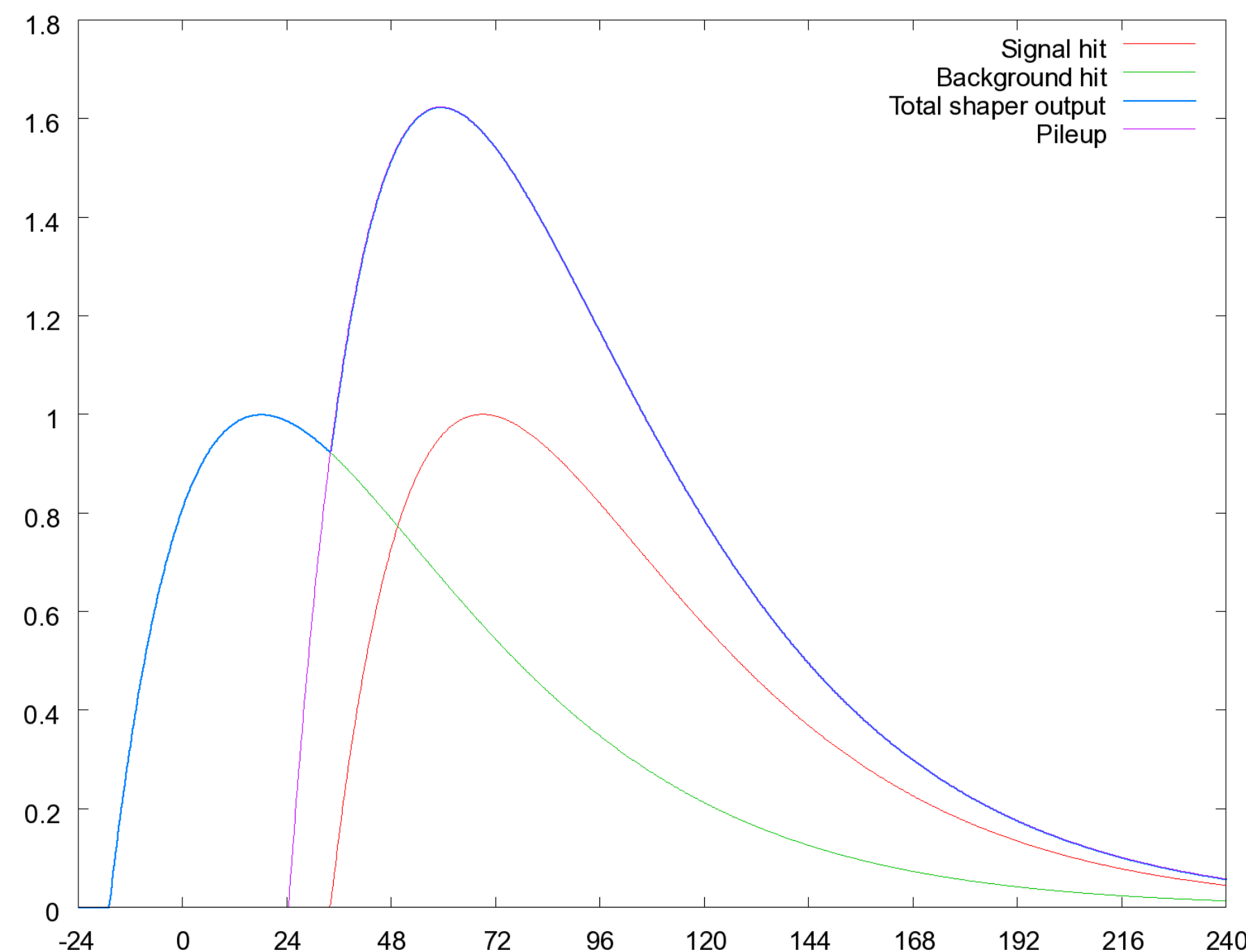


Figure 1: Effect of pileup on a signal hit at 34 ns and a background hit at -17 ns; the apparent hit time is shifted earlier by 9.6 ns.

There is no way to distinguish a “pileup” hit from a pure signal hit, except by fitting the samples taken before the pileup. This is only possible if at least two samples are taken before pileup; otherwise the time and height of the earlier hit are underconstrained.

