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ECL timing correction and resolution for simulated events in Release-00-07-00

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Abstract

Starting with Release-00-07-00, ECL data (ECLCalDigits and ECLClusters) will have associated times reported in nanoseconds, rather than the (uncalibrated) clock ticks used in previous releases. This note discusses the conversion from clock ticks to ns for simulated data, the timing resolution as a function of energy for nominal background levels, and a quantity useful for estimating the background levels present in an event.

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I. INTRODUCTION

The information for each crystal is stored as an ECLDigit, which summarizes the result of a fit to the waveform. It includes amplitude (18 bits), fit time (12 bits), and status (2 bits). With background mixing, there are several thousand ECLDigits per event, out of 8736 crystals total. Distributions of fit time t_f versus amplitude are shown in Fig. 1 and 2. The horizontal axes can be translated into MeV using the conversion 20 ADC counts = 1 MeV. Fig. 1a illustrates the small but non-zero offset present in the fit times. A comparison with Fig. 1b indicates the deterioration of time resolution caused by backgrounds.

There are digits for which the time is fixed to the nominal trigger time in the fit. These are identified by setting $t_f = -2048$, and are visible in Fig. 2. Without background, these tend to be at amplitudes below 10 ADC counts (0.5 MeV). With background mixing, they can extend to 2 MeV and above.

There is an excess population of events at $t_f = 0$ visible in Fig. 1, particularly in the right-hand plot. This is under investigation.

The amplitude and fit time are converted into physics units (GeV and ns) in eclDigit-CalibrationModule, and stored as an ECLCalDigit. This module also calculates the timing resolution for each Digit, and provides an overall estimate of the background level for the event. These three tasks (conversion, resolution, background level) are discussed in the following sections for simulated data. The results are specific to the version of ECLDigitiz-erModule; these studies use svn 26660, which will be used in Release-00-07-00.

II. TIME CONVERSION

The fit time t_f for an ECLDigit with a successful waveform fit is reported as a 12-bit integer, corresponding to [-2047,2047]. Times outside this range are set to ± 2047. It is converted to the corrected time t for cellID (crystal number) i using

$$t = a(t_f + b_i).$$

The offset b_i adjusts the times so that a photon produced at the interaction point that travels directly to crystal i will be reconstructed with a time $t = 0$ on average. The offset corrects for the difference in flight time for each crystal, which is present in both data and Monte Carlo (MC), and in real data for the difference in cable lengths.

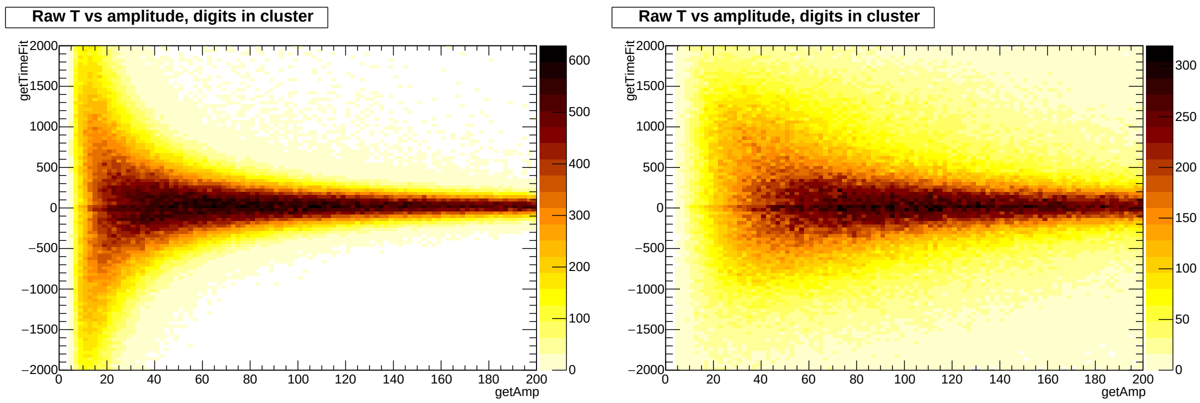

FIG. 1: Fit time versus amplitude for ECLDigits within 25 cm of a high-energy photon in $e^+e^- \to \gamma\gamma$ events, (left) without background mixing and (right) with background mixing. Times are not corrected for the crystal-to-crystal variation in flight times. The vertical scale is selected to exclude the fits without time information at $t_f = -2048$ and the over and underflows at ± 2047.

