

2 **In-situ calibration of the single-photoelectron** 3 **charge response of the IceCube photomultipliers**

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4 **ABSTRACT:** This article outlines the in-situ calibration of the single-photoelectron charge distributions for each of the Hamamatsu Photonics R7081-02 (MOD) photomultipliers in the IceCube Neutrino Observatory. The accurate characterization of the individual PMT charge distributions is important for event reconstruction and calibration. We discuss the single photoelectron identification procedure and how we extract the single-photoelectron charge distribution using a deconvolution of the multiple photoelectron charge distribution, and we examine various correlations between the shape of the single-photoelectron charge distribution and various hardware components. The time dependence of the individual PMT charge distributions is also investigated.

5 **KEYWORDS:** IceCube, single photoelectron, charge distribution, PMT.

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25 1. Introduction

26 The IceCube Neutrino Observatory [1, 2] is a cubic-kilometer-sized array of 5,160 photomultiplier tubes (PMTs) buried in the Antarctic ice sheet, designed to observe high-energy neutrinos
 27 interacting with the ice [3]. In 2011, the IceCube Collaboration completed the installation of 86
 28 vertical *strings* of PMT modules, eight of which were arranged in a denser configuration known as
 29 the DeepCore sub-array [4]. Each string in IceCube contains 60 digital optical modules (DOMs),
 30 which contain a single PMT each, as well as all required electronics [5]. The primary 78 strings
 31 (excluding DeepCore) are spaced 125 m apart in a hexagonal grid, with the DOMs extending from
 32 1450 m to 2450 m below the surface of the ice sheet. The additional DeepCore strings (79-86) are
 33 positioned between the centermost strings in the detector, reducing the horizontal DOM-to-DOM
 34 distance in this region to 42 m and 72 m. The lower 50 DOMs on these strings are located in the
 35 deepest 350 m of the detector near the clearest ice, while the upper ten provide a cosmic ray veto
 36 extending down from 1900 m to 2000 m below the surface.
 37

38 Each DOM consists of a 0.5" thick spherical glass pressure vessel that houses a single down-
 39 facing 10" PMT from Hamamatsu Photonics. The PMT is coupled to the glass housing with optical

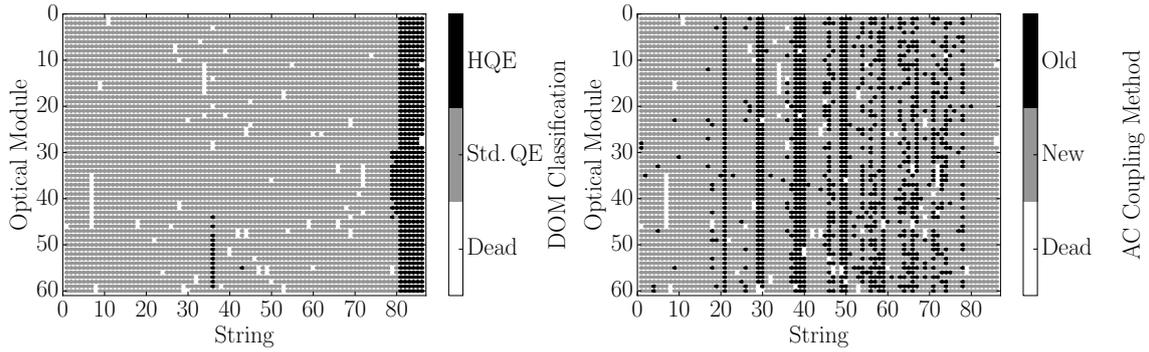


Figure 1. Left: A mapping of the HQE (black) and Standard QE DOMs (gray). Right: The version of AC coupling, old toroids (black) and new toroids (gray). DOMs that have been removed from service are shown in white.

40 gel and is surrounded by a wire mesh of mu metal to reduce the effect of the Earth’s ambient
 41 magnetic field. The glass housing is transparent to wavelengths 350 nm and above [6].

42 Of the 5,160 DOMs, 4,762 house a R7081-02 Hamamatsu Photonics PMT [7], specified for
 43 wavelengths ranging from 300 nm to 650 nm, with peak quantum efficiency of 25% near 390 nm.
 44 These are classified as Standard Quantum Efficiency (Standard QE) DOMs. The remaining 398
 45 DOMs are equipped with the Hamamatsu R7081-02MOD PMTs, which, having a peak quantum
 46 efficiency of 34% near 390 nm (36% higher efficiency than the Standard QE DOMs), are classified
 47 as High Quantum Efficiency (HQE) DOMs [4]. These DOMs are primarily located in DeepCore
 48 and on strings 36 and 43, as shown in the left side of Fig. 1.

49 The R7081-02 and R7081-02MOD PMTs have 10 dynode stages and are operated with a gain
 50 of 10^7 and high voltage around 1200 V. A typical amplified single photoelectron will generate a
 51 ~ 6 mV peak voltage at the input to the front-end amplifiers. The PMTs operate with the anodes at
 52 high voltage and the signal is AC coupled to the front-end amplifiers. There are two versions of AC
 53 coupling in the detectors, both of which use custom-designed wideband bifilar wound 1:1 toroidal
 54 transformers¹. The locations of DOMs with the different versions of AC-coupling, new and old
 55 toroids, are shown on the right side of Fig. 1. The DOMs with the old toroids were designed with
 56 an impedance of 43Ω , while the new toroids are 50Ω [8]. All HQE DOMs are instrumented with
 57 the new toroids.

58 IceCube relies on two observables per DOM to reconstruct events: the total number of detected
 59 photons and their timing distribution. Both the timing and the number of photons are extracted from
 60 the digitized waveforms. This is accomplished by deconvolving the waveforms into a series of
 61 scaled single photoelectron pulses (so-called pulse series) and the integral of the individual pulses
 62 (divided by the load resistance) defines the observed charge. It will often be expressed in units of
 63 PE, or photoelectrons, which further divides the measured charge by the charge of a single electron
 64 times the nominal gain (10^7). Accurate characterization of the individual PMT charge distributions

¹Conventional AC-coupling high-voltage ceramic capacitors can produce noise from leakage currents and impractical requirements on the capacitors in order to meet the signal droop and undershoot requirements. The toroidal transformer effectively acts as a high-pass filter with good signal fidelity at high frequencies. It also provides higher reliability than capacitive coupling and reduces the stored energy, which might cause damage if there is HV discharge in the system [6]. However, the toroidal-transformer AC coupling also introduces signal droop and undershoot.

65 is crucial for calibration and event reconstructions relying on charge information. The charge
66 distribution can also be used to assess long-term detector performance and identify discrepancies
67 between data and Monte Carlo. It is therefore critically important to accurately measure the single-
68 photoelectron (SPE) charge distribution in order to understand the IceCube detector behavior.

69 When one or more photons produce a voltage at the anode sufficient to trigger the onboard
70 discriminator (set via a DAC to approximately 1.3 mV, or equivalently to 0.25 PE), the signal ac-
71 quisition process is triggered. The signal is fed into four parallel input channels. Three of the
72 channels pass first through a 75 ns delay loop in order to capture the leading edge of the pulse and
73 then into three high-speed (300 MSPS for 128 samples) 10-bit waveform digitizers (Analog Tran-
74 sient Waveform Digitizer, ATWD), each of which has a different level of amplification: 15.7 ± 0.6 ,
75 1.79 ± 0.06 , and 0.21 ± 0.01 [8]. There are also three extra ATWDs on board each DOM: one is
76 used for calibration and the other two operate in a ping-pong fashion to remove dead time associ-
77 ated with the readout. The signal to the fourth channel is first shaped and amplified and then fed
78 into a 10-bit fast analog-to-digital converter (fADC) operating at a sampling speed of 40 MSPS.
79 Further detail regarding the description of the DOM electronics can be found in Refs. [5, 9].