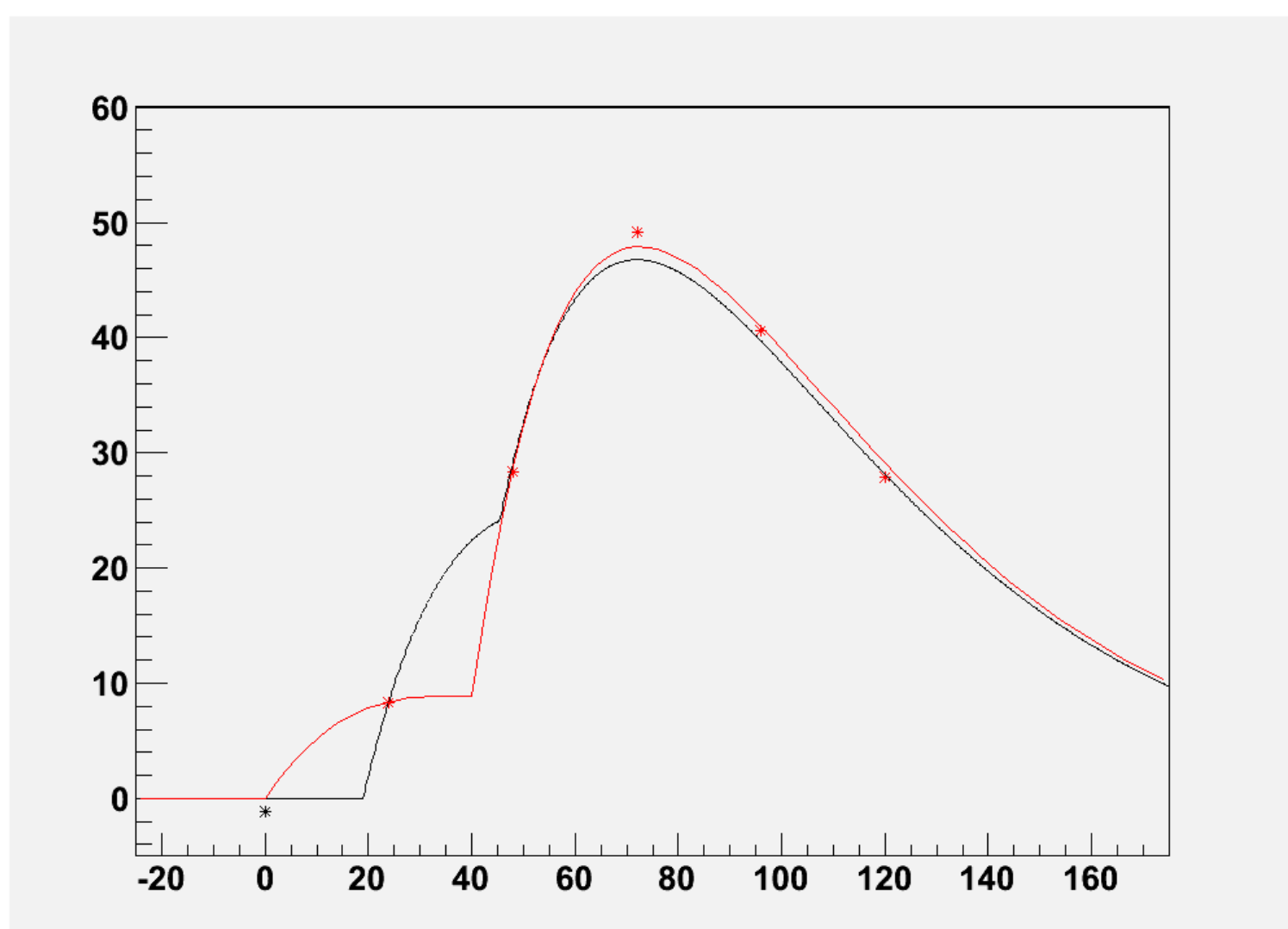


Figure 2: Example of an underconstrained fit. Samples (red asterisks) match both the actual hit times and heights (black curve) and the fitted times and heights (red curve); many other fits are possible.