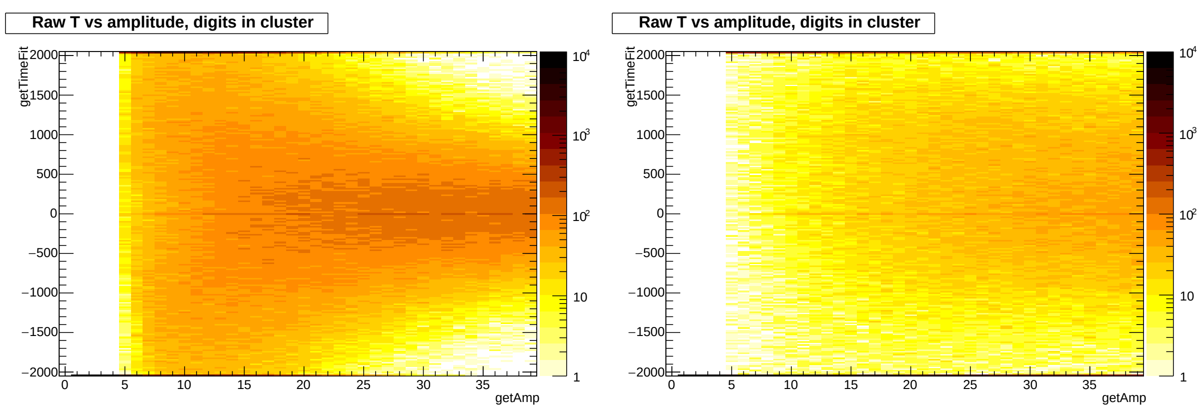

FIG. 2: Fit time versus amplitude for ECLDigits within 25 cm of a high-energy photon in $e^+e^- \to \gamma\gamma$ events, (left) without background mixing and (right) with background mixing. These are the same events as Fig. 1, but with different horizontal and vertical scales, and a logarithmic z axis. Digits without time information are at $t_f = -2048$.

The scale factor a converts ADC clock ticks into nanoseconds. The frequency of each ADC is derived from the 508.887 MHz RF frequency of SuperKEKB via integer arithmetic: $f_{ADC} = f_{RF}/24/12 = 1.77$ MHz. It should therefore be the same for all crystals.

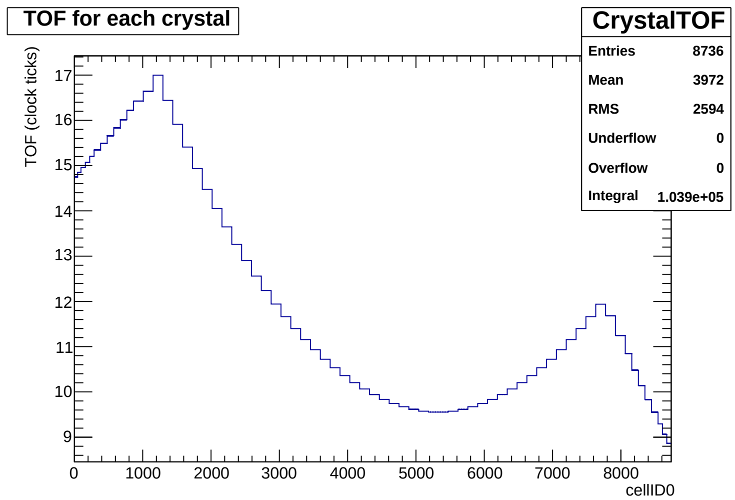

FIG. 3: Flight time from the interaction point to the crystal center for each crystal. The range 9–17 clock ticks corresponds to 4.4 to 8.3 ns.

A. Timing offset for each crystal

The offset b_i for each crystal is determined using $e^+e^- \to \gamma\gamma(\gamma)$ events produced without background mixing. (50,000 events, BabayagaNLO, $10° < \theta_{COM} < 170°$, generated on the CLUMEQ cluster at McGill university). Events are required to have exactly two seed crystals with energy greater than 2 GeV in the center-of-mass frame. Only crystals within 25 cm of a seed crystal are used in the study. On average, there are 31 Digits per seed (only crystals with amplitudes ≥ 5 ADC counts are stored), and 8 crystals within the 25 cm that are not read out.

In MC, the offset varies from crystal to crystal only due to differences in flight time from the interaction point. The flight time is calculated using the position of the crystal center via GetCrystalPos from ecl/geometry/ECLGeometryPar (Fig. 3).

The time of flight (TOF) for each crystal f_i is subtracted from the ECLDigit fit time to obtain the residual time offset common to all crystals in MC. Histograms of the TOF-corrected time distributions are filled as a function of amplitude. There are 94 such histograms covering the amplitude range from 20 to 124940 ADC counts (1 to 6247 MeV). The lower energy range of each histogram is 10% higher than the preceding one. Sample distributions (without backgrounds, and after TOF correction) are shown in Fig. 4. The distributions are fit with double Gaussians constrained to have the same mean.