80 This article discusses the accurate determination of how individual DOMs collect charge in
81 order to improve calibration and the detector description as used in the IceCube Monte Carlo sim-
82 ulation. It describes the procedure for determining the PMT's gain characteristics as seen in the
83 SPE charge distributions using in-situ data from the IceCube detectors. The SPE charge distribu-
84 tion refers to the measured charge probability density function of the individual DOMs generated
85 by the amplification of a pure sample of single photoelectrons. The extraction of the SPE charge
86 distribution was recently made possible with the development of two pieces of software:

- 87 1. A specially-designed unbiased pulse selection was developed to reduce the multiple photo-
88 electron (MPE) contamination while accounting for physical phenomena (e.g., late pulses,
89 afterpulses, pre-pulses, and baseline shifts) and software-related effects (e.g., pulse splitting).
90 This is further described in Sec. 2.1.
- 91 2. A fitting procedure was developed that separates the remaining MPE contamination from the
92 SPE charge distribution by deconvolving the measured charged distribution. This is further
93 described in Sec. 2.3.

94 By using in-situ data to determine the SPE charge distributions, we accurately represent the
95 individual PMT response as a function of time, environmental conditions, software version and
96 hardware differences, and we sample photons uniformly over the surface of the photocathode. This
97 is beneficial since it also allows us to inspect the stability and long-term behavior of the individual
98 DOMs, verify previous calibration, and correlate features with specific DOM hardware.

99 **1.1 Single-photoelectron charge distributions**

100 In an idealized scenario, a single photon produces a single photoelectron, which is then amplified by
101 a known amount and the measured charge corresponds to 1 PE. However, there are many physical
102 processes that create structure in the measured charge distributions. For example:

- 103 • **Statistical fluctuation due to cascade multiplication** [10]. At every stage of dynode am-
104 plification, there is a stochastic spread in the number of emitted electrons that make it to the

105 next dynode. This in turn causes a spread in the measured charge after the gain stage of the
106 PMT.

107 • **Photoelectron trajectory.** Some electrons may deviate from the favorable trajectory, reduc-
108 ing the number of secondaries produced at a dynode or the efficiency to collect them on the
109 following dynode. This can occur at any stage, but it has the largest effect on the multipli-
110 cation at the first dynode [11]. The trajectory of a photoelectron striking the first dynode
111 will depend on many things, including where on the photocathode it was emitted, the unifor-
112 mity of the electric field, the size and shape of the dynodes [10], and the ambient magnetic
113 field [12, 13].

114 • **Late or delayed pulses.** A photoelectron can elastically or inelastically scatter off the first
115 dynode. The scattered electron can then be re-accelerated to the dynode, creating a second
116 pulse. The difference in time between the initial pulse and the re-accelerated pulse in the
117 R7081-02 PMT was previously measured to be up to 70 ns [6, 14]. The two sub-pulses have
118 lower charges, but the sum of the two tends to add up to the original charge. Collecting either
119 the initial pulse or the late pulse will result in the charge being reconstructed in the low-PE
120 region [15].

121 • **Afterpulses.** When a photoelectron or the secondary electrons produced during the electron
122 cascade gain sufficient energy to ionize residual gas in the PMT, the positively charged ion-
123 ized gas will be accelerated in the electric field towards the photocathode. Upon impact with
124 the photocathode, electrons can be again released from the photocathode, creating what is
125 called an afterpulse. For the R7081-02 PMTs, the timescale for afterpulses was measured
126 to occur from 0.3 to 11 μ s after the initial pulse, with the first prominent afterpulse peak
127 occurring at approximately 600 ns [6]. The spread in the afterpulse time is dependent on
128 the position of photocathode, the charge-to-mass ratio of the ion produced, and the electric
129 potential distribution [16], whereas the size of the afterpulse is related to the momentum and
130 species of the ionized gas and composition of the photocathode [17].

131 • **Pre-pulses.** If an incident photon passes through the photocathode without interaction and
132 strikes one of the dynodes, it can eject an electron that is only amplified by the subsequent
133 stages, resulting in a lower measured charge (lower by a factor of approximately 25). For
134 the IceCube PMTs, the prepulses have been found to arrive approximately 30 ns before the
135 signal from other photoelectrons from the photocathode [6].

136 • **MPE contamination.** When multiple photoelectrons arrive at the first dynodes within sev-
137 eral nanoseconds of each other, they can be reconstructed by the software as a single, MPE
138 pulse.

139 • **Electronic noise.** This refers to the fluctuations in the analog-to-digital converters (ATWDs
140 and FADC) and ringing that arises from the electronics.

141 Beyond the physical phenomena above that modify the measured charge distribution, there is
142 also a lower limit on the smallest charge that can be extracted. For IceCube, the discriminator limits

143 the trigger pulse to be above approximately 0.25 PE, and subsequent pulses in the readout time
 144 window are subject to a software-defined threshold. The software threshold was set conservatively
 145 to avoid extracting pulses that originated from electronic noise. This threshold can be modified to
 146 gain access to lower charge pulses and will be discussed in Sec. 2.2.

147 The standard SPE charge distribution model used by the IceCube Collaboration, known as the
 148 TA0003 distribution [6], represented the above effects as the sum of an exponential plus a Gaus-
 149 sian. The exponential component represented charge of poorly amplified pulses and the Gaussian
 150 represented the spread in statistical fluctuations due to the cascade multiplication. The TA0003
 151 distribution was previously used to describe all the PMTs in the IceCube detectors.

152 Recently, IceCube has performed several lab measurements using the R7081-02 PMTs with in-
 153 time laser pulses, demonstrating that the in-time charge distribution includes a steeply falling low-
 154 charge component below the discriminator threshold. To account for this, a new functional form
 155 including a second exponential was introduced. This form of the charge distribution $f(q)_{SPE} =$
 156 $\text{Exp}_1 + \text{Exp}_2 + \text{Gaussian}$, is referred to as the *SPE template* in this article. Explicitly, it is:

$$f(q)_{SPE} = E_1 e^{-q/w_1} + E_2 e^{-q/w_2} + N e^{-\frac{(q-\mu)^2}{2\sigma^2}}, \quad (1.1)$$

157 where q represents the measured charge; E_1 , E_2 , and N represent normalization factors of each
 158 components; w_1 and w_2 are the exponential decay widths; and μ , σ are the Gaussian mean and
 159 width, respectively. This is the assumed functional shape of the SPE charge distributions and the
 160 components of Eq. 1.1 are determined in this article for all in-ice DOMs. IceCube defines 1 PE as
 161 the location of the Gaussian mean (μ) and calibrates the gain on the individual PMTs during the
 162 start of each season to meet this definition. The choice of where we define 1 PE is arbitrary, since
 163 linearity between the total charge collected and the number of incident photons is satisfied up to
 164 ~ 2 V [8]. This is because the average of the distribution is a set fraction of the Gaussian mean and
 165 the mean of a N -fold convolution is the sum of means. Any bias in the total observed charge can
 166 be absorbed into an efficiency term, such as the quantum efficiency.