Fitting Methods

χ^2 is minimized when its partial derivative is 0 with respect to all fit parameters. The condition $\frac{\partial \chi^2}{\partial A_k} = 0$ yields the following:

$$\sum_i \left(\frac{\sum_j A_j f(t_i - t_j)}{\sigma_i} \right) \frac{f(t_i - t_k)}{\sigma_i} = \sum_i \left(\frac{y_i}{\sigma_i} \right) \frac{f(t_i - t_k)}{\sigma_i}$$

This system of equations can be solved as a matrix equation to efficiently obtain the best-fit values of A_j given a set of t_j ; this works generally, even if the shaping curve is not exactly the ideal CR-RC curve. The problem is reduced to that of finding best-fit values of t_j , and this can be done analytically or numerically.

Analytic Fitting

For a fully analytic fit, we notice that the samples can be partitioned into sets, each of which can be fitted by a single shaping curve; these can be fitted individually, and then pileup can be subtracted to extract the heights and times of all the hits.

The individual fits can be made analytically if we assume the ideal CR-RC curve; to find the values of A and t_0 to minimize χ^2 , we set $\frac{\partial \chi^2}{\partial A} = 0$, $\frac{\partial \chi^2}{\partial t_0} = 0$.

There are currently two weaknesses to this method. One is that an analytic fit using one set of samples does not know about the other samples; the other is that the analytic fit sometimes yields unphysical results with negative peak heights. Both problems are shown in Figure 3 below. It is expected that these effects can be dealt with as special cases.