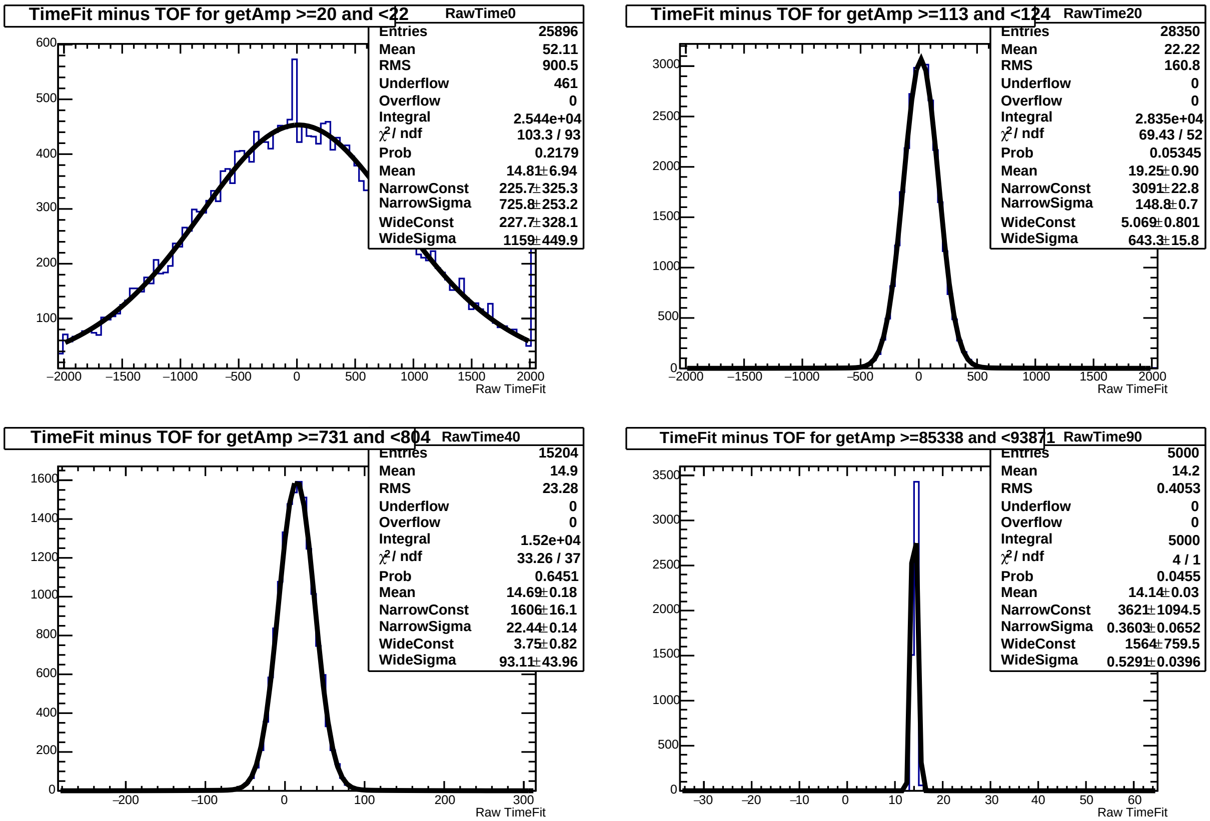

FIG. 4: Fit time distributions after flight time corrections (clock ticks), for various energy ranges, without background mixing. Energy in MeV is the amplitude divided by 20.

The fit mean is plotted versus histogram number in Fig. 5a. The mean shows a small deviation from constant at low energies, but this deviation is negligible compared to the effective sigma, defined as full width at half maximum (FWHM) divided by 2.35 (Fig. 5b). The time distributions at the highest energies are confined to just two time bins, resulting in a poor definition of effective sigma. The final offset b_i for each crystal is just $b_i = -f_i - 14.23$, where 14.23 is the "pol0" fit to Fig. 5a (Fig. 6).

B. Scale factor from clock ticks to nanoseconds

The design of the waveform fitting routine is such that there should be four clock ticks per period of the accelerator RF clock. The conversion factor should therefore be $a = 1/4f_{RF} = 0.491$ ns/clock tick. This relationship is verified using ParticleGun, which allows