167 1.2 IceCube datasets and software definitions

168 The largest contribution to the IceCube trigger rate comes from downgoing muons produced in
 169 cosmic ray induced showers [18]. Cosmic ray muons stopping in the detector cause the individual
 170 trigger rate to decrease at lower depths. Further, climate variations during the formation of the ice
 171 sheet caused depth-dependent changes in the optical properties of the ice. The optical properties
 172 also affect the trigger rate; in particular, the “dust layer” from 2100 to 2200 m below the surface is
 173 a region in the ice with relatively large scattering and absorption coefficients [19].

174 An induced signal in the PMT that passes through the AC coupling toroid located on the
 175 base of the PMT is compared to a discriminator threshold. If a DOM and its nearest or next
 176 to nearest neighbor observe a discriminator threshold crossing within a set time window, a *Hard*
 177 *Local Coincidence* (HLC) is initiated and the corresponding waveforms are sampled 128 times and
 178 read out on the three ATWDs.

179 After waveform digitization, there is a correction applied to remove the measured DC base-
 180 line offset. The signal droop and undershoot introduced by the toroidal transformer AC coupling

181 is compensated for in software during waveform calibration by adding the expected temperature-
182 dependent reaction voltage of the undershoot to the calibrated waveform. If the undershoot voltage
183 drops below 0 ADC counts, the ADC values are zeroed and then compensated for once the wave-
184 form is above the minimum ADC input. Scaled single photoelectron pulse shapes (that take into
185 account the version of the AC coupling) are then fit to the waveforms using software referred to as
186 "WaveDeform" (waveform unfolding process), which determines the individual pulse time stamps
187 and charges and populates a pulse series [20].

188 The pulse series used in this analysis come from two datasets provided by IceCube:

- 189 1. The **MinBias dataset**. This dataset records the full waveform readout of randomly-triggered
190 HLC events at a rate that corresponds on average to 1/1000 events. The largest contribution
191 to the IceCube trigger rate comes from downgoing muons produced in cosmic-ray-induced
192 showers [18] and therefore is the largest signal component in this dataset. These muons tend
193 to have small energies when they reach the detector, thus they produce minimal MPE con-
194 tamination. The full waveform of these events allows us to extract the raw information about
195 the individual pulses. This will be used to measure the individual PMT charge distributions.
- 196 2. The **BeaconLaunch dataset**. This is a forced triggered filter that is typically used to mon-
197 itor the individual DOM baseline. It includes the full ATWD-window waveform readout.
198 Since this dataset is forced-triggered, the majority of these waveforms represent baseline
199 fluctuations with minimal contamination from the occasional coincidental pulse that makes
200 it into the readout window. This dataset will be used to examine the noise contribution to
201 the charge distributions. Note: when using this dataset, the weight of every pulse is multi-
202 plied by a factor of 28.4 to account for the livetime difference between the MinBias dataset
203 and the BeaconLaunch dataset. Weight, in this context, refers to the number of photons in
204 the MinBias dataset proportional to one photon in the BeaconLaunch dataset for which both
205 datasets have the same equivalent livetime.

206 This analysis uses the full MinBias and BeaconLaunch datasets from IceCube seasons 2011
207 to 2016 (subsequently referred to as IC86.2011 to IC86.2016). Seasons in IceCube typically start
208 in June of the labeled year and end approximately one year later. Calibration is performed at the
209 beginning of each season.

210 2. Extracting the SPE templates

211 2.1 Single photoelectron pulse selection

212 The pulse selection is the method used to extract candidate, unbiased, single photoelectron pulses
213 from data while minimizing the MPE contamination. It avoids collecting afterpulses, rejects late
214 pulses from the trigger, reassembles late pulses, accounts for the discriminator threshold, reduces
215 the effect of droop and baseline undershoot, and gives sufficient statistics to perform a season-to-
216 season measurement. An illustrative diagram of the pulse selection is shown in the left side of
217 Fig. 2, while a description of the procedure is detailed below.

218 We restrict the pulse selection to only extract information from waveforms in which the trigger
219 pulse does not exceed 10 mV and no subsequent part of the waveform exceeds 20 mV. This reduces
220 the effect of the baseline undershoot due to the AC coupling or other artifacts from large pulses.

221 In order to trigger a DOM, the input to the front-end amplifiers must exceed the discriminator
 222 threshold. To avoid the selection bias of the discriminator trigger, we ignore the trigger pulse as
 223 well as the entire first 100 ns of the time window. Ignoring the first 100 ns has the added benefit
 224 of also removing late pulses that could be attributed to the triggering pulse. To ensure we are not
 225 accepting afterpulses into the selection, we also enforce the constraint that the pulse of interest
 226 (POI) is within the first 375 ns of the ATWD time window. This also allows us to examine the
 227 waveform up to 50 ns after the POI. In the vicinity of the POI, we check that WaveDeform did not
 228 reconstruct any pulses up to 50 ns prior to the POI, or 100 to 150 ns after the POI (the light gray
 229 region of Fig. 2 (left)). This latter constraint is to reduce the probability of accidentally splitting a
 230 late pulse in the summation window.

231 If a pulse is reconstructed between 100 and 375 ns after the time window is opened and the
 232 voltage criteria are met, it is accepted as a candidate photoelectron and several checks are performed
 233 on the waveform prior to and after the pulse. The first check is to ensure that the waveform is near
 234 the baseline just before the rising edge of the POI. This is accomplished by ensuring that the
 235 waveform does not exceed 1 mV, 50 to 20 ns prior to the POI, and eliminates cases where the POI
 236 is a late pulse. We also ensure the waveform returns to the baseline by checking that no ADC
 237 measurement exceeds 1 mV, 100 to 150 ns after the POI. These constraints are illustrated as the
 238 horizontal red dotted lines and black arrows in the left side of Fig. 2.

239 If all the above criteria are met, we sum the reconstructed charges from the POI time, given by
 240 WaveDeform, to +100 ns (the dark gray area in Fig. 2 (left)). This ensures that any nearby pulses
 241 are either fully separated or fully added. WaveDeform may occasionally split an SPE pulse into

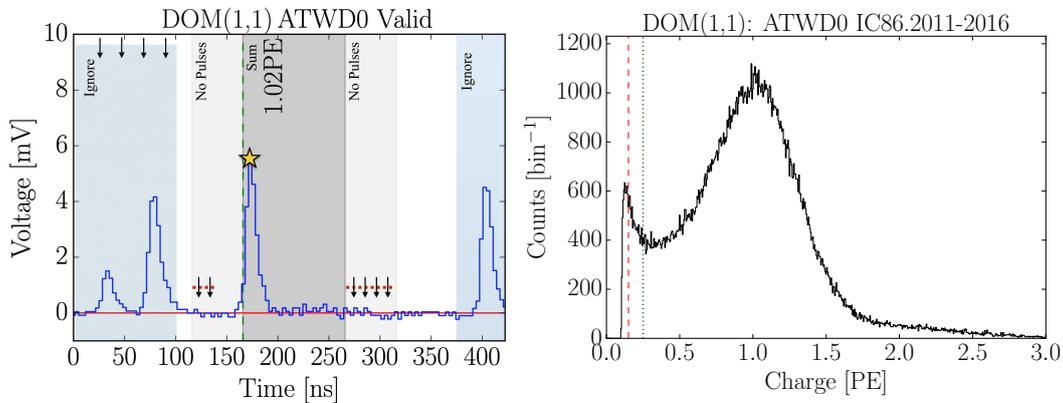


Figure 2. Left: An illustrative diagram of the pulse selection criteria for selecting a high-purity and unbiased sample of single photoelectrons. The digitized ATWD waveform is shown in blue. The pulse of interest is identified with a yellow star. This example waveform was triggered by a small pulse at 25 ns (recall that the delay board allows us to examine the waveform just prior to the trigger pulse), followed by a potential late pulse at 70 ns. At 400 ns, we see a pulse in the region susceptible to afterpulses. Waveform voltage checks are illustrated with arrows, and various time windows described in the text are drawn with semi-opaque regions. The POI is reported to have a charge of 1.02 PE, given by WaveDeform, and would pass the pulse selection criteria. Right: The collected charges from string 1, optical module 1 (DOM 1,1), from the MinBias dataset collected from IC86.2011 to IC86.2016 that pass the pulse selection. The discriminator threshold at 0.25 PE is represented as a dotted black vertical line. For visual purposes, a vertical dashed red line is also included at 0.15 PE.