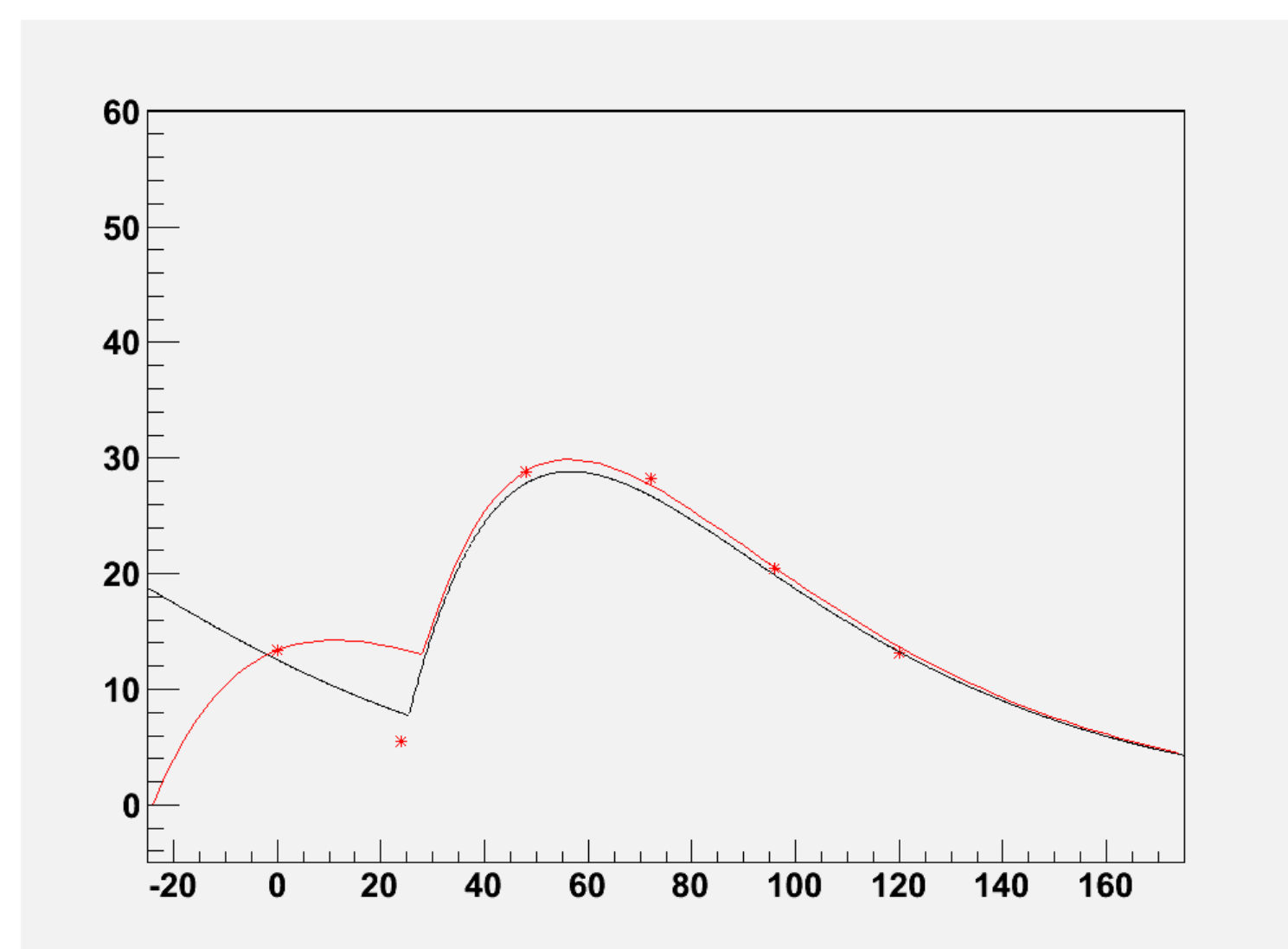


Figure 3: Attempt at an analytic fit for a two-hit event. An analytic fit to samples 1 and 2 gives an unphysical result, so the best fit is one that fits sample 1 with one peak, and samples 2–6 with the second peak. Because the first peak doesn’t try to fit sample 2, sample 2 is “buried” by the first peak.

Numeric Fitting

The values of t_j can be fit by searching the space of possible t_j . Most gradient-based fitting methods are ineffective for this problem because the global minimum (where all samples are fit) is often at one end of a narrow “valley” (where one sample is not fit), but a method that follows this valley should work. Further work is needed.