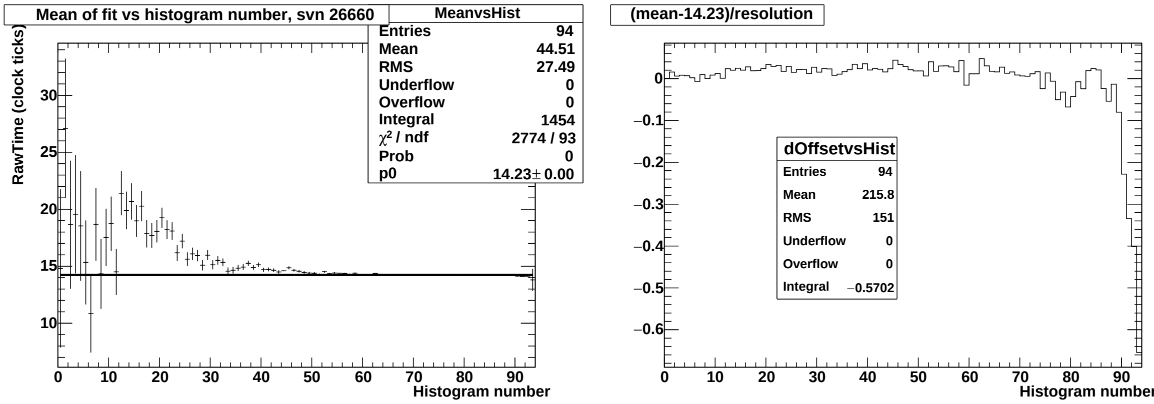

FIG. 5: (a) Mean fit time, after TOF correction, versus histogram number. First histogram corresponds to 1 MeV, last histogram to 6 GeV, with energies increasing by 10% per histogram. (b) Mean fit time divided by FWHM/2.35 versus histogram number.

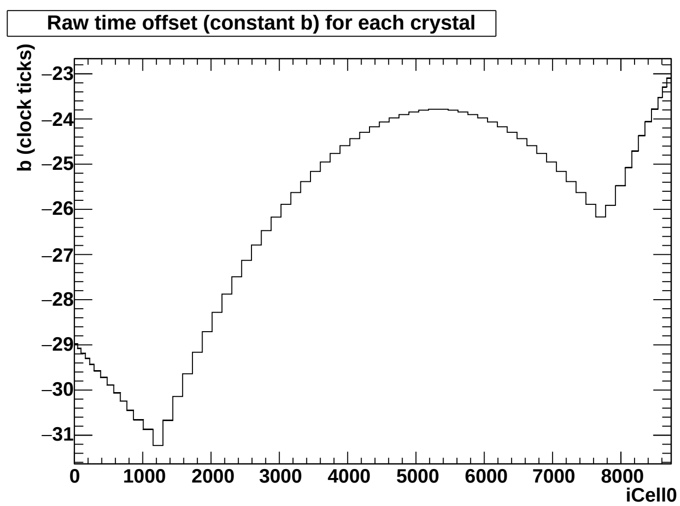

FIG. 6: Time offset b_i for each crystal (clock ticks).

the user to specify (in ns) the true time of the generated event. Single 1 GeV photons are generated uniformly over $17^\circ < \theta_{lab} < 150^\circ$ for true times of 0 ns, ± 50 ns, and ± 100 ns. For each time, the above process is repeated (including correction for the flight time for each crystal), with 54 fit time histograms corresponding to amplitudes from 100 (5 MeV) to 18300 (915 MeV). Each histogram is fit with a double Gaussian, and the resulting plot of mean versus histogram number is fit with a pol0. The value of this pol0 is the mean fit time for the generated true time. As shown in Fig. 7, the relationship is linear, with a slope of 2.0355 clock ticks per ns, corresponding to a scale factor of 0.491 ns per clock tick, as

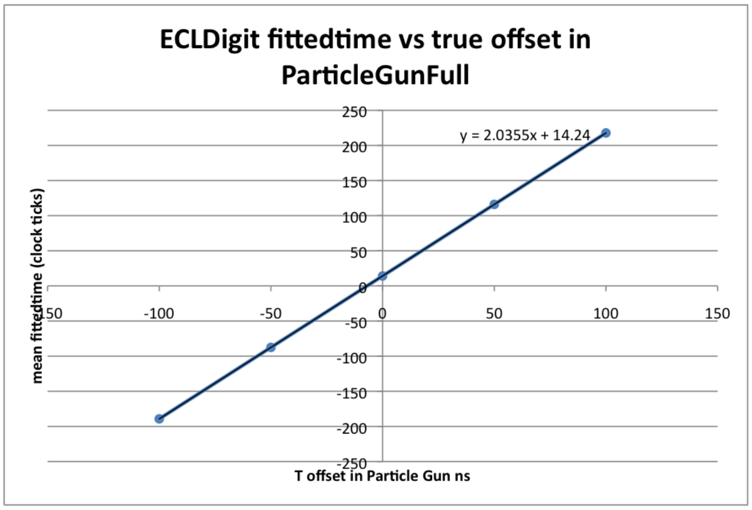

FIG. 7: Mean fit time (clock ticks) versus true event time (ns), from a study using 1 GeV photons generated by ParticleGunFull. As expected, the slope is four times the accelerator RF frequency in GHz.

expected.