242 multiple smaller pulses, therefore it is always critical to perform a summation of the charge within
 243 a window. The 100 ns summation also means that the pulse selection will occasionally accept MPE
 244 events.

245 2.2 Characterizing the low-charge region

246 Fig. 2 (right) shows the charge distributions of the selected pulses that pass the single photoelectron
 247 pulse selection for string 1, optical module 1, DOM(1,1). In the low-charge region (below 0.25 PE),
 248 we see a second threshold at approximately 0.13 PE. This is a software-defined threshold that comes
 249 from a gradient-related termination condition in WaveDeform. The threshold was set to avoid
 250 electronic noise being interpreted as PMT pulses and contaminating the low-charge region.

251 The steeply falling component of the region from 0.13 PE to 0.25 PE is in agreement with the
 252 in-time laser tests mentioned in Sec. 1.1 and emphasizes the importance of collecting data below
 253 the discriminator. This section will assess the noise contribution to this region and examine the
 254 effect on the charge distribution and noise contribution by lowering the WaveDeform threshold.

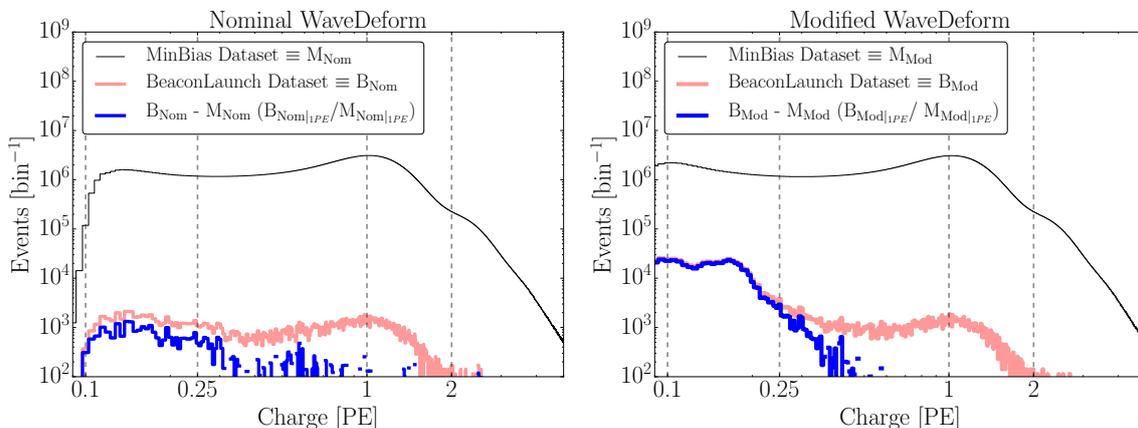


Figure 3. The cumulative charge distributions of all DOMs for the MinBias and BeaconLaunch datasets. The blue histogram shows the expected contribution from noise. This was found by subtracting the shape of the MinBias dataset from the BeaconLaunch dataset. Left: The charge distributions for the standard WaveDeform settings. Right: The charge distributions for the modified WaveDeform settings.

255 Fig. 3 (left) shows the charge distributions for the MinBias (black) and the BeaconLaunch
 256 (red) datasets using the default settings of WaveDeform. As mentioned in Sec. 1.2, occasionally
 257 a photoelectron will be coincident with the forced BeaconLaunch time window. These charges
 258 populate a SPE distribution. Subtracting the shape of the MinBias charge distribution from the
 259 BeaconLaunch dataset yields an estimate of the amount of electronic noise contamination (blue).
 260 The bin with the largest signal-to-noise ratio (SNR) above 0.1 PE was found to have a SNR of
 261 0.0013. The SNR for the full distribution was found to be 0.0005. Fig. 3 (right) shows the same
 262 data after lowering the WaveDeform threshold. Correspondingly, the bin with the largest SNR was
 263 found to have a SNR of 0.017, whereas the total SNR was found to be 0.0015.

264 The modified WaveDeform datasets show a minimal increase in the contribution of noise to
 265 the low-charge region. From this, we are able to extract charge information down to approximately

266 0.10 PE and improve the overall description of the charge distribution below the discriminator. This
 267 will help constrain the values defining Exp_1 .

268 **2.3 Fitting procedure**

269 The fit assumes that there is a negligible three-PE contribution, which is justified by the lack of
 270 statistics in the 3 PE region as well as the significant rate difference between the 1 PE and 2 PE
 271 region, as shown in Fig. 2 (right). The 2 PE charge distribution is assumed to be the SPE charge
 272 distribution convolved with itself [21]. A python-based piece of software called the "convolutional
 273 fitter" is used to determine the components of Eq. 1.1 from the measured charge distribution that
 274 includes the MPE contamination.

275 The Exp_2 component, as well as the Exp_1 , of Eq. 1.1 represent poorly amplified photoelec-
 276 trons, and we do not allow it to extend beyond the high-charge region of the Gaussian component.
 277 In particular, we include a constraint on the parameter w_2 to ensure that it falls off with the
 278 Gaussian component:

$$w_2 < \frac{\mu + 2\sigma}{4 - \text{Ln}(N/E_2)}. \quad (2.1)$$

279 This equation was found by setting the Exp_2 to be $1/e^2$ that of the Gaussian component at two
 280 sigma (the Exp_1 is neglected from this equation since it falls off in the low-charge region). Eq. 2.1
 281 is used as a constraint during the fit to the charge distributions.

282 Pulses that fall below the WaveDeform threshold and are not reconstructed contribute to an
 283 effective efficiency of the individual DOMs. This analysis assumes the same shape of the steeply
 284 falling exponential component (Exp_1) for all DOMs in the detector to avoid large fluctuations in
 285 the individual DOM efficiencies. The modified WaveDeform data will strictly be used to determine
 286 the Exp_1 component. Specifically, using the modified WaveDeform, we will background-subtract
 287 the BeaconLaunch distribution from the MinBias data, fit the resulting distribution to determine
 288 the components of Eq. 2.1, and use only the measured shape and normalization of Exp_1 in all
 289 subsequent unmodified WaveDeform fits.

290 As described in Sec. 1.1, the Gaussian mean (μ) is used to determine the gain setting for each
 291 PMT. Therefore, it is particularly important that the fit quality in this region accurately describes the
 292 data. While fitting to the full charge distribution improves the overall fit agreement, the mismatch
 293 between the chosen functional form (Eq. 1.1) and a true SPE charge distribution can cause the
 294 Gaussian component to pull away from its ideal location. To compensate for this, the convolutional
 295 fitter prioritizes fitting to the data around the Gaussian mean. This is accomplished by first fitting
 296 to the full distribution to get an estimate of the Gaussian mean location. Then, the statistical
 297 uncertainty is reduced in the region ± 0.15 PE around the original estimated Gaussian mean, and
 298 the distribution is re-fitted.