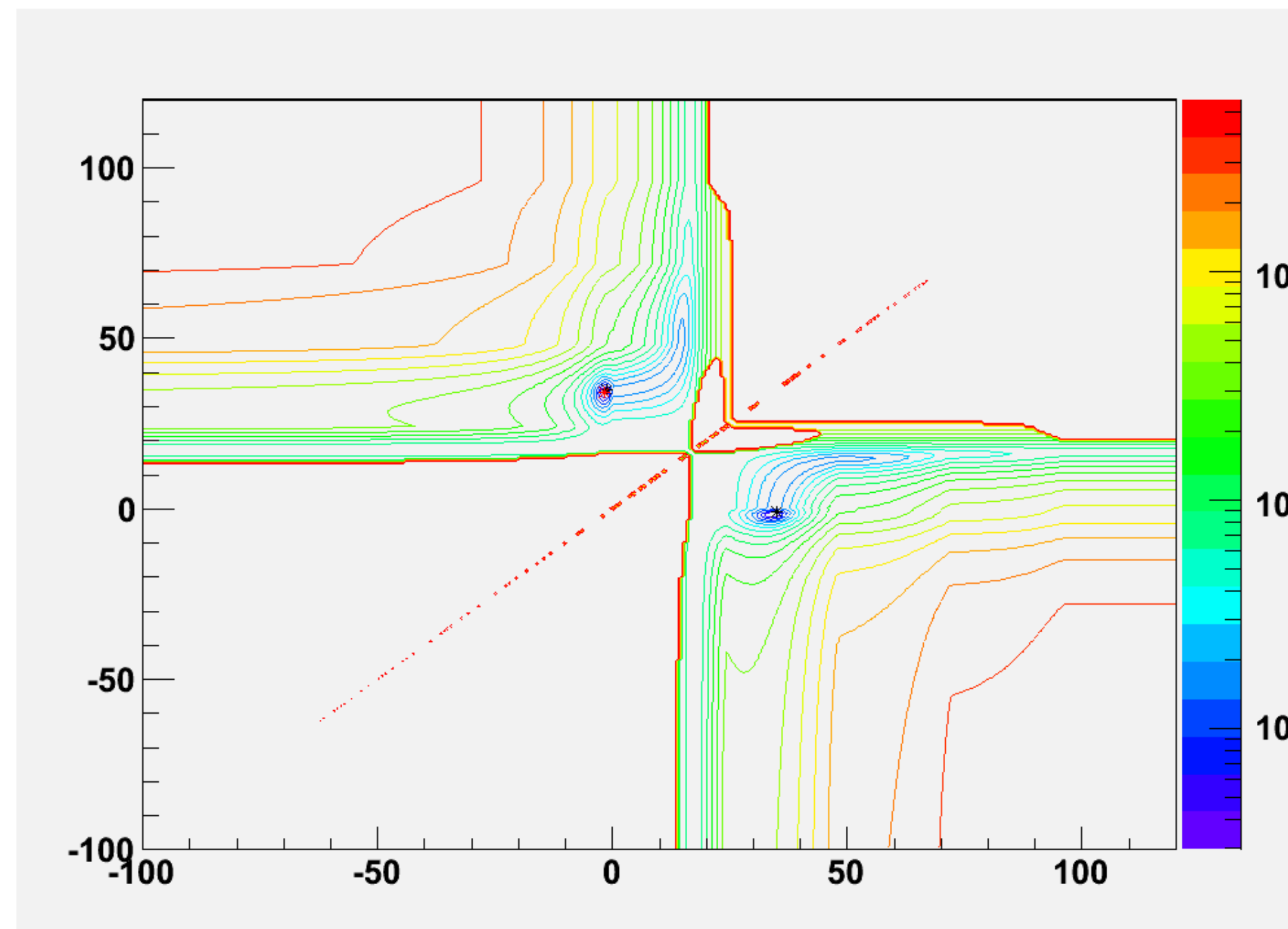


Figure 4: Contour plot of χ^2 values for a two-hit event, fitted with two peaks. A_1 and A_2 are fit analytically, given values of t_1 and t_2 (x and y coordinates, relative to time of first sample). Black asterisks mark the true values of (t_1, t_2) ; red marks the fitter output. The “valley” consists of fit parameters for which only samples 2–6 are fit; the global minimum occurs where sample 1 is fit as well.