III. TIMING RESOLUTION

The timing resolution is studied using $e^+e^- \to \gamma\gamma$ events with background mixing. As for the above study, only digits within 25 cm of > 2 GeV seed crystals are included in the study. On average, there are 30 Digits per seed, and 9 crystals within the 25 cm that are not read out. The digits are divided into the 94 energy ranges, but in this case the corrected time is used, incorporating the offsets and scale factor found in Sec. II. The time distributions are fit with a double Gaussian with common mean. The resolution is taken to be the FWHM/2.35. Due to poor fit quality at lower energies, only histograms for energies greater than 2.75 MeV (amplitude ≥ 55) are used. A sample of distributions is shown in Fig. 8.

Figure 9 shows the resulting resolution σ as a function of $x_E \equiv 1/E$. The fit consists of three linear functions constrained to be continuous. There are eight parameters to the fit, four (x_E, σ) points. The first and last points are constrained to be $x_E = 0$ and $x_E = 400$ respectively, leaving six parameters free in the fit. The uncertainty on resolution is assumed to be 3%. The set of eight parameters from Fig. 9 is used in eclDigitCalibrationModule to

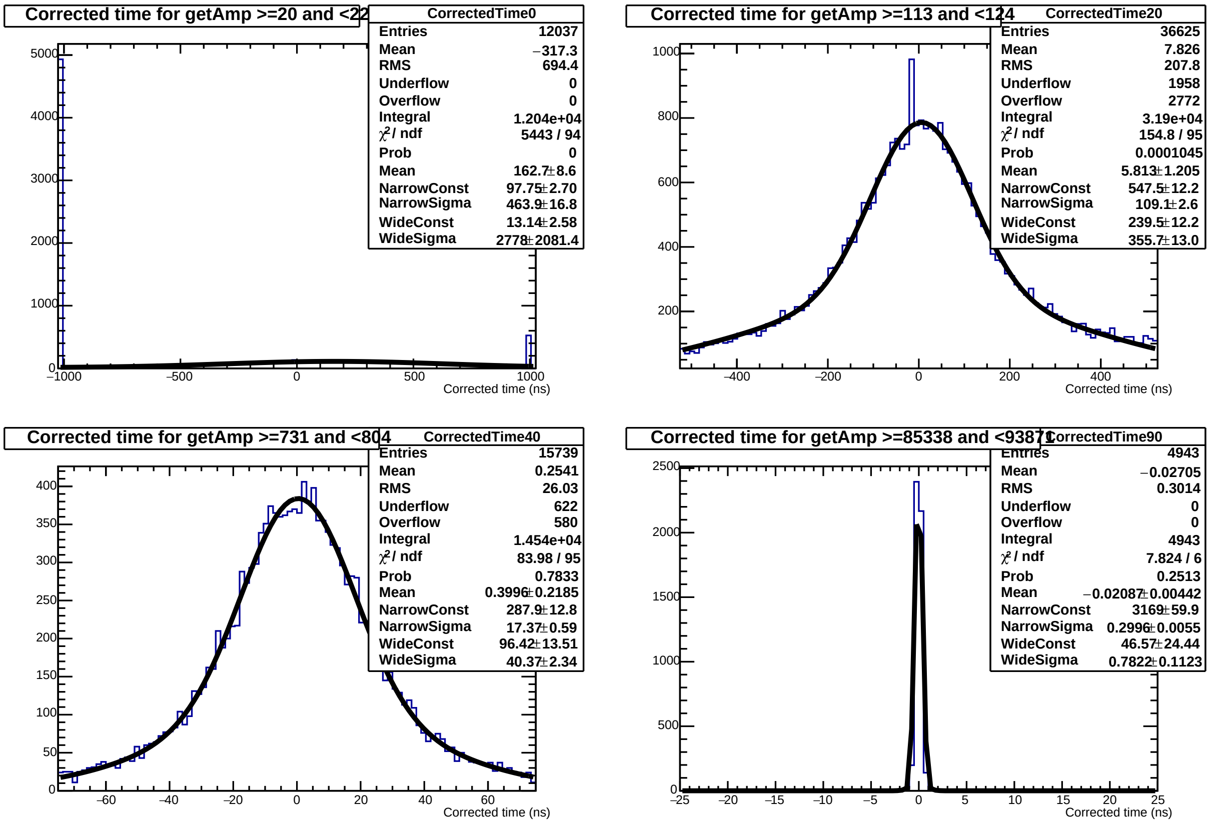

FIG. 8: Fit time distributions after corrections (ns), for various energy ranges, with background mixing. Energy in MeV is the amplitude divided by 20.

estimate the timing resolution for each ECLCalDigit.