299 Upon fitting the MinBias data with the predetermine values for Exp_1 , the residual of each fit is
 300 calculated by measuring the percentage difference between the fit and the data. The average resid-
 301 ual will then be used as a global scaling factor for all SPE templates to account for the difference
 302 between the chosen model (Eq. 2.1) and the actual data.

303 All the DOMs with "failed fits" are not included in this article. A DOM is classified as having
 304 a failed fit if it does not pass one of the validity checks on the data requirements (e.g. number of

valid pulses) or goodness of fit. The majority of these DOMs have been removed from service (approximately 109 DOMs) and the remaining approximately 6 DOMs are known to have various issues. In the IceCube MC simulation chain, these DOMs are assigned the average SPE template.

2.4 SPE template fit results

Using the background-subtracted modified WaveDeform dataset, the Exp_1 component was determined by fitting the distribution from 0.1 PE to 3.5 PE. The result of the fit yielded $E_1 = 6.9 \pm 1.5$ and $w_1 = 0.032 \pm 0.002$ PE. The shape of Exp_1 is then used to describe the low-PE charge region for all subsequent fits.

Using the MinBias dataset with the measured values of Exp_1 , the SPE templates are extracted for every DOM, separately for each IceCube season (IC86.2011 to IC86.2016). The fit range for Exp_2 and the Gaussian components is selected to be between 0.15 PE and 3.5 PE. An average fit was also performed on the cumulative charge distribution, in which all the data for a given DOM was summed together (labeled as "AVG").

We can divide the DOMs into subsets of hardware differences: the HQE DOMs with the new toroids, the Standard QE DOMs with the new toroids, and the Standard QE DOMs with the old toroids. The mean value and standard error of the IC86.AVG fit parameters, excluding Exp_1 , for the subset of hardware differences are listed in Table 1. The average residual for all DOMs from 0 to 1 PE is shown in Fig. 4.

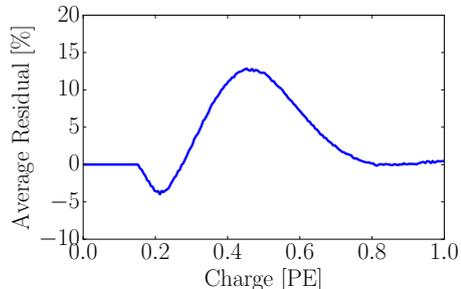


Figure 4. The measured average residual of the SPE templates fit.

Hardware Configuration	Exp_2 Amp. (E_2)	Exp_2 Width (w_2)	Gaus. Amp. (N)	Gaus. Mean (μ)	Gaus. Width (σ)
HQE / New Toroid	0.644 ± 0.003	0.405 ± 0.003	0.715 ± 0.002	1.0202 ± 0.0010	0.311 ± 0.001
Std. QE / New Toroids	0.566 ± 0.001	0.403 ± 0.001	0.751 ± 0.001	1.0238 ± 0.0004	0.316 ± 0.001
Std. QE / Old Toroids	0.525 ± 0.002	0.420 ± 0.002	0.813 ± 0.002	1.0074 ± 0.0007	0.294 ± 0.001

Table 1. The average values and standard error of each fit parameter for the subset of hardware configurations listed in the first column.

An example fit is shown in Fig. 5 for the cumulative charge distribution for DOM (1,1). The collected charge distribution is shown in the black histogram, while the convolutional fit is shown as the black line (multiplied by the residual). The extracted SPE template (also multiplied by the residual) for this DOM is shown in blue.

3. Discussion

3.1 Correlations between fit parameters and DOM hardware differences

It is evident from the data provided in Table 1 that the average shape of the SPE templates is dependent on the DOM hardware. Most notably, when we examine the subset of DOMs instrumented

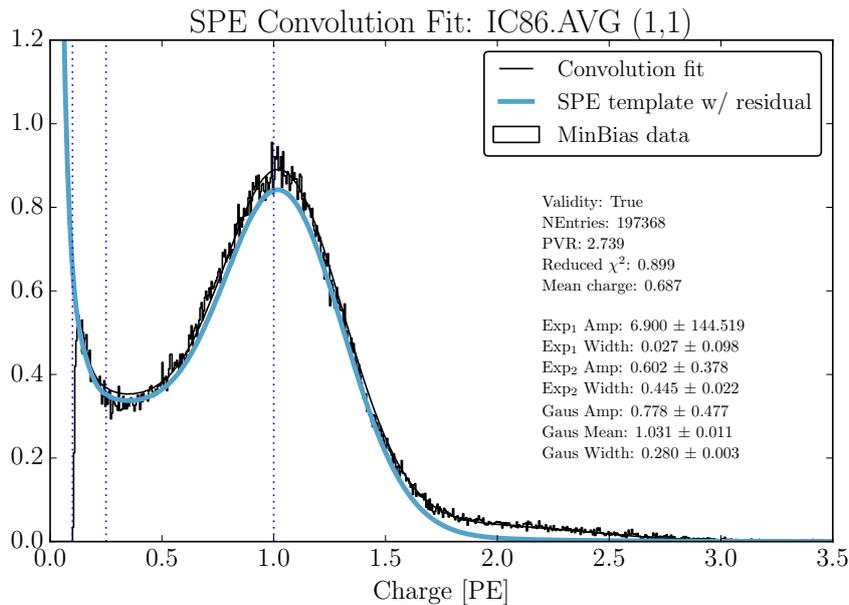


Figure 5. An example fit including the residual correction for DOM(1,1) using the WaveDeform dataset for seasons IC86.2011 to IC86.2016. The result from the convolutional fitter is shown as a solid black line. The extracted SPE template is shown blue.

337 with the new toroids, the average HQE DOM were found to have a particularly larger E_2 component
 338 ($13.8 \pm 0.6\%$) and smaller Gaussian amplitude ($-4.77 \pm 0.03\%$). Consequently, the average HQE
 339 peak-to-valley ratio is measured to be 2.322 ± 0.013 , corresponding to $-12.12 \pm 0.06\%$ lower than
 340 the average Standard QE DOMs. Also, interestingly, the mean charge of the average HQE DOM
 341 was found to be $-3.34 \pm 0.01\%$ lower than for the Standard QE DOMs. IceCube compensates for
 342 the change in the mean measured charge in simulation, by increasing the HQE DOM efficiency by
 343 the equivalent amount. This ensures that the total amount of charge collected by the HQE DOMs
 344 remains the same prior to, and after, inserting the SPE templates into simulation.

345 Similarly, using only the subset of Standard QE DOMs, the SPE templates comparing the
 346 method of AC coupling were found to have a measurably different shapes. The average Gaus-
 347 sian amplitude and width for the DOMs instrumented with the old toroids were found to be
 348 $+8.31 \pm 0.01\%$ and $-6.80 \pm 0.03\%$, respectively. With these differences, we find a peak-to-valley
 349 ratio of 2.643 ± 0.008 for the old toroid DOMs and 3.012 ± 0.012 for the new toroid DOMs.
 350 The average Gaussian mean of the fit for the DOMs with the old toroids was also found to be
 351 $-1.6 \pm 0.1\%$ lower than those with the new toroids. This corresponds proportionally to a change in
 352 the expected gain. The mean charge, however, between these two hardware configurations remains
 353 very similar ($-0.346 \pm 0.001\%$).