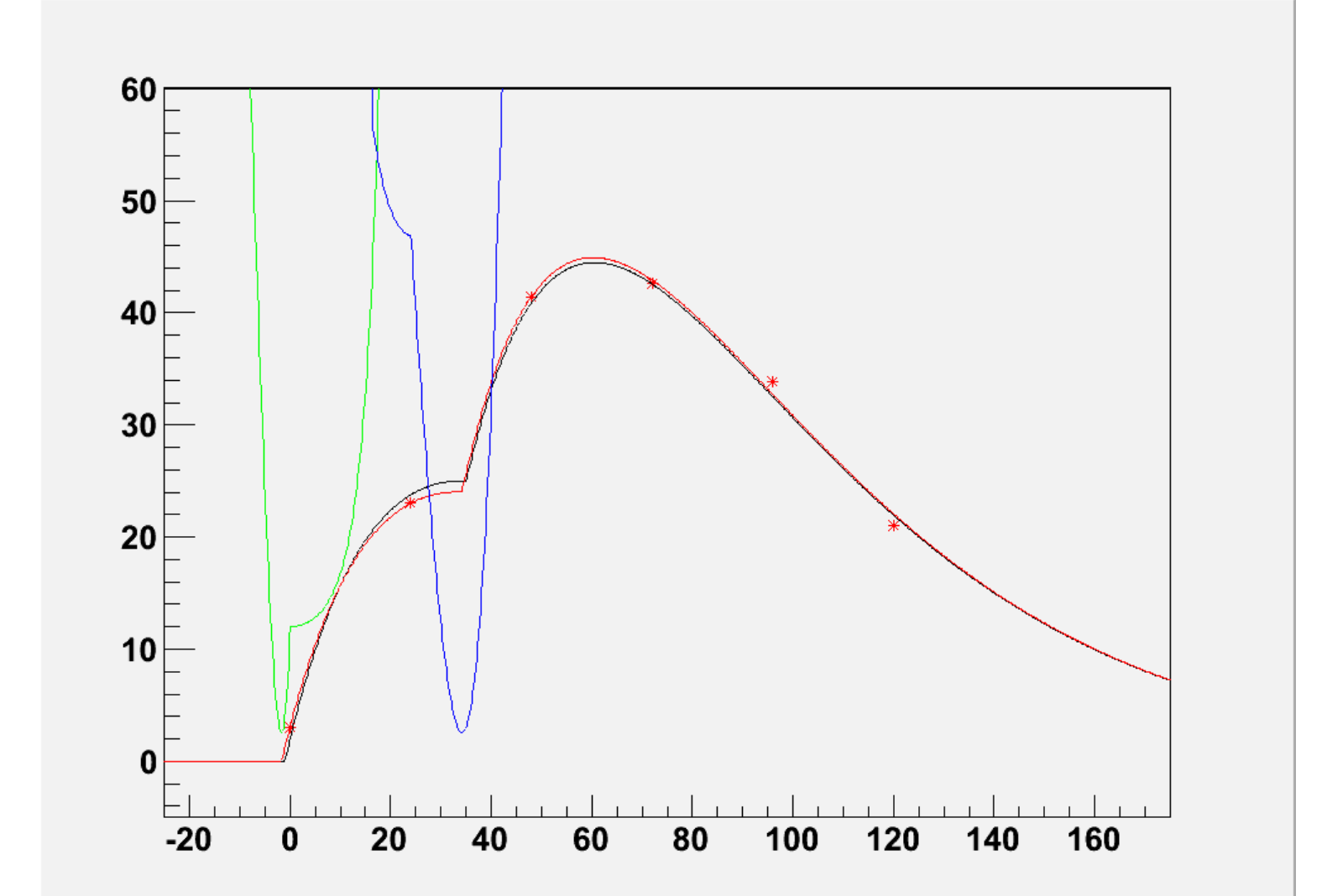


Figure 5: For the fit above: samples (red asterisks), actual hit parameters (black curve), fitted hit parameters (red curve), and χ^2 dependence on t_1 and t_2 (green and blue curves).

Time and Height Resolution

To test performance of the fitters, we generated one-peak and two-peak events and compared the reconstructed values of parameters to the true values. For these tests, we assume all hits have the same height (in reality we expect a Landau distribution of heights), with a signal-to-noise ratio of 25; we assume that we can time the trigger so the signal hit is always between samples 2 and 3 (between 24 and 48 ns after the first sample).