This study of resolution ignores two significant effects. First, the timing resolution varies strongly with background level (Fig. 10). A more complete study will need to include the variation of the parameters from Fig. 9 with background level. Second, the effective resolution (FWHM/2.35) is not the optimal quantity for use by the reconstruction code, in that it does not correctly account for the significant tails. Figure 11 shows the fraction of the area of the double Gaussian fit that is included in a range of $\pm 2.58\sigma$ as a function of the histogram number. This is as low as 77% in the presence of backgrounds, compared to the 99% that would be expected for a single Gaussian. This is somewhat pessimistic, in that the study did not verify that the digits included in the fits were actually from the signal photon. The red curve in Fig. 10b is the time distribution of digits found within 25 cm of a fake seed located 16 crystals away in phi from the true seed location. Clearly, some component

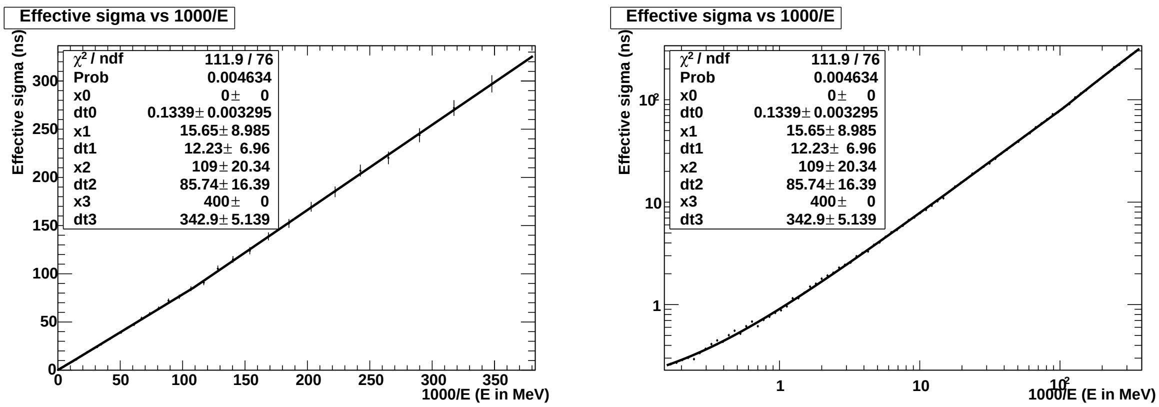

FIG. 9: (a) Effective digit time resolution (FWHM/2.35) versus $1/E$ for digits within 25 cm of a seed crystal in $e^+e^- \rightarrow \gamma\gamma$ events, with background mixing. Fit is piecewise linear with three components. (b) Log-log version.

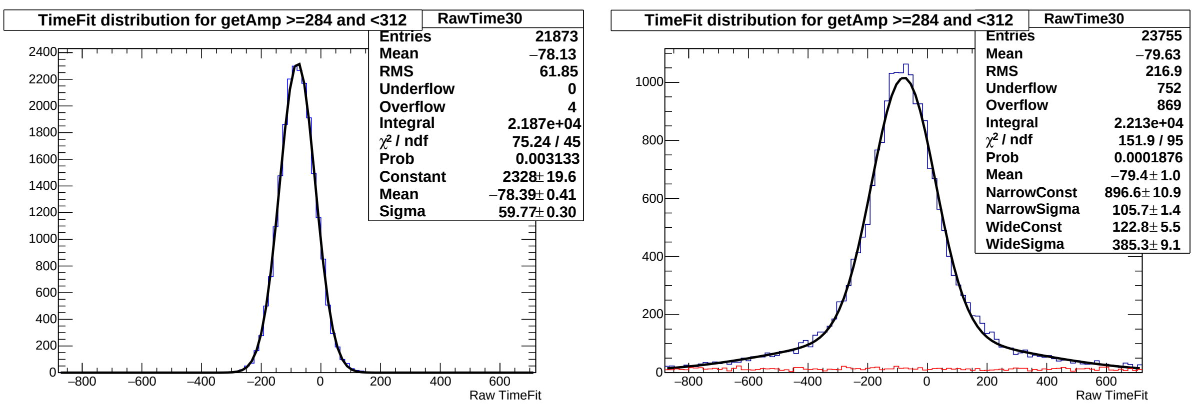

FIG. 10: Fit time distribution for 15 MeV digits without flight time correction for (a) no background mixing and (b) with background mixing. These plots were produced with an earlier version of ECLDigiterModule that had a different time offset than the version finally included in Release-00-07. The red curve in (b) is the distribution for digits within 25 cm of a fake seed crystal.

of the far tails are purely background, while others will be lower energy digits that have been promoted to higher energies by the backgrounds. In the absence of backgrounds, the coverage is close to 99%.