354 Although the DOMs instrumented with the old toroids were deployed into the ice earlier than
 355 those with the new toroids, the differences above is still noted when examining individual deploy-
 356 ment years; therefore, the shape differences are not attributed to the change in the DOM behavior
 357 over time. The DOMs with the old toroids were the first PMTs to be manufactured by Hamamatsu,

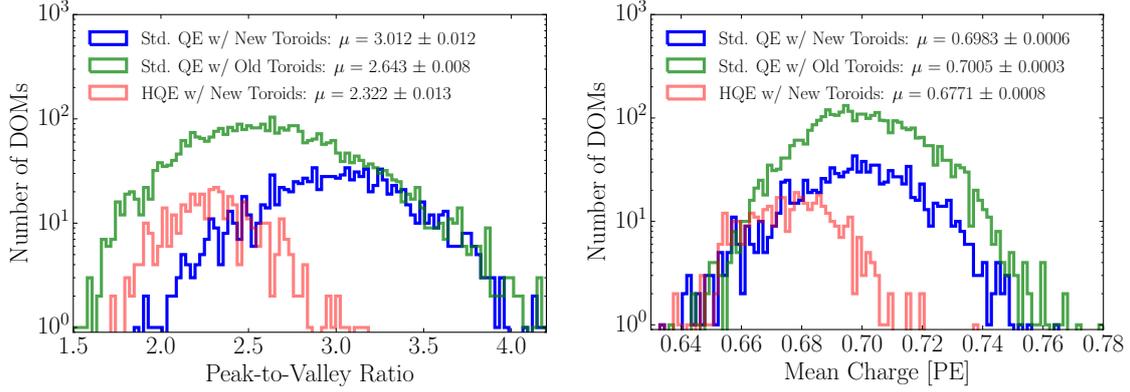


Figure 6. Comparison between the R7081-02MOD HQE DOMs and standard R7081-02 DOMs. Left: The peak-to-valley ratio for the two subsets of quantum efficiencies. Right: The mean charge of the individual DOM SPE templates.

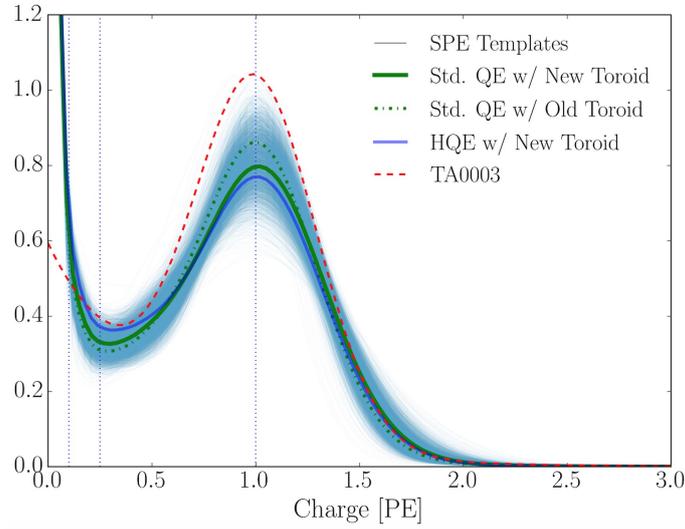


Figure 7. A comparison between the SPE templates (light blue band) and the TA0003 (dashed red line) distribution. The average SPE template for the Standard QE and HQE DOMs is shown as the thick blue and green lines, respectively. The SPE templates include the residual correction, and all curves are normalized.

358 so this difference may also be attributed to a gradual change in the process parameters over the
 359 course of PMT manufacturing, i.e. a change in the production procedure rather than the actual AC
 360 coupling version. It is also possible that the differences originate from the transfer function that
 361 models a single photoelectron waveform used in WaveDeform.

362 Fig. 6 shows the distribution of the measured peak-to-valley ratios and mean charge for the
 363 three different subsets of DOM hardware.

364 Fig. 7 illustrates the average shape differences in the measured SPE templates between the
 365 HQE DOM with the new toroids (thick blue line), Standard QE with the new toroids (thick green
 366 line), Standard QE with the old toroids (dash-dot green line), compared to the measured SPE tem-
 367 plates from the AVG charge distributions (thick blue lines). The figure also shows how the TA0003

368 distribution compares to this recent measurement. The shape difference in the TA0003 is attributed
 369 to better control of the low-charge region, the difference in functional form (described in Sec-
 370 tion 1.1), and the fact that the SPE templates sample uniformly over the entire photocathode at
 371 random incident angles.

372 3.2 Fitting parameters variation over time

373 The SPE templates were extracted for each IceCube season independently to investigate the time
 374 dependence of the fit parameters. For every DOM in the detector, the change over time of each
 375 fit parameter (excluding Exp_1) was calculated. Fig. 8 shows the change in a given fit parameter,
 376 relative to the mean value, per year. The measured distribution was found to be consistent with
 377 statistically scrambling the yearly measurements. The average of each fit parameters are found
 378 to deviate less than 0.1%, which is in agreement with the stability checks performed in Ref. [8].
 379 This observation holds for the individual subset of DOMs with different hardware configurations
 380 as well.

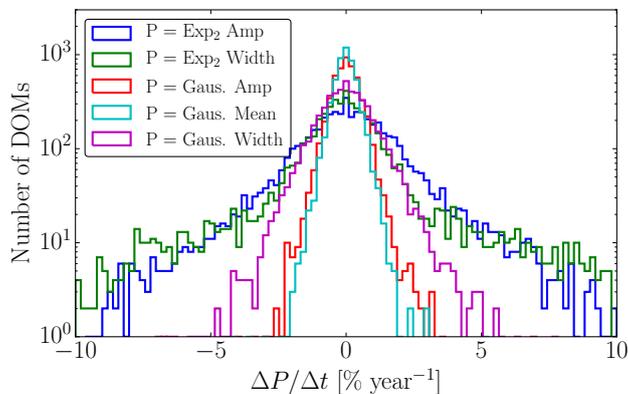


Figure 8. The change in the individual DOM fitted parameters over time, represented as percentage deviation from the mean fit parameter value.

381 3.3 Quantifying observable changes when modifying the PMT charge distributions

382 Changing the assumed gain response in simulation, as deduced from data, has different implications
 383 depending on the typical illumination level present in different analyses. These differences are
 384 outlined in the following discussion.

385 The PMT response is described by a combination of a "bare" efficiency, η_0 , and a normalized
 386 charge response function, $f(q)$. The bare efficiency represents the fraction of arriving photons that
 387 result in any nonzero charge response, including those well below the discriminator threshold. The
 388 normalization condition is:

$$\int_0^{\text{inf}} f(q) dq = 1. \quad (3.1)$$

389 Generally, $f(q)$ and η_0 have to be adjusted together to maintain agreement with a quantity known
 390 from lab or in-ice measurements, such as the predicted number of pulses above threshold for a dim
 391 source.

392 **Dim source measurements** Where light levels are low enough, sub-discriminator pulses do not
 393 contribute any observed charge because they do not satisfy the trigger threshold, and the probability
 394 of two photons arriving together is negligible. Given some independent way of knowing the number
 395 of arriving photons, a lab or in-ice measurement determines the trigger fraction above threshold
 396 $\eta_{0.25}$ and/or the average charge over threshold $Q_{0.25}$, either of which can be used to constrain the
 397 model as follows:

$$\eta_{0.25} = \eta_0 \int_{0.25q_{pk}}^{\text{inf}} f(q) dq \quad (3.2)$$

$$Q_{0.25} = \eta_0 \int_{0.25q_{pk}}^{\text{inf}} qf(q) dq \quad (3.3)$$

398 Here, the discriminator threshold is assumed to be 0.25 times the peak position q_{pk} . It is also
 399 useful to multiply observed charges by q_{pk} , since we set each PMT gain by such a reference, and
 400 then a measurement constraint would be stated in terms of $Q_{0.25}/q_{pk}$.