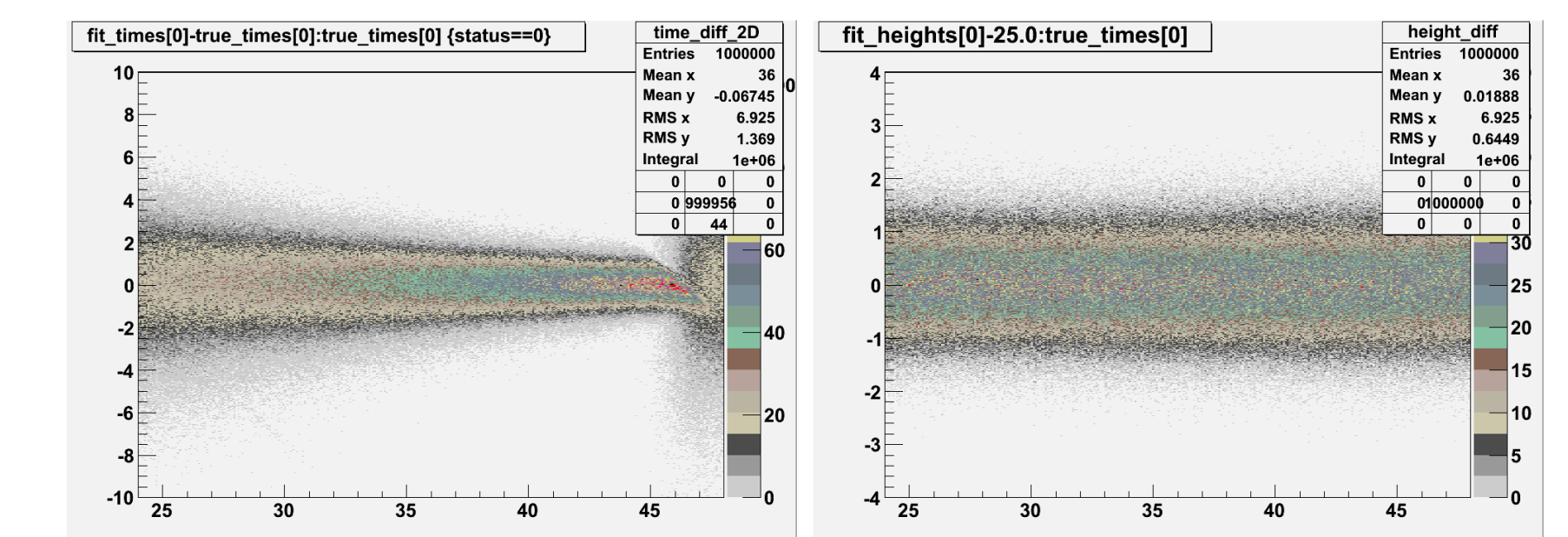


Figure 6: Time and height resolution for single hits. $\sigma_t = 1.37$ ns, $\sigma_A/A = 0.026$.