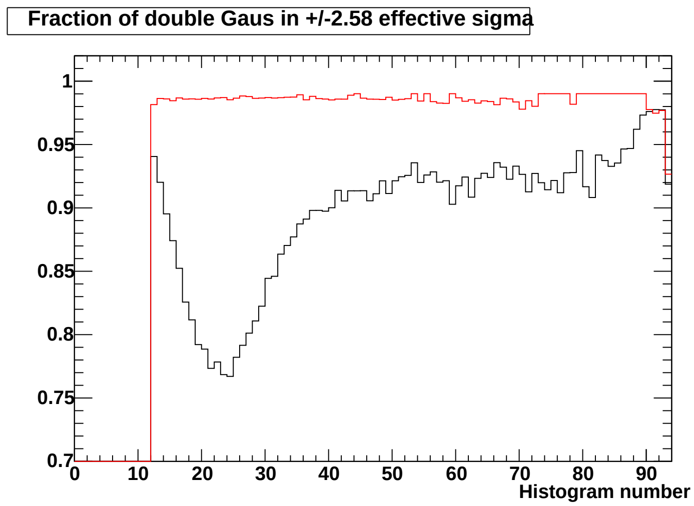

FIG. 11: Fraction of the double Gaussian fit that is within ± 2.58 times the effective resolution (FWHM/2.35) versus histogram number. Black curve is with background mixing, red curve is without. First histogram corresponds to 1 MeV, last histogram to 6 GeV, with energies increasing by 10% per histogram.

IV. ECL BACKGROUND LEVEL

The background levels in the ECL will vary slowly with time, as luminosity and current increase. However, there could also be short term variations due to injection and the presence of the clearing gap in the bunch train. eclDigitCalibrationModule needs to be aware of the background level in order to obtain the correct time resolution, once the dependence on background levels is implemented. This accomplished by counting ECLCalDigits that have a high probability of being backgrounds.

This study uses $e^+e^- \to \gamma\gamma$ generated in build-2016-04-01 (Release-00-07-00 candidate release) with background mixing levels ranging from 0 to 1 times nominal values. Earlier studies with $B\overline{B}$ and $\mu^+\mu^-$ events gave background numbers that agreed with those from $\gamma\gamma$ events to within a few percent.

Energy thresholds ranging from 0 to 10 MeV were studied. For each energy threshold, an ECLCalDigit was counted as a background digit if the absolute value of its time was greater than the time threshold for that energy. The time threshold was selected to reject $> 99\%$ of ECLCalDigits above the energy threshold in events without background mixing. The time distributions of all digits above 7 MeV, without background mixing, and with nominal

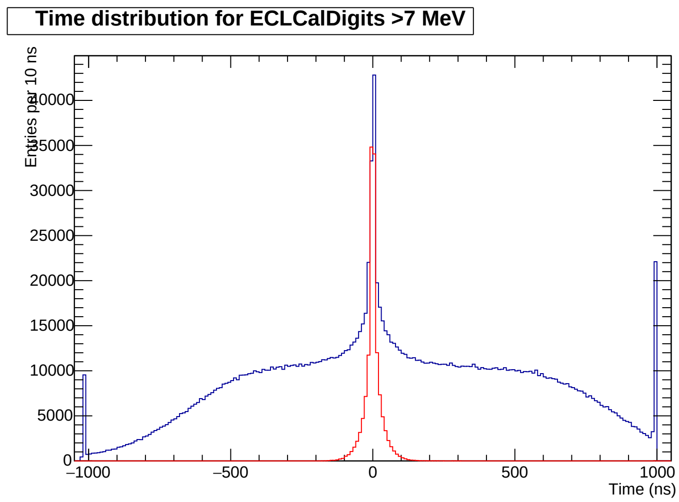

FIG. 12: Time distribution (ns) of ECLCalDigits with energies greater than 7 MeV. Red curve is for $e^+e^- \to \gamma\gamma$ events without background mixing; blue curve is with nominal mixing. Digits with $|t| > 110$ ns are included in the count of background digits.

background mixing, are shown in Fig. 12. The timing cut is 600 ns for a 2 MeV threshold, 230 ns at 4 MeV, 110 ns at 7 MeV, and 80 ns at 10 MeV.