401 **Semi-bright source measurements** Once the ATWD window is open, subsequent pulses are not
 402 limited by the discriminator threshold. WaveDeform introduces a software termination condition at
 403 0.1 PE (described at the end of Section 2.1). The average charge of an individual pulse that arrives
 404 within the time window is:

$$Q_{0.10} = \eta_0 \int_{0.10q_{pk}}^{\text{inf}} qf(q) dq \quad (3.4)$$

405 **Bright source measurements** For light levels that are large, the trigger is satisfied regardless
 406 of the response to individual photons, and the total charge per arriving photon therefore includes
 407 contributions below both the discriminator and the WaveDeform thresholds:

$$Q_0 = \eta_0 \int_0^{\text{inf}} qf(q) dq \quad (3.5)$$

408 As such, the total charge is directly proportional to the average charge of the SPE template,
 409 having a strong dependence on Exp_1 .

410 3.3.1 Model comparison

411 When the charge distribution model is changed in a way that preserves agreement with the mea-
 412 sured $\eta_{0.25}$ or $Q_{0.25}/q_{pk}$, i.e., η_0 is adjusted properly for changes in $f(q)$, the physical effect can be
 413 summarized by the change in the bright-to-dim ratios $Q_0/Q_{0.25}$, and $Q_0/Q_{0.10}$. Conveniently, these
 414 ratios depend only on the shape of $f(q)$. Table 2 compares these ratios in terms of the TA0003
 415 charge distribution and the SPE templates described here. It is shown that there are sub-percent
 416 level differences in the physically-observable bright-to-dim ratios.

417 3.4 SPE templates in simulation

418 The IceCube Monte Carlo simulation chain assigns a charge to every photoelectron generated at
 419 the surface of the photocathode. The charge is determined by sampling from a normalized charge
 420 distribution probability density function. A comparison between describing the charge distribution
 421 using the SPE templates and the TA0003 distribution follows.

Model	Detector	$Q_0/Q_{0.25}$	$Q_0/Q_{0.10}$	$\eta_{0.25}/Q_{0.25}$
TA0003	All DOMs	1.017	1.0031	1.05
SPE Templates	HQE + New Toroids	1.021 ± 0.002	1.0041 ± 0.0004	1.05 ± 0.02
	Std. QE + New Toroids	1.018 ± 0.002	1.0035 ± 0.0005	1.03 ± 0.02
	Std. QE + Old Toroids	1.017 ± 0.002	1.0033 ± 0.0005	1.05 ± 0.02

Table 2. The distribution in bright-to-dim ratios for the previous charge distribution (TA0003) and the individual DOM SPE templates for the IceCube and DeepCore detectors.

422 Two simulation sets consisting of the same events were processed through the IceCube Monte
423 Carlo simulation chain to the final analysis level of an update to the IC86.2011 sterile neutrino
424 analysis [22]. Here, the events that pass the cuts are $>99.9\%$ pure upgoing (a trajectory ori-
425 ented upwards relative to the horizon) secondary muons produced by charged current muon neu-
426 trino/antineutrino interactions. The muon energy range of this event selection is between approxi-
427 mately 500 GeV and 10 TeV.

428 Fig. 9 (left) shows the distribution of the total measured charge in a single DOM during each
429 event. The data is shown for the full IC86.2012 season but is statistically equivalent to any of the
430 other seasons. The simulation set using the TA0003 charge distribution is shown in orange, and that
431 using the SPE templates is shown in blue. The bottom of the plot shows the ratio of the measured
432 quantity relative to data. Fig. 9 (right) shows the distribution of the measured total charge on a
433 DOM (after noise removal) divided by the number of channels, or DOMs, that participated in the
434 event. Both plots in Fig. 9 have been normalized such that the area under the histograms is the
435 same.

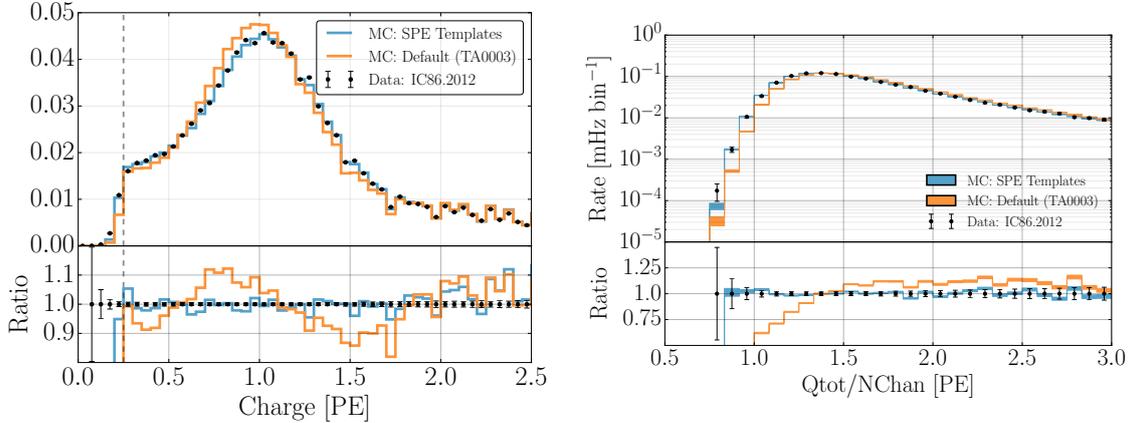


Figure 9. A comparison between the SPE templates (blue) and the TA0003 (orange) model for describing the SPE charge distribution in Monte Carlo. The simulation is compared to the 2012 IceCube season. Left: The total measured charge per DOM, per event at analysis level. Right: The distribution of the total measured charge of an event divided by the number of DOMs that participated in the event.

436 The SPE templates clearly improve the overall MC description of these two variables. IceCube
437 includes a systematic uncertainty in all analyses, which scales the DOM efficiency to account for
438 effects that change the total observed charge. This systematic compensates for the overall mean
439 charge shift introduced using the SPE templates; however, the SPE templates now introduce DOM-

440 to-DOM differences. This is not expected to change the IceCube physics results since analyses are
441 sensitive to the overall detector performance rather than the individual DOM variations.

442 **3.5 SPE templates for calibration**

443 The gain setting on each DOM is calibrated at the beginning of the season such that the Gaussian
444 mean charge distribution corresponds to a gain of 10^7 , or equivalently 1 PE. Since the method used
445 to extract the Gaussian mean described in this article is different from the previous method used
446 for calibration of the DOMs, the total measured charge from a DOM is expected to change with
447 the updated calibration.

448 The Gaussian mean component of the fit of every year is found to be on average $2.00 \pm 0.03\%$
449 higher than unity with a standard deviation of 3.54%, corresponding to a systematic overestimation
450 of the measured charge in the detector. This correction to the measured charge can be implemented
451 retroactively by dividing the reported charge from WaveDeform by the corresponding Gaussian
452 mean for a given DOM. Alternatively, the MC can account for this difference by simply inserting
453 the SPE templates with Gaussian mean matching the values found in the data. Both of these
454 solutions will be used in future IceCube data/MC production.

455 **4. Conclusion**

456 This article outlines the procedure used for collecting a relatively pure sample of single photoelec-
457 tron charges for each of the in-ice DOMs in IceCube. MPE contamination was removed under the
458 assumption that it is the convolution of the SPE distribution from multiple times.