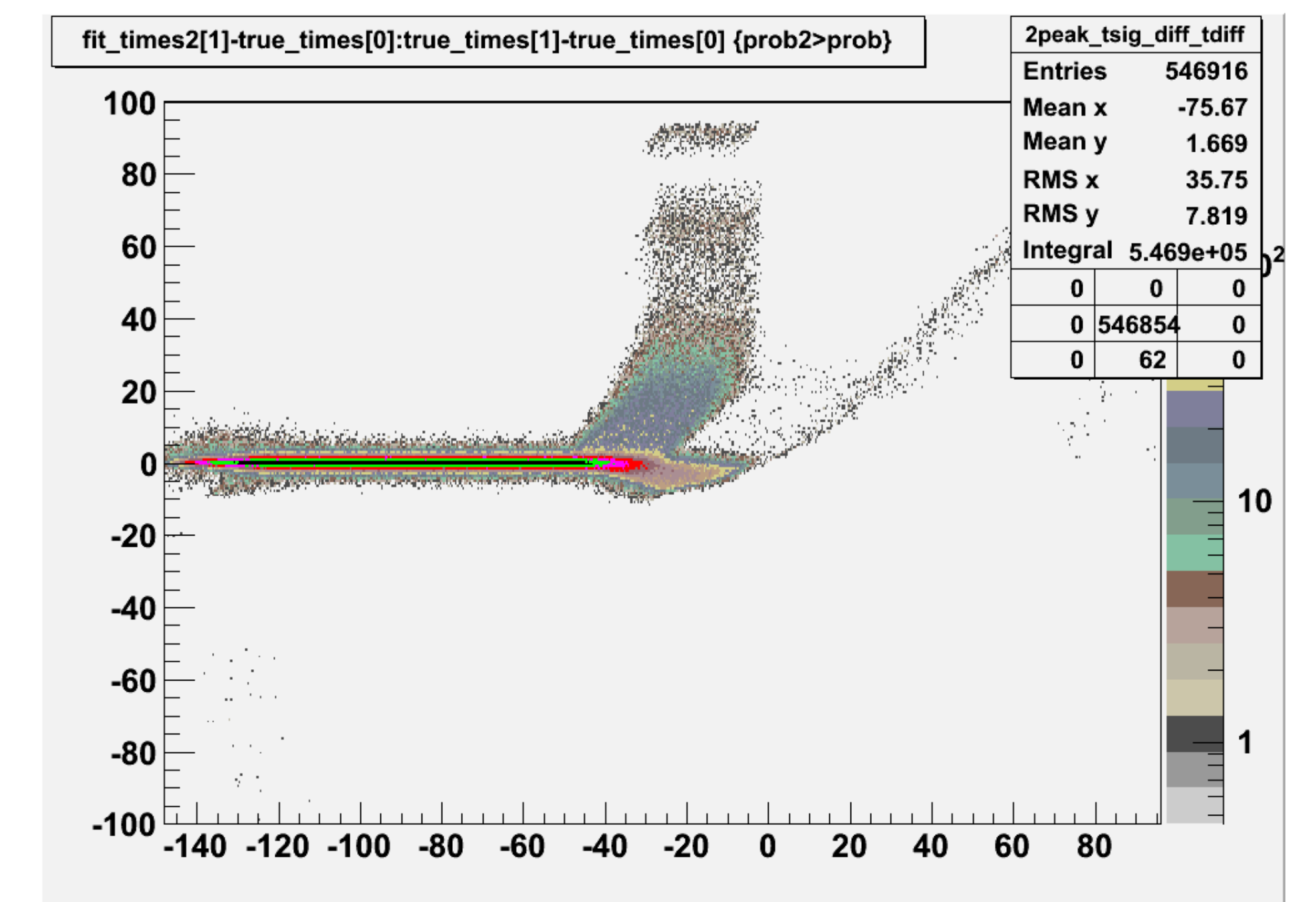


Figure 7: Error in two-peak fit for the signal time. x -coordinate is difference between the true hit times; y -coordinate is the difference between fitted and true signal hit times.

Identifying Multiple Hits

To be useful, our fitter must be able to distinguish single-hit events from multiple hits. This is not possible if multiple hits fall in the same time interval between samples, but in all other cases we can fit the samples with a single peak and multiple peaks, and compare the goodness of fit.

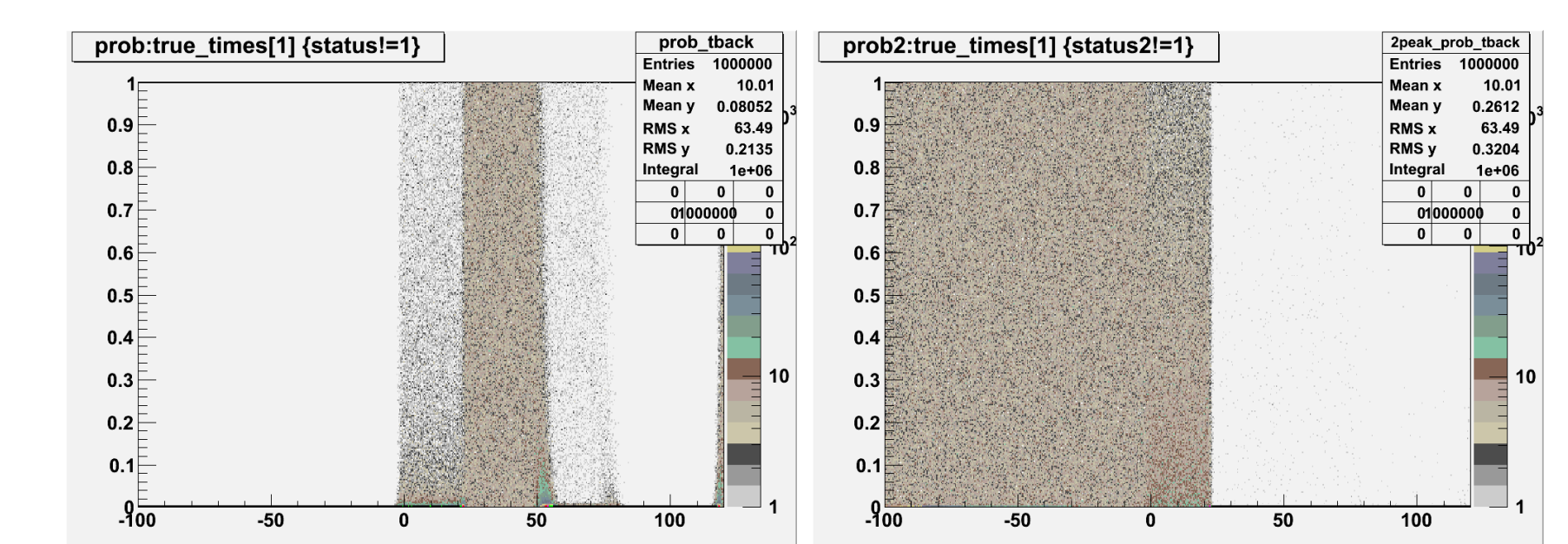


Figure 8: χ^2 probabilities for single-peak (left) and two-peak (right) fits to two-peak events. x -coordinate is time of the background hit. A single-peak fit is good when the background hit and signal hit are both between samples 2 and 3; the two-peak fit is good when there are two samples for the background hit before pileup, and less good (not enough degrees of freedom) when there is only one.