Figure 13 shows the average number of selected digits as a function of the generated background level for a variety of energy thresholds. The number of ECLCalDigits with $E > 7$ MeV and $|t| > 110$ ns is used as the criteria to characterize the background level in each event in Release-00-07-00. This choice gives the lowest statistical error among the options that produce a linear relationship between the number of background digits and the true background level. The distribution of the number of background digits per event is reasonably Gaussian (Fig. 14). At nominal background levels, there is an average of 281 background digits per event, with an RMS of 40. For comparison, in generic $B\overline{B}$ events without background mixing, there is an average of 70 digits per event above 7 MeV with times less than 110 ns. The number of background digits in each event is found in eclDigitCalibrationModule and stored in the dataobject ECLEventInformation, and can be accessed via GetBackgroundECL().

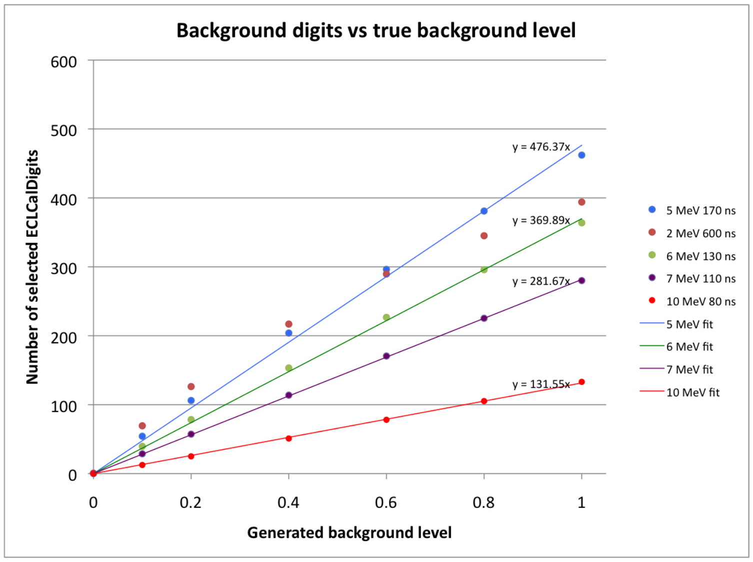

FIG. 13: Average number of selected background digits for various energy and time selection criteria. Linear fits are shown for energy thresholds of 5 MeV and above. The linearity improves as the energy threshold increases. The combination $E > 7$ MeV and $|t| > 110$ ns will be used to select background digits.

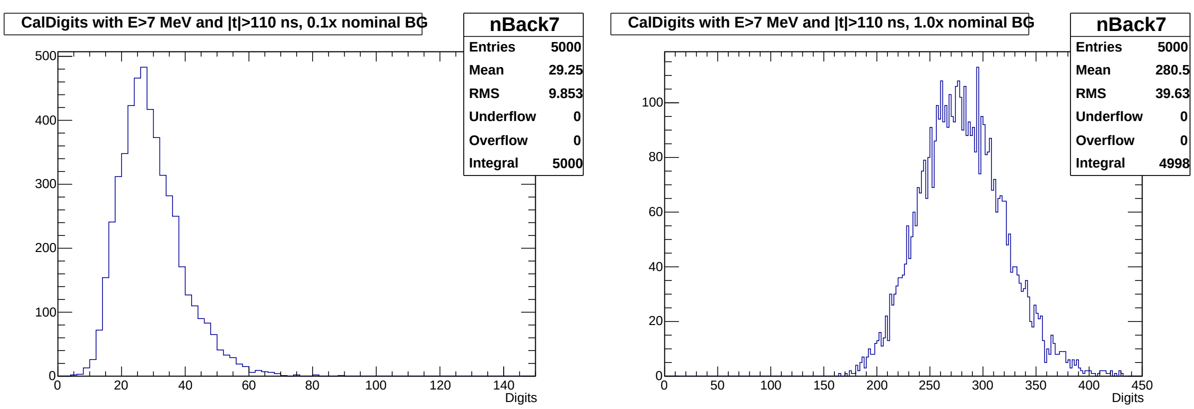

FIG. 14: Number of selected background digits per event, with (a) 0.1× and (b) 1.0× nominal background levels.

V. SUMMARY

Constants required to convert the uncalibrated times in ECLDigit to calibrated times in ECLCalDigit are introduced for Release-00-07-00. An offset is found for each crystal, which corrects for the flight time from the interaction point and for an overall offset in the results returned by the waveform fit in simulated data. The conversion from clock ticks to nanoseconds is 0.491 ns per clock tick, as expected from the code design.

The timing resolution is estimated for each ECLCalDigit, assuming nominal background levels. This simplified result does not correctly account for the non-Gaussian tails in the timing distributions, nor does it account for the variation in timing resolution with background levels.

The background level in each event is estimated by counting the number of ECLCalDigits with $E > 7$ MeV and $|t| > 110$ ns. This quantity scales linearly with the generated background level in MC events, with an average of 280 such digits per event at nominal background levels.