459 The SPE templates were extracted for each DOM and each season in the IceCube detector and
460 investigated for time dependent behaviour and correlations with hardware-related features. Neither
461 detector shows more than a 0.1% deviation in any of the fitted parameters over the investigated
462 seasons, in agreement with Ref. [8]. Yearly variations in the fit parameters are consistent with
463 statistical fluctuations. The HQE DOMs were found to have a smaller peak-to-valley ratio than
464 the Standard QE DOMs, as well as an overall $-3.34 \pm 0.01\%$ lower mean charge. The DOMs
465 instrumented with the old toroids were found to have a narrower and larger Gaussian component.

466 The SPE templates were implemented into the MC simulation production chain and the results
467 were compared to the default charge distribution (TA0003). A significant improvement in the
468 description of the low-level variables, total charge per DOM and total charge per event over the
469 number of channels, was shown. IceCube includes a systematic that scales the bare efficiency of
470 the DOMs to maintain agreement with a quantity known from lab or in-ice measurements. After
471 accounting for this shift, the effect on physics analysis, as shown by the bright-to-dim ratios, is
472 expected to percent level changes in the measured charge.

473 The new method for extracting the calibration constant that determines the gain setting on each
474 of the PMTs (the Gaussian mean of the fit) has been revised and shows that the average gain was
475 $2.00 \pm 0.03\%$ larger than expected. This will be accounted for in future IceCube data reprocessing
476 and simulation.

477

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496 **References**

- 497 [1] J. Ahrens *et al.*, “Icecube preliminary design document,” URL: <http://www.icecube.wisc.edu/science/publications/pdd>, 2001.
498
- 499 [2] A. Achterberg, M. Ackermann, J. Adams, J. Ahrens, K. Andeen, D. Atlee, J. Baccus, J. Bahcall,
500 X. Bai, B. Baret, *et al.*, “First year performance of the icecube neutrino telescope,” *Astroparticle*
501 *Physics*, vol. 26, no. 3, pp. 155–173, 2006.
- 502 [3] I. Collaboration *et al.*, “Evidence for high-energy extraterrestrial neutrinos at the icecube detector,”
503 *Science*, vol. 342, no. 6161, p. 1242856, 2013.
- 504 [4] R. Abbasi, Y. Abdou, T. Abu-Zayyad, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Allen,
505 D. Altmann, K. Andeen, *et al.*, “The design and performance of icecube deepcore,” *Astroparticle*
506 *physics*, vol. 35, no. 10, pp. 615–624, 2012.
- 507 [5] R. Abbasi, M. Ackermann, J. Adams, M. Ahlers, J. Ahrens, K. Andeen, J. Auffenberg, X. Bai,
508 M. Baker, S. Barwick, *et al.*, “The icecube data acquisition system: Signal capture, digitization, and
509 timestamping,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators,*
510 *Spectrometers, Detectors and Associated Equipment*, vol. 601, no. 3, pp. 294–316, 2009.
- 511 [6] R. Abbasi, Y. Abdou, T. Abu-Zayyad, J. Adams, J. Aguilar, M. Ahlers, K. Andeen, J. Auffenberg,
512 X. Bai, M. Baker, *et al.*, “Calibration and characterization of the icecube photomultiplier tube,”
513 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers,*
514 *Detectors and Associated Equipment*, vol. 618, no. 1-3, pp. 139–152, 2010.
- 515 [7] Hamamatsu, “Datasheet,” URL: <https://www.hamamatsu.com/>, 2018.
- 516 [8] M. Aartsen *et al.*, “The icecube neutrino observatory: Instrumentation and online systems, jinst 12
517 (03)(2017) p03012,” *arXiv preprint arXiv:1612.05093*, pp. 1748–0221.
- 518 [9] R. Stokstad, “Design and performance of the icecube electronics,” 2005.
- 519 [10] Hamamatsu, “Resources: Basics and applications,” URL:
520 https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf, 2018.
- 521 [11] Hamamatsu, “Handbook resources, chapter 4,” URL:
522 https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE-Chapter4.pdf, 2018.
- 523 [12] J. Brack, B. Delgado, J. Dhooghe, J. Felde, B. Gookin, S. Grullon, J. Klein, R. Knapik, A. LaTorre,
524 S. Seibert, *et al.*, “Characterization of the hamamatsu r11780 12 in. photomultiplier tube,” *Nuclear*
525 *Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and*
526 *Associated Equipment*, vol. 712, pp. 162–173, 2013.
- 527 [13] E. Calvo, M. Cerrada, C. Fernández-Bedoya, I. Gil-Botella, C. Palomares, I. Rodríguez, F. Toral, and
528 A. Verdugo, “Characterization of large-area photomultipliers under low magnetic fields: Design and
529 performance of the magnetic shielding for the double chooz neutrino experiment,” *Nuclear*
530 *Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and*
531 *Associated Equipment*, vol. 621, no. 1-3, pp. 222–230, 2010.
- 532 [14] F. Kaether and C. Langbrandtner, “Transit time and charge correlations of single photoelectron events
533 in r7081 photomultiplier tubes,” *Journal of Instrumentation*, vol. 7, no. 09, p. P09002, 2012.
- 534 [15] B. Lubsandorzhev, P. Pokhil, R. Vasiljev, and A. Wright, “Studies of prepulses and late pulses in the
535 8" electron tubes series of photomultipliers,” *Nuclear Instruments and Methods in Physics Research*
536 *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 442, no. 1-3,
537 pp. 452–458, 2000.

- 538 [16] K. Ma, W. Kang, J. Ahn, S. Choi, Y. Choi, M. Hwang, J. Jang, E. Jeon, K. Joo, H. Kim, *et al.*, “Time
539 and amplitude of afterpulse measured with a large size photomultiplier tube,” *Nuclear Instruments
540 and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated
541 Equipment*, vol. 629, no. 1, pp. 93–100, 2011.
- 542 [17] S. Torre, T. Antonioli, and P. Benetti, “Study of afterpulse effects in photomultipliers,” *Review of
543 scientific instruments*, vol. 54, no. 12, pp. 1777–1780, 1983.
- 544 [18] M. Aartsen, K. Abraham, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens, D. Altmann,
545 T. Anderson, M. Archinger, *et al.*, “Characterization of the atmospheric muon flux in icecube,”
546 *Astroparticle physics*, vol. 78, pp. 1–27, 2016.
- 547 [19] M. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, D. Altmann,
548 J. Auffenberg, X. Bai, *et al.*, “Measurement of south pole ice transparency with the icecube led
549 calibration system,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
550 Spectrometers, Detectors and Associated Equipment*, vol. 711, pp. 73–89, 2013.
- 551 [20] M. Aartsen, R. Abbasi, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, D. Altmann, C. Arguelles,
552 J. Auffenberg, X. Bai, *et al.*, “Energy reconstruction methods in the icecube neutrino telescope,”
553 *Journal of Instrumentation*, vol. 9, no. 03, p. P03009, 2014.
- 554 [21] R. Dossi, A. Ianni, G. Ranucci, and O. J. Smirnov, “Methods for precise photoelectron counting with
555 photomultipliers,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
556 Spectrometers, Detectors and Associated Equipment*, vol. 451, no. 3, pp. 623–637, 2000.
- 557 [22] M. Aartsen, K. Abraham, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens, D. Altmann,
558 K. Andeen, T. Anderson, *et al.*, “Searches for sterile neutrinos with the icecube detector,” *Physical
559 review letters*, vol. 117, no. 7, p. 071801, 2